An investigation into the wear characteristics of bandsaw blades and their influence on the sawing rates and costs of bandsaw operations.

TAYLOR, Robert W.

AN INVESTIGATION INTO THE WEAR CHARACTERISTICS OF BANDSAW BLADES AND THEIR INFLUENCE ON THE SAWING RATES AND COSTS OF BANDSAW OPERATIONS

By

ROBERT WILLIAM TAYLOR

A Dissertation Submitted To The Council For National Academic Awards For The Degree Of

MASTER OF PHILOSOPHY

Department Of Mechanical And Production Engineering
Sheffield City Polytechnic

December 1976

CONTENTS

ABSTRACT

The work includes summaries of the mechanics of wear in sliding systems under light loading, and severe wear mechanisms under metal cutting conditions. Applications of different wear mechanisms to cutting tool wear, and the problems associated with defining cutting tool life and failure criteria are discussed.

Applications of dimensional analysis to the metal cutting problem are presented and include sections on: tool temperature, tool life / cutting speed relationships, tool life / temperature and temperature / time relationships, Colding's three dimensional tool life equation and an analysis of the Taylor constant.

The development of empirical cutting tool life equations is reviewed and includes Taylor type relationships, equations based on the concept of the chip equivalent and Colding's tool life equation. The effects of cutting conditions, tool geometry, tool material and workpiece material on cutting tool life are considered.

The fundamentals of sawing are outlined and the variations of modern power hacksaw and bandsaw machines discussed. This section includes a description of modern saw blades and saw blade nomenclature.

A comprehensive review of previous work carried out on both the power hacksaw and bandsaw operations shows the present state of

knowledge in this field.

The experimental work based on an adaptation of Colding's three dimensional tool life equation forms the first thorough investigation of bandsaw blade wear and its effects on cutting rates and economics. Relationships between the wear rate of the band and relevant parameters such as band speed, machine load and geometry of the workpiece are shown. Wear rate and cutting rate have been expressed in terms of a cutting constant, which defines the penetration of the teeth and its decay with use. A computer based simulation of the bandsaw operation has been developed and used to investigate the influence of relevant engineering parameters on productivity and cutting economics. The data obtained from the simulation model has been used to determine cutting rates and costs of bandsaw operations using constant feed rate and constant thrust load principles. The data is based on tests carried out on workpiece material classified as difficult to cut and trends obtained are believed to be typical of those that would be obtained when cutting the more common materials. For the first time, direct comparisons are made between carbon blades and high speed steel bi-metal blades under various bandsaw conditions, and the bandsaw and power hacksaw operations are directly compared.

The investigation results in the following conclusions. The bandsaw operation may be a low cost, high cutting rate operation when high speed steel bi-metal blades are used under optimised operating conditions. High speed steel bi-metal blades should be preferred to carbon. A bandsaw machine operating with constant feed rate is superior to one operating with a constant thrust load system. A reduction in the total cost per cut can usually be obtained by optimising feed rates at the expense of blade life. The bandsaw operation can be as economical as the power hacksaw operation whilst achieving a higher cutting rate.

ACKNOWLEDGEMENTS

The author wishes to express his sincere appreciation to his First Supervisor and Director of Studies, Mr. P. J. Thompson BSc. MSc. CEng. MIMechE. MIProdE., Principal Lecturer in Production Technology, Sheffield City Polytechnic.

He would also like to thank the authorities at Sheffield City Polytechnic for permission to undertake the work.

Particular thanks are due to Mr. D. Taylor A.I.M. Manager of Technical Services, James Neill (Services) Ltd., and to his staff for their assistance and helpful advice.

Finally, the author expresses his gratitude to Mr. Stuart Leigh for his help with modifications to the bandsaw machine.

LIST OF SYMBOLS

a material constant for a particular blade type (64)

a half the width of the blade (122)

a constant

a intercept (171)

a-i exponents in dimensional analysis

a' wear index (144)

A constant (2)

A chip cross-sectional area (7)

A cross-sectional area of the workpiece (142)

A average cutting rate for bandsaw (198)

Ar proportion of the cross sectional area of the workpiece cut through per band revolution (196)

As proportion of the cross sectional area of the workpiece cut through per stroke of the saw (142)

b width of cut (2)

b Colding's wear index (33)

b exponent at tool life T (61)

b material constant for a particular blade type (64)

b half blade thickness (122)

b constant

b' wear index (144)

b_{1-3} specific values of Colding's wear index (195)

B Colding's wear index (33)

B breadth of the workpiece

B'	reciprocal of the instantaneous workpiece breadth
Bc	critical breadth, for workpiece breadths greater than this value the cutting constant remains constant (148)
c	distance to the workpiece from the end fixing device (123)
c	wear index (162)
C	mean height of a wear particle (1)
C	constant (47)
C	material constant for a particular blade type (65)
C	Colding's constant (102)
C	cost per section cut (147)
C'	wear constant (111)
C''	wear constant (112)
C_1	constant, not defined (17)
C_1	constant (43)
C_2	constant in equation derived from dimensional analysis (19)
C_2	constant (44)
C_3	constant (49)
C_B	cost of a blade (147)
C_B	cost of a band (199)
C_c	cost per section cut by bandsaw (199)
C_R	cost rate per hour (147,199)
C_T	"Taylor" constant in the tool life - speed relationship (23)
C_T	constant at tool life T (61)
C_{oo}	intercept when $\Pi_4 = 1.0$ (38)

d depth of cut (43)

d distance from the centre of rotation of the blade to the cutting edge (124)

d wear index (162)

D depth of a rectangular workpiece

D_o diameter of the workpiece = $2R_o$ (156)

E modulus of elasticity

E electromotive force generated in the chip-tool interface (58)

f instantaneous thrust force per unit thickness per tooth (79)

f' the component of the thrust force per tooth due solely to the cutting edge radius (172)

fa average instantaneous thrust force per unit thickness per tooth (91)

fi tooth loading per unit thickness (84)

fm mean thrust load per tooth per unit thickness (63)

f'a the average value of the component of the thrust force per tooth due solely to the cutting edge radius (182)

f(.) function of (.) (10)

F instantaneous thrust load after a small blade displacement from the beginning of the cutting stroke (75,141)

F total instantaneous thrust load acting between workpiece and saw blade (97)

Fm mean total thrust load (75)

Fm mean thrust load acting between workpiece and saw blade during one cutting stroke of a power hacksaw (98,143)

F_L lateral (horizontal) component of the cutting force acting on the workpiece (135)

F_T thrust (vertical) component of the cutting force acting on the workpiece (135)

$g-g_1$ constant in Woxen's tool life equation (51,53)

G modulus of rigidity (122)

G slenderness ratio (depth of cut / feed) (46)

Gs constant in Woxen's tool life equation (52)

G_T constant in Woxen's tool life equation (50)

h volumetric specific heat of work material (6)

H consolidated heat value (15)

H peak-to-valley height of the ridges in the cut surface (137)

i tooth number taken from the tooth just beginning to cut (84)

I second moment of area of the cross section of the blade (123)

j exponent in V_T-q relationship (54)

J constant in V_T-q relationship (54)

k plane strain yield shear stress = $\sigma_0/\sqrt{3}$ (82)

k_1 diffusion rate constant (4)

ks unit cutting force for any chip cross-sectional area (6)

K constant (1,3)

K thermal diffusivity in Colding's equation (28,56)
(of workpiece)

K cutting constant (63)

K' constant (60)

K_1 factor dependent on the size and geometry of the contacting interface and its asperities (4)

Ka average cutting constant (154,179)

$\dot{K}a$ rate of change of the average cutting constant (161)

Kc cutting constant obtained at large workpiece breadths (148)

Ke effective cutting constant (103)

$\dot{K}e$ rate of change of the cutting constant (104)

Ko cutting constant for an un-worn blade (103,144)

Ko cutting constant for an un-worn band (190)

Ks Kronenberg's straightening factor (40)

K_T thermal diffusivity at tool life T (61)

$(Ka)_1$ cutting constant at the beginning of a cut (164)

$(Ka)_m$ mean cutting constant (164)

$(Ka)_o$ average cutting constant for an un-worn blade (161)

l effective length of the blade = L-B (122)

L length cut (5)

L free length of the blade (122)

L length of the band loop (187)

m temperature exponent in dimensional analysis (24)

m number of set patterns in contact with the workpiece (116)

m' constant (60)

max maximum value

M constant in the V-T-q relationship dependent on tool / work materials (55)

M cutting constant for a fully established chip (79)

M number of sections cut off during the useful life of the blade (146)

n mean number of contacting junctions per linear distance (1)

n slope of temperature-time relationship (38)

n Taylor's tool life exponent (39,52,60)

n cutting force index (79)

n number of cutting strokes (103)

$n-n_1$ constant (41,42)

n_1 exponent of tool life (23)

n_2 constant (48)

n_c number of teeth in contact with the workpiece (65)

n_t number of teeth having a partly formed deformation zone (84)

n_{max} blade life in terms of the number of cutting strokes (103)

N normal load on the surface (1)

N number of cutting strokes needed to cut through a rectangular workpiece (71,145)

N number of band revolutions (197)

Nc number of teeth making contact with the workpiece during a cutting stroke (72)

Ne the equivalent number of teeth to make one complete traverse of the workpiece (73)

N_s number of cutting strokes to cut through a workpiece (153)

p	number of teeth per unit length (64)
P	thrust component of the cutting force acting on the blade (135)
q	chip equivalent (28)
q_a	average chip equivalent per band revolution (179)
q_o	constant in Woxen's tool life equation (50)
Q	lateral component of the cutting force acting on the blade (116)
Q'	force acting lateral to the cutting edge due to blade distortion (121)
r	nose radius of cutting tool (43)
R	contact time ratio = Tc / T (105)
R	contact time ratio = B / L (187)
R	component of the cutting force acting normal to the cutting edge (114)
Ra	arithmetical mean deviation roughness number (139)
Rc	average cutting rate (146)
Ro	workpiece radius (155)
R_A	component of the cutting force acting normal to the cutting edge for a tooth in line with the blade (115)
R_B	component of the cutting force acting normal to the cutting edge for a set tooth having an inferior cutting edge and a large setting angle (115)
R_C	component of the cutting force acting normal to the cutting edge for a set tooth having a superior cutting edge and a small setting angle (115)

S	feed rate (inches per revolution) (43)
S	stroke of the saw (67)
S	blade tension force (122)
S_b	lateral blade stiffness (121)
S_s	shear strength (14)
S_t	torsional blade stiffness (121)
t	thickness of the blade (66)
t_1	depth of cut in two-dimensional representation (14)
T	tool life (min) (15,52)
T	time (141,186)
Tc	blade life in terms of the actual time a tooth is in contact with the workpiece (102,187)
Tc	cutting time (152)
Te	temperature at tool-chip interface (6)
T_B	time to change the blade (min) (146,198)
T_L	tool life (min) (35)
T_L	time to index the workpiece between consecutive cuts (min) (146,198)
T_X	arbitrary constant in Woxen's tool life equation (52)
U	constant (33)
U	blade tension constant $= \frac{1}{2}\sqrt{\frac{S}{EI}}$ (123)
$\dot{vol}$	rate of volume removed (95)
$(vol)_c$	workpiece volume removed during a cut = A.w (154)
$(vol)_s$	volume of material removed during one cutting stroke (67)

V	cutting speed
V	cutting speed of a bandsaw blade (95,174)
Vm	mean cutting speed during the cutting stroke (109)
w	wear land (2,3,5)
w	width of the slot produced
W	wear volume per unit distance of sliding (1,2)
W	wear volume per unit time (4)
W	thermal conductivity of work material (6)
x	exponent dependent on tool material (62)
$\dot{x}$	small displacement of the blade (66)
y	length of cut made by a tooth (79)
y	lateral displacement of the cutting edge (124)
y'	lateral displacement of the blade due to bending (121)
y_c	critical length of cut made by a tooth to fully establish a deformation zone (79)
y_o	initial value of the lateral displacement of the cutting edge (124)
z	exponent of the chip cross sectional area (44)
z	thickness ratio = w / t (74)
Z	time, indicating continuous cutting (36)

α diffusivity (102)

α angle between the direction of cutting and the mean plane of cutting i.e. the 'run-out' angle (128)

α_o initial value of the angle between the direction of cutting and the mean plane of cutting (130)

α_1, α_2 functions

β setting angle (115)

β cost factor = C / C_B

γ cost ratio = C_R / C_B

δ instantaneous depth of cut achieved per tooth (66)

δ_a average depth of cut per tooth (63)

δ_u undeformed chip thickness (114)

Δ slot depth

Δ_c slot depth when the instantaneous breadth is B_c (155)

Δs increase of the slot depth produced per cutting stroke (70)

Δ_1, Δ_2 particular values of slot depth (151)

$\Delta(vol)$ volume of material removed during a small blade displacement (66)

ΔK variance in the cutting constant (115)

ΔK change in the cutting constant per band revolution (185)

ΔKe change in the effective cutting constant per stroke of the saw (144)

$\Delta\beta$ variance in the setting angle (115)

ε quick return factor

η fractional reduction in K_o at the chosen end point of the wear test (103)

θ	temperature (14)
θ	angular position of the blade (121)
θ	angle (156)
θ_C	angle when the instantaneous breadth is B_c (156)
θ_E	angular position of the blade due to clamping error (121)
λ	friction angle = $\tan^{-1}\mu_A$
μ_A	apparent coefficient of friction
υ	cutting rate achieved during a bandsaw operation i.e. distance cut per unit time (96)
υ	distance cut per unit time (141)
$\Pi_1 - \Pi_8$	dimensionless quantities in dimensional analysis (6)
σ_o	flow stress of the workpiece material at large strains (82)
σ_y	yield or flow stress for the weaker material in contact (1)
ϕ	shear plane angle (81)
ϕ	number of cutting strokes per unit time (104,153)
ϕ	angle between the direction of cutting and centre line of the blades cross section (115)
ϕ	band revolutions per minute (186)
ϕ_o	initial value of the angle between the direction of cutting and the centre line of the blades cross section
ψ	chip factor (88)
ψ'	reciprocal of the chip factor
ψ_1	geometric factor = f(a,b) (122)
ψ_2 & ψ_4	workpiece position factor = f(c / l) (122,123)
ψ_3	blade tension factor = f(Ū) (123)
ω	angle to which the cut is out-of-square

1 GENERAL INTRODUCTION

More manufactured products begin life with a cut-off operation than with any other machining method. The cut-off operation is frequently the first of a long sequence of operations and although frequently neglected needs, as a constituent operation in the manufacturing cycle, to be considered and optimized in the same way as other production processes.

Sawing is the most widely used method in performing the cut-off function. Sawing machines that accomplish this function include bandsaws, hacksaws and circular saws. Different machines cut with different rates, material losses, surface finish, safety, ease of handling, power consumption, etc. So the choice of a means of cut-off can be a complex one, and to complicate the choice, there are non-sawing techniques available. Whereas all sawing involves the cutting action of a series of small teeth, other basic machining methods can be adapted so that essentially the same job can be accomplished.

This investigation is concerned with the wear characteristics of bandsaw blades and is based, mainly on previous work that has been carried out on the power hacksaw process; particular attention will be directed to these two processes in this introduction. However, the introduction also reviews the processes of circular sawing; high-speed sawing; friction sawing and slicing with knife-edge bands along with some of the techniques that cannot be classified as sawing, but, nevertheless are used to cut-off metal and other materials. These include: single point cut-off on a lathe; shearing; abrasive cut-off; electric-discharge and electro-chemical cut-off. It is felt that the following process reviews will help the reader to recognise their potential use as alternatives to the more wide-spread methods of band and hacksawing.

1.1 ALTERNATIVE METHODS OF CUT-OFF

1.1.1 Single Point Cut-Off

The primary metalworking tool is the lathe, and single point cut-off is one of the basic methods of parting stock.

Traditionally, lathe cut-off tools are thin and flat, and take a necking-down cut. When the cut starts on the outside diameter of the workpiece, cutting can be just as effective as normal turning, with high speed, good feed rate, good chip characteristics, and good surface finish. As the tool tip approaches the centre of the work though, conditions get more severe.

The first thing that happens is loss of surface speed; that is the speed of the work relative to the tool tip, due to a decrease in diameter. If good characteristics depend on high surface speed, the tool is likely to be affected by forces and pressures beyond its design limits. Tool-design problems include the tendency to jam in a tight neck (because of design or overheating), to wander or flex, or to cut under or over centre. These problems intensify as the tool feed nears the centre of the workpiece.

Solutions to these problems might include variable speed drive units. But short of that, there are three important rules to follow. First, the support to the tool must be as firm and solid as possible. Second, the overhang of the tool must be kept to a minimum to reduce deflection of the tip. Finally, the tool shape must be strong; front relief should be as little as possible to prevent rubbing and friction-heat build-up.

Single point cut-off operations embody another problem in that the tool actually parts the material continuously until breakthrough, but unless there is an automatic pick-off mechanism or some kind of outboard support to keep the workpiece from moving away from the plane of cutting, the piece will flex and damage the tool.

Special purpose cut-off lathes are available; these machines typically spin tube stock at up to 1000 revolutions per minute, and cut-off either with single point tools or with circular blades mounted on the front slide.

1.1.2 Shearing

Shearing is a general name for most sheet metal cutting, but in a specific sense, it designates a cut in a straight line completely across strip, sheet, or bar. Good shearing depends on four factors: blade rake, clearance, sharpness and machine adjustment.

Bar shears are available in two general types: guillotine, with blade support at both ends; and open-end machines. Open-end bar shears are usually fitted with straight blades, but can have 'V'-notched or cut out blades. Guillotine shears often have a set of blades of various shapes, all on the same lever to allow easy feeding.

Most tube shears work with a 'V'-shaped blade that punches through the top wall, shears down the sides, and punches out the bottom of the tube, all in a continuous stroke. However, this action usually causes a nick to be produced in the end of the tube.

1.1.3 Abrasive Cut-Off

1.1.3.1 Abrasive Disc

This type of operation is fundamentaly that of the grinding process. An abrasive cut-off disc is a thin grinding wheel with thickness no more than 1/48 the diameter.

The process is extremely fast. Typical cut-off times are 5 seconds for a 25.4mm. diameter high speed steel round and 2 seconds for a 38.1mm. diameter brass pipe. Cutting times depend on wheel size, surface speed and machine horse power.

Normal grinding precautions are essential because the wheel speed of abrasive cut-off units is very high. Most wheels are marked by the manufacturer to indicate maximum operating revolutions per minute, and this statistic should be taken very seriously. At recommended speed, a cut-off wheel has high radial strength, and there is a reasonable safety margin left to keep down the danger from shock and vibration induced wheel break up. If a wheel is run at a higher speed, most or all of its strength may be taken up by centrifugal force, and even the least amount of shock incurred when the blade enters the workpiece could cause wheel shatter. Modern abrasive cut-off machines are well guarded, and wheels have reserve strength, so the method is not particularly hazardous.

The speed with which material can be cut off with abrasive methods has its drawbacks. In a mechanical sense, one of these is power. Machines with 37, 75 and 102kW. driving motors are not uncommon. Replacement wheels are also a factor to consider. While the initial cost of an abrasive machine is often far less than that of a sawing unit with similar capacity, annual abrasive-wheel costs can occasionally exceed the cost of the machine itself.

Considerable amounts of cut-off work is done with small portable power machines, which usually are provided with reinforced resinoid-bonded wheels for dry cutting.

For high volume production, cut-off is done on large machines with special coolant systems and complex materials handling systems. For these big machines, water or water based emulsions are used as normal coolants, and they are applied to both sides of the wheel through piping systems. Larger machines may incorporate oscillators to help the abrasive wheel feed into the workpiece.

1.1.3.2 Cutting With Diamond-Edge Bands

When you have to cut super hard or friable materials, a diamond-edge saw band can accomplish tremendous feats. These bands have a uniformly high concentration of industrial diamonds fused to the cutting edge by a special process that prevents chipping or peeling as the band flexes over the saw band carrier wheels of a high speed band machine. They are designed especially for straight or contour cutting of abrasive plastics, ceramics, epoxy, fibre glass, granite, hard carbons, glass, silicon, germanium, barium titanate and many other extensively used materials.

Diamond-edge saw bands operate at an optimum velocity of between 10 and 15m/s., hence the necessity of a high speed band machine, they make cut-offs in heavy sections that would be impossible by any other method. A diamond-edge saw band will cut through fibre glass at a rate of $1\text{-}1.6 cm^2/s.$, hard carbons at a rate of $0.86\text{-}1.7 cm^2/s.$ and glass at a rate of $0.2\text{-}1.6 cm^2/s.$

Although it is possible to perform dry diamond band sawing, it is usually carried out with flood coolant because the abrasive cutting edges of this type of band tool generate tremendous heat. The coolant flushes the cutting edges keeping them clean and cool.

1.1.3.3 Cut-Off With Abrasive Coated Wire

This process was used by the Egyptians to cut (2½ TONS) 2540 kg. stone blocks for the Pyramids.

A wire or similarly flexible tool is drawn back and forth (or in a continuous motion) across the workpiece, and an abrasive agent is sprinkled into the cut or bonded to the wire. The technique has come a long way; wire-sawing machines were recently used to cut precious Moon rocks, with an absolute minimum of material loss. Todays sawing wires are diamond encrusted (similar to the diamond-edge saw band) enabling them to cut any material, regardless of hardness. Since the diamond abrasive material is uniformly bonded around the entire circumference of the wire, very precise contouring can be achieved.

It is this combination of cutting and contouring capability that makes diamond-encrusted wire saws particularly useful in cutting carbides. In the unsintered (green) state, carbides can be cut off at a rate of $.43cm^2$ /s. Even when the technique is used on sintered carbides, the resulting finish is often so good that additional grinding is unnecessary. Surface finish is a factor of wire tension, since the higher the tension on a wire, the straighter it becomes, with improved cut and surface finish. Latest sawing wires, made of heat treatable alloys which are coated with copper to improve diamond bonding, have tensile strengths of over $3.4kN/mm^2$. This results in a 0.02mm. diameter wire that can be operated at a tension of 3.49kg.

1.1.3.4 Line Grinding

Line grinding is a band machining process. Line grinding bands are similar to diamond-edge saw bands but are less expensive. They have an abrasive cutting edge bonded to the steel band in a continuous coating. There are two kinds of coating available: those coated with silicon carbide grind ceramic, glass, quartz, marble, granite and vitrified materials. Those coated with aluminium oxide are best for grinding metals, especially heat treated alloy steels, heat resistant steels, wear resistant non-ferrous alloys and other 'non-machinables'.

Line grinding bands have extremely long fatigue life, and their continuous abrasive action quickly removes hardened material.

They produce a clean, smooth finish and the only limit to their working depth is the capacity of the band machine.

The abrasive cutting action of line grinding bands generates high temperatures, just as diamond-edge bands do. Therefore, the coolant application is the same as for diamond-edge sawing. Band speeds between 15-25m /s. are best for most kinds of line grinding. To sharpen the abrasives on the band you can dress it before starting the cut by moving a diamond dressing stick lightly back and forth over the cutting edge while running the band. A clean smooth running band will grind efficiently, with a minimum of heat and wear when light feeding forces are used.

1.1.4 Electro-Cut-Off Methods

1.1.4.1 Electro-Discharge Band Machining

One of the newest and most unique of all band machining methods is the electric-discharge process. For machining such materials as aluminium, stainless steel and titanium honeycomb as well as other fragile, cellular structures made of metal foil, thin wall tubing or a combination of the two, its use is steadily increasing.

The principle of electric-discharge band machining is known as quenched arc cutting. A low voltage, high amperage current is fed into a knife type band at a rate that causes it to discharge a sustained arc off the knife edge into the material being cut. At the same time a flood of coolant limits, or 'quenches' the arc to prevent it from burning the surrounding work material. The arc literally disintegrates the material but the band never touches it. With all the factors properly balanced, the resulting finish is burr free and equivalent to that produced by electrolytic grinding.

Cutting rates are relatively high. For work requiring fine finish, 0.5-5.4cm^2 /s. are common. Since the electric arc makes the actual 'cut', neither the work nor the band tool experiences the kind of stresses that occur in sawing, grinding or milling. Therefore, fixturing, or clamping devices need only be strong enough to hold the workpiece in place so its own weight does not deflect it. Hand feeding is impractical, therefore all electric-discharge band machines have power feed worktables.

1.1.4.2 Electrolytic Cutting

For this process a metal or graphite wheel with abrasive particles is used. The wheel and spindle are insulated from the rest of the machine and current is passed from the wheel to the workpiece. Actual contact of the wheel and work is prevented by the insulating abrasive particles which protrude from the surface of the wheel and leave a gap into which a stream of electrolyte is directed. The workpiece is fed into the wheel, and some metal is removed abrasively but about 90per cent by electrolytic action.

The process can be used as a cut-off operation with metal bonded diamond wheels for cutting carbide tools, while the introduction of carbon bonded solid abrasive wheels has extended its scope to stainless and hardened steels.

1.1.5 Friction Sawing

Friction sawing is literally what the name implies: cutting by friction.

This technique uses either a solid, large diameter circular blade rotating at high speed or a bandsaw moving at anywhere between 20-76m /s., to create friction instead of chips. Friction heats the workpiece to a point between red heat and its melting point. With the material in this condition, the weakened surface can no longer resist the sliding action of the blade and the material is literally wiped away.

Oxygen carried in the gullets between the blade teeth causes the blade to burn its way through the work. The resulting action is similar to that of a cutting torch, although many materials that cannot be flame cut may be friction cut. But not all materials can be cut with friction. The process works well on steel and iron, but not so well on such non-ferrous metals as aluminium, brass and magnesium. Some plastics; the thermosetting type filled with hard materials such as glass and mica, can be succesfully friction cut;

thermoplastics, of course, cannot.

Even though friction sawing generates tremendous heat, it is confined to a small area immediately ahead of the saw band, and to a small extent, to the sides of the teeth set. Since the ferrous metals which lend themselves to friction sawing are poor heat conductors, the heat penetration into the sides of the cut is quite shallow. The extent of this heat penetration depends upon the thermal conductivity of the metal being cut, but it seldom is more than 0.005mm.

In contrast with the temperature at the point of cut, the saw band remains relatively cool. The reason is that the band is long and any tooth or portion of it is only in momentary contact with the workpiece. In its long journey around the saw band carrier wheels each tooth has ample time to cool before it again engages the work.

A limiting factor to the process is workpiece thickness. Because high pressures between the saw band and the work must be maintained to generate the heat required, friction sawing is practical for only workpieces 25.4mm. or less in thickness.

Because friction sawing softens and removes material just ahead of the saw band by creating frictional heat, tooth sharpness is not as critical a factor as it is in conventional sawing. In fact, the heavy feeding pressure and fast band speed required to produce the frictional heat require dull teeth. This dullness actually makes the teeth more efficient heat generators because a blunt surface produces greater friction than a sharp one. A low carbon, flexible friction cutting blade is better than a very hard one since it is less likely to crack from flexing over the drive wheels. Because the blade is moving fast, coarser tooth pitches can be used on thin materials than in conventional sawing, with little danger of tearing out teeth.

Blade life is determined more by set, or blade waviness, than by tooth sharpness. When the set has been worn off the blade will still friction cut, but it is difficult to guide it accurately. Special friction-cutting bandsaw blades are available with increased set to minimize this problem.

Friction cutting can also be done on circular sawing machines as long as surface speed is fast enough. Most circular friction machines, however, are specialized pieces of equipment and have very high power, accurate speed control and a high pressure water pump for blade cooling.

Although convection air currents set up by the blade rotation do help in cooling the blade, this often is not enough. Compared with a friction-cutting bandsaw blade, a circular blade has much more metal, and therefore retains heat better.

While heat is the cutting force in circular friction sawing, it is also a limiting factor, especially in cutting heavy stock. Heat increases directly as the length of contact between the workpiece and the blade increases. This contact arc can be controlled somewhat by the saw arrangement. A downstroke machine, most often used for cutting bar, rod, angle and similar stock, is set up for the most efficient friction cutting with the contact arc between the blade and work nearly horizontal. On square or rectangular section, the arc length can only be as long as the workpiece is wide. Pivot-stroke machines and horizontal feed units lengthen the arc as the circular blade cuts diagonally through the stock.

1.1.6 High Speed Band Sawing

High speed sawing is a term referring to the speed of the saw band as it cuts the work. The normal range of band speeds embraced by this term is 10-30m /s. High speed sawing should not be confused with friction sawing previously discussed. True, friction sawing requires extremely high band speeds; higher actually than the high speed sawing application. But in friction sawing you use high band speeds to generate enough heat in ferrous metals to remove the metal in semi-molten form. In high speed sawing you use high band speeds to saw a wide range of materials faster. High speed sawing, in fact, occupies a position between the normal band machining of ferrous materials, which must be sawn at low band speeds, and friction sawing, which requires the fastest band speeds.

Materials which lend themselves to high speed band sawing include wood, paper, plastics, rubber, fibrous products and such free-machining non-ferrous metals as aluminium, brass, bronze, zinc and magnesium. These materials may be in bar, sheet, plate, extruded, cast or tube form.

1.1.6.1 Slicing With Knife-Edge Bands

High speed and friction sawing along with conventional sawing all use blades with teeth, whether they be made of carbon alloy or high speed steel. However high speed band machines can be used with knife-type blades that have no cutting teeth.

Knife blades are made especially for cutting soft and fibrous materials that would tear or fray if cut with tooth-type bands. The continuous cutting edge has little downward drag, so no tearing occurs and the finish produced is excellent. These blades are available in three edge forms: knife, wavy and scallop. The knife-edge band comes with either a single or double cutting edge; wavy-edge and scallop-edge bands have double bevel cutting edges.

Since knife-edge bands cut efficiently at relatively high speeds they are made to withstand maximum flexing over the band carrier wheels. They are made of special alloy steels, so they can be precision ground to razor sharpness and hold that sharpness through long usage.

Knife-edge bands slice through, or separate material without providing clearance for the back of the band as in conventional tooth sawing; hence produce no chips, dirt or dust. The kind of knife-edge band used depends upon the nature of the material cut. When cutting loose, fibrous material such as stacked wool cloth, fibre glass insulation or packing materials, the straight knife-edge band works best because there is very little tendency of the material to bind. More compact materials offer increased resistance to cutting; for these materials a wavy-edge band cuts better. With even more compact materials such as stacked cotton cloth, cellulose sponge, and soft paper the scallop-edge band should be preferred.

Knife-edge bands find widespread use in cutting cloth and fabric of all kinds in the furniture and in the garment industry. Dresses, skirts, shirts, suits and many other articles of clothing are regularly cut from patterns by knife-edge bands. Other applications for knife-edge bands include the cutting to length of copper transformer coils wound around a long tube. Soft aluminium corrugated material can be cut using a scallop-edge band and results in a smooth burr-free, high quality finish. Another efficient way to cut this type of material is by electro-discharge band machining which has already been described.

1.1.7 Circular Sawing

Circular sawing was developed in Germany round about 1910. Circular sawing uses a continuous cutting blade with many teeth, which can rotate through a large range of speeds. The process is often called 'cold' sawing which distinguishes it from the kind often seen in foundries, where the workpiece is actually cut hot.

Since circular sawing is done at the fixed periphery of the wheel, machine design is affected. Surface speed at the blades cutting edge varies directly with wheel radius. Cutting speed can thus be changed without an elaborate motor transmission by designing the machine to accept different blade sizes. Nevertheless, most circular sawing machines do offer several spindle speeds, even if they are not designed with the special high speed gearing needed for abrasive disc and friction cut-off applications.

Machines can be built in several basic feed configurations: horizontal, vertical, pivot and variations on these. With vertical feed, the rotating blade travels downward in a straight line to engage the workpiece. Blade feed motion is assisted by gravity, and the workpiece can be positioned directly beneath the centre line of the saw blade for optimum cutting accuracy and minimum vibration. Some vertical feed machines push a table-recessed blade up into the workpiece.

Other machines are designed for horizontal feed. The blade here is pushed into the workpiece from the side. Variations on basic horizontal feed units include specialized plate cutting saws which traverse the blade along the length of plate. A third basic feeding configuration is pivot motion where the blade is fed through an arc from a pivot point like a chopping motion. The pivot feed motion can sometimes be manually fed, but air or hydraulic feed is used on almost all other machines.

The deeper a sawing blade penetrates into the workpiece the greater its tendency to jam in the cut. Teeth in a circular blade get their rigidity from the entire blade and, in many operations, most of the blade body follows the teeth into the cut. This means that a circular blade must cut a wider slot into the workpiece than other types of blades to prevent jamming. In a typical operation, a bandsaw might need a 1.52-3.175mm. slot width to prevent jamming; the same cut-off operation on a circular saw might need a slot width of 6.35mm. This additional material loss may be of some significance, depending on specific cases. To allow for blade clearance a parabolic cross-sectional geometry is used in solid steel blades; in carbide tipped blades, the cutting tips are wider than the straight sided body. Both these designs increase the radial side clearance of the body for free cutting into the workpiece.

Two different types of tooth patterns are common in large circular saws: alternate-bevel patterns and high-low patterns. Alternate -bevel tooth patterns use an adjoining pair of teeth to cut the clearance. Both teeth in the pair are the same height, and each has a side bevel: one left, one right. The first tooth removes a chip out of one side of the cut, the next tooth cuts material from the other side.

In the high-low pattern, the first tooth is high and chamfered (usually to a 45degree angle) on both sides. This tooth removes material from the centre section of the cut. The following tooth is lower than the first (between 0.254-0.508mm. lower) and it opens up the cut removing material from both sides of the slot made by the preceding tooth. Each pair of teeth produces three cutting chips: for this reason the pattern is alternatively known as the 'triple-chip' method. This method places the greatest possible chip load on each tooth. The height difference in each pair of teeth (called lead) is the major determining fact for the blade feed rate into the workpiece: infeed should never exceed lead.

Other considerations in the tooth design are back clearance angles, rake angles, and pitches for different materials. Increased side clearance and back clearance angles allow more room for chip removal. Greater clearance will reduce the tendency to load the saw, and thus will increase saw life. However, too much clearance will reduce tooth strength. A high rake angle reduces cutting forces, but also reduces the strength of the tooth.

Circular saw blades are available in segmented styles, thus greatly reducing replacement costs, should teeth be damaged. As another cost saving, cold saw blades are designed to be reground. For instance an 81.28cm. diameter degmented blade from one manufacturer (cost price £225) is designed to be ground (a £17 service not counting freight) until a total of 25.4mm. of radius is removed. Each grinding removes approximately 0.762mm., so about 33 regrinds per blade are possible.

Blade manufacturers often introduce controlled amounts of stress in blades by hammering them. This process is called tensioning, and it is not unlike tensioning a hacksaw or bandsaw blade, in that it helps to hold the blade true under cutting force.

Circular saws are carbide more than any of the other major sawing methods; carbon tool steel and high speed steel are also commonly used. Requirements for a circular saw material include resistance to thermal shock, high hardness and toughness, and the ability to maintain these properties at cutting temperatures. Carbon steel is generally acceptable, but hardness drops at high cutting temperatures. Elevated temperatures are better handled with high speed steel combined with proper use of coolant. Tungsten carbide has the highest hardness and is less sensitive to heat: it is however, sensitive to mechanical shock.

Cooling the circular saw blade / workpiece interface is similar to the cooling used with other sawing methods. It depends largely on speed and type of material being cut. Flood cooling with oil or water-soluble fluids is most often used, but some applications need special methods. One of these is traverse sawing; having a down feed blade travel over a long length of plate. Mist cooling is often used in this situation, and the blade is shrouded in a cover to contain the coolant.

Circular sawing machines, perhaps more than any others, make optimum use of large scale material handling and automatic gauging systems. In fact, many cold saws destined for high volume production situations are sold mostly on the merit of their conveying and material handling systems, with little emphasis on the virtues of the saws themselves. The nature of the circular sawing operation permits automatic gauging to a high degree.

In the simplest type of length gauging, a swing arm and a deadstop are provided. The operator controls vice opening manually, and pushes the material in towards the blade. From this basic configuration, automation can take over virtually the entire operation. In the most highly automated structural fabrication plants, storage tables, acting as magazines, cross feed random length material to automatic input tables which in turn feed the production saw. After gauging and cut-off, the sliced pieces are discharged via conveyors to the next operation. The number of possible variations between the simple hand feed and the totally automated cut-to-length line are almost limitless.

Material clamping and vices, like feeding systems, can range from simple to highly complex. Factors to consider include mitreing capability, double mitreing, slotting capability, how many sides of workpieces can be clamped, the shortest length that can be fully clamped and attachments for bundle cutting.

1.2 POWER HACKSAWING

Power hacksawing is different from bandsawing in that the blade makes a discontinuous cut. A single blade is tensioned in a bow, with pins, while it is drawn back and forth across the workpiece. Cutting is done only during half of the stroke cycle. The blade returns to its starting position on the second half; the return stroke. Another design basic is the construction of the machines frame itself. Older designs use cast iron frames to hold the saw rigid and stable. More modern machines use welded steel frames for higher strength, plus better adaptability. Although cast gear boxes and guideways provide excellent vibration resistance and good lubrication characteristics.

While the basic operating motion of the hacksaw is different from that of other sawing machines, hacksaw teeth can readily be compared to those on a bandsaw blade. Hacksaw blades are constructed of materials similar to those used for bandsaw blades. Blades range in size from 305mm. long, 15.8mm. wide, 0.8mm. thick for small, general duty machines to 135cm. long, 5-18cm. wide and 3.8mm. thick for heavy duty 7.5kW. machines. Power hacksawing is usually done with high speed steel blades. Although high speed steel blades provide the best overall cutting characteristics, they do have a safety drawback. Should a solid high steel blade, fully tensioned in the clamping arrangement, break during cutting, the blade itself will have a tendency to shatter in sharp pieces. The welded-edge hacksaw blade has largely overcome this dangerous problem. In a welded-edge blade, a strip of high speed steel is first welded to the cutting edge of a blade body made of steel alloy. Cutting teeth are then milled into the high speed steel edge. With such bi-metal blades, both heavier feed pressures and higher blade speeds can be used. Bandsaw blades are also available with welded high speed steel cutting edges.

When cutting the hacksaw blade actually curves away from the workpiece because of the heavy forces exerted on it. Some manufacturers design their blades with pin holes closer to the cutting edge, that is, below the vertical centre of the blade. Tension is greater near the teeth, and the rest of the blade absorbs these bowing forces better.

Blades are held in the saw frame by pins through holes; if the pin diameter is much smaller than the hole diameter the ends of the blade may break off. Proper matching of the blade to the machine is very important.

1.2.1 Power Hacksaw Machines

The essential features of a power hacksaw machine are the swing-arm assembly, which carries the saw blade and its bow, a mechanical drive to impart the reciprocating motion to the blade, and a device for developing a thrust load between the blade and workpiece. The machine applies the thrust load during the cutting stroke and lifts the blade clear of the workpiece during the return stroke. A number of different types of machines are available and may be classified by the method used to develop the thrust load.

The operator can control the cutting performance by choice of the blade, the magnitude of the thrust load, and the number of cutting strokes per minute. Power hacksaw machines are used exclusively for cutting-off operations.

1.2.1.1 Gravity Feed Machines

This type of machine develops the thrust load by virtue of the gravity force acting on a massive blade bow and swing-arm assembly. In some machines an adjustable mass is provided on the swing-arm assembly so that the gravity force can be adjusted. While these machines are mechanically simple they are limited in respect of the magnitude of the thrust load which can be generated and, therefore are light duty machines. The magnitude of the thrust load is not constant during the cutting stroke due to the reciprocating movement of the blade bow and the action of the lift-off mechanism.

1.2.1.2 Hydraulic Machines

The thrust load developed by this type of machine is produced by the action of a hydraulic device, the most common of which may be said to operate on a restricted back flow principle [1]. In this type of machine the saw bow is carried in a slideway housed in the swing-arm assembly. This assembly rotates about a fulcrum. The slideway in the swing-arm assembly and the blade clamps on the saw bow are arranged so that a small taper exists between the cutting edge of the blade and the swing-arm slideway. The effect of this taper is such that during the cutting stroke the blade and the swing-arm assembly ride over the workpiece to rotate about the pivot point. This rocking motion is transmitted via mechanical linkage to the piston of a hydraulic cylinder, causing the piston to displace oil through a flow control valve. The back pressure thus created develops pressure in the hydraulic cylinder and causes a torque to develop about the pivot point of the swing-arm assembly. This torque produces the thrust load between the blade and the workpiece. The magnitude of this load is governed by the flow valve setting, deflection of the blade, the cutting performance achieved, and the cutting speed. As the operator only has control over the flow valve setting and the cutting speed, the system is subject to much variation beyond his control. Also, the magnitude of the thrust load varies throughout the cutting stroke, FIGURE 1. reaching a peak value at approximately mid-stroke position. However, this system is common and is capable of developing a large thrust load; hence the use of hydraulic machines for heavy duty applications.

1.2.1.3 Positive Displacement Machines

A few machines are available in which the feed rate of the blade is directly controlled by a mechanical screw device. In this type of machine the blade is indexed into the workpiece by a fixed amount per cutting stroke. Such direct control of the cutting rate is unique to this type of machine. In these machines already described the feed rate is only indirectly controlled by adjustment of the thrust load. The thrust load developed between the blade and the workpiece by a positive displacement machine arises as a result of the depth of cut the blade teeth are forced to make as a result of the positive feed. The magnitude of the thrust load depends on the rate of blade feed, the metal cut, the geometry of the workpiece, and the condition of the blade teeth. Once the teeth become worn the thrust load developed by a given feed rate increases and can increase to such an extent that the blade fractures. This lack of control over the thrust load and the resultant tendency to break blades are the main disadvantages of the positive displacement (feed rate) machine.

1.2.2 Developments In Power Hacksawing

Until the introduction of the horizontal bandsaw for cut-off work, powered hacksaw machines were the heart of cutting off operations. It is not difficult to see why recent advances made in bandsawing machines are now being applied to the hacksaw machine.

These advances include increased capacity and versatility; the use of fully and semi-automatic cycles, and hydraulically raising the saw bow. Some machines have infinitely variable stroke speeds too. Hydraulic systems have been developed to control the downfeed according to the material being cut. Materials handling equipment is being introduced along with accelerated return stroke, to try and upgrade the performance of the power hacksaw machine to that of band machining.

1.3 BANDSAWING

Bandsawing like circular sawing, is a continuous cutting operation. An endless blade (properly called a band) is tensioned between two shrouded, rotating wheels, and a portion of it is exposed to do the cutting. A typical band may be 31.75mm. wide by 1.27mm. thick; the loop length will be as long as the machine design requires. Teeth are on one edge of the band only; as it travels in a continuous motion they feed against the workpiece and chips are milled away. Early bandsaws were limited by the basic design of the moving band.

1.3.1 A Brief History Of The Bandsaw

1.3.1.1 Early Woodcutting Bandsaws

In 1808 Englishman William Newberry patented the bandsaw. This was the first mechanical arrangement to use a saw band that cut in one direction continuously. Newberry experienced difficulty in that band breakage was frequent since no one had yet found a way to make strong, smooth band joints, hence the first bandsaw was not a practical proposition.

The bandsaw was 're-invented' by Lemuel Hedge, an American in 1849 and in 1855, by a Frenchman named Perin. By this time a satisfactory method of brazing metal had been developed so that a steel saw band could run over carrier wheels for a long time without snapping. With these developments the bandsaw became very popular with timber mills because of the smaller slot width produced by the thin bandsaw blade.

Band machines of this type were amongst the most spectacular industrial exhibits at the Chicago Worlds Fair in 1893. By this time all of the basic machine tools (Boring Mill, John Wilkinson, 1775 Bersham England; Screw Cutting Lathe, Henry Maudslay, 1800 London England; Planer, Richard Roberts, 1817 Manchester England; Milling Machine, Eli Whitney, 1818 New Haven Connecticut; Power Feed Press Drill, James Nasmyth, 1840 Manchester England; Grinder circa 1880) except the metal cutting bandsaw had been invented. The invention of the metal cutting bandsaw was still 40 years away, not because of any difficulty in devising a machine for the tool, but because steel makers had not come up with a steel suitable for cutting metal.

Spring tempered steel, which made the first woodcutting bandsaw practical just was not good enough for cutting metal. In 1898 in Philadelphia, Frederick Taylor and Mounsel White perfected a way to heat-treat alloy steels so that they would cut other metal under the severe conditions produced. This was the kind of steel needed for metal cutting, but the process of rolling it into thin strip form suitable for a saw blade was years away.

1.3.1.2 Invention Of The Metal Cutting Bandsaw

Leighton A. Wilkie invented the first practical metal cutting contour bandsaw. Wilkie thought of the increased productivity and reduced cost that would result if he could develop a bandsaw capable of cutting contours in metal with the same efficiency his wood cutting bandsaw cut timber. He adapted a wood saw so that it became more rigid and supplied more power, and built a brazer into the saw frame so he could join the saw blade into a band after passing it through a starting hole in the workpiece when making internal cuts. In 1933 he patented his machine confident he had a metal cutting bandsaw. More experimental and development work produced saw guides that would hold the saw blade rigid at the point of cut and a continuous file band for finishing cuts.

In May 1935 he sold the first band machine built specially to saw and file metal; it was essentialy a bench-type sawing machine mounted on a cast base. Its blade life was limited to cutting an average of only $148cm^2$. of mild steel. Even so the metal cutting industry quickly realised its potential and versatility as the fastest precision method for removing unwanted metal.

1.3.1.3 Improving The Metal Cutting Bandsaw

Since the saw blade must be under great tension to cut metal effectively a high strain on the column which supports the idler wheel is developed. The feeding pressure applied to the workpiece exerts a downward force on the idler wheel and so imparts a further strain on the column support. Since the deflection or vibration in the column is magnified at the point of cutting the importance of a rigid column cannot be exaggerated.

A much more rigid frame was one of the first improvements made to the metal cutting bandsaw. Another vital improvement was the incorporation of a high-low speed pulley system which enabled the operator to select a band speed suitable for the material he was sawing. In 1937 a variable speed pulley replaced the high-low system. In the same year a resistance-type butt welder was developed and replaced the brazer used on earlier machines.

The butt welder makes a much stronger band in the weld area and results in much longer blade life. Butt welding fuses the ends together to form a continuous band of steel of constant thickness. The earlier brazing operation formed a joint by overlapping the ends of the blade, adding solder as a welding agent and then grinding down the overlap. This resulted in a joint much weaker than the rest of the band so the saw guides had to be set to pass this thick part of the band. The rest of the band was not properly supported, and inaccurate sawing resulted. By 1938, developments had progressed to the point where a vertical bandsaw took on the characteristic appearance it still has today.

1.3.1.4 Improvements To Saw Blades

The standard carbon alloy blade which could cut $148cm^2$. of mild steel in 1935, gradually improved until in 1939 it was more than 10 times better and could cut an average of $1935cm^2$. Then in 1953, after many years of testing, research engineers came up with a solid high speed steel saw blade. This was probably the greatest single advance in saw blades since the invention of the metal cutting bandsaw machine.

With its greater hot hardness, tooth tip hardness, resistance to abrasion and tensile strength, high speed steel blades cut up to 10 times faster and lasted 30 times longer than carbon alloy blades under normal conditions and sawing conventional materials.

It could saw from 19000-64000cm^2. of steel and up to 96000cm^2. of non-ferrous metals.

In 1965 the bi-metal blade was introduced. These are composite blades consisting of flexible alloy steel bands electron beam welded to high speed steel strip. The teeth are then cut into the high speed steel strip through to the flexible band so that the finished blade has high speed steel tipped teeth. As the high speed steel cutting edge does not have to be flexible, it can be harder than a conventional solid high speed steel blade. This hardness, coupled with the flexibility and fatigue resistance of the band, is reflected in the life of the band. High speed steel bi-metal blades can cut up to 129000cm^2. of metal at improved cutting rates. A further development of the composite blade is one which has teeth which are made of a cobalt high speed tool steel. This combination is said to offer excellent resistance against wear and abrasion under service conditions which generate high tool temperatures.

1.3.1.5 The Modern Band Machine Evolves

Concurrent with saw blade developments was the improvement of machine design and construction. Development of an improved version of the variable speed drive in 1937 that increased the range of band speeds to 0.25-4m /s. This increased speed made it possible to cut softer materials. The following year continued improvements raised the band speeds to 7.6m /s., further increasing the number of non-ferrous materials the bandsaw could cut. In 1943, the high speed band machine was introduced and it was capable of developing band speeds up to 76m /s. Mechanical drive units that could turn the saw band at higher speeds once again emphasized the need for greater rigidity. Designers had already met the challenge, beginning in 1938, by using an all welded, steel frame construction instead of the three piece, cast iron construction of earlier models. Along with increased band speeds came an increase in the diameter of band carrier wheels to reduce band flex fatigue. The 30.48cm. wheels of the original bandsaw increased to 35.6cm. and then 40.6cm. Today, the size ranges up to 91.4cm.

By the end of the 1940's the development of better saw blades, more rigid construction and higher band speeds had extracted the full capability of machine design. Designers were under pressure to come up with machines of greater built-in potential. The modern power-table band machine supplied the answer. Its added power and hydraulically actuated feeding force provided faster, more accurate sawing and embraced a whole new group of materials that previously could not be band machined efficiently. The first of these power-table machines appeared in 1949 but these prototypes were followed by more sophisticated models in 1953.

As band machines became more widely used, the need arose for machines designed for specialized rather than general work. The big, powerful power-table model was too much machine and too costly to use for making an occasional cut in the machine shop, and the small fixed table machine was incapable of handling production slotting or shaping a 2.74m., 500kg. connecting rod from a solid piece of metal. So manufacturers gradually provided users with a complete range of vertical bandsaws, from the lightweight, low-cost utility machines for intermittent work to the huge band mills and articulated contour machines. They also provided a complete range of horizontal cut-off saws, from the small, light duty models to huge models capable of sawing 60cm. rounds or bars and high speed models especially designed for cut-off production.

1.3.2 Modern Bandsaw Machines

A modern bandsaw machine carries a continuous cutting band, contains a drive which maintains a constant cutting speed, and enables a thrust load to be applied between the band and the workpiece. During cutting the band is applied normally constant. The operator can control the cutting performance by choice of the band, the band speed, and the magnitude of the thrust load. A number of different machines are available and they may be classified according to the orientation of the band and the method used to develop the thrust load.

1.3.2.1 Vertical Band Machines

In this type of machine the band is carried vertically while the workpiece is moved in the horizontal plane. In the most common form of this machine the workpiece is fed over a fixed work table and manually controlled. With this arrangement the thrust load needed to achieve a cutting action is provided by the operator. More sophisticated machines exist in which the workpiece is carried on a power feed table; such machines are capable of automatic control and, like the positive displacement power hacksaw machines, the thrust load developed is governed by the feed rate of the blade. While vertical bandsaw machines can be used for parting-off operations their main use is for cutting intricate shapes in materials in the form of sheet and slab.

1.3.2.2 Horizontal Band Machines

In this type of machine the band is carried horizontally on either a swing arm assembly pivotted at one end, PLATE I, or by means of vertical hydraulic cylinders. Both these have means by which the thrust load can be developed and adjusted. The workpiece, normally in the form of a bar or tube, is held stationary in a clamping vice during actual cutting. Gravity fed machines exist for light duty work in which the thrust load is developed by virtue of the gravity force acting on a massive swing-arm assembly. Other more heavy duty machines are available in which the thrust load is developed and controlled by a hydraulic device. Horizontal band machines, like power hacksaw machines, are used exclusively for cutting-off operations.

1.3.3 Band Machining - A Unique Principle

Band machining has certain advantages over other machining methods. It cuts to shape rapidly, its operation is relatively safe and easy, it saves material and can be a very low cost operation. All these features result from the unique way the band machine removes unwanted material in sections instead of in piles of wasted chips. Producing chips requires a great deal of effort and a method that produces the desired shape with the least production of chips is very efficient. This efficiency provides distinct advantages in that the power required is small. Even more important is the speed with which the operation can be carried out. With band machining, because a minimum amount of material is removed to achieve the desired shape, the job can be rapidly completed.

1.3.3.1 Cutting Forces Aid Workholding

The effort required to make a cut is resisted by the material being cut. When cuts are heavy, massive machines and workholding fixtures are needed. The ease with which the work may be held for band machining not only results from the relatively light cutting force, but also from the unique characteristics of this force. Unlike most other machining methods, the cutting force from band machining is continuous, approximately uniform and acts downward into the table on a vertical machine, or into the vice in the case of a horizontal machine, which helps to hold the workpiece in position. In addition, the force required to feed the work into the band combines with the cutting force to create an even more stable work holding condition.

It is for these reasons that hand guiding of intricate contour cutting on vertical machines is the most practical method. It is impractical to hand hold and guide work on other standard machine tools. On a vertical band machine the operator can devote his attention to following layout lines, making intricate work both fast and accurate. The machine itself can be designed for maximum convenience and versatility since resisting heavy cutting pressure is not the main consideration.

1.3.3.2 The Unique Band Tool

Saws are cutting tools with narrow toothed or abrasive edges. They change the shape of materials by parting them along a pre-determined layout line. The unwanted portions are then removed. In order to exert cutting force, saw blades must be held by a frame; it is this necessity that severely limits the capacity of the power hacksaw, but not the bandsaw. It is the need for a tool holder that restricts all other part-cutting tools such as slitting saws for milling machines and cut-off tools for lathes.

The heavier the cut, the larger the tool must be and, in turn, the more massive the tool holder. The more massive the tool holder, the less freedom there is of cutting parameters such as depth of cut. This limitation applies to the basic cutting tool, the single point cutter, which is indispensable for lathe, shaper and planer work. Another limitation of the single point cutting tool concerns the tooth load, the force exerted by one tooth in order to remove a chip. The maximum tooth load determines the most material that can be removed in a given period of time without causing physical damage to the teeth. If this is not sufficient to bring the work to the desired size and shape, additional cuts with the tool are necessary. With machines such as planers and power hacksaws this requires a reciprocating motion. On the forward stroke the work is partially cut to size and then the tool is idle on the back or return stroke.

1.3.3.3 Reciprocation Is Inefficient

Reciprocating machines, such as the planer, shaper, and power hacksaw are inefficient. One half of the cutting motion is lost in the return stroke. Power is wasted for the deceleration and acceleration at each end of each stroke. The tool is subjected to repeated shocks since the action is discontinuous.

A partial solution was the development of the multiple tooth rotary cutter which can remove more of the unwanted material in fewer passes and still not exceed maximum tooth load. The milling cutter is an obvious example. The more teeth that can be shaped around the cutter, the more uniform the cutting action. Increasing the number of teeth also decreases the tooth size, and this in turn reduces the permissable tooth load. A tremendous number of cutters are therefore needed to take care of the many different materials, types of cuts and levels of production.

These cutting tooth problems are greatly simplified for band tools. For example, consider the relationship between tooth size and number of teeth. By their diameter, milling cutters are restricted in the number of teeth, they can contain. In order to have a large number of teeth, each tooth must be made very small. This reduces chip clearance drastically. In contrast, due to the length of the saw band each tooth in the band can be designed to have ample chip clearance and because the band is long, wear is spread over many cutting edges. Consequently a band tool stays sharp longer and has to be replaced less frequently, thus greatly reducing down time for tool changing.

1.3.3.4 Superior Heat Dissipation

Heat dissipation is another aspect in which band tools are superior. Nearly the entire effort expended in machining is ultimately dissipated as heat. Although most of the heat is removed with the chips, both the tool and the work become heated, and both can be damaged. That is the reason for the development of high speed and carbide cutting tools that hold their hardness at high temperatures. In spite of these improved cutting tool materials and the use of coolants, heat remains a limiting factor in machining.

A single point cutting tool is continuously in contact with the workpiece during the cutting stroke. It is therefore seriously affected by heat build up. In a multi-tooth cutting tool each tooth can cool between passes through the work. In this respect a milling cutter is superior to a single point cutter. A bandsaw blade with its many teeth, no one of which is cutting more than a small percentage of the time, dissipates the cutting heat better than any other cutting tool.

1.3.4 Developments In Bandsawing

Much work has been going on into bandsaw machine design to take full advantage of the developments in blade materials and design. On production bandsawing machines the blade tension is usually applied hydraulically or manually and on some machines full tension is applied during the cutting cycle only, to prevent unnecessary fatigue during idle time. Another advanced feature on machines is some system of monitoring the resistance met by the band during the cut and automatically adjusting the feed pressure accordingly. This being of particular benefit when cutting tubes or sections where the area of contact between the band tool and the work is constantly changing. These and other developments have been applied to both scissor and pillar type bandsaws of varying sizes.

One of the largest available pillar type bar cutting bandsaw is capable of cutting bar up to 104cm. diameter and is constructed on the twin pillar principle but with the sawing head running on rack and pinion guides and mechanically counterbalanced.

Although pillar type bandsaws have a parallel cutting motion which results in consistent square blank cut-off to close tolerances, the scissor type of machine is generally far more popular. There are many such machines on the market offering advanced features, increased capacities and overall improvement in cutting performance. Developments in these machines seem to be concentrated on improved versatility such as automatic swivelling for cutting mitres, semi and full automatic cycles, increased power and improved work clamping. Nearly all modern machines have infinitely variable blade speeds and make good use of hydraulics.

At the Paris machine tool exhibition of 1975 there were several machines on view making use of concrete in their bed and framework. One well known manufacturer in the bandsaw world has developed a construction technique involving concrete for its machines. This concrete construction is supported and reinforced by a strong exterior shell of steel sheet or plate as well as interior reinforcing members. The resulting construction produces components with strength and structural stability characteristics as good or better than those of either iron castings or steel weldments and with 4 times the vibration damping capabilities of either.

1.4 SAW BLADE NOMENCLATURE

While there are obvious differences between hacksaw and bandsaw blades, the geometries of the cutting edges, which primarily control the cutting performance, are very similar. The following are brief discussions on some of the more important geometric factors of the cutting edge of saw blades.

More detailed discussions of these and other properties of saw blades will be found in the relevant publications of the British Standards Institution [2,3]. FIGURE 2., shows the nomenclature of metal cutting saw blades.

Pitch of Teeth:

Normally stated as the number of teeth per unit length of the cutting edge, and, as will be discussed later, is an important parameter in deciding the cutting performance of the blade. The pitch of the teeth commonly used for cutting metals varies in the range 1-12 teeth per cm.

Set Pattern:

In order to achieve clearance between the sides of the saw blade and the slot produced, some of the teeth are bent (set) away from the centre line of the blade. The following set patterns are used for this purpose:

(i) alternate set: right-left-right etc.

(ii) raker set: centre-right-left etc.

(iii) wavy set: the teeth are set in a periodic manner. This set pattern is used only for fine pitch of teeth.

Overall Set:

Is the overall thickness of the blade measured across the set teeth. It controls the width of slot generated and, therefore the amount of material removed during cutting.

Gullet:

Is the chip space formed between adjacent teeth. A number of gullet shapes are used but it is believed that they do not have a major influence on cutting performance, provided that 'clogging' of the teeth does not occur.

Rake Angle:

Is the inclination of the cutting face of the teeth measured from the normal to the cutting edge. Blades with positive and negative rake angles are available, but the most common tooth profile has a zero rake angle, sometimes called the 'radial' rake tooth profile.

FIGURE 3., shows a typical tooth profile illustrating principle angles.

Cutting Edge Sharpness:

The sharpness of the cutting edges is not usually specified when describing the cutting edge geometry. Examinations of the cutting edges of saw blade teeth have shown them to be irregular. Describing the cutting edge profile as a radius, measurements carried out on unused blades have shown the radius to vary in the range 0.02-0.076 mm. [4].

1.4.1 Recent Blade Developments

Since the introduction of the composite high speed steel blade the only real development on the blade scene is the bi-metal band which has teeth made of a cobalt high speed tool steel. This combination is said to offer excellent resistance against wear and abrasion under service conditions which generate high tool temperatures.

Fabrication of the blade is accomplished by edge butt welding a strip of the cobalt tool steel to a strip of carbon steel of the same thickness, using the electron beam welding process. The teeth being then milled into the cobalt tool steel and then heat treated to impart optimum properties to the composite blade. Tests on low alloy steels, stainless steels and precipitation hardened alloys are said to show that the cobalt bi-metal blade can out perform other bi-metal blades and solid high speed steel blades by as much as 4 to 1.

1.5 ECONOMICS OF MACHINING

It is not sufficient to devise a feasible procedure for the manufacture of a desired component. The procedure must be economically justified and cutting conditions may be established which give satisfactory results very rapidly. However, this may entail rapid tool wear and hence require frequent tool changes or resharpening. Thus there is a need to relate technological factors involved in the cutting process to the economics of the situation.

1.5.1 Variables And Criteria For Selecting Economic Conditions

The variables affecting the economics of a machining operation, the tool material, the machine tool capacity and the cutting conditions are numerous. Since these variables are readily accesible on the machine tool, their selection has been considered part of the machine operators duties. However, the economical selection of the cutting conditions involves technical and cost data not readily available to the operator, so that an optimum selection can seldom be achieved by this approach. The situation is further complicated by the fact that in general most manufacturing machine tools are used for more than one type of component, and these may give different economic returns.

Two criteria frequently used in the optimization of machining operations are the 'maximum production rate' criterion and the 'minimum cost per component' criterion. These two will always give a different cost and production rate. The minimum cost criterion will give a lower production rate, while the maximum production rate criterion will have a higher cost per component. The overall optimum situation will generally be fairly close to the conditions established by these criteria, usually somewhere between the two.

In selecting economic operating conditions, machine tool capabilities must be accounted for. Often the desired condition may be unattainable on the machine tool proposed for a particular operation. It is then necessary to either change the operating conditions or review the machine tool selection. The change may involve purchase of a new machine, re-scheduling of another machine, or possibly modifying the existing machine. On the other hand, it may happen that the machine conditions selected on economic grounds are using the chosen machine tool far below its capacity (power, speed, feed etc.). In this case, the machine selection should be reviewed, to see if a machine with lower capacity can be used for this operation.

The capacity limits of a machine tool, limiting the selection of machining conditions may be listed as follows:

(i) machine tool maximum feed.

(ii) machine tool maximum speed.

(iii) machine tool maximum power.

(iv) maximum allowable cutting or thrust force.

(v) feed and speed limits for the desired component surface finish.

(vi) machine tool feed and speed increments.

Improved tool materials and tool geometry which give longer tool life values will reduce the number of tool replacements and hence lower the cost per component. Similarly, work materials giving less tool wear can reduce the cost per component. Overhead costs cannot normally be expected to drop, so that cost reductions will have to be based on improved techniques. The cost per component can also be lowered by decreasing machining time. Increasing the cutting speed or feed reduces the machining time but reduces the tool life at a faster rate.

The production rate is dependant on the cutting conditions and the tool life. Decreases in non-productive time and time required to change the cutting tool, will increase the production rate. Increases in cutting speed will reduce the machining time per component and increase the tool changing time per component; a minimum time per component or maximum production rate will therefore result. Variations in cutting speed will give optimum values of cost per component and production rate.

In general, the speed for maximum production rate will differ from the speed for minimum cost.

1.6 AIM OF THE INVESTIGATION

The aim of this investigation is to undertake wear tests on bandsaw blades in which relevant parameters including band speed, machine load, workpiece geometry and blade geometry are varied. To correlate these results using dimensional analysis in order to reduce the wear performance of the blade to easily definable parameters. Also, to use the parameters obtained in a computer simulation of the bandsaw operation using both constant feed rate and constant thrust load principles, in order to estimate sawing rates and costs.

1.6.1 Relationship To Previous Work

Previous work [5,6,7] has produced a technique based on dimensional analysis and it has been used to analyse blade wear applied to the power hacksaw operation.

This investigation extends this technique to the bandsaw operation for the first time.

1.6.2 Plan Of Work

The investigation consisted of the five main work areas shown:

(i) to survey previous work undertaken on sawing operations and cutting tool wear.

(ii) to develop an experimental rig based on a commercial bandsaw machine in which the relevant engineering parameters can be measured.

(iii) to undertake a systematic series of wear tests and to correlate the results using dimensional analysis.

(iv) to develop an algorithm to simulate the bandsaw operation suitable for use on a digital computer.

(v) to use the computer simulation to estimate the sawing rates and costs of the bandsaw operation under different combinations of load, speed and geometries.

The thesis covers each section in the same order as they appear above.

2 CUTTING TOOL WEAR

2.1 INTRODUCTION

Cutting tools are subjected to extremely severe conditions when in use because they are in metal to metal contact with the chips and workpieces under conditions of very high stress and temperature. The cutting conditions are further aggravated by extreme stress and temperature gradients near the surface of the tools.

Tools wear by the actions of many mechanisms on both the rake and clearance faces. The effects of wear can be observed when a cutting tool is examined, a cavity or crater frequently occurs on the rake face and the clearance face is often worn, to produce a flat surface extending back from the cutting edge, known as a wear land.

Great developments have been made in material cutting operations in recent years, tool materials have been improved, the size and speed of machine tools have increased considerably and machine tool control has been improved. Therefore it is of great importance for economical machining that the phenomenon of tool wear is better understood.

Wear may be classified into two groups of differing severity, namely, mild and severe wear. Mild wear occurs during the sliding of lightly loaded surfaces under both dry and lubricated conditions, in for example modern bearing assemblies, whilst severe wear conditions exist in metal cutting applications.

The analysis of wear is complicated by the fact that wear is not a process involving one unique mechanism. There are several alternative mechanisms which are known to be operating; either singly or in combinations, depending on the physical conditions existing.

The following is intended to give an introduction to the mechanisms of wear under both mild and severe conditions. In addition, the specification of tool life and failure criteria are discussed followed by a study of wear during metal cutting based on dimensional analysis. Some important tool life equations are given and the variables affecting tool life are discussed without regard to any particular metal cutting operations.

2.2 MILD WEAR MECHANISMS IN SLIDING SYSTEMS UNDER LIGHT LOADING

Under the action of sliding the contacting asperities between two surfaces can be destroyed in a number of different ways. Any one type of destruction depends on both the properties of the surface materials and the external conditions such as load and speed. The mutual interaction of the surfaces regulated by the applied load gives rise to certain types of destruction mechanisms of the frictional bonds. During sliding the surface layers are heated which causes changes in the material properties. Over certain ranges of conditions, governed by temperature and mutual interaction of the surfaces, the type of destruction of the frictional bonds may remain unchanged, consequently, there will be a characteristic wear mechanism for a particular range of conditions. However in general more than one mechanism will be operating. Numerous authors [8-11] have classified wear into several types, and four main wear mechanisms have been identified and they are:

(i) adhesive wear (due to welding of surface asperities)

(ii) abrasive wear (due to the cutting action of hard particles)

(iii) diffusion wear (due to atomic or molecular interactions across the tool / work interface)

(iv) fatigue wear (due to either repeated mechanical or temperature interactions)

Within each of these, several variations in mechanism can exist and frequently more than one process is taking place at the same time. It is convenient to discuss wear in these four categories.

2.2.1 Adhesive Wear Mechanism

In the case of adhesive wear the mating surfaces come close enough together to form strong bonds. If the bonds established are stronger than the local strength of the material a particle may transfer from one surface to the other. After this has occured several times a loose fragment may be formed and leave the system as a wear particle. If these particles are very small (sub-microscopic) this process is called 'attritious wear'. If the particles are visible under the microscope the process is referred to as 'galling'. Galling is characterized by considerable welding and tearing of the softer rubbing surface at high wear rate, and the formation of relatively large wear particles. Under mild wear conditions (attrition), the surface finish of the sliding surfaces improves, apparently due to the removal of high spots. The wear rate is relatively low when attrition wear conditions exist. The mild or attrition wear mechanism is believed to differ from severe wear, by the formation of an oxide film. In the early stages of rubbing, contact regions grow by metal transfer. An oxide film then forms on the contact regions, preventing metallic contact. Eventually a balance between the formation and removal of the protective oxide film is reached, with the wear rate being controlled largely by the rate of oxide formation. If the applied load is increased the protective film may be destroyed and galling conditions will result. It is relatively difficult to achieve pure adhesive wear, for the material transferred during adhesive wear will often cause some abrasive wear.

2.2.2 Abrasive Wear Mechanism

Abrasive wear involves the loss of material by the formation of chips by cutting, as in abrasive machining. Since the process involves cutting it depends on the hardness, the elastic properties, and the geometry of the two mating surfaces. The abrasive resistance of a material depends on the amount of elastic deformation a surface can sustain.

Kragelskii [12] has reviewed the conditions governing transition between different deformation modes of a surface loaded by a sliding indentor (which may be considered to represent a surface asperity). Depending on the strength of adhesion of frictional bonds and the relative depth of penetration, h / R (where h = depth of penetration, R = radius of the penetrating asperity), Kragelskii shows that a transition occurs between plastic deformation and micro-cutting of the surface, when h / R is equal to or greater than 0.1.

2.2.3 Diffusion Wear Mechanism

Wear has been referred to as a process of atomic transfer at contacting asperities, which means wear purely by diffusion. More recent concepts consider diffusion to be an integral part of other wear mechanisms. Some diffusion must occur in the adhesion mechanism of contacting asperities. Diffusion may also be classified as part of the abrasion wear mechanism under certain conditions. One of the well known examples of this is in the wear of tungsten carbide tools when used to cut steels. The diffusion rate is temperature dependant and is a direct product of the rubbing speed. However the amount of material transferred by diffusion is dependant on the time of contact of the mating surfaces which is an inverse function of speed.

2.2.4 Fatigue Wear Mechanism

Kragelskii [12] describes a fatigue wear mechanism which has been proposed by a number of Russian workers. He describes how each surface asperity is associated with a wave of deformation; for some distance in front of the asperity the material is compressed, and behind the asperity the material is elongated because of the frictional force. Each cross section of the rubbing surface is successively subjected to compressive and tensile stresses. It is this change in surface stresses, which even though very small, may lead to wear by a fatigue failure of the surface. In theory, wear particles are created by cracks, formed below the surface, spreading and moving up to the surface. Generally it is thought that oxidation of the surface may take place, the oxide layer itself being removed by a fatigue process. Kragelskii points out that this model of wear can be used to explain wear in the presence of a lubricant film. The lubricant does not remove the load acting on the surface but merely balances it and the frictional force is reduced. The material below the surface is still subject to a fluctuating stress and so wear may occur by fatigue, even though there may be no metal to metal contact.

The fatigue wear mechanism has been presented as a completely alternative explanation to the adhesion mechanism. However, there seems to be reasonable cause to consider that both mechanisms play a part in the wear process, the conditions of sliding dictating which is the more important mechanism in any situation.

2.3 SEVERE WEAR MECHANISMS UNDER METAL CUTTING CONDITIONS

In 1973, Wright and Trent [13] made a considerable contribution to formulating concepts of wear mechanisms. They investigated the wear mechanisms occuring on high speed steel tools used to machine steels, cast iron and nickel based alloys under practical conditions. Wright and Trent presented evidence of five different wear processes and mechanisms:

(i) superficial plastic deformation by shear at high temperature.

(ii) plastic deformation of the cutting edge.

(iii) wear based on diffusion.

(iv) attrition wear.

(v) abrasion wear.

2.3.1 Superficial Plastic Deformation By Shear At High Temperature

Wright and Trent observed this mechanism on tools used at relatively high cutting speeds (3m /s.) where a 'crater' formed on the rake face under the chip. They show metallographic evidence that a 'flow-zone' occurs adjacent to the rake surface of the tool. The top of this zone moves with the chip while the bottom is bonded to the tool. This flow zone becomes the major heat source raising the temperature of the tool, and causing the surface layers of the tool to shear in the direction of chip flow to form a shallow crater, with tool material swept to the back to form a ridge.

Wright and Trent state that certain requirements must be met for the occurence of this wear mechanism:

(i) the flow pattern under conditions of seizure (seizure occurs when two surfaces become interlocked or metallurgically bonded so that sliding no longer takes place at the interface) must be such that a very thin layer of the work material at the interface forms a flow zone, with very high strain rate which constitutes a heat source giving very high temperatures.

(ii) the cutting speed must be high.

(iii) the material being cut must be relatively high melting point so that stress and temperature in the flow zone are high enough to shear the tool steel.

(iv) the tool material must be so softened that it can be sheared by the work material.

We are told that the occurence of a crater on a tool cannot be taken as evidence that this mechanism is operative. Wright and Trent report that shallow craters were observed on tools after machining at low speeds with no evidence of plastic deformation. When speed and feed were raised, the rapid cratering by plastic deformation became the factor limiting the maximum rate of metal removal and leads to rapid rates of wear.

2.3.2 Plastic Deformation Under Compressive Stress

The vertical component of the cutting force is supported by that portion of the tool rake face in contact with the under side of the forming chip. When cutting steels, the mean stress on this contact area is reported to be over 750MN $/m^2$. This stress is largely compressive and is superimposed on the shear stress acting at the interface. This compressive stress tends to deform the tool in a direction normal to the rake face, and a basic requirement of a cutting tool material is high yield stress in compression. This change of shape due to deformation may alter the flow pattern over the tool, causing accelerated failure by greatly increased heating at the cutting edge. The last stages are accompanied by generation of high temperatures at the tool flank and wear by the shear process as for cratering.

2.3.3 Diffusion Wear

Wright and Trent show metallographic evidence that conditions exist where diffusion across the tool / work interface is probable. When cutting steel and cast iron at fairly high speed and feed rate they report a gradual structural change across the interface, suggesting interdiffusion. They also observed features, consistent with a wear process in which matrix atoms from the tool diffused into the work material, on the surfaces of craters of tools used at relatively low cutting speeds.

Wright and Trent summarise by saying that with high speed steel tools primary cratering at moderate speeds is probably based on diffusion, but temperatures are relatively low and craters develop slowly. As the cutting speed is raised, diffusion wear does not become rapid because it is superseded by the plastic deformation process, which is so rapid that it completely masks any diffusion process which may be taking place. With high speed steel tools wear based on diffusion is probably of minor importance on the rake face. However, they report that some flank wear may be based on diffusion.

2.3.4 Attrition Wear

Metallographic evidence is given showing the character of the work process in which fragments of the tool of microscopic size are torn from the tool. There is a suggestion of fracture along grain boundaries and the work material is firmly bonded to the tool surface. A worn tool surface is most probably formed by the pulling away of fragments of the tool material subjected to localised tensile stresses when the work material is torn off. Sections through tools used for increasing times have shown a slow uneven nibbling away of the edge, the wear rate probably depending largely on the stability of the flow pattern of a built up edge. Attrition wear rate is probably influenced greatly by factors such as rigidity and tool rake angle.

2.3.5 Abrasion

To abrade a high speed steel tool there must be particles in the work material harder than the martensitic matrix. Wright and Trent found direct evidence for abrasion only on tools used for cutting stainless steel (En58B), and only a few examples of abrasion were found on all the tool / work interfaces examined. They concluded that abrasion mechanics may account for the difference in wear rate when cutting different steels and that abrasion gives an initial high wear rate which diminishes rapidly with time.

2.4 APPLICATION OF WEAR MECHANISMS TO CUTTING TOOL WEAR

Typically cutting tools wear by the rubbing of the chip and workpiece against the rake and clearance faces. Since this is a sliding process one would expect that the wear mechanisms known to apply to lightly loaded surfaces will apply to metal cutting. However, there are three special factors in the wearing of cutting tools, which make it a more severe wearing problem:

(i) the surface against which the tool is rubbing is newly cut from the work material (virgin metal), and there is little time for oxidation to form.

(ii) the surface on which the tool is rubbing has severely work hardened in the plastic processes involved in forming the chip.

(iii) the temperatures and pressures at the chip / tool interface are extreme.

Most of the studies used in developing wear relationships deal with the wear of a soft metal rider rubbing against a harder surface. In metal cutting the wear we are interested in is that of a hard metal rider (the tool) rubbing on a softer surface.

The flow pattern around the cutting edge plays a decisive role in determining which wear mechanism becomes operative and the rate of wear. Wright and Trent account three ways in which the flow pattern can influence the wear mechanisms:

(i) the rate of flow at and near the tool / work interface can have a direct influence on the rate of wear, as is clear in the case of attrition wear, cratering by high temperature shear and in diffusion wear, in which the atoms of tool material diffusing into the work are carried away.

(ii) the pattern of flow can have an indirect influence because the character and location of the heat source depends on the flow pattern and temperature distribution has been shown to be important in controlling wear, (diffusion wear and cratering by plastic deformation).

(iii) the flow pattern can have an indirect influence because it can greatly modify the distribution of stress (both compressive and shear stress) near the cutting edge, thus controlling processes in which the tool shape is changed by plastic deformation.

As cutting speed increases, temperatures rise, and as the limiting rate of metal removal is approached, the rates of cratering wear, flank wear and deformation of the cutting edge increase rapidly and tool life falls. Which one of the wear mechanisms is dominant depends on many factors including tool material, tool geometry, and the character of the work material; but all are sufficiently dependant on temperature that fairly simple tool life-cutting speed relationships hold. It is in this region that tool life may be found to conform, at least approximately, to the Taylor relationship. At lower cutting speeds other wear mechanisms come into operation not dependant on temperature and the relatively simple relationships between cutting speed and tool life no longer hold.

2.4.1 Adhesion Wear Theory

Shaw and Dirke [14] have applied an adhesion wear theory to the formation of a wear land on a cutting tool. They obtained the wear volume per unit distance of sliding as

$$W = K\,(n.C)\,N/\sigma_y \qquad (1)$$

Shaw and Dirke state that the quantity K will:

(i) be less for the harder metal of a sliding pair.

(ii) be greater for metals having a strong tendency to weld.

(iii) increase with temperature.

(iv) increase with time of contact (inverse of sliding speed).

(v) decrease as low shear strength films are formed between the surfaces (by introduction of a cutting fluid).

Shaw and Dirke suggest that the product (n.C) may be assumed independant of load and thus (1) states that wear rate should be a linear function of applied load (N). Other workers have shown that this is the case over a wide load range, up to very high loads where catastrophic wear occurs. Shaw and Dirke explain the growth of the wear land on the clearance space of a tool in terms of (1) and when plotted against time, or length of cut, they observed three distinct stages of wear land growth. An initial region of rapid wear, then an approximately constant wear rate region, and finally a much more rapid or even catastrophic wear region. This general nature of wear land growth has been reported by many workers and is illustrated in FIGURE 4., based on a very fine depth of cut milling operation [15] .

J. Taylor [16] suggests that it is reasonable to assume that the 'volume rate of tool wear is proportional to the area of the wear scar'. From this assumption, relations for the growth of wear land and depth of crater with respect to time can be established. Considering an orthogonal cut the wear land can be assumed to form as a plane surface parallel to the direction of cut, as shown in FIGURE 5. The wear volume (W) at any given wear land (w), can be given by:

$$W = \frac{1}{2} A b w^2 \tag{2}$$

The wear proportionality assumed by Taylor [16] may be written:

$$\frac{dW}{dt} = K w b \tag{3}$$

2.4.2 Diffusion Wear Theory

A number of workers have considered that the mechanism of tool wear must involve chemical action and diffusion. Trent [17] has demonstrated welding and preferred chemical attack of tungsten carbide in tungsten-titanium carbide tools. Bhattacharyya and Gosh [18] have shown micrograph evidence of the diffusion of tool constituents into the workpiece and chip.

There are several ways in which the wear process may be dependant on the diffusion mechanism. Cook and Nayak [19] have suggested the following:

(i) gross softening of the tool. Diffusion of carbon in a relatively deep surface layer of the tool may cause softening and subsequent plastic flow of the tool. This may produce major geometrical changes in the tool, which result in high forces and complete failure of the tool.

(ii) diffusion of major tool constituents into the work. The tool matrix may dissolve into the work and chip surfaces as they pass the tool. This process may constitute the removal of tool material. In cast alloy, carbide or ceramic tools this may be the prime wear mechanism. With high speed steel tools iron diffusion is possible.

(iii) diffusion of minor tool constituents into the work. A component of the tool material may dissolve away leaving a thin surface layer with deteriorated material properties. With high speed steel tools the carbon content of a surface layer may be reduced by diffusion.

(iv) diffusion of a work material component into the tool. A constituent of the work material diffusing into the tool may alter the physical properties of a surface layer. For example, it is conceivable that diffusion of lead into the tool may produce a thin brittle surface layer, subject to removal fracture.

(v) diffusion of a tool constituent influencing the work material. Opitz [20] has suggested that the major influence of a diffusion mechanism on the wear of carbide tools is not from loss of constituents from the tool, but from the influence of these constituents on the strength of the chip material. A carbon enrichment increases the strength of the chip surface and this in turn draws more material out of the tool.

The mechanisms (i) to (v) are not mutually exclusive. All may play a part in the tool wear process, or for particular conditions, one mechanism may predominate. However, all the mechanisms depend on diffusion, and clearly the examination of diffusion rate relationships is likely to provide realistic wear rate estimates. Dorinson [21] applied a reaction rate equation to tool wear. He has shown that an equation of this form can lead to a linear relationship between the natural logarithms of the rake face wear rate and the cutting speed. This provides a possible explanation of the empirical tool life relationship originally proposed by F.W. Taylor [22]. Dorinson analysed a model of the wear process in which material from the chip diffused into the tool and chemical reaction (alloying), produced a soft layer at the tool surface. Dorinson developed an equation for wear per unit time, which involved geometrical factors of both the workpiece and the tool, together with the diffusion rate constant which is temperature dependant. The wear volume per unit time can be written:

$$W = k_1 q \; K_1 \tag{4}$$

2.4.3 Electrochemical Effects In Tool Wear

Due to the high temperatures between dissimilar materials at the tool / chip interface, a thermo-electric current flow is set up between the tool / chip / workpiece / machine tool. Opitz [23] has suggested that this current may aid the diffusion of carbon ions from carbide tools into the work material. Opitz has also claimed that by electrically insulating the cutting tool from the machine tool the wear rate of the tool is reduced. A further reduction is claimed if an opposing electro-motive force is applied to the tool. Some workers have reported that they could find no change in tool wear with either electrical insulation or with a back electro-motive force. It seems that the presence of an oxide film at the tool / chip interface determines whether or not this mechanism takes effect.

2.5 CUTTING TOOL LIFE - WHAT IS IT?

Tool life represents the useful life of a tool, expressed in time (or other units) from the start of a cut to some end point defined by a failure criterion. A tool that no longer performs the desired function is said to have failed and hence reached the end of its useful life. At such an end point the tool is not necessarily unable to cut the workpiece but is merely unsatisfactory for the purpose required. The tool may be resharpened and used again; used on a less demanding machining operation, or scrapped.

2.5.1 Specification Of Tool Life And Failure Criteria

Tool life may be and has been specified in a number of ways, namely:

(i) actual cutting time to failure.

(ii) total time to failure, as in the case of a continuous cutting process (milling).

(iii) length of work cut to failure.

(iv) volume of metal removed to failure.

(v) number of components produced to failure.

(vi) cutting speed for a given time to failure.

Tool life can be readily expressed in physical quantities and hence seems a simple concept, yet it is actually based on some definition of tool failure. A tool fails when it no longer performs its function, so the failure criterion will depend on the requirements of the component being produced. In a finishing operation the surface finish and dimensional accuracy will be of major importance and the tool will fail when the specified conditions can no longer be achieved. With form tools, accuracy is vital and only limited changes in tool shape can be tolerated. Also these failures are principally related to the wear on the clearance face of a tool as discussed previously.

Various tool failure criterion have been used to determine tool life, these include:

(i) chipping or fine cracks developing at the cutting edge.

(ii) wear land size on the clearance face.

(iii) crater depth, width or other parameters of the crater in the rake face.

(iv) a combination of (ii) and (iii).

(v) volume or weight of material worn off the tool.

(vi) total destruction of the cutting tool.

(vii) limiting value of surface finish produced on the component.

(viii) limiting value of change in component size.

(ix) fixed increase in cutting forces, power or cutting time required to perform a cut.

These various tool failure criteria have been introduced gradually as the full implications of tool life became clearer, though the problem is by no means fully solved. The first six are based on measurements of cutting tool wear, while the remainder are mainly a result of the tool wearing when in use.

Studies of the tool flank wear have shown that the wear land growth follows three stages, yielding a curve similar to a creep test curve, FIGURE 6.

Various explanations have been put forward by many workers and have been discussed previously. The adhesion wear theory and the diffusion theory have been applied to wear land growth. Shaw and Dirke [14] using the adhesion wear theory claimed that the approximate linear second stage of the wear land curve is represented by L proportional w, if the normal force (N), on the wear land (w) is proportional to the wear land size. If the normal force is constant then L is proportional w^2. Taylor's experimental data [16] shows that L is proportional w for a wide range of cutting conditions. Taylor claimed that these results are consistent with the adhesion wear theory.

Colding [24,25] measured tool wear by radioactive methods and showed that the volume wear rate is constant in stage II wear (FIGURE 6.), so that:

$$L \propto \text{volume wear} \propto w^2 \qquad (5)$$

The diffusion wear theory as applied by Colding suggests that wear rate is constant provided that temperature is constant. While these theories have been applied to cutting tool wear with some success, none has quantitatively predicted the tool wear and resort to some experimental testing must be sought. It now becomes apparent that all these wear theories show that many variables play an important part in the life of a cutting tool.

2.6 DIMENSIONAL ANALYSIS APPLIED TO METAL CUTTING

2.6.1 Dimensional Analysis

The idea of dimensional consistency is used in the procedure known as dimensional analysis in which variables of a given situation are grouped into dimensionless parameters which are less numerous than the original variables. Such a procedure is very helpful in experimental work in which the very number of significant variables presents an imposing task of correlation. By combining the variables into a smaller number of dimensionless parameters, the work of experimental data reduction is considerably reduced.

The methods of dimensional analysis are of very wide application but it was only in 1939 that it was first applied to metal cutting.

2.6.2 Applications Of Dimensional Analysis To Various Metal Cutting Problems

2.6.2.1 Tool Temperature

Kronenberg [26] assumes that temperature of a cutting tool is primarily affected by the physical quantities shown below:

Variable	Symbol	Dimension
temperature	Te	θ
chip cross sectional area	A	L^2
cutting speed	V	LT^{-1}
unit cutting force	ks	$ML^{-1}T^{-2}$
thermal conductivity of work material	W	$ML\ T^{-3}\theta^{-1}$
volumetric specific heat of work material	h	$ML^{-1}T^{-2}\theta^{-1}$

To find the relationship between these variables we have to find two dimensionless quantities designated Π_1 and Π_2, it is advisable to select a core of five of the six variables for each group such that:

$$\Pi_1 = V^a\ ks^b\ W^c\ h^d\ Te \qquad (6)$$

$$\Pi_2 = V^e\ ks^f\ W^g\ h^i\ A \qquad (7)$$

The exponents have to be determined such that Π_1 and Π_2 become dimensionless. Substituting the dimensions of the variables into the Π , equations gives:

$$M^o L^o T^o \theta^o = L^a T^{-a} . M^b L^{-b} T^{-2b} . M^c L^c T^{-3c} \theta^{-c} . M^d L^{-d} T^{-2d} \theta^{-d} . \theta$$

The exponent must equal zero; consider:

$$\begin{array}{lll} [L] & a - b + c - d & = 0 \\ [T] & -a - 2b - 3c - 2d & = 0 \\ [M] & b + c + d & = 0 \\ [\theta] & -c - d + 1 & = 0 \end{array}$$

from which $a = 0 \quad b = 0 \quad c = 0 \quad d = 0$

and $\Pi_1 = ks^{-1} . h . Te$

or
$$\Pi_1 = \frac{h . Te}{ks} \tag{8}$$

Repeating the process for Π_2 gives:

$$\Pi_2 = V^2 . h^2 . A . W^{-2}$$

$$\Pi_2 = \frac{V^2 \; h^2 \; A}{W^2} \tag{9}$$

Π_1 and Π_2 may be expressed in the form:

$$\Pi_1 = f(\Pi_2) \tag{10}$$

Kronenberg found the relationship between Π_1 and Π_2 by replotting

Kronenberg found the relationship between Π_1 and Π_2 by replotting 7., data obtained by Gottwein [27] in the form Π_1 and Π_2. FIGURE 7.1 shows numerous values of Π_1 and Π_2 which have been computed and ll on a straight line, although the values cover a great range of cutting speeds, cutting forces, chip cross sectional areas etc. This shows the advantage of using dimensional analysis which makes it possible to represent all tests by a single line; ordinarily, data must be represented on various diagrams which do not show their mutual interdependance.

The equation of the straight line FIGURE 7., is:

$$\Pi_1 = C\ (\Pi_2)^n \qquad (11)$$

where C is the magnitude of Π_1 when $\Pi_2 = 1$. The exponent n is the slope of the line of FIGURE 7., and equals 0.22.

The equation now becomes:

$$\frac{h\ Te}{ks} = C\left[\frac{V^2 h^2 A}{W^2}\right]^{0.22} \qquad (12)$$

or

$$Te = C\ \frac{ks\ V^{0.44} A^{0.22}}{W^{0.44}\ h^{0.56}} \qquad (13)$$

Kronenberg made the following conclusions from this relationship, namely:

(i) the major quantity affecting the cutting temperature is the unit cutting force (and thus the shear strength of the work material). Temperature varies directly proportional to the unit cutting force.

(ii) the two thermal quantities of specific heat per unit volume and the heat conductivity of the work material, have the second largest effect on temperature. The lower they are the higher the temperature.

(iii) the cutting speed has considerably more effect on the temperature than the chip cross sectional area.

Based on the hypothesis that an exponential relationship between cutting variables such as Π_1 and Π_2 is often found in metal cutting investigations, [28] , when plotted on bi-logarithmic paper, the equations (11) and (12) could be derived even without actual cutting tests. This shows the power of dimensional analysis. Actual testing then would have been necessary only for a series of runs where the cutting speed was varied while the chip cross sectional area was constant. This would have given the numerical value of exponent n. A few further tests, varying the chip cross sectional area would suffice to derive the entire temperature relationship.

Shaw and Loewen [29] investigated temperatures in metal cutting and derived complete formulas which they finally simplified to the following equation:

$$Te = \frac{S_s \; V^{0.5} \; t_1^{0.5} \; \theta^{0.5}}{W^{0.5} \; h^{0.5} \; J} \tag{14}$$

If equation (14), (based purely on cutting tests) is compared with Krononberg's (13), (based on dimensional analysis), the two equations agree in many respects except in the exponents for the feed and the cutting speed. These exponents are equal in Shaw and Loewen's equation (namely both 0.50) while the feed exponent (0.22) is only half the cutting speed exponent (0.44) in Kronenberg's equation. Equal exponents for feed and speed do not agree with common experience where the cutting speed has a greater effect on the temperature than the feed. Hence, by dimensional analysis it is possible to derive an equation expressing the different effects of speed and feed, while Shaw and Loewen's equation based on cutting tests, failed to take this into consideration. From evaluation of tests by Herbert [30] and Chao and Trigger [31] exponents are obtained for the cutting speed-temperature relationship of from 0.35-0.43, and 0.195-0.212, respectively.

2.6.2.2 Tool Life - Cutting Speed Relationship

Dimensional analysis leads to very interesting investigations of the tool life-cutting speed relationship. Kronenberg [26] introduces a single new quantity, namely the 'consolidated heat value (H)'.

The following shows the physical quantities considered in the tool life-cutting speed relationship:

Variable	Symbol	Dimension
temperature	Te	θ
tool life	T	T
chip cross sectional area	A	L^2
cutting speed	V	LT^{-1}
unit cutting force	ks	$ML^{-1}T^{-2}$
thermal conductivity of work material	W	$MLT^{-3}\theta^{-1}$
volumetric specific heat of work material	h	$ML^{-1}T^{-2}\theta^{-1}$
consolidated heat value (W.h)	H	$M^2T^{-5}\theta^{-2}$

The variables are analysed in the same way as in the tool temperature relations. A new set of dimensionless products Π_3 and Π_4, are obtained, namely:

$$\Pi_3 = \frac{Te\ H^{1/2}}{T^{1/2}\ ks\ V} \tag{15}$$

$$\Pi_4 = \frac{A}{V^2\ T^2} \tag{16}$$

It is now assumed that Π_3 is an exponential function of Π_4 and that the relationship may be expressed:

$$\Pi_3 = C_1(\Pi_4)^m \qquad (17)$$

By substituting (15) and (16) into (17) we have:

$$Te = \frac{ks\ C_1\ A^m}{H^{0\cdot5}}\ V^{1-2m}\ T^{0\cdot5-2m} \qquad (18)$$

We want to find out how tool life changes with cutting speed if the temperature remains constant when machining a given work material at a given feed and depth of cut.

The chip cross sectional area (feed x depth of cut) in (18) is a constant under these conditions and the unit cutting force and the consolidated heat value, are also constant for a given work material. Hence, the fractional value of (18) is constant and may be represented by C_2, such that:

$$C_2 = \frac{ks\ C_1\ A^m}{H^{0\cdot5}} \qquad (19)$$

Equation (18) can now be simplified to:

$$V^{1-2m}\ T^{0\cdot5-2m} = Te/C_2 \qquad (20)$$

If temperature remains constant then (20) may be written:

$$V^{1-2m} \; T^{0\cdot5-2m} = \text{constant} \tag{21}$$

Now one of the most important features of dimensional analysis is the possibility of making assumptions and drawing conclusions, which can be later verified or modified by sample testing.

Let us assume that the exponent m in (17-21) has the same value as n had in the previous section on tool temperature.

Substituting for m = 0.22 in (21) gives:

$$V^{0\cdot56} \; T^{0\cdot06} = \text{constant}$$

Dividing the exponents by 0.56 gives:

$$V \; T^{0\cdot107} = \text{constant} \tag{22}$$

It will be seen that (22) is identical to the well known Taylor equation [22] for the tool life-cutting speed relationship:

$$V \; T^{n_1} = C_T \tag{23}$$

Dimensional analysis leads to the Taylor equation in a very simple way, while Taylor needed a number of years to establish this relationship. It can be concluded that the Taylor relationship applies to constant temperature as long as the values of (19) do not change.

2.6.2.3 Generalization Of The Taylor Equation

Experience and tests have proved that the exponent n_1 in the Taylor equation changes with the work and tool materials. Dimensional analysis may be used to try and generalize and extend the Taylor equation beyond its present range [26] . A generalized equation can be obtained for the tool life-cutting speed relation by dividing (21) by the exponent (1-2m), to give:

$$V \,.\, T^{[(0{\cdot}5-2m)/(1-2m)]} = C_T \qquad (24)$$

2.6.2.4 Colding's Generalization Of Taylor's Equation

Previous investigations have shown the importance of temperature, thermal properties of the work material, energy per unit volume of metal removed, chip equivalent (or feed and depth of cut), and cutting speed on tool life [29,32,33,34] . Since tool life is a direct function of temperature where Taylor's equation is valid Colding [35] has neglected cutting temperature and substituted the thermal properties of the workpiece.

Colding makes use of the chip equivalent which is a function of the specific energy necessary to cut the metal, on the premise that for a constant combination of work and tool material this variable will be accounted for. A definition of a chip equivalent is given in a later section. Since the chip equivalent accounts for feed, depth of cut, nose radius and side cutting edge angle, Colding considers that chip equivalent is as important a variable as the cutting speed.

The quantities regarded for Colding's analysis are shown below:

Variable	Symbol	Dimension
tool life	T	T
cutting speed	V	LT^{-1}
chip equivalent	q	L^{-1}
thermal conductivity	k	$MLT^{-3}\theta^{-1}$
volume specific heat	ρc	$ML^{-1}T^{-2}\theta^{-1}$
thermal diffusivity	K ($k/\rho c$)	$L^{2}T^{-1}$

An application of the principles of dimensional analysis to the quantities shown above yields:

Let core = Tq

therefore $\pi_5 = T^{a} q^{b} V$

and $\pi_6 = T^{c} q^{d} K$

Considering Π_5 $\qquad \Pi_5 = T^a q^b V$

$$L^o T^o = T^a L^{-b} LT^{-1}$$

$[T] \quad 0 = a - 1 \qquad a = 1$

$[L] \quad 0 = -b + 1 \qquad b = 1$

$$\Pi_5 = T q V \tag{25}$$

Considering Π_6 $\qquad \Pi_6 = T^c q^d K$

$$L^o T^o = T^c L^{-d} L^2 T^{-1}$$

$[T] \quad 0 = c - 1 \qquad c = 1$

$[L] \quad 0 = -d + 2 \qquad d = 2$

$$\Pi_6 = T q^2 K \tag{26}$$

Now as before Π_5 and Π_6 may be expressed in the form:

$$\Pi_6 = f(\Pi_5) \tag{27}$$

Substituting (25) and (26) into (27) gives:

$$K T q^2 = f(V T q) \tag{28}$$

Now let us choose another core.

Let core = VT

This gives us $\Pi_7 = V\ T\ K$

and $\Pi_8 = V\ T\ q$

Considering $\Pi_7 = V^a\ T^b\ K$

$$L^o\ T^o = L^a\ T^{-a}\ T^b\ L^2\ T^{-1}$$

$$[T] \quad 0 = -a + b - 1 \qquad b = -1$$

$$[L] \quad 0 = a + 2 \qquad a = -2$$

$$\Pi_7 = V^{-2}\ T^{-1}\ K \quad \text{or} \quad \Pi_7 = K/V^2\ T$$

which gives
$$\Pi_7 = \frac{V^2\ T}{K} \tag{29}$$

Considering Π_8 $\quad \Pi_8 = V^c\ T^d\ q$

$$L^o\ T^o = L^c\ T^{-c}\ T^d\ L^{-1}$$

$$[T] \quad 0 = -c + d \qquad d = 1$$

$$[L] \quad 0 = c - 1 \qquad c = 1$$

which gives
$$\Pi_8 = V\ T\ q \tag{30}$$

As before Π_7 and Π_8 may be expressed in the form:

$$\Pi_8 = f\ (\ \Pi_7\ ) \tag{31}$$

Substituting (29) and (30) into (31) gives:

$$V\ T\ q = f\left[\frac{V^2\ T}{K}\right] \tag{32}$$

Equations (28) and (32) are Colding's three dimensional tool life equations.

Colding expressed (28) in the form of an exponential function giving:

$$K\ T\ q^2 = U\left[V\ T\ q\right]^{B/2} \tag{33}$$

Where B is the slope of a line produced by plotting the logarithm of the dimensionless groups based on cutting tests.

2.6.2.5 Analysis Of The Taylor Constant

The Taylor constant of (23) has been defined as the cutting speed for a 1 minute tool life. Kronenberg [26] has analysed this constant by means of (20) from which:

$$C_T = \left[\frac{Te}{C_2}\right]^{1/(1-2m)}$$

or when substituting (19)

$$C_T = \left[\frac{Te\ H^{0\cdot 5}}{A^m\ ks\ C_1}\right]^{1/(1-2m)} \tag{34}$$

Kronenberg has shown [26] that the Taylor-line (on a bi-logarithmic co-ordinate system) is a line of constant temperature. From (34) it may be concluded that this is true as long as the constant defined by this equation, does not change.

This conclusion has been confirmed by tests carried out by

Kronenberg [36]. It was found that the relationship between cutting speed and temperature at the chip / tool interface is represented by a straight line on a bi-logarithmic co-ordinate system, except in cases where the feed was changed. This agrees with (34) since the unit cutting force would change when the chip cross sectional area changes: hence the Taylor constant would also change.

2.6.2.6 Tool Life - Temperature Relationship

Kronenberg [26] has used (18) for forming conclusions with regard to the tool life-temperature relationship.

Solving (18) for the tool life, yields:

$$T_L = \left[\frac{Te \quad H^{0.5}}{A^m \quad ks \quad C_1 \quad V^{(1-2m)}} \right]^{1/(0.5-2m)} \tag{35}$$

Kronenberg has tabulated values of the exponent m such that m frequently lies between 0.188-0.228. It follows from (35) that the tool life would vary with the eigth to the twenty third power of the temperature. Schallbrock [37] and his associates have actually found that tool life varies with the twentieth power of temperature. This is excellent confirmation of both the dimensional analysis and of Schallbrock's tests. This also agrees with Kronenberg's values derived theoretically for the exponent m, because a variation with the twentieth power corresponds to a temperature exponent of 0.225.

2.6.2.7 Temperature - Time Relationship

Kronenberg [26] has used the variables of section 2.6.2.2 and applied them to the problem of the temperature-time relationship. The tool life is replaced by the time Z indicating continuous cutting. All dimensions remain the same and the corresponding dimensionless quantities are (compare with (15) and (16)) namely:

$$\Pi_3 = \frac{Te \quad H^{1/2}}{Z^{1/2} \; ks \; V} \tag{36}$$

$$\Pi_4 = \frac{A}{V^2 \quad Z^2} \tag{37}$$

These two dimensionless quantities must be correlated in order that the desired relationship between time and cutting temperature may be found. However, Kronenberg could only find one source of sample data which included unit cutting force, time, cutting speed, and chip cross sectional area. This source lacked uniformity in that more than one variable was changed from test to test. Kronenberg therefore makes some important conclusions based on assumptions (which are most likely to be correct) that tests would result in a straight line on bi-logarithmic paper.

Letting the slope of such a straight line be n and letting C_{oo} be the value of Π_3 for Π_4 = 1.0 (the intersection of the straight line with the y-axis at $\Pi_4 = 1.0$) the equation for the temperature-time relationship is formed thus:

$$Te = \frac{C_{oo}\, A^{n}\, ks\; V^{(1-2n)}\, Z^{(1/2-2n)}}{H^{1/2}} \tag{38}$$

Using this relationship Kronenberg has been able to bring out a basic fact very clearly, namely that the temperature rises almost instantaneously at the start of the cut. Hence it may often be sufficient to run short time cuts when temperature investigations are undertaken. Kronenberg has validated this claim by measuring temperature oscillograms during actual cutting [26].

2.7 EMPIRICAL CUTTING TOOL LIFE EQUATIONS

2.7.1 The Taylor Type Relationship

The best known tool life equation is that of F. W. Taylor [22] :

$$V\ T^{n} = C_T \tag{39}$$

This formula indicates a linear relationship between log T and log V (n is a constant) as shown in FIGURE 8., for any given conditions of feed rate, depth of cut, and tool geometry.

Taylor considered the exponent to be constant, resulting in linearity.

Experience has shown that in general a curve results from a log T-log V plot and that constant exponent is a special case which occurs in certain conditions. FIGURE 9., shows linear Taylor plots obtained at the University of Manchester Institute of Science and Technology [38].

FIGURES 9-12., and general experience of tool life testing suggests that non-linear Taylor plots are most likely to occur in the following conditions:

(i) when machining high strength thermal resistant materials with all types of tool materials.

(ii) when machining in conditions which give very long tool lives.

(iii) at high rates of metal removal.

(iv) in finish turning conditions as indicated by Kronenberg [26] .

The conditions used by Taylor when he developed his V-T relationships were:

(i) Taylor used plain carbon steel and high speed steel tools; the only tool available at that time.

(ii) only cast steel and forged steel workpieces were used.

(iii) only one type of turning tool was used; the 'Taylor Tool' with a large nose radius.

(iv) Taylor employed only large cuts; these corresponding to rough machining conditions.

(v) the failure criterion employed was 'complete tool failure' and the tool life was expressed as the cutting speed to produce failure in 20 minutes.

(vi) only one speed range was used; this being speeds to give what Taylor termed 'Type II tool wear'.

Taylor defined three types of tool wear and these are:

I that in which the heat generated in cutting has no effect on the tool hardness and on the wear rate.

II that in which the heat produced softens the tool slightly during the greater part of its life, leading to increased wear, increased temperature, and finally, rapid failure.

III that in which the heat generated, completely softens the cutting tool, leading to rapid failure.

The Taylor equation seems to be reasonably valid when machining carbon and alloy steels with all types of tool material in semi-roughing conditions (depth of cut 1.27-3.81mm. and feeds of less than 0.5mm.) when cutting with speeds to give tool life of between 10 and 50 minutes.

Kronenberg [42] has suggested a method of 'straightening' a curved log T-log V plot. This is achieved by adding or subtracting a constant straightening factor to or from all values of speed and tool life and re-plotting the results in the form:

$$(V \pm K_S)T^n = (C_T \pm K_S) \qquad (40)$$

The curvature of the original data determines whether the straightening factor is added or subtracted, as indicated in FIGURE 13. Kronenberg used trial and error to determine the straightening factor, taking as a guide the fact that the greater the curvature of the original data, the larger the straightening factor must be. Having suggested a value for the straightening factor, it may be mathematically checked to show whether it is correct. For a straight line, the slope must be constant:

$$n_1 = \frac{\mathrm{Log}[\,V_2 + (K_S/V_1) + K_S\,]}{\mathrm{Log}\,(T_1/T_2)} \qquad (41)$$

Yellowly and Barrow [43] have shown that equation (40) implies that

$$n_1 = n \pm \frac{K_S\ n}{V} \qquad (42)$$

Therefore, if the amount of non-linearity is small the straightening factor and exponent can be obtained by plotting $1/V$ against n_1.

Equation (39) only relates cutting speed to tool life for a particular tool / workpiece combination, and does not consider other cutting variables and tool geometry. To connect tool life with several variables, Taylor derived the equation:

$$V_T = \frac{C_1\left[1 - \frac{8}{7}(32r)^2\right]}{S^{2/5} + \frac{2\cdot12}{5+32r}\left[\frac{48}{32r}d\right]^{2/15} + 0\cdot06\sqrt{32r + \frac{0\cdot8(32r)}{6(32r)+48d}}} \tag{43}$$

Although this equation includes the important variables, feed and depth of cut, it is too complex and limited to be of any practical use. Taylor considered that feed and depth of cut could not be combined into a single variable.

Kronenberg [26] used the data obtained by Taylor and found that in most cases the area of cut (feed x depth of cut) could be used as a single variable. By plotting data in the form of log V_T-log A, he developed the relationship:

$$V_T = \frac{C_2}{(1000\,A)^z} \tag{44}$$

Where C_2 is a constant; that is the cutting speed for an area of cut of $0.0065cm^2$., and z the slope of the log V_T-log A plot.

Combined with Taylor's relationship (39), equation (44) becomes:

$$V\,T^n = \frac{60^n\,C_2}{(1000\,A)^z} \tag{45}$$

A slope effect was introduced by a consideration of a 'slenderness ratio' G, such that G = depth of cut / feed.

$$VT^{n} = \frac{C_2 \; (G/5)^{u} \quad 60^{n}}{(1000\ A)^{z}} \tag{46}$$

The term G / 5 relates G to an average value of G which Kronenberg considered to be 5. Although equation (46) considers both feed and depth of cut, the nose radius is not accounted for. Thus, the equation omits a relatively important variable and is felt to be inferior to equations using the concept of chip equivalent which are discussed later.

Although Taylor connected tool life with cutting speed, feed and depth of cut in separate equations, he never attempted to combine them. This is now done regularly and is known as the 'Extended Taylor Equation'. Taylor connected tool life with cutting speed; (39), and he connected tool life with feed rate:

$$V_T = C / s^{n_1} \tag{47}$$

He connected tool life with depth of cut:

$$V_T = C / d^{n_2} \tag{48}$$

The extended equation becomes:

$$T = \frac{C_3}{V^{1/n} \; S^{1/n_1} \; d^{1/n_2}} \qquad (49)$$

This equation is used extensively but it still omits tool geometry and assumes that the exponents are constant. As in the simple Taylor equation, this is not generally so and large errors can occur. The general trend of tool life with the cutting speed, feed and depth of cut is shown schematically in FIGURE 14. The amount of curvature in a particular case depends on the tool and workpiece combination and the cutting conditions.

It is usually noticed that $^1/_n > {}^1/_{n_1} > {}^1/_{n_2}$ so that the cutting speed has the greatest influence on tool life. The constants in the extended Taylor equation can only be found through empirical tests. Provided the exponents are reasonably constant, equation (49) is quite useful, but the evaluation of the exponents and the constant, is quite laborious as at least three sets of tests involving fifteen tool life values are required.

2.7.2 Equations Based On The Chip Equivalent Concept

In 1931 / 32 Woxen [45,46] proposed a tool life relationship based upon cutting temperature, by evaluating a heat balance in steady state cutting conditions.

He assumed that:

(i) the actual area of cut, to be a measure of the quantity of heat generated at a certain cutting speed.

(ii) the engaged cutting edge length, to be a measure of the quantity of heat carried off at that instant.

Woxen showed that cutting temperature was a direct function of the chip equivalent, for a given cutting speed and tool / workpiece combination. The chip equivalent is defined as the ratio between the length of the tool edge contacting the work and the area of cut as shown in FIGURE 15.

In some cases the inverse of the chip equivalent is used and is called the 'Equivalent Chip Thickness'. The proposal by Woxen that temperature is a function of chip equivalent has been substantiated by several workers using tool / work thermocouple techniques [34,47]. Woxen assumed that the conditions resulting in constant temperature also resulted in a constant tool life. Using this assumption he was able to predict the shape of a cutting speed-temperature plot, as shown in FIGURE 16. These plots of cutting speed-chip equivalent were constructed from the cutting speed-temperature plots in the following manner.

A vertical line was drawn through curves of cutting speed-temperature at a certain value of temperature as shown in FIGURE 16. From the points of intersection a temperature curve of cutting speed-chip equivalent was constructed for a constant temperature. This results in the right hand diagram of FIGURE 16., and as Woxen believed that conditions which result in a constant cutting temperature also resulted in a constant tool life, he interpreted his cutting speed (constant temperature)-chip equivalent plot as a cutting speed (constant tool life)-chip equivalent plot, FIGURE 17.

By constructing a number of these curves, he found that the shallow curve produced could, in each case be approximated to a straight line with little error. When extrapolated to zero, these straight lines for several cutting temperatures (and hence tool lives) all had the same intercept.

Woxen proposed the variation of tool life with chip equivalent and cutting speed as:

$$V_T = G_T (q_o + q) \tag{50}$$

He found that in general cutting speed (constant tool life)-chip equivalent plots were not linear and introduced a factor to account for this fact and ammended his equation to:

$$V_T = G_T \left[\frac{q_o + q}{1 + gq} \right] \tag{51}$$

To introduce tool life as a separate factor, Woxen assumed that the Taylor equation (39) was generally valid and added a term so that the relationship became:

$$V = \left[\frac{T_x}{T}\right]^n G_s \left[\frac{q_o + q}{1 + gq}\right] \qquad (52)$$

Woxen recognized that the Taylor exponent could vary and added a further term to overcome this difficulty, thus:

$$V = \left[\left[\frac{T_x}{T}\right]^n + g_1 T\right] G_s \left[\frac{q_o + q}{1 + gq}\right] \qquad (53)$$

Although the equations developed by Woxen seem to be valid for a wide range of cutting conditions, they are rather complex and difficult to use. It appears that Woxen never plotted his results on bi-logarithmic scales, he always used his assumption of the linearity of the cutting speed (constant tool life)-chip equivalent plots. These plots seem to deviate from linearity in the same way, consequently Woxen was able to employ a correction factor. If $\log V_T$ is plotted against $\log q$ the resulting lines are often linear, thus tool life can be expressed as:

$$V_T = J\, q^j \qquad (54)$$

Equation (54) can be expanded to include tool life as a separate term, resulting in:

$$V T^n = M q^j \qquad (55)$$

Colding [35] and Brewer and Rueda [48] used relationships of the form of (55) and showed that the exponents are not necessarily constant.

2.7.3 Colding Tool Life Equation

Dimensional analysis has proved to be a very handy method in many fields of engineering. To perform such an analysis it is most important to know the fundamental physical quantities affecting the cutting process. Previous investigations have shown the importance of temperature, thermal properties of work material, energy per unit volume of metal removed, chip equivalent (or feed and depth of cut), and cutting speed on tool life [29,32,33,34].

There also seems to be general agreement that tool life is a direct function of temperature in the region where Taylor's equation is valid. Therefore, in a dimensional analysis aiming at a generalization of Taylor's original equation (39) temperature should not be included in the analysis, but the thermal properties of the workpiece. To take into account the specific energy necessary to cut the metal, the chip equivalent, being a function of specific energy, might very well take care of this variable for a constant combination of work and tool material. As the chip equivalent in particular takes care of feed, depth of cut, nose radius, and side cutting angle, the chip equivalent therefore would be a variable as important as the cutting speed. The quantities regarded essential by Colding for the analysis have been shown in Section 2.6.2.4, and the application of the principles of dimensional analysis to these quantities yields either:

$$V\,T\,q = f\left[\frac{V^2\,T}{K}\right] \tag{56}$$

or in a more general form:

$$K\,T\,q^2 = \phi\,(V\,T\,q) \tag{57}$$

In an attempt to establish the law governing the relations (56) and (57) a convenient way is often to plot actual data on bi-logarithmic graph paper. However, owing to the lack of temperature, diffusivity, and tool life data for corresponding cutting speeds etc., Colding's investigations were limited to plotting the relations (56) and (57) for varying chip equivalent and cutting speed values, holding tool life constant. As tool life is assumed to depend entirely on temperature, then thermal diffusivity must also assume a constant value for constant tool life. In doing so Colding found that (56) gave curves while (57) yielded straight lines

FIGURE 18., shows the terms of (57) plotted, where three test series covering high speed steel tools cutting of 0.6C, 0.45C, and Cr-Ni steels, and two test series for carbide tools cutting carbon and Cr-Ni steels are represented. As the values of thermal diffusivity are unknown, this was set equal to 1.

The relative displacement between the relations for tool life equal to 60 and 1 minute, in FIGURE 18., has no meaning: only the slopes are important. The slopes are different for the two tool life values chosen as well as between different materials. It is seen that over a large range of chip equivalent values the relations are essentially straight.

To further test the validity of the assumption of the dependance of tool life on temperature, tests by Colding [49] using the tool-thermocouple methods are shown in FIGURE 19. Assuming a relation equivalent to (57):

$$KEq^2 = U(VEq)^{1/2} \tag{58}$$

The plotted relations valid for two different carbide grades and 0.6C and Cr-Ni steel, are of the same shape and slope as those in FIGURE 18. The straight line dependance is neither valid for large values of chip equivalent when based on electro-motive force measurements nor when based on tool life data. This observation is important, since it confirms the great dependance of tool life upon temperature and chip equivalent. The relations shown in FIGURES 18,19., indicate that a straight line approximation seems justified in the chip equivalent region corresponding to rough machining. Woxen [32,46] has concluded that straight line relations regarding (52) are obtained for the chip equivalent region corresponding to finish machining.

It may be assumed that a relation of the form:

$$K\,T\,q^2 = C\,(V\,T\,q)^{b/2} \tag{59}$$

may be applied in either the region of rough cutting or finishing. In (59) b is the slope in FIGURES 18,19., corresponding to a certain tool life.

2.8 VARIABLES AFFECTING CUTTING TOOL LIFE

The variables affecting the tool life may be listed as:

(i) cutting conditions; speed, feed and depth of cut.
(ii) tool geometry.
(iii) tool material.
(iv) work material.
(v) cutting fluid.

The type and condition of the machine tools used are also very important.

2.8.1 Effects Of Cutting Conditions

The variables, speed, feed rate and depth of cut are important since they control the rate of metal removal and production rate. Tool life and cutting speed can usually be related by an equation of the form of (39). Similar trends occur for the feed and depth of cut, so that the tool life may be expressed as (49).

Equation (49) is an extension of the Taylor equation, and has been suggested by a number of workers [26] . The values of the exponents and the constant in (49) will depend on the failure criterion. It is also found that the exponents will vary with different tool and work materials. The exponents describe the effects of the variables on tool life. The larger the exponent the steeper the cutting speed-tool life slope and the greater the change in tool life for a given change in cutting speed. It is usually found that $1/n > 1/n_1 > 1/n_2$ so that the cutting speed has the greatest influence on the tool life, followed by the feed and depth of cut, respectively. The influence of these variables is often explained in terms of cutting temperatures. It has been suggested that tool life is a direct function of temperature irrespective of the cutting conditions and from a practical point of view it is to be expected that the cutting temperature will rise with increases in the three variables; this having been confirmed by

Takeyama and Murata [50]. The tool life equation has been expressed in terms of the cutting velocity and the chip equivalent or its reciprocal called the equivalent chip thickness. One such equation shows the effect of chip equivalent on the cutting speed for a fixed tool life as (54).

Combining (39) with (54) the tool life equation becomes:

$$T = \frac{K' \, q^{m'}}{V^{1/n}} \tag{60}$$

FIGURES 20,21., show the effects of cutting speed on tool life for various speeds, feeds and depths of cut.

Colding [35] considered tool life to be a direct function of temperature so that the latter was not included as a variable in his analysis. The size of cut was represented by the chip equivalent, such that the chip equivalent takes care of the feed and depth of cut. Colding established the two dimensionless groups shown in (59). Colding plotted experimental data for fixed tool life values of 1 and 60 minutes respectively and since he assumed temperature and tool life to be directly related, then for a fixed tool life, thermal diffusivity was considered constant and given an arbitrary value of 1. By plotting the dimensionless groups on logarithmic co-ordinates it was shown that approximately linear relations were obtained for a wide range of chip equivalent values, although the slopes for 1 and 60 minute tool life were not equal, FIGURE 18., shows the trends.

Colding re-arranged (59) and compared it to the Taylor type tool life equation thus:

$$V\,T^{1-2/b} = \left[\frac{K_T}{C_T}\right]^{2/b} q^{4/b-1} \qquad (61)$$

2.8.2 Effect Of Tool Geometry

Increasing the normal rake angle of a cutting tool reduces the cutting forces and the heat generated in cutting. Increasing the rake angle can reduce the path for heat transfer, which can tend to increase the cutting temperatures. From the temperature aspect, an optimum rake angle may occur which gives rise to a maximum tool life.

Tests by Crawford and Merchant [52] in which steel was face milled with a single tooth fly cutter of various rake angles gave results which indicated that with 0 or 10 rake, tool life decreased regularly with increasing cutting speed in the accepted manner. When larger rake angles were used, the tool life at high cutting speeds was improved while the life at low cutting speeds was reduced. FIGURE 22., shows the effects of rake angle on tool temperature. FIGURE 23., shows the effects of cutting speed on tool life for different rake angles.

Crawford and Merchant also found that the size of the built up edge decreased with an increase in cutting speed or true rake angle. The nose radius of cutting tools affects tool life. The larger the nose radius, the longer the life, or in other words, the higher the cutting speed for a given tool life. An increase in nose radius generally causes a reduction in tool tip temperature [53]. As would be expected therefore, the lower temperature and longer tool life go together. In practice, it may be necessary to reduce nose radius to avoid chatter and vibration.

2.8.3 Effect Of Tool Material

The requirements of cutting tools are high hardness and toughness, good wear resistance, mechanical and thermal shock resistance and the ability to maintain these properties at the temperatures occuring during cutting. Tests on the variation of tool hardness with temperatures up to 760°C have been conducted [54]. FIGURE 24., shows the effect of temperature on the hardness of various tool materials. In this representation we can take hardness as a guide to wear resistance. As a rough guide the toughness of these tool materials may be ranked in the reverse order to their hot hardness, so that carbon steel and high speed steel head the toughness list.

A brief review of carbon and high speed steel tool material is of interest at this stage.

2.8.3.1 Carbon Steel

Carbon steel with about 1 per cent carbon has been used as a cutting tool material. Although a number of alloying elements are usually added, the tool is still classed as a carbon tool steel. Additions of chromium and manganese improve the hardenability and the inclusion of tungsten increases the wear resistance. Tungsten forms hard tungsten carbide particles which are dispersed in the tool material. This tool material can be used at slow cutting speeds and for materials which develop low cutting temperatures. Carbon tool steel is relatively cheap and may be economically justified in small production runs.

2.8.3.2 High Speed Steel

High speed steel tools are steel alloys with a high percentage of tungsten (or molybdenum) and chromium, together with vanadium. These steels have a high hot hardness and are tough and shock resistant. High speed steel tools can be used for roughing and finishing cuts and are not susceptible to chipping of the cutting edge. For higher hardness and abrasive wear resistance higher percentages of cobalt (5-12%) and vanadium (2-5%) are added. Additions of vanadium usually require higher carbon content to achieve the required hardness.

The effect of cutting speed on tool life for various common tool materials is shown in FIGURE 25.

2.8.4 Effect Of Work Material

The work material, like the tool material, is a major variable affecting the tool life. The common variables considered are work material composition and micro-structure (heat treatment), its hardness and work hardening properties. The hardness of the work material is the easiest variable to measure and relate to tool life. As might be expected the harder the work material, the lower the tool life, although there are exceptions. Kronenberg [26] has shown that the cutting speed for a fixed tool life is related to the hardness of the workpiece by an equation of the type:

$$V_T = \frac{\text{constant}}{(\text{Brinell Hardness Number})^x} \qquad (62)$$

The constant depends on the work material and tool material, while the exponent varies with tool material.

FIGURE 26., shows the relation between cutting speed, for a fixed tool life, and Brinell hardness of the workpiece when turning steel. It is apparent that the Brinell hardness, which gives an average hardness measurement is not the only work material variable to account for the effect of work material properties on tool life. The hardness of the work material constituents and their proportions will all influence the average hardness and the life of a cutting tool.

3 A REVIEW OF PREVIOUS WORK ON THE POWER HACKSAW AND BANDSAW OPERATIONS

3.1 INTRODUCTION

Early published work on cutting-off operations have been primarily concerned with a general description of circular sawing, bandsawing and power hacksawing [58-60] , and cost comparisons between these alternative processes [61-63].

From about 1970 onwards investigations increased endeavouring to understand the actual cutting mechanism of the saw blade.

Sarwar and Thompson [4] investigated the cutting action of a single blade tooth. They found that the depth of cut achieved per blade tooth was small when compared to the cutting edge radius; even when the blade was new. Previously little work had been undertaken on metal cutting operations in which the depth of cut is far less than the cutting edge radius. The cutting edge radii was found to be in the range 20-76μm., for blades of various pitch of teeth, see FIGURE 3. The depth of cut achieved per tooth was found to be 2-30μm., depending on the thrust load applied to the saw frame. This led to an interest in the cutting action of a tool having a larger cutting edge radius than the depth of cut. Sarwar and Thompson concluded that with this geometric arrangement the actions of 'ploughing' and 'piling up', combine to give an unusual cutting action. They classified the cutting action of a hacksaw blade by three groups, namely:

(i) metal removal by a ploughing and piling up action.

(ii) metal removal by ploughing and continuous or segmented chip formation.

(iii) metal removal by a combination of (i) and (ii).

They discovered that another distinguishing feature of this type of cutting action was the high value of the thrust component of the cutting force when compared with the cutting component. In addition, considerable variation in the thrust component occurred at the beginning of each cut. In the piling up action the thrust load gradually increased until a steady state had been reached. This steady state was associated with the termination in growth of contact between the chip and tool. The cutting tool had to progress along the cut for a considerable distance when compared with the depth of cut, before the steady state condition was achieved. This effect is reported to have a significant effect on the cutting action of a multi-point cutting tool such as a power hacksaw blade, and Sarwar and Thompson suggested that the size effect observed when sawing workpieces of different breadths was directly attributed to this phenomenon.

3.2 EMPIRICAL RELATIONSHIPS OF THE POWER HACKSAW OPERATION

Thompson and Sarwar [1] carried out further investigations into the mechanics and economics of power hacksawing.

A method of instrumentation evolved by which the load, developed between the blade and the workpiece, could be measured on a hydraulic power hacksaw machine, against the position in the stroke of the saw. The three mutually normal components of the cutting force were measured, via the workpiece, by a dynamometer clamped in the workpiece vice of the machine. The load measuring element of the dynamometer consisted of the Kistler 9257A piezo-electric, three component dynamometer and its associated charge amplifiers, [64]. The displacement of the blade was measured by a linear transducer and transducer meter. At slow rotational speeds of the saw, the outputs from these instruments were displayed on an 'X-Y' plotter; loads against blade displacement, FIGURE 1.

They investigated the cutting action of both new and worn blades.

3.2.1 Cutting Action Of New Blades

Thompson and Sarwar [1] carried out cutting tests and showed that the average depth of cut achieved per tooth is very small. These measurements together with those of the cutting edge radius, show that in the majority of applications the depth of cut is less than the cutting edge radius. The cutting action of a hacksaw blade was considered to be that of a blunt cutting tool.

FIGURE 27., shows the variation in the average depth of cut per tooth against the mean thrust load per tooth per unit thickness for

an En1a workpiece and blades of different pitch. The relationship was written as:

$$\delta a = K . fm \qquad (63)$$

Thompson and Sarwar investigated the size effect by plotting the variation in the cutting constant against the reciprocal of the number of teeth in contact with the workpiece, FIGURE 28. The size effect was summarized as follows:

when B $\geqslant$25mm. for En1a

$$K = a + bp \qquad (64)$$

when 2p< B<25mm. for En1a

$$K n_c = C \qquad (65)$$

3.2.2 Cutting Action Of Worn Blades

Thompson and Sarwar [1] carried out cutting tests in which the wear flat produced at the tip of each tooth was measured. FIGURE 29., shows the loss in height of a tooth with increases in the number of cuts made, and is similar to that obtained by measuring flank wear on a single point cutting tool, and it shows primary, secondary, and tertiary regions. The primary region is reported to be due to manufacture when the cutting edge is dulled by flame hardening. FIGURE 30., shows the variation between the average depth of cut per tooth and the mean thrust load per tooth per unit thickness, for a blade in three stages of wear. This shows how wear reduces the cutting constant and shifts the curve along the thrust force axis. Thompson and Sarwar concluded that some initial load was needed before material is removed by worn blades.

Expressions were derived for the average depth of cut achieved per tooth and also for the determination of the mean thrust load per tooth per unit thickness.

3.2.3 Determination Of The Average Depth Of Cut Per Tooth

The volume of material removed during a small displacement of the blade in the cutting stroke, FIGURE 31., is given by:

$$\Delta(\text{vol}) = t \; n_c \; \delta \; x \qquad (66)$$

As the thrust load varies during the cutting stroke, the instantaneous depth of cut achieved per tooth also varies. Hence, the volume of material removed during one cutting stroke becomes:

$$(\text{vol})_s = t \; n_c \int_0^s \delta \; dx \qquad (67)$$

Since the instantaneous depth of cut is difficult to measure experimentally, Thompson and Sarwar found it convenient to introduce the average depth of cut, achieved during the cutting stroke per tooth, defined as:

$$\delta a = \frac{1}{S} \int_{0}^{S} \delta \, dx \qquad (68)$$

Combining (67) and (68) and substituting Bp for n_c gives:

$$(vol)_S = t \; B \; p \; \delta a \; S \qquad (69)$$

The volume of material removed during the cutting stroke may also be found from the loss in volume of the workpiece. For a rectangular workpiece this becomes:

$$(vol)_S = w \, B \, \Delta s \qquad (70)$$

Combining (69) and (70) gives:

$$\delta a = \frac{w}{t} \cdot \frac{D}{N} \cdot \frac{1}{S\,p} \qquad (71)$$

The number of teeth which make contact with the workpiece during the cutting stroke is:

$$Nc = (S + B)p \qquad (72)$$

However, the teeth which are in contact with the workpiece at the beginning and at the end of the cutting stroke do not travel across the full breadth of the workpiece. The equivalent number of teeth which may be said to make one complete traverse of the workpiece is shown to be:

$$Ne = S\,p \tag{73}$$

Combining (71) and (73) gives:

$$\delta a = \frac{D}{N}\,\frac{z}{Ne} \tag{74}$$

3.2.4 Determination Of The Mean Thrust Load Per Tooth Per Unit Thickness

Thompson and Sarwar [1] defined the mean thrust load per tooth per unit thickness as the mean load acting between the blade and the workpiece during the cutting stroke per tooth per unit blade thickness; assuming that each tooth in contact carries equal load.

The mean total thrust load acting between the blade and the workpiece is given by:

$$Fm = \frac{1}{S}\int_{0}^{S} F\,dx \tag{75}$$

The mean thrust load per tooth per unit blade thickness is given by:

$$Fm = fm \; n_c \; t \tag{76}$$

For broad workpieces this may be written:

$$fm = \frac{Fm}{B p t} \tag{77}$$

Since the load developed between the blade and the workpiece, and its variation during the cutting stroke, depends on the type and characteristics of the sawing machine, the mean thrust load per tooth per unit blade thickness is a machine parameter controlled by the machine settings etc.

The number of cutting strokes needed to cut through a rectangular workpiece may be found by combining (63), (71) and (77) thus:

$$N \; S \; Fm = \text{constant} \tag{78}$$

3.3 A THEORETICAL STUDY OF THE CUTTING ACTION OF POWER HACKSAW BLADES

3.3.1 The Chip Formation Process

Thompson [65] has attempted to explain the variation of the cutting constant with tooth pitch and workpiece breadth.

At the onset of the work it was thought that there were two possible causes of these variations. The first was attributed to the effect of blade deflection and relative movement such deflection produced between individual teeth in contact with the workpiece. It was thought that sufficient difference in the depth of cut could be achieved by individual teeth due to blade deflection to explain the variation in the cutting constant with changes in both the pitch of the teeth and workpiece breadth. To check this possibility tests were carried out in which the cutting constant was measured for a particular blade and subsequently the width of the same blade reduced, by grinding the back of the blade, and the cutting constant re-measured. Such tests produced negligible change in the cutting constant in spite of the fact that the flexibility of the blade had been increased. As a result of these tests Thompson [65] concluded that blade deflection plays a minor role in determining the metal removal rate of the blade.

The second possible cause investigated was due to some feature of the mode of chip formation. Sarwar and Thompson [4] had shown that a deformation zone is produced in front of each tooth which once fully established is unaffected by further metal removal. The deformation zone associated with this steady state is large and not instantaneously established when the tooth first makes contact with the workpiece. During the earlier stage of chip formation when the size of the deformation zone is increasing it has been shown [4] that both components of the cutting force acting on the tooth gradually increase until a final steady state is achieved corresponding to the fully established deformation zone.

According to this model of chip formation some of the teeth in contact with the workpiece will be acted on by a constant thrust force and those teeth which have just begun their cutting action will be acted on by a thrust force which increases with tooth movement along the cut. Sarwar and Thompson [4] have shown that the length of cut a tooth must make before the cutting force component acting on it, reaches steady state conditions, is constant for a given workpiece material and does not vary with the depth of cut. This means that the thrust load per tooth varies over the teeth in contact with the workpiece, reaching a constant value on those teeth which have achieved a considerable length of cut. Thompson [65] based his analysis on this type of chip formation and assumed that the size of the chip produced is not sufficient to fill the chip space between the teeth, therefore blade 'clogging' does not occur.

Thompson [65] postulated that the thrust load per tooth increased with the length of cut in the period before the deformation zone was fully established, in accordance with [4]. Once the deformation zone becomes established the thrust load was considered to remain constant, thus:

when $y \leqslant y_c$

$$f = M S \left[\frac{y}{y_c} \right]^n \qquad (79)$$

when $y \geqslant y_c$

$$f = M\,\delta \tag{80}$$

Thompson subdivided his analysis and covered three specific ideas:

(i) chip formation once the deformation is fully established.

(ii) the average thrust load per tooth per unit thickness.

(iii) the cutting constant.

3.3.2 Chip Formation Once The Deformation Is Fully Established

Thompson based his model on a deformation zone consisting of a slip line field of the Lee-Shaffer type [66]. FIGURE 32(a)., shows the fully established deformation zone where the workpiece is separated from the chip by a shear plane A-B and the chip makes contact with the saw tooth along the plane A-C. A wedge of material surrounds the cutting edge forming a chip. FIGURE 32(b)., shows the corresponding Mohr's stress diagram, from which:

$$\phi + \lambda - \alpha = \pi/4 \tag{81}$$

The thrust component of the cutting force is determined by considering the forces acting on the shear plane A-B in FIGURE 32(a)., giving:

$$f = k\,\delta\,(\mathrm{Cot}\,\phi - 1) \tag{82}$$

Comparing (80) with (82) gives:

$$M = k(\operatorname{Cot}\phi - 1) \tag{83}$$

Equations (81) and (83) enable the cutting constant for a fully established chip to be determined for a given apparent coefficient of friction and material which Thompson shows in FIGURE 33.

3.3.3 The Average Thrust Load Per Tooth Per Unit Thickness

Equation (79) gives the tooth loading per unit thickness, this can be written generally as:

$$f_i = M\,\delta\left[\frac{i}{n_t}\right]^n \tag{84}$$

since

$$y = i\,p$$

and

$$y_c = n_t\,p \tag{85}$$

The total thrust load acting may be written:

$$F = t\left[\sum_{i=n_t}^{i=n_c} f_i + \sum_{i=0}^{i=n_t} f_i\right] \tag{86}$$

This can be expressed as:

$$F = M \delta t \left[n_c - n_t + \sum_{i=0}^{i=n_t} \left[\frac{i}{n_t}\right]^n \right] \qquad (87)$$

The total thrust loads according to Thompson's model are shown in FIGURE 34.

Because of the experimental difficulty in measuring individual tooth loads an average tooth load per unit thickness has been used and is given by (77).

By combining (77) and (87) this may be written:

$$fm = M \delta \psi \qquad (88)$$

when $n_c \geqslant n_t$

$$\psi = \frac{1}{n_c} \left[n_c - n_t + \sum_{i=0}^{i=n_t} \left[\frac{i}{n_t}\right]^n \right] \qquad (89)$$

and $n_c \leqslant n_t$

$$\psi = \frac{1}{n_c} \sum_{i=0}^{i=n_c} \left[\frac{i}{n_t}\right]^n \qquad (90)$$

3.3.4 The Cutting Constant

Previous work [1] has given a linear relationship between the average depth of cut per tooth and the mean thrust load per tooth per unit thickness measured over one stroke (63,71 and 77).

If (68) is combined with (88) this gives:

$$\delta a = \frac{1}{M \psi S} \int_0^S fa \; ds \qquad (91)$$

By definition:

$$fm = \frac{1}{S} \int_0^S fa \; ds \qquad (92)$$

Hence putting (92) into (91) gives:

$$\delta a = \frac{1}{M \psi} fm \qquad (93)$$

Combining (63) with (93) gives:

$$K = \frac{1}{M \psi} \qquad (94)$$

Equation (94) enables the cutting constant to be related to the characteristics of the chip formation and variations in the cutting constant to be investigated.

Thompson's analysis [65] has shown that as the number of teeth in contact with the workpiece increases, the cutting constant approaches the value associated with the fully established chip, hence when:

$$n_c \longrightarrow \infty\,, \; K \longrightarrow 1/M$$

Theoretical values of apparent coefficient of friction using the Lee-Shaffer type model, obtained from FIGURE 33., gave good agreement with experimental values which were based on (94), such that:

$$\frac{1}{\psi} = M\,K \quad \text{but} \quad M = \frac{1}{(K)_{n_c \rightarrow \infty}}$$

therefore

$$\psi^{-1} = \frac{K}{(K)_{n_c \rightarrow \infty}}$$

FIGURE 35., shows computed values of the reciprocal of the chip factor for various values of the cutting force index, together with experimental values obtained with a blade having 10 teeth per 25mm. This comparison indicates that a cutting force index equal to 1 is needed for close agreement. FIGURE 36., shows computed values of

the reciprocal of the chip factor for a force index of unity, together with experimental values obtained with blades of different tooth pitch. From these results Thompson calculated that the average critical length of cut made by a tooth (y_c) to fully establish a deformation zone is 14.8mm.

Thompson suggests that the reason for variation in the cutting performance with change in the breadth of the workpiece is as follows. For workpieces with small breadths a high proportion of the teeth in contact will have a partly established deformation zone. Therefore, the applied thrust load appears more effective as larger depths of cut are possible for a given average tooth loading. This condition leads to a high cutting constant and an apparently improved blade cutting performance. When the breadth of the workpiece is large a high proportion of the teeth in contact will have a fully established deformation zone and the cutting constant will be, to a large extent, dependant on the thrust load produced by the fully established deformation zone. This leads to a low cutting constant and an apparent reduction in the cutting efficiency of the blade.

Thompson's model also explains why the pitch of the teeth influences the cutting performance of a blade for a given workpiece breadth. The pitch of teeth controls the number of teeth in contact with the workpiece and the number of teeth associated with a partly formed deformation zone. These factors have been shown to affect the total thrust load needed to achieve a given depth of cut per tooth and, therefore, the average tooth loading. The cutting constant and the cutting efficiency of the blade increase with an increase in tooth pitch due to these effects.

3.4 FACTORS INFLUENCING THE SAWING RATE DURING THE POWER HACKSAW AND BANDSAW OPERATIONS

Thompson [67] derived expressions for the cutting rates achieved by various sawing operations and compared the characteristics of power hacksaw and bandsaw operations.

Based on cutting tests, Thompson assumed that the cutting action of power hacksaw and bandsaw blades are identical and that the linear relationship (63) between the instantaneous depth of cut per blade tooth and the instantaneous average thrust load per tooth per unit blade thickness applied.

Equation (69) may be written:

$$\dot{vol} = B p t \delta V \tag{95}$$

Equation (70) may be written:

$$\dot{vol} = w B \upsilon \tag{96}$$

3.4.1 The Power Hacksaw Operation

Combining (63), (67) and (70), (77) gives:

$$(vol)_S = K \int_0^S F \, dx \tag{97}$$

or

$$(vol)_S = K \, Fm \, S \tag{98}$$

Combining (98) and (70) gives:

$$Fm = \frac{wB}{K} \left[\frac{\Delta_S}{S} \right] \tag{99}$$

hence

$$N = \frac{w \, B \, D}{K} \quad \frac{1}{S \, Fm} \tag{100}$$

Thompson [67] has shown the variation between the total thrust load developed by a positive sawing machine for a given feed per cutting stroke, (99) and the number of cutting strokes needed to cut through a rectangular workpiece, (100); see FIGURE 37.

3.4.2 The Bandsaw Operation

The rate at which volume is removed by a bandsaw operation is given by (95) and (96) which are combined with (63) and (77) to give:

$$\nu = \frac{K}{Bw} F V \tag{101}$$

Equation (101) shows that the distance cut per unit time is directly proportional to the thrust load applied and the speed of the band. FIGURE 38., shows the variation between these parameters and is based on experimental work carried out by Thompson [67].

A detailed experimental investigation of the factors influencing the cutting constant has been undertaken [1]. FIGURE 28., is based on data obtained by a power hacksaw, but FIGURE 39., compares data obtained by both power hacksaw and bandsaw operations.

All tests carried out by Thompson [67] were obtained under conditions in which the blades were free from clogging; the geometries of the power hacksaw tests were such that they were carried out in the area A-B-C in FIGURE 40.

3.5 FACTORS INFLUENCING THE WEAR RATE OF POWER HACKSAW BLADES

3.5.1 Dimensional Analysis - Blade Wear Testing

Thompson and Taylor [5] attempted to identify the wear mechanisms involved in power hacksaw blade wear. They adapted a method based on dimensional analysis first proposed by Colding [35] which relates some of the engineering parameters associated with power hacksaw operations to the wear rate of the blade. Some attempt has also been made to identify the fundamental wear mechanisms involved, using the system of classification proposed by Wright and Trent [13].

Thompson and Taylor listed some of the features of a power hacksaw operation which influence blade wear; these are:

(i) the surface against which the blade is rubbing is newly cut from the work material and there is little time for oxide or other films to form.

(ii) the surface on which the blade is rubbing has severely work hardened in the plastic processes involved in forming the chip.

(iii) the temperature and pressure at the sliding interface are exceptionally high, the specific cutting energy obtained can be as high as 6.0 G.J. / unit volume, (m^3).

(iv) the blade teeth are not in continuous contact with the workpiece and they achieve an intermittent cutting action.

The percentage of time an individual tooth is in contact with the workpiece can vary between 10-28 per cent.

(v) as the blade teeth wear the depth of cut they achieve decreases and, hence, the geometry of chip formation varies throughout the blade life. Typical variation in the average depth of cut achieved is 3.5-14μm., at a mean thrust load per tooth of 78Nmm^{-1}.

(vi) the cutting speed varies approximately sinusoidally during each cutting stroke, typical variation is from zero to a maximum of 72m.min^{-1}., at a cutting rate of 76 strokes per minute.

(vii) the thrust load acting between an individual blade tooth and workpiece, also, varies throughout each cutting stroke. Typical variation is from zero to a maximum of 175Nmm^{-1}., at a cutting rate of 76 strokes per minute.

Thompson and Taylor felt that a rigorous investigation of the wear mechanisms involved in hacksaw blade wear was outside the scope of their investigation [5], but some microscopic examinations of the sections of teeth during phase II (linear phase) of the wear process were undertaken. They compiled FIGURE 41., from these observations, and indicated that two main processes produced hacksaw blade wear, these processes are:

(i) superficial plastic deformation by shear at high temperature.

(ii) plastic deformation of the cutting edge.

3.5.2 Thompson And Taylor - Adaptation Of Colding's Tool Life Equation

Colding's three dimensional tool life equation is given by (59) and may be written:

$$\propto Tc\, q^2 = C(V\, Tc\, q)^{b/2} \tag{102}$$

Colding's tool life equation is based on lathe tool data and since the physical conditions controlling the wear of power hacksaw blades are quite different from those controlling the wear of lathe tools, it is necessary to express the tool life, chip equivalent and cutting speed in terms of parameters that can be measured during a power hacksaw blade wear test.

Thompson and Taylor modified these variables as shown below.

3.5.2.1 Tool Life

Experimental data had shown a linear relationship between the effective cutting constant and the number of cutting strokes in the second wear phase, FIGURE 42. Based on these results:

$$\frac{dKe}{dn} = \frac{Ko}{n_{max}}(1-\eta) \tag{103}$$

and

$$\dot{K}e = \frac{dKe}{dn} \cdot \frac{dn}{dT_L} = \frac{dKe}{dn} \cdot \phi \qquad (104)$$

where

$$n_{max} = \phi T_L$$

Colding's tool life is based on the time the tool is in contact with the workpiece and being subjected to the conditions which produce wear. In fact for a turning operation there is no difference between this and actual time, but as a power hacksaw tooth achieves an intermittent cutting action there is a significant difference between these times, which must be taken into account, thus:

$$T_C = R\, T_L \qquad (105)$$

where

$$R = B/2S$$

Combining (103) and (105) gives:

$$T_C = R \frac{Ko}{\dot{K}e} (1 - \eta) \qquad (106)$$

3.5.2.2 The Chip Equivalent

The chip equivalent in terms of power hacksawing parameters is:

$$q = 1/\delta a \tag{107}$$

However, as the blade wears the cutting efficiency decreases, leading to a reduction in the average depth of cut and an increase in the chip equivalent. As the chip equivalent is related to the interface temperature, Thompson and Taylor considered that the general level of temperature would be indicated by taking a mean value for the chip equivalent. In addition, as it was desired to relate changes in the effective cutting constant to other parameters, they found it more convenient to express the chip equivalent in terms of the thrust load and the mean cutting constant, so:

$$q = \frac{2}{Ko\ fm\ (1 + \eta)} \tag{108}$$

3.5.2.3 Cutting Velocity

During each cutting stroke the cutting velocity varies from zero at either end of the stroke to a maximum value at mid-stroke position. For the purpose of dimensional analysis Thompson and Taylor considered it adequate to replace the cutting speed used by Colding with the mean cutting speed based on blade displacement, thus:

$$Vm = \frac{1}{S} \int_{0}^{S} V \, dx \qquad (109)$$

or

$$Vm = 2 S \phi \qquad (110)$$

3.5.3 The Modified Blade Life Equation

Substituting the adapted parameters into Colding's tool life equation, (102), gives:

$$\propto \frac{R}{\dot{K}e} \frac{1}{Ko} \frac{1}{fm^2} = C' \left[Vm \frac{R}{\dot{K}e} \frac{1}{fm} \right]^{b/2} \qquad (111)$$

where

$$C' = C \left[2 \left[\frac{1 - \eta}{1 + \eta} \right] \right]^{\frac{b}{2} - 1} \left[\frac{1 + \eta}{2} \right]$$

The constant C', resulting from the modification depends on the chosen end point (FIGURE 42.).

The blade life equation may be re-arranged to give:

$$\frac{dKe}{dn} = C'' \, B \left[\frac{Vm\,Ko}{\alpha}\right]^{\frac{1}{b/2-1}} \left[fm\right]^{\frac{2-b/2}{b/2-1}} \tag{112}$$

when

$$C'' = C'^{\frac{1}{b/2-1}} \tag{113}$$

3.5.4 Wear Testing Procedure And Results

Thompson and Taylor [5] carried out a number of wear tests under differing conditions of load, speed and workpiece breadths for blades of different pitch. The procedure they used for obtaining data is as follows.

At each applied thrust load and cutting rate the blade is used to cut through the rectangular test bar a number of times. Measurements are taken of the mean thrust load and the number of cutting strokes required to cut through the workpiece, from these measurements the effective cutting constant is determined for each cut. By this procedure the effective cutting constant can only be determined once per section cut, FIGURE 42., and is shown against the mean number of cutting strokes performed, hence, if the blade had previously performed 2000 cutting strokes and requires a further 300 to cut through the test bar, the corresponding effective cutting constant is shown against 2150 strokes.

Each set of results were shown on a diagram similar to FIGURE 42., and the change in the cutting constant per cutting stroke (the wear rate), determined. The adapted Colding parameters were calculated and the results displayed on a bi-logarithmic plot based on the dimensionless groups in (111). FIGURES 43., and 44., show results obtained for En44E and carbon steel respectively, with and without coolant. The constant and Colding's wear index (111) were determined, using a minimum error routine on a computer. In keeping with Colding's procedure [35], the diffusivity was taken as unity in every case. The corresponding cutting constant for an unused blade was taken to be the constant determined during the first cut. The variation in the initial cutting constant against the reciprocal of the number of teeth in contact with the workpiece for both workpiec materials are given in FIGURES 45., and 46.

FIGURE 47., shows a bi-logarithmic plot of the change in the effective cutting constant per cutting stroke against the thrust force per tooth per unit thickness for En44E cut dry; experimental results and theoretical predictions are shown. FIGURE 48., shows the influence of coolant flow rate on the initial cutting constant and the change in the effective cutting constant per cutting stroke when cutting En44E. FIGURE 49., shows the variation of the blade wear rate against the breadth of workpiece; experimental results are compared with

predictions based on (112).

FIGURE 50., shows the influence of some common workpiece sections on the wear rate for En44E cut dry. FIGURE 50., tends to exaggerate the effect of workpiece size and shape, since it does not take into account the number of strokes needed to pass through the various levels in the sections shown. The total damage caused by cutting a given section will depend on the wear rate produced at each level in the section and the number of strokes needed to pass each level.

3.6 THE LATERAL DISPLACEMENT OF A SAW BLADE AND ITS INFLUENCE ON THE QUALITY OF CUT

3.6.1 Introduction

Thompson and Taylor [6] investigated the effects of the lateral displacement of a power hacksaw blade on the quality of cut. The authors listed five factors which they believed caused the lateral movement of the cutting edge. These factors are listed below and are primarily associated with geometric and metallurgical differences between the set teeth on either side of the cutting edge.

(i) because of an error during manufacture the 'setting' of the teeth which give side clearance to the blade has not occurred symmetrically, this error can lead to geometric differences between one side of the blade and the other.

(ii) due to poor end fixing the blade is held inclined to the mean plane of cutting. Such a situation is known to lead to excessive wandering of the blade and the production of an out-of-square cut.

(iii) it is believed that some methods of end fixing lead to a situation in which the strengthening effect of the blade tension is not transmitted effectively to the cutting edge. Such an effect is influenced by the position of the pin holes in the blade and leads to a greater tendency for the cutting edge to wander.

(iv) heat treatment during manufacture is known to 'round' the cutting edges of the blade and can under certain undesirable conditions lead to adverse metallurgical changes in the surface of the blade. It is possible that such effects can occur in a way which effects one side of the blade more than another thus producing a difference in the cutting effectiveness of the set teeth.

(v) during use the cutting edge can wear more on one side than the other. This will occur when the temperature generated as a result of the cutting action is higher on one side of the cut than the other. Such an effect occurs when the length of the workpiece on either side of the cut is different. Also, a temperature difference can be created by unequal flow of cutting fluid on either side of the blade.

Thompson and Taylor evolved a theoretical model to explain the mechanism of an out-of-square cut: the model is explained here.

As the cutting edge wanders away from the mean plane of cutting the body of the blade is elastically twisted and laterally bent. The stiffness of the blade generates a reaction at the cutting edge which opposes this lateral displacement. The stiffness of the blade depends on the blade section and the tension load applied along the length of the blade. As the elastic reaction produced is proportional to the lateral displacement of the cutting edge a situation is created in which little restraint is applied to prevent the initiation of the cutting edge wandering from the mean plane of cutting. Sideways movement of the cutting edge occurs during each cutting cycle and leaves a ridged impression in the side wall of the slot produced, this is the cause of the rough surface finish produced. Also, under extreme conditions the movement of the cutting edge at right angles to the plane of cutting is not completely corrected during the cutting cycle so that permanent and preferential displacement to one side occurs, this leads to an out-of-square cut.

Thompson and Taylor [6] considered that the surface finish produced is also affected by the ploughing of the workpiece metal around the blade teeth [4] during the normal cutting action. As each blade tooth travels across the workpiece the amount of metal accumulated in front of the tooth and the amount passing around the tooth as a result of the ploughing action increases. The metal which passes around the set teeth; that is the teeth close to the walls of the slot, flows past the cut surface and causes considerable roughening of the slot walls. The extent of the roughening depends on the amount of metal flowing past the teeth and, therefore, is more pronounced on the side of the workpiece which is positioned at the end of the cut. This effect has been found to cause considerable differences in the surface finish produced on one side of the workpiece compared with the other, PLATE II. This effect has been shown to depend on the workpiece material and is considerably reduced when a cutting fluid is used.

3.6.2 Lateral Displacement Of The Cutting Edge During The Cutting Stroke

FIGURE 51., shows the cutting edges of three consecutive teeth on a blade which has raker set; one tooth in line with the blade, one set to the right and one set to the left, [3]. Thompson and Taylor [6] assumed that all teeth on the blade achieve an orthogonal cutting action, and that the relationship between the component of the cutting force acting normal to a cutting edge and its undeformed chip thickness [1] and [65] is:

$$R = \frac{\delta u \ t}{K} \qquad (114)$$

In order to describe the difference in the cutting effectiveness of the two set teeth it is taken that the inferior edge has a cutting constant $(K - \Delta K)$ and the superior edge a constant $(K + \Delta K)$, where ΔK is a variance in the cutting constant. FIGURE 51., shows the difference in the setting angles and variation in the undeformed chip thickness that occurs due to the sideways movement of the cutting edge.

From the geometry of the cut and the definition of the cutting constant we have:

$$R_A = \frac{\delta t}{K} \cos \phi$$

$$R_B = \frac{\delta t}{(K - \Delta K)} \cos(\beta + (\Delta\beta + \phi))$$

$$R_C = \frac{\delta t}{(K + \Delta K)} \cos(\beta - (\Delta\beta + \phi)) \tag{115}$$

Because the above components of the cutting forces acting normal to the cutting edges of the set teeth differ, there is a resultant lateral force generated by the cutting action. Resolving forces in the lateral direction for all teeth in contact with the workpiece gives:

$$Q = m\left[R_B \sin(\beta + \Delta\beta) - R_C \sin(\beta - \Delta\beta)\right] \tag{116}$$

Assuming that $\Delta\beta$ is small this may be written:

$$Q = m\left[(R_B - R_C)\sin\beta + (R_B + R_C)\Delta\beta\cos\beta\right] \tag{117}$$

Combining (115) and (117) and neglecting products of small quantities gives:

$$Q = \frac{2\delta tm}{K}\left[\frac{\Delta K}{K}\cos\beta\cos\phi\sin\beta - \sin\phi\sin^2\beta + \Delta\beta\cos\phi(\cos^2\beta - \sin^2\beta)\right] \tag{118}$$

Thompson and Taylor discovered that ϕ is small and hence (118) may be simplified thus:

$$Q = \frac{2\delta tm}{K}\left[\frac{\Delta K}{K}\cos\beta\sin\beta - \phi\sin^2\beta + \Delta\beta(\cos^2\beta - \sin^2\beta)\right] \tag{119}$$

Substituting (63) gives:

$$Q = 2ftm\left[\frac{\Delta K}{K}\cos\beta\sin\beta - \phi\sin^2\beta + \Delta\beta(\cos^2\beta - \sin^2\beta)\right] \tag{120}$$

This expression gives the lateral force generated by the cutting edge as a result of the cutting action. This force is opposed by the lateral load generated as a result of the elastic distortion of the blade. FIGURE 52., shows the direction of action of the components of the cutting force and the blade tension as they are applied to the blade. The blade is shown in its twisted and displaced position after lateral movement of the cutting edge has occured.

Thompson and Taylor [6] assumed that the only contact between the blade and workpiece occurs at the cutting edge and, hence, it is also assumed that the sideways displacement and blade twist are not so excessive as to cause the body of the blade to make contact with the sides of the slot produced.

In order to derive a general solution it is assumed that the blade is clamped so that it is initially inclined to the mean plane of cutting, thus allowing the effects of clamping error to be considered. The torsional and lateral bending stiffnesses are defined thus:

$$\begin{aligned} d\,Q' &= S_t(\theta - \theta_E) \\ Q' &= S_b\, y' \end{aligned} \qquad (121)$$

The torsional and lateral bending stiffnesses are both functions of the blade tensioning force, the geometry of the blade and the position of the workpiece along the blade. Using standard texts, Thompson and Taylor [6] have shown that these stiffnesses are given by the following if the cutting force is assumed a concentrated load and that the workpiece offers such a restraint that no bending or twisting of the blade occurs across the breadth of the workpiece.

This latter assumption enables the effective length of the blade to be taken as the free length of the blade less the breadth of the workpiece.

$$S_t = \left[G a b^3 \psi_1 + \frac{S a^2}{3} \right] \frac{4}{l} \psi_2 \qquad (122)$$

where

$$\psi_1 = \frac{16}{3} - 3{\cdot}36 \frac{b}{a} \left[1 - \frac{1}{12} \frac{b^4}{a^4} \right]$$

and

$$\psi_2 = \frac{1}{4} \left[\frac{1}{\frac{c}{l} \left[1 - \frac{c}{l} \right]} \right]$$

also

$$S_b = \frac{192\, E I}{l^3} \psi_3 \psi_4 \qquad (123)$$

where

$$\psi_3 = \frac{1}{12} \left[\frac{U^3 \operatorname{Cosh} U \ \operatorname{Sinh} U}{\operatorname{Cosh} U \operatorname{Sinh} U (U - \operatorname{Tanh} U) - (\operatorname{Cosh} U - 1)^2} \right]$$

and

$$\psi_4 = \frac{1}{16} \left[\frac{(l/c)^3 - 3(l/c)^2 + 3(l/c)}{(1 - c/l)^3} \right]$$

FIGURE 53., shows the variation in the lateral bending stiffness and torsional stiffness for a standard power hacksaw blade against blade tension forces when the workpiece is at the centre of the blade, that is when

From the geometry of FIGURE 52., and assuming the angle of twist is small, then:

$$y = y' + d\,\theta$$

and (124)

$$y_o = d\,\theta_E$$

Combining (121) and (124) gives:

$$Q' = (y - y_o)\left[\frac{S_b \quad S_t}{S_t + d^2 S_b}\right] \qquad (125)$$

and

$$\theta - \theta_E = (y - y_o)\left[\frac{d\ S_b}{S_b + d^2 S_b}\right] \qquad (126)$$

Equation (126) shows that the angle of twist of the blade is proportional to the lateral displacement of the cutting edge. For lateral equilibrium of the blade the lateral force produced by the cutting action (120) and the reaction of the cutting edge due to the bending and twisting of the blade (125) are equal thus:

$$Q = Q'$$

giving

$$(y - y_o)\left[\frac{S_b \, S_t}{S_t + d^2 S_b}\right] = 2ftm\left[\frac{\Delta K}{K}\cos\beta\sin\beta - \phi\sin^2\beta + \Delta\beta(\cos^2\beta - \sin^2\beta)\right] \tag{127}$$

Equation (126) together with (127) enables the run-out angle to be related to the lateral displacement of the blade, since:

$$\alpha = \theta + \phi \tag{128}$$

Thompson and Taylor [6] go on to illustrate many of the features of the lateral movements of saw blades by application of the previous analysis.

3.6.2.1 Conditions Needed For No Lateral Displacement

Ideally it would be desirable to have conditions where there is no tendency for lateral displacements to occur. Consider the case where no clamping error is present, hence, $y_o = 0$ and $\theta_E = 0$. This ideal condition is given when $\alpha = \phi = \theta = 0$ and $y = 0$. Substituting these into (127) gives:

$$0 = 2ftm\left[\frac{\Delta K}{K}\cos\beta\sin\beta + \Delta\beta(\cos^2\beta - \sin^2\beta)\right] \tag{129}$$

$$0 = 2ftm\left|\frac{\Delta K}{K}\cos\beta\sin\beta + \Delta\beta(\cos^2\beta - \sin^2\beta)\right)$$

Equation (129) can be satisifed when either $\beta = \Delta\beta = 0$ or when $\Delta K = \Delta\beta = 0$. However, the first condition implies that the teeth are not set and, hence, blade clearance would not be achieved. The second condition requires every cutting edge to have the same cutting efficiency and all set teeth to be set to the same angle, this requires a degree of manufacturing perfection which is unlikely to be achieved.

3.6.2.2 The Initial Run-Out Angle

On commencement of cutting no lateral movement of the cutting edge has occured and the blade is in an undistorted condition, hence, $y = y_o$ and $\theta = \theta_E$. In this position the blade does not generate any lateral reaction and, therefore, for the blade to be in equilibrium the lateral load generated by the cutting edge must be zero. This is achieved by the cutting edge adopting an extreme run-out angle, thus:

$$\alpha_o = \phi_o + \theta_E$$

and from (127)

$$0 = 2ftm\left[\frac{\Delta K}{K}\operatorname{Cos}\beta\operatorname{Sin}\beta - \phi_o\operatorname{Sin}^2\beta + \Delta\beta(\operatorname{Cos}^2\beta - \operatorname{Sin}^2\beta)\right]$$

or

$$\phi_o = \frac{\Delta K}{K}\operatorname{Cot}\beta + \Delta\beta(\operatorname{Cot}^2\beta - 1) \qquad (130)$$

From (130) it is seen that the initial angle between the direction of cutting and the centre line of the blades cross section, ϕ_o , is a useful measure of the combined effect of all the cutting edge inaccuracies.

The tendency for a cutting edge to wander from the mean plane of cutting is described in terms of a θ_o value, and using this concept (127) may be written:

$$(y-y_o)\left[\frac{S_b\ S_t}{S_t+d^2S_b}\right] = 2ftm(\phi_o-\phi)\mathrm{Sin}^2\beta \qquad (131)$$

3.6.2.3 The Maximum Lateral Displacement Of The Cutting Edge During A Bandsaw Operation

During a bandsaw operation the thrust load per tooth and the stiffness of the blade are constant and independent of blade movement. This enabled Thompson and Taylor to make a simple analytical solution for the maximum lateral blade displacement. The maximum displacement of the cutting edge occurs when the direction of cutting is parallel to the mean plane of cutting, that is when $\alpha = 0$ or $\phi = -\theta_{max}$. Substituting these values into (131) gives:

$$(y_{max}-y_o)\left[\frac{S_b\ S_t}{S_t+d^2S_b}\right] = 2ftm(\phi_o+\theta_{max})\mathrm{Sin}^2\beta \qquad (132)$$

Combining (126) with (132) gives:

$$\theta_{max} = \frac{\theta_E \; S_t + 2ftm\,\phi_o\, d\, Sin^2\beta}{S_t - 2ftmd\, Sin^2\beta} \tag{133}$$

and

$$y_{max} - y_o = \left[\frac{S_t + d^2 S_b}{S_b(S_t - 2ftmd\,Sin^2\beta)}\right] 2ftm(\phi_o + \theta_E)Sin^2\beta \tag{134}$$

Equation (134) gives the maximum displacement of the cutting edge and indicates that even if the cutting edge is perfect ($\phi_o = 0$), the presence of the clamping error causes the blade to wander from the mean plane of cutting during the early stages of the cut. The equilibrium condition will only be obtained after a considerable depth of cut has been achieved as a result of a continuous forward cutting action.

3.6.2.4 A Computer Method For The Determination Of The Lateral Displacement Of The Cutting Edge During A Power Hacksaw Operation

During the power hacksaw operation the thrust load per tooth and the blade stiffness vary throughout the cutting stroke. This leads to a situation in which both the run-out angle adopted by the cutting edge and the penetration of the blade into the workpiece are functions of the blade displacement. Hence, the lateral displacement of the cutting edge becomes a function of not only the characteristics of the cutting edge but, also, a function of the variation in the thrust load and the variation in blade stiffness during the cutting stroke.

Thompson and Taylor [6] developed an algorithm suitable for a computer routine in which the stroke of the saw is divided into a number of equal increments and the shape of the slot produced as the cutting edge wanders, is determined by a step by step calculation in which equilibrium described by (132) is assumed valid at each position in the stroke. The algorithm is made up of the following stages:

(i) obtain the new position of the workpiece after the blade has been displaced by an increment.

(ii) obtain the thrust load per tooth for the new position of the workpiece, thus:

$$f = f(x)$$

(iii) determine the increase in the slot depth achieved during the incremental movement of the blade [1, 67]:

$$d\Delta = \frac{K f n t \, dx}{B w}$$

(iv) obtain both the lateral bending and torsional stiffnesses of the blade for the old position of the workpiece:

$$S_b = f(x) \quad \text{and} \quad S_t = f(x)$$

(v) determine the lateral force acting at the cutting edge based on the previously known lateral displacement of the cutting edge, using (125).

(vi) determine the angle of twist of the blade using (126).

(vii) obtain the angle ϕ from (131) for a given value of ϕ_0.

(viii) obtain the run-out angle from (128).

(ix) determine the sideways movement of the cutting edge during the incremental movement of the blade, assuming a linear variation, thus:

$$dy = d\Delta \,\mathrm{Tan}\, \alpha$$

(x) determine the new lateral position of the cutting edge, thus:

$$y_{i+1} = y_i + dy$$

(xi) repeat.

The algorithm enables the variation in the lateral displacement of the cutting edge with slot depth to be determined. Its accuracy depends on the number of increments used to divide the stroke. FIGURE 54(a) and (b)., show typical results obtained by Thompson and Taylor, with the algorithm in which the stroke is divided into fifty increments and the variation in the thrust load per tooth is considered sinusoidal.

3.6.3 Relationship Between The Lateral Displacement Of The Cutting Edge And The Components Of The Cutting Force Measured By A Dynamometer

The nature of the power hacksaw operation does not permit direct measurement of the lateral movement of the cutting edge to be undertaken. However, one effective way of deducing this movement is to relate it to the measured components of the cutting force. FIGURE 52., shows the cutting force and its components relative to the blade. The direction of action of these forces are reversed when considering their action on the workpiece. During the cutting stroke there is no net lateral force acting on the blade since the lateral force due to the cutting action is equal and opposite to the blade reaction due to bending and twisting of the blade, such that $Q = Q'$. Hence, by resolving forces parallel and normal to the axis of the workpiece gives, for small angles of twist:

$$F_T \simeq P$$

and

$$F_L \simeq P\theta \simeq F_T(y - y_o)\left[\frac{d\,S_b}{S_t + d^2 S_b}\right] \qquad (135)$$

During the return stroke the only force acting is the blade reaction Q', since $P = Q = 0$. Again resolving forces parallel and normal to the axis of the workpiece gives, for small angles of twist:

$$F_T \simeq Q'\theta \qquad \text{(negligible)}$$

and

$$F_L \simeq -Q = -(y - y_o)\left[\frac{S_b\,S_t}{S_t + d^2 S_b}\right] \qquad (136)$$

This analysis shows that during the cutting stroke the lateral component is proportional to the thrust component of the force acting on the workpiece, whilst during the return stroke it is proportional to the cutting edge displacement and acts in the opposite direction to the cutting displacement.

3.6.4 A Model For The Lateral Displacement Of The Cutting Edge And The Variation In The Components Of The Forces Acting On The Workpiece During Both The Cutting And Return Strokes Of A Power Hacksaw

The previous Analysis gives the sideways displacement of the cutting edge during the forward cutting stroke. However, during the subsequent return stroke it is known that the small reaction which exists (Q'), between the cutting edge and the side of the slot causes the set teeth to cut into the side of the slot, thus allowing the cutting edge to move back towards the mean plane of cutting. The following is a description of these cyclic movements and is an explanation of them based on numerous experimental observations [6]. The explanation has been divided into two sections, the first deals with the variation which lead to a rough surface finish but a square cut whilst the second deals with the variation which leads to the production of a non-square cut.

FIGURE 55., shows the lateral movements of the cutting edge occuring during a typical cutting cycle and their affects on the profile of

the cut surface. FIGURE 56., shows the corresponding variations in the thrust and lateral components of the force acting on the workpiece.

3.6.4.1 When The Blade Is Achieving A Square Cut

During the forward cutting stroke the thrust force provided by the saw machine (F_T), undergoes the usual variation which is shown in FIGURE 56. At the same time the cutting edge of the blade is displaced sideways in one or the other of the lateral directions, progressively moving further away from the mean plane of cutting throughout the cutting stroke. The lateral component of the force acting on the workpiece (F_L), undergoes the variation shown in FIGURE 56(i)., and is proportional to the thrust force provided by the saw machine, as described above. At the end of the cutting stroke the cutting edge has moved from the mean plane of cutting and the lateral force at this instant is acting in the opposite direction to the blade displacement, since Q' is the only force acting.

During the return stroke the lateral force is such that it enables the set teeth to cut into the side wall of the slot. As this force is acting to return the cutting edge to the mean plane of cutting, movement of the cutting edge back to the mean plane is achieved. This is done concurrently with the movement of the blade up and down the slot in the normal mode of blade clearance. These variations in cutting edge movement and the lateral force are shown in FIGURES 55(i) and 56(i), (b to c).

On completion of this cycle of events the cutting edge of the blade is on the mean plane of cutting, no permanent lateral displacement has occured and, therefore, the blade produces a square cut. However, the lateral movement of the cutting edge which has occured during the cutting cycle produces a ridge in the surface which leads to surface roughness.

3.6.4.2 When The Blade Is Cutting Out-Of-Square

The pattern of events described above is similar to that occuring when the blade is cutting out-of-square. The only difference is the extent to which the blade is displaced from the mean plane of cutting at the end of the cutting stroke. When 'run-out' is occuring the displacement is large.

During the return stroke which follows the lateral force is either insufficient or the set teeth are so inferior that full correction of the cutting edge back to the mean plane of cutting cannot occur. This means that at the end of the cutting cycle the blade is left permanently displaced in one of the lateral directions. This is repeated every cutting cycle and hence, the blade 'runs-out' of square.

The movements of the cutting edge and the corresponding variations in the components of the cutting force are shown in FIGURES 55(ii) and 56(ii). However, as the blade is displaced further from the mean plane of cutting on repetition of the previous cycle the lateral force variation shown is progressively increased, this is shown in FIGURE 57.

3.6.5 Surface Roughness Produced By A Power Hacksaw Operation.

In the previous model the lateral displacement of the cutting edge undergoes a cyclic pattern which is repeated every cutting cycle, this produces ridges in the cut surface which give rise to the primary texture of the surface.

The computer analysis in section 3.6.2.4 enables the profile of the ridge produced to be determined, from which the peak-to-valley height of the surface roughness can be determined when the blade is cutting square and the cutting edge returns to the mean plane of cutting at the end of each cutting cycle. When the blade is cutting out-of-square the mean plane of cutting is no longer the plane of the cut surface and, hence, the peak-to-valley height is influenced by the 'run-out' angle, see FIGURE 54(b). The peak-to-valley height for the surface when the blade is running out-of-square is given by:

$$H \simeq y_{max} - y_0 - \varpi \Delta_{y = y_{max}} \tag{137}$$

Thompson and Taylor [6] have shown that $\varpi \simeq \theta_E$ hence:

$$H \simeq y_{max} - y_0 - \theta_E \Delta_{y = y_{max}} \tag{138}$$

For the ridge profiles produced the arithmetical mean deviation roughness number is approximately given by:

$$R_a \simeq \frac{1}{4} H \qquad (139)$$

Thompson and Taylor [6] carried out many cutting tests using a standard power hacksaw, bright drawn mild steel workpiece and standard issue blades. They carried out surface finish tests in which all the surface finish measurements were taken using conventional measuring equipment, and cutting force tests in which the components of the cutting force were measured, via the workpiece.

3.6.6 Empirical Results

The theoretical model indicated that the maximum lateral displacement was a function of the slot depth, see FIGURE 54(a). Also, previous work [1] has shown that the slot depth was related to the average depth of cut per tooth, (71). In view of these relationships Thompson and Taylor decided to display the variation in the roughness number against the average depth of cut per tooth, thus relating the surface roughness to the cutting action of the blade teeth, FIGURE 58(a) and (b).

FIGURE 58(a)., shows roughness values obtained on the side of the surface close to the edge at which the blade teeth began their cut in the region where the influence of the ploughing action was least.

Also, it shows measurements taken during tests in which a new blade was used for every section cut and includes roughness values from both sides of the slot, as such it represents the mean performance of standard production blades. This figure includes theoretical predictions of the roughness value based on the algorithm described previously and (138) and (139) in which $\theta_E = 0$. Comparison of the predictions and experimental values indicated that for the standard blades tested $\phi_O = 0.20$. This result indicated that substantial inaccuracies exist in the cutting edges of standard production blades.

Measurements of the setting angles of the teeth on a standard blade were undertaken; these are shown below.

SECTION NO.	(β) FOR THE TEETH SET TO THE RIGHT Deg.	(β) FOR THE TEETH SET TO THE LEFT Deg.	AVERAGE β Deg.	$\Delta\beta$ Deg.
1	9.80	8.70	9.25	-0.55
2	8.20	8.30	8.25	+0.05
3	9.05	10.25	9.65	+0.60
4	7.60	9.10	8.35	+0.75
5	6.15	7.80	6.98	+0.83
		AVERAGE VALUES	8.49	+0.33

The setting angle measurements were carried out on an optical projector using five sections cut from the blade. They showed that not only did substantial errors exist in the setting angle but, for all but one of the sections, the teeth set to the left were set to a larger angle than the right, such errors are sufficient to give rise to a significant lateral force during cutting. Also, the contribution such inaccuracies made to the ϕ_O value was given by:

$$\phi_O = \Delta\beta(\mathrm{Cot}^2\beta - 1) = 0{\cdot}25 \qquad (140)$$

This contribution was so close to the value obtained from FIGURE 58(a)., that it was reasonable to conclude that cutting edge lateral displacements of new blades were due solely to setting angle errors.

FIGURE 58(b)., shows results obtained from a single standard production blade and the influence of clamping errors. Clamping errors were introduced during the cutting tests by the use of tapered wedge blocks in the end fixing devices. From the tests carried out without clamping error ($\theta_E = 0$), it was shown by comparison with theoretical predictions based on the algorithm given that for the blade used, $\phi_O = 0.22$. Some measurements were undertaken to determine the angle of the non-square cut produced. These measurements presented considerable difficulty but the approximate values obtained are shown in FIGURE 58(b). They indicated that the presence of a clamping error always led to the production of an out-of-square cut and, also, that:

$$\omega \simeq \theta_E$$

FIGURE 58(b)., includes theoretical predictions of the roughness number based on the algorithm and (138) and (139), where $\phi_O = 0.22$

and $\omega = \theta_E$. Comparing these predictions with the experimental values showed reasonable agreement.

FIGURES 59(a-c)., show measured roughness values taken from regions of the cut surfaces which were considerably influenced by the ploughing action of the teeth. The solid lines indicate predictions based on the theoretical model and as such represent the mean trend lines obtained for regions of the cut surface not affected by ploughing. Comparison showed that the presence of ploughing increases the roughness values but that the increase depends on the pitch of the blade teeth and the average depth of cut per tooth. The influence of ploughing was least when the pitch of the teeth and the average depth of cut per tooth were both large.

FIGURE 60., was based on measured values of the roughness number again taken in regions affected by ploughing. It showed that the mean cutting speed of the blade influenced the surface roughness but that this influence was affected by the average depth of cut per tooth.

FIGURE 61., showed that the surface roughness in regions affected by ploughing was considerably influenced by the environment. When a cutting fluid was used the surface roughness was improved, the extent of the improvement was shown to depend on the rate of flow of the coolant. Under the test conditions used coolant flow rates of between 1.5-2.5 litres per minute were needed to achieve the maximum improvement in surface finish.

3.7 ESTIMATING BLADE LIFE, CUTTING RATES AND COSTS BY A COMPUTER SIMULATION OF THE POWER HACKSAW OPERATION

In order to utilize previous work [6] fully it is necessary to simulate the power hacksaw operation on a computer.

Thompson and Taylor [7] developed an algorithm suitable for a computer program to simulate the power hacksaw operation, and used it to investigate the affects of numerous machine parameters on the performance of the operation. The method of simulation devised is based on the metal removed and blade wear produced during a single cutting stroke. In the simulation the depth of slot produced in the workpiece is determined on the assumption that the effective cutting constant remains unaltered during the stroke, the decrease in the effective cutting constant produced during the stroke is determined and the effective cutting constant suitably reduced for the subsequent stroke of the saw. This cycle of events is repeated continuously until the effective cutting constant is so small that it indicates that the blade should be replaced.

This is obviously a simplification since during the actual cutting operation the metal removal and blade wear process occur simultaneously. However, Thompson and Taylor considered that a single stroke of the saw is such a small unit of blade life that this simplification does not lead to serious error in prediction.

3.7.1 Cutting Time

Combining (63), (77), (95) and (96) gives:

$$\frac{d\Delta}{dT} = \left[\frac{Ke}{Bw}\right] F\ V = \upsilon \tag{141}$$

From (141) the cutting time for all saw operations may be derived.

During a power hacksaw operation both the thrust load and the blade speed vary throughout the stroke. In addition, for all but workpieces that have either square or rectangular cross section the breadth varies throughout the cut, hence:

$$w \int B\, d\Delta = \int Ke\, F\, V\, dT$$

but $\quad B\, d\Delta = dA$

and $\quad V = \dfrac{dx}{dT}$

therefore $$w \int_0^{As} dA = \int_0^{s} Ke\ F\ dx \tag{142}$$

Thompson and Taylor assumed that the variation in the effective cutting constant is negligible during a single cutting stroke of the saw, then (142) can be written:

$$A_S = \left[\frac{Ke}{w}\right] Fm\ S \tag{143}$$

Thus it is possible to determine the proportion of the cross section of the workpiece cut through by each stroke of the saw.

The cutting constant in (143) corresponds to the breadth of workpiece at the position in the section at which the cutting stroke occurs and on the amount of damage the blade has experienced during previous strokes.

Before the total number of strokes needed to cut through the entire section can be determined it is necessary to know the influence of wear on the cutting efficiency of the blade and more precisely the influence of wear on the effective cutting constant. Once the number of cutting strokes has been determined the cutting time is known for a given stroke rate.

3.7.2 The Effects Of Wear

Thompson and Taylor [5] have shown that the cutting constant decreases as a result of damage caused by wear, as shown in FIGURE 42., and that the reduction in the effective cutting constant per stroke of the saw is:

$$\Delta Ke = C'' B \left[\frac{Vm\ Ko}{\infty} \right]^{a'} fm^{b'} \tag{144}$$

For normal sinusoidal blade motion $\epsilon = 1.0$, while for instantaneous blade return $\epsilon = 0.5$. FIGURE 62., shows typical variations in the change in the effective cutting constant for various mean cutting speeds and machine loads.

For consecutive cutting strokes of the saw it is possible to write:

$$(Ke)_{N+1} = (Ke)_N - \Delta Ke \tag{145}$$

Combining (143) with (145) it is possible to determine the number of strokes needed to cut through a workpiece when the cutting efficiency of the blade is continuously impaired by damage caused by wear.

3.7.3 Algorithm For A Computer Program

FIGURE 63., shows an algorithm suitable for a computer routine to simulate a power hacksaw operation. The algorithm indicates how the above method for taking into account blade wear may be used. A computer program based on such an algorithm enables the number of sections a blade is capable of cutting during its useful life, and the average cutting time for these sections, to be determined. From the data obtained from such a simulation the cutting rate and cost of power

hacksawing can be determined.

3.7.4 The Average Cutting Rate

It is unrealistic to base estimates of the average cutting time on any assumed effective cutting constant. The only true estimate must be based on the gradual decay of the effective cutting constant over the useful life of the blade. As the rate of decay ia a complex function of many parameters the average cutting time is similarly influenced by such parameters.

In addition to the factors influencing the average cutting time, the cutting rate is affected by the time taken to index the workpiece to a position suitable for cutting between operations and by the time needed to change the blade. Such times depend on the method of operation and are not affected by the parameters that influence the cutting time. Hence, for the purpose of estimating the average cutting rate these two non-productive times have been considered constant, thus:

$$R_C = \frac{60}{\left[T_A + T_L + \frac{T_B}{M}\right]} \qquad (146)$$

3.7.5 Cutting Cost

The cost of achieving a cut by a power hacksaw operation may be cosidered to be made up of the following three major sub-costs:

(i) time costs, including:

(a) cutting time cost.

(b) workpiece index time cost.

(c) blade replacement time cost.

(ii) blade replacement cost.

(iii) scrap cost.

As the cost analysis that follows is to be used to determine optimum sawing conditions the scrap cost is neglected, because it remains constant for all machine settings; although it is known to be between 5-37 per cent of the total cost of achieving a cut by a power hacksaw operation.

3.7.5.1 Cost Rate

The cost rate is defined as the total cost of operating the sawing machine per hour of use and is made up of the following components:

(i) labour cost rate.

(ii) machine cost rate, including purchase and maintenance costs.

As such the cost rate depends, in part, on the percentage utilization of the machine and, therefore, on the amount of cutting undertaken and the reliability of the machine.

Based on the above the cost per cut is given by:

$$C = C_R \left[\frac{T_A + T_L}{60} \right] + C_R \left[\frac{T_B}{60M} \right] + \frac{C_B}{M}$$

or (147)

$$\beta = \gamma \left[\frac{T_A + T_L}{60} \right] + \frac{1}{M} \left[\frac{T_B \gamma}{60} + 1 \right]$$

3.7.5.2 Non-Productive Times

The following non-productive times are based on standard times accepted in the sawing trade as norms:

(i) time to index workpiece between cuts = 0.50 minutes.

(ii) time to change a blade = 1.67 minutes.

3.7.6 Wear Data

The following data was obtained using standard power hacksaw blades made from M2 high speed steel. The coolant used was a Shell Dromus 'B' soluble oil coolant with a water / oil ratio of 30 / 1. The coolant flow rate was 2 litres per minute. The method for obtaining this data, shown on the next page, and details of the initial cutting constant are given by Thompson and Taylor [5], see section 3.5.4.

WORKPIECE MATERIAL	COOLANT	C" $\times 10^{-17}$	b	a'	b'
En44E	DRY	5610.0	2.824	2.429	1.429
	SOLUBLE OIL	58.3	2.678	2.946	1.946
En9	DRY	70.0	2.746	2.678	1.678
	SOLUBLE OIL	7.18	2.734	2.726	1.726

3.7.7 Simulation Results

A computer programme based on the algorithm described has been used to investigate the effects of various machine parameters on the average cutting rate and cost using the previous data.

FIGURE 64., shows typical variations in the cutting time against the number of pieces cut from different machine loads. This information is used to compute the average cutting time in the algorithm described.

FIGURES 65-73., show the effects of cutting stroke rate, thrust force, stroke of the saw, quick return motion, the breadth / depth ratio of the workpiece and the pitch of the blade teeth on the blade life, average cutting rate and cost for the materials and coolants considered. In every case the factor η that specifies the end of the useful life of the blade has been taken to be 0.15. Many of the machine parameters have been considered over larger ranges than those currently available on existing machines so that the effects of extending the range can be assessed; in every case typical ranges for existing machines have been indicated.

3.8 THE CHARACTERISTICS OF SAW OPERATIONS WHEN CUTTING CIRCULAR SECTIONS

3.8.1 Introduction

All investigations so far undertaken into bandsaw and power hacksaw operations [1,4-7,65,67], have been carried out using workpieces which have sections of constant breadth. This has been done to ensure that the parameters which control the cutting and blade wear rates are constant throughout the cut. A clear understanding of the basic factors influencing these rates have been obtained from such investigations. This earlier work indicates that when the breadth of the workpiece is small two effects influence the improvement in the cutting rate. The first is associated with the reduction in the average chip size and the second with the increase in the mean load per tooth for a given machine load. Hence, for a workpiece which has a varying breadth the cutting rate will change as the cut progresses, in accordance with the change in breadth. Thompson and Heaver [68] have investigated these effects using workpieces having circular cross sections.

In the analysis of the cutting rate it is assumed that the cutting performance of the blade at a given breadth in the circular section corresponds to that obtained with a rectangular workpiece of the same breadth. It follows that when cutting sections of varying breadth both the cutting and wear rates are large in regions when the breadth is small; for a circular workpiece this occurs at the top and bottom of the section.

3.8.2 Blade Cutting Characteristics

Using (94) Thompson and Heaver consider both large and small workpiece breadths.

3.8.2.1 Large Workpiece Breadths

When the instantaneous breadth of the workpiece is large the majority of the teeth in contact with the workpiece are associated with a fully established chip and the chip factor $\longrightarrow 0$, hence:

$$\text{when } B \geqslant B_C \qquad K = K_C = \frac{1}{M} \tag{148}$$

3.8.2.2 Small Workpiece Breadths

When the instantaneous breadth of the workpiece is small the effects of the transient formation of the chips become dominant and the cutting constant is dependent on the chip factor. Differentiating (94) gives:

$$\frac{dK}{dB'} = \frac{1}{M}\frac{d\psi'}{dB'} = K_C \frac{d\psi'}{dB'}$$

However, from an earlier theoretical study Thompson and Heaver show that when the breadth of the workpiece is small and provided that more than three teeth are in contact with the workpiece:

$$\frac{d\psi'}{dB'} \propto \frac{d\psi'}{dn_c'} \doteq \text{constant}$$

Hence $$\frac{K}{K_c} = \frac{a}{B} + \frac{b}{K_c}$$

Also, when $K = K_c$, $B = B_c$ or:

$$1 = \frac{a}{B_c} + \frac{b}{K_c}$$

FIGURE 74., shows, in dimensionless form, the variation in the cutting constant against the reciprocal of the workpiece breadth for a number of metals and tooth pitch. It indicates that the factor b / K_c is small and can be neglected, giving:

$$a = B_c$$

Hence, when $B \leqslant B_c$:

$$KB = K_c B_c \tag{149}$$

3.8.3 Machine Characteristics

Expressions for the cutting rates for both power hacksaw and bandsaw operations can be obtained by equating the rate of loss of volume from the workpiece to the rate of volume removed by the blade. The rate at which volume is removed by the blade is given by (95).

Combining (63) with (76) and (95) gives:

$$\dot{vol} = K \; F \; V \tag{150}$$

Equating (70) and (150) and integrating gives:

$$\alpha_1 = \alpha_2$$

where
$$\alpha_1 = w \int_{\Delta_2}^{\Delta_1} \frac{B}{K} \, d\Delta$$

and
$$\alpha_2 = \int_0^{T_c} F \, V \, dT \tag{151}$$

In the above expressions the function α_1 depends on the variation in the cutting constant and the shape of the workpiece, whilst α_2 depends entirely on machine parameters.

3.8.3.1 The Bandsaw Operation

During a bandsaw operation the blade speed and the thrust force are normally constant, hence, α_2 becomes:

$$\propto_2 = F V \int_0^{T_c} dT = F V T_c \tag{152}$$

3.8.3.2 The Power Hacksaw Operation

During a power hacksaw operation both the blade speed and the thrust force vary throughout a single cutting stroke. However, $\propto_2$ may be determined thus:

$$dx = V\, dt$$

Hence, (151) becomes:

$$\propto_2 = N_s \int_0^{S} F\, dx = N_s\, Fm\, S$$

but $$N_s = T_c\, \phi \quad \text{and} \quad V_m = 2\, S\, \phi \tag{153}$$

therefore $$\propto_2 = \frac{1}{2}\, Fm\, V_m\, T_c$$

The above shows that the effects of workpiece shape are not dependent on the type and characteristics of the saw operation considered.

3.8.4 Shape Factor

As a result of the variation in the cutting constant with change in breadth it is evident that the time required to cut through a workpiece will depend on the shape of the workpiece. These shape effects are solely confined to the function α_1, namely:

$$\alpha_1 = w \int_{\Delta_2}^{\Delta_1} \frac{B}{K}\, d\Delta$$

An average cutting constant K_a, has been defined by Thompson and Heaver, which is constant across the section and which yields the same cutting time as that given when the actual variation in the cutting constant is considered. Hence:

$$\alpha_1 = \frac{w}{K_a} \quad dA = \frac{(vol)_c}{K_a} \qquad (154)$$

since $\quad B\, d\Delta = dA$

3.8.4.1 Large Diameter Workpieces

When the diameter of the workpiece is large $(D_o \geqslant B_c)$ the cross section may be considered to be divided into three regions, as shown in FIGURE 75. In the regions where the breadth of the section is less than B_c, that is at the top and bottom of the section, the cutting constant varies according to (149), whilst over the central region the cutting constant remains constant. Hence, (151) may be written:

$$\propto_1 = \frac{2w}{K_c}\left[\frac{1}{B_c}\int_0^{\Delta_c} B^2\, d\Delta + \int_{\Delta_c}^{R_o} B\, d\Delta\right] \tag{155}$$

This may be written in circular co-ordinates to give:

$$\propto_1 = \frac{w D_o^2}{K_c}\left[\frac{D_o}{B_c}\int_0^{\theta_c} \mathrm{Sin}^3\theta\, d\theta + \int_{\theta_c}^{\pi/2} \mathrm{Sin}^2\theta\, d\theta\right] \tag{156}$$

where $\mathrm{Sin}\,\theta_c = \frac{B_c}{D_o}$

Integrating (156) gives:

$$\propto_1 = \frac{wD_o^2}{K_c}\left[\frac{2}{3}\,\frac{D_o}{B_c}\left[1 - \mathrm{Cos}\,\theta_c\left[1 + \frac{1}{2}\left[\frac{B_c}{D_o}\right]^2\right]\right] + \frac{1}{4}\left[\pi - 2\theta_c + \mathrm{Sin}\,2\theta_c\right]\right] \tag{157}$$

Equating (154) and (157) gives the following expression for the average cutting constant when $D_o \geqslant B_c$:

$$\frac{K_a}{K_c} = \frac{\pi}{\left[\frac{8}{3}\,\frac{D_o}{B_c}\left[1 - \mathrm{Cos}\,\theta_c\left[1 + \frac{1}{2}\left[\frac{B_c}{D_o}\right]^2\right]\right] + \pi - 2\theta_c + \mathrm{Sin}\,2\theta_c\right]} \tag{158}$$

3.8.4.2 Small Diameter Workpieces

When the diameter of the workpiece is small ($D_o \leqslant B_c$) the cutting constant varies across the entire cross section of the workpiece. The appropriate expression for the function $\propto_1$ can be obtained from (157) where $\theta_c = \pi / 2$, giving:

$$\propto_1 = \frac{2}{3} \frac{w D_o^{3}}{K_c B_c} \tag{159}$$

Equating (159) and (154) gives the appropriate expression for the average cutting constant when $D_o \leqslant B_c$:

$$\frac{K_a}{K_c} = \frac{3\pi}{8} \frac{B_c}{D_o} \tag{160}$$

FIGURE 76., shows the theoretical distribution of the average cutting constant against the diameter of the section and is based on (158) and (160).

3.8.5 Wear Factors

Colding's tool life equation (102) can be written in terms of parameters associated with saw operations for the secondary phase of wear:

$$\propto \frac{R}{\dot{K}_a} \frac{1}{(K_a)_o} \frac{1}{fm^2} = C' \left[V_m \frac{R}{\dot{K}_a} \frac{1}{fm} \right]^{b/2} \tag{161}$$

Where the average cutting constant is given by equating (153) and (154) and:

$$\dot{K}_a = \frac{\partial K_a}{\partial N} \phi$$

$$R = \frac{D_o}{2S}$$

and
$$Fm = fm\, D_o\, p\, t$$

By considering the diffusivity of the workpiece metal to be unity, as suggested by Colding [35]; (161) becomes:

$$\frac{\partial K_a}{\partial N} = C'' D_o \left[V_m (K_a)_o \right]^c fm^d \tag{162}$$

This gives an expression for the change in the average cutting constant per cutting stroke in terms of constants which can be determined from wear tests as previously discussed [5].

3.8.5.1 Cutting Time

It has been shown that the number of cutting strokes needed to cut through a workpiece depends both on the shape of the cross section and the amount of damage produced as a result of blade wear. The concept of the average cutting constant may be used to take shape factors into account. However, the method required to take blade wear into account depends on the rate of wear.

Combining (153) and (154) gives the mean cutting constant in terms of machine parameters appropriate to a power hacksaw operation, thus:

$$(K_a)_m = \frac{(vol)_c}{N_s} \frac{1}{Fm} \frac{1}{S} \tag{163}$$

3.8.5.2 Small Wear Rates

When the wear rate is small the average cutting constant can be considered independent of wear during the cutting of a single section, hence:

$$(K_a)_1 = (K_a)_m$$

and

$$T_c \, \phi = N_s = \frac{(vol)_c}{(K_a)_1} \frac{1}{Fm} \frac{1}{S} \tag{164}$$

3.8.5.3 Large Wear Rates

When the wear rate is large sufficient variation in the cutting constant occurs during the cutting of a single section for the above to lead to an under estimate of the cutting time. However, during the linear, secondary phase of wear:

$$(K_a)_m = (K_a)_1 - \frac{1}{2} \frac{\partial K_a}{\partial N} N_s$$

Combining this with (163) gives:

$$\frac{1}{2}\frac{\partial K_a}{\partial N} N_S^{\,2} - (K_a)_1 N_S + \frac{(vol)_c}{Fm\, S} = 0$$

or

$$T_c\,\phi = N_S = \frac{(K_a)_1 - \sqrt{(K_a)_1^2 - 2\dfrac{\partial K_a}{\partial N}\dfrac{(vol)_c}{Fm\,S}}}{\dfrac{\partial K_a}{\partial N}} \qquad (165)$$

The above expression takes into account the effects of damage due to wear occurring during the cutting of a single section and leads to an improved estimate of the cutting times when the wear rate is large.

3.8.6 Test Procedure And Results

3.8.6.1 Cutting Characteristics

The values of K_c and B_c for each material were obtained from cutting tests carried out on rectangular sections, FIGURE 74. Many of these tests had been carried out as a result of earlier investigations [5]. It was found that B_c was approximately 25mm., for all workpiece metals considered.

Values of K_c obtained, are shown on the next page.

METAL	NUMBER OF BLADE TEETH PER 25mm	K_c mm^2 N^{-1} x 10^{-4}	
		DRY	COOLANT
En1a	4	3.08	-
	6	2.15	-
	10	1.25	-
En9	4, 6 & 10	3.55	3.90
En44E	4, 6 & 10	2.30	2.88

3.8.6.2 Cutting Rate Tests

The object of these tests, carried out by Thompson and Heaver [68], was to obtain the change in the average cutting constant with variation in bar diameter. Test bars of a common diameter were cut with a variety of thrust loads in the range 400-1800N. An average cutting constant was determined for each load using (163) and the cutting time measured. A mean value of the cutting constants obtained was computed and taken to be representative for the bar diameter used. This was repeated for several bar diameters in the range 17-75mm., and for test bars made from En1a and En9. The blades were replaced frequently to eliminate the effects of wear.

FIGURE 76., shows the results of these tests and includes a theoretical variation in the average cutting constant based on (158) and (160).

3.8.6.3 Wear Tests

The En44E wear test bar was cut through a number of times using a single blade under conditions of constant thrust load and stroke rate. The time taken for each cut was measured and the number of cutting strokes required determined. The average cutting constant was determined for each cut using (163). The variation in the average cutting constants obtained were displayed against the number of cutting strokes performed by the blade.

FIGURE 77., shows a typical result from this procedure. Each average cutting constant was shown at the mid-point of the cutting strokes undertaken by the blade. From graphs such as FIGURE 77., the variation in the average cutting constant per cutting stroke was determined for the linear, secondary phase of wear. This procedure was repeated for a number of different thrust loads in the range 700-1700N., and a number of different stroke rates.

The data obtained was used to calculate the values of the groups shown in (161) and a bi-logarithmic plot produced, FIGURE 78. From the slope and intercept of this plot the wear indices and constants were determined. This procedure was repeated both with and without the application of coolant.

The values of the indices obtained are shown on the next page.

METAL	COOLANT	COLDING'S WEAR INDEX	
		RECTANGULAR SECTION	CIRCULAR SECTION
En44E	DRY	2.82	2.59
En44E	COOLANT	2.68	2.61

FIGURE 79., shows the variation in the number of cutting strokes required to cut through the wear test bar under conditions of constant load, against the cutting constant for the blade at the beginning of the cut, and is based on experimental data.

FIGURE 79., also shows the predictions of the number of cutting strokes required, based on (164) and (165), both with and without the effect of wear taken into account.

4 DEVELOPMENT OF EXPERIMENTAL SAWING EQUIPMENT

4.1 INTRODUCTION

The prime requirement of the experimental bandsaw rig was to utilize a commercially available bandsaw machine in which the relevant engineering parameters could be measured.

The type of horizontal bandsaw used for this investigation was one where the band is carried on a swing arm assembly pivotted at one end, PLATE I, and was supplied by J. Neill (Services) Ltd., the collaborating organization. This machine uses a hydraulic cylinder and valve to control downfeed motion when making a cut. Previous attempts at measuring thrust loads on a horizontal bandsaw machine [67] had indicated that a gravity system of loading the saw blade leads to a much more adaptable and controllable piece of apparatus than one which uses a hydraulic system to develop the load. It was decided that the bandsaw used should be modified so that the thrust load developed between the workpiece and the band would be achieved by a gravity system of loading.

The relevant engineering parameters which need to be measured are, a) the thrust load developed between the band and the workpiece, b) band speed, c) workpiece and band geometry, d) coolant flow rate.

Band speed is easily measured with a tachometer and speeds available on the saw are shown in section 4.2.1. Workpiece geometry and tooth pitch of the band are readily determined. The method of measuring the thrust load is shown in section 4.2.4. Coolant flow rate measurements are discussed in a later section.

4.2 MODIFICATIONS

4.2.1 Type Of Machine

The type and manufacture of the commercial saw is shown below:

type	SAWMASTER BANDSAW
	SERIAL No. 7BS 411
manufacture	QUALTERS & SMITH BROS. Ltd.
	MACHINE TOOL MAKERS
	BARNSLEY YORKSHIRE ENGLAND

This machine has four speeds, adjusted via pulleys, and when measured with a tachometer registered:

23.8 m/min

40 m/min

55 m/min

66 m/min

These speeds were considered acceptable for testing purposes.

4.2.2 Hydraulic Cylinder

When the hydraulic cylinder was disconnected, PLATE III, and sawing attempted, the weight of the swing arm assembly caused the teeth of the band to be ripped off as soon as contact was made. It became evident by these trials that this weight exerted too large a thrust load between the band and workpiece and that the excess load produced by removing the hydraulic system would need to be counterbalanced in some way.

4.2.3 Counterbalance

A counterbalance weight was fitted to the saw by means of an outrigger welded to the hinge pin which was suitably extended. The front end of this outrigger was welded to the swing arm assembly by means of mild steel straps. The outrigger is positioned so that it is horizontal when the band is half way through a 50mm. square workpiece. A total mass of 91kg. of lead was needed to counterbalance the swing arm assembly, on a lever of approximately 0.8m. The lead mass and outrigger can be seen in PLATE III.

4.2.4 Instrumentation

The load measuring system is essentially the same as that which has been successfully used in previous investigations [5,6,67] .

In order that the load measuring transducer could be fitted in the required position for convenient sawing, the front pan of the saw was extended and a 12mm. thick steel plate fitted under the existing work holding vice of the saw, PLATE I. This steel plate, when bolted to the saw bed beneath the original vice, made an ideal position for mounting the force transducer and its base plate, for load measurements, and was also used in all the future cutting tests to mount the work holding fixture so that both load transducer and test workpieces were in the same position relative to the band. With the work holding fixture bolted on the front of the saw, the test bar is held at the same height, and presented to the band as if it were clamped in the original vice supplied.

PLATE IV, shows the force transducer and work clamping arrangement for load measurement.

The measuring system consists of a transducer, an electronic amplifying and matching unit and an indicating or recording instrument. The first two components in the system employ the piezoelectric multi-component force measurement principle [64].

The components of the system are described below:

(i) Transducer: the transducer used is the KISTLER TYPE 9257A piezoelectric, three component dynamometer which converts the physical variable (force) into a proportional electrical charge.

(ii) Charge Amplifier: is the KISTLER TYPE 5001 which converts the electrical charge into a proportional voltage, taking into account the individual transducer sensitivity so that the output voltage is in an even scale of Newtons / Volt. With the charge amplifier the piezoelectric part of the measuring chain ends. A recording instrument forms the next link in the system.

(iii) Ultra-Violet Oscillograph: is the SOUTHERN INSTRUMENTS SERIES 10-100 oscillograph fitted with suitable galvanometers. Driving and adapting the galvanometers is conveniently effected by means of galvo-amplifiers.

(iv) Galvo-Amplifier: these are KISTLER TYPE 5211 amplifiers.

The complete force measuring system can be seen in PLATE IV.

4.2.5 Adjustable Thrust Load

It is of prime importance that the thrust load developed between the band and the workpiece can be varied so that cutting tests can be carried out under different values of load. This feature is necessary for the wear tests which will be described later.

A sliding weight system was developed so that thrust loads could be varied within the range of loads developed by bandsaw machines used in the industry. The system developed gave a load range of 0-500N, where 500N is considered a maximum in the trade. Typically thrust loads less than 500N are used for most bandsaw operations.

4.2.5.1 Jockey Weight

A sliding weight was fitted on the outrigger as shown in PLATE III, and consists of a cast iron jockey weight of 36kg., suitably machined so that it can be adjusted and clamped along the outrigger and hence either increase or decrease the moment of the swing arm assembly about the hinge pin, as required. To give a load range extending to 500N it was convenient to use two jockey weights, both sliding on the outrigger.

4.2.5.2 Tentative Cutting Tests

Cutting tests were undertaken with the equipment displayed in PLATE IV. The thrust load was measured from the onset of cutting, right through until the section was cut off. A workpiece measuring 50mm. square was used for this test.

It is an important design criteria that a constant thrust load is maintained throughout the section cut. These tentative tests showed that the load increased by approximately 270 per cent from the start of cut to finish. This load increase is due to the increase in moment as the swing arm assembly rotates about the hinge pin when passing from the top of the workpiece through to completion of cut.

PLATE V, shows the angular progression of the band as it passes through the workpiece. FIGURE 80., shows the load variation as the band passes through a workpiece. This data was produced by incrementing the saw part way into the workpiece and measuring the load via the measuring system previously described. The angle of rotation was measured using a Clinometer, which is a device that provides the engineer with speedy angular measurements in assembly, testing and installing machine tools. The Clinometer details are shown below:

type	WATTS 90° CLINOMETER
manufacture	HILGER & WATTS Ltd.
	No. 97039

This Clinometer has a sensitivity of 1 second per division.

During angular measurements the device was clamped to the outrigger and zero set so that the band teeth were just contacting the workpiece.

The thrust load was recorded at 14 increments through the workpiece.

4.2.5.3 Spring System

A spring system was designed and fitted to the saw to elliminate the variation in thrust load as the cut progressed through the workpiece.

This spring system consists of a lever arrangement welded to the hinge pin of the saw, and a spring bolted to the saw frame and screwed to the bottom of the lever, PLATE VI. The spring / lever arrangement can also be seen in PLATE III.

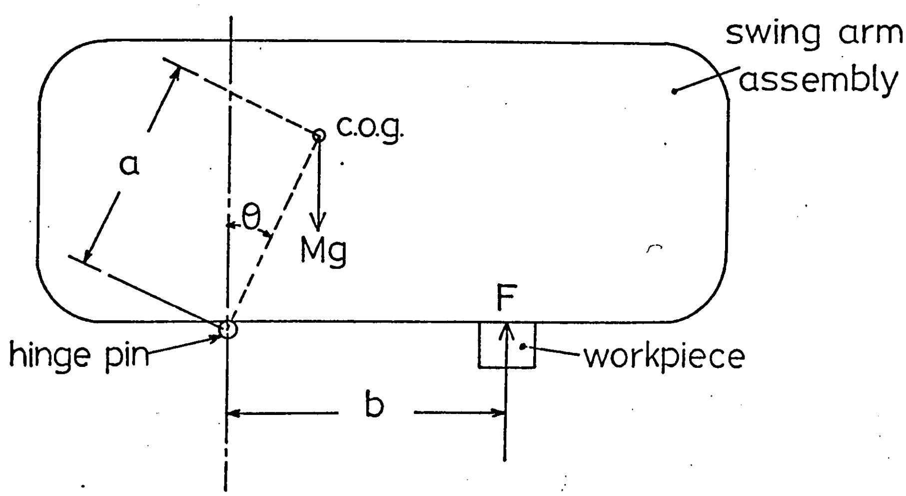
FIGURE 81., shows the load variation as the band passes through a workpiece, with the spring system fitted. Comparison between FIGURES 80., and 81., shows the improvement achieved. FIGURE 81., indicates a 3 per cent load fluctuation throughout the workpiece section.

For the 50mm. square workpiece, typical load measurements are shown below against the band position in the workpiece.

HEAVY THRUST LOAD SETTING	POSITION OF BAND IN WORKPIECE	LIGHT THRUST LOAD SETTING
326N	a	60N
335N	b	60N
330N	c	60N
330N	d	55N

With so little load variation, the thrust load was considered to be 'constant' for these investigations.

Design calculations for the spring system are shown below:



Consider the previous diagram:

For equilibrium

$$Mg\ a \sin\theta = F\ b$$

giving

$$F = Mg\ {}^{a}/_{b} \sin\theta$$

since θ is small $\sin\theta \doteq \theta$

hence

$$F = Mg\ {}^{a}/_{b}\ \theta \qquad (166)$$

where $\theta = 0$ $\quad F = 0$ hence self balancing.

From (166)

$$F = \beta\theta \qquad (167)$$

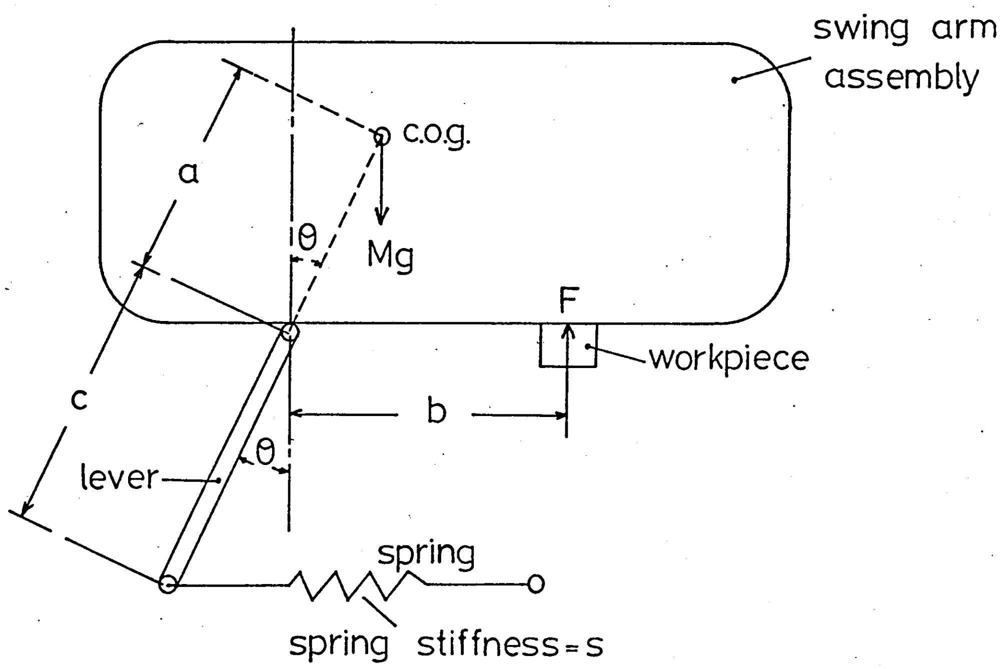
where

$$\beta = Mg\ {}^{a}/_{b}$$

From the cutting tests of section 4.2.5.2 and from FIGURE 80., the value of β is given by the slope of the line.

Thus $\beta = 200 / 0.147$ N / radian (168)

Consider the spring / lever arrangement as shown diagrammatically on the following page.



For balance: Spring moment = Weight moment

$$(s\ c)\ c\ \theta = Mg\ a\theta \tag{169}$$

Substitute β, hence (169) becomes:

$$s\,c^2 = \beta\ b$$

giving

$$c = \sqrt{\frac{\beta\ b}{s}} \tag{170}$$

The value of β is known from (168), and the value of b is measured from the saw and is 33cm.

The spring stiffness is found by a simple experiment, the details of which are shown on the following page.

LOAD kg.	EXTENSION mm.
5	3.5
10	13.5
15	22.5
20	32.5
25	41.5
30	50.5
35	60.0
40	69.0
45	77.5
50	87.0

Note:
The extensions shown are the mean of unloading and loading tests.

The load / extension plot to find the spring stiffness is shown in FIGURE 82.

From FIGURE 82., the spring stiffness is 5.339N / mm.

Substituting all the values into (170) gives a value :

$$C = 29\text{cm.}$$

Thus the length of the lever in the spring system was made 29cm., long.

4.2.5.4 Calibration

The sliding jockey weight system was calibrated so that the thrust load could be adjusted to give a certain value and then be fixed. Once the system had been calibrated the instrumentation used for measuring the load could be removed and the dynamometer / workholding device be replaced by a permanent workholding fixture, PLATE VII. This permanent fixture is dimensionally equal to the dynamometer arrangement so that the workpiece is held in the same location as for the calibration tests.

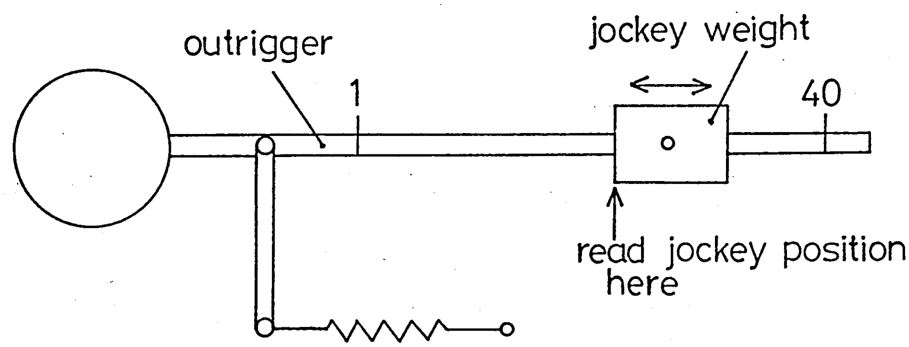
The outrigger was calibrated for both single and double jockey weights to give a total usable load range of 40-470N, the jockey positions can be seen in PLATE III.

Calibration details are shown below.

Single jockey weight:

POSITION ON OUTRIGGER	THRUST LOAD N	POSITION ON OUTRIGGER	THRUST LOAD N
1	32	22	182
2	38	24	195
4	52	26	208
6	67	28	222
8	80	30	235
10	100	32	248
12	112	34	262
14	126	36	274
16	138	38	288
18	153	40	300
20	170		

The single jockey weight system is shown diagrammatically below.



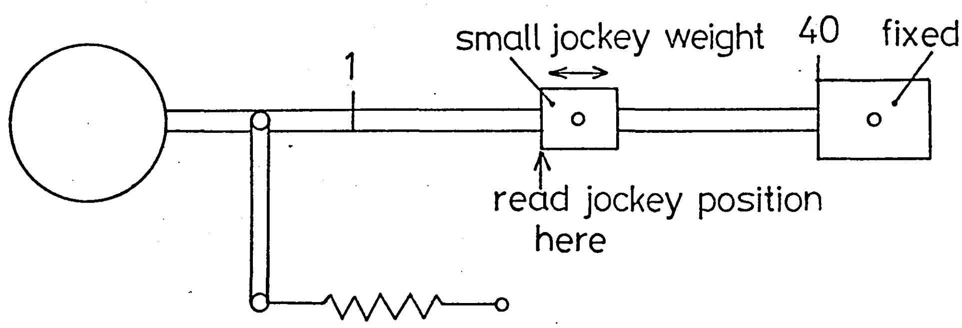
The calibration curve for this arrangement is shown in FIGURE 83.

Double jockey weight:

When the two jockey weights are used the large 36kg., weight is clamped at position number 40 on the outrigger while the smaller 26kg., weight is moved along the outrigger.

POSITION ON OUTRIGGER	THRUST LOAD N	POSITION ON OUTRIGGER	THRUST LOAD N
1	343	20	410
2	349	22	421
4	354	24	429
6	360	26	430
8	368	28	440
10	374	30	448
12	384	32	455
14	389	34	465
16	395	35	468
18	403		

The double jockey weight system is shown diagrammatically on the following page.



The calibration curve for this arrangement is shown in FIGURE 84.

5 BAND WEAR TESTING

5.1 THEORY OF BANDSAW

Cutting tests carried out with un-worn bands have shown that there is a linear relationship between the depth of cut per tooth and the thrust load per tooth per unit thickness.

The slope has been defined as a cutting constant, thus:

$$\left.\begin{aligned} \delta &= Kf - a \\ \text{when} \quad F &= f\,B\,p\,t \\ \text{and} \quad \delta &= \frac{w\,v}{t\,p\,V} \end{aligned}\right\} \qquad (171)$$

FIGURES 85., and 86., show the variation of these two parameters for various band speeds and workpiece breadths.

Tests have shown that the cutting constant decreases with wear, FIGURES 87., and 88., and that:

$$a = K\,f' \qquad (172)$$

A similar phenomenon has been reported by previous workers [1] for the wear of power hacksaw blades (see section 3.2.2 and FIGURE 30.).

Consider the volume metal removal rate of the band:

$$\dot{vol} = \delta \, t \, n_c \, V \qquad (173)$$

Substituting (171) into (173) gives:

$$\dot{vol} = t \, n_c \, V \, (Kf - a)$$

$$\dot{vol} = t n_c V K f - a t n_c V$$

$$n_c = Bp \qquad\qquad F = f\,Bpt$$

$$\dot{vol} = KVF - a\,t\,BpV \qquad (174)$$

The volume removal rate may also be found from the loss in volume of the workpiece:

$$\dot{vol} = \vartheta \, w \, B \qquad (175)$$

Equating (174) and (175) gives:

$$\vartheta wB = KVF - a\,t\,BpV$$

$$\vartheta = V\left[\frac{KF}{w.B} - \frac{atp}{w}\right] \tag{176}$$

Equation (176) can be written in the form:

$$K = \frac{B}{F}\left[\frac{\vartheta w}{V} + atp\right] \tag{177}$$

Equation (177) can be written in the form:

$$F = \frac{B}{K}\left[\frac{\vartheta w}{V} + atp\right] \tag{178}$$

5.2 ADAPTING COLDING'S EQUATION

Colding's three dimensional tool-life equation, based on the wear of lathe tools, has been discussed in section 2.7.3 and equation (59) shows the relationship.

The physical conditions controlling the wear of bandsaw blades are quite different from those controlling the wear of lathe tools. An individual tooth on the band performs an intermittent cutting action whilst a lathe tool does not, and the chip formation mechanism is very different, [1,4].

However, as the three parameters considered by Colding to influence tool life are so basic it was considered that his tool life equation may be valid for the bandsaw operation.

Before Colding's equation can be applied to this operation it is necessary to express tool life, chip equivalent and cutting speed in terms of parameters that can be measured during a bandsaw blade wear test. The method of modification is set out below.

5.2.1 Chip Equivalent

In section 3.5.2.2 the chip equivalent is defined as the ratio of the length of the cutting edge engaged with the workpiece to the cross-sectional area of the undeformed chip.

In terms of bandsaw parameters the average chip equivalent per band revolution is:

$$q_a = \frac{1}{\delta_a} \qquad (179)$$

where $\delta_a = K_a f - a$

now $K_a = \dfrac{K_o + \eta K_o}{2}$

$$K_a = \frac{K_o(1 + \eta)}{2}$$

giving $$\delta_a = \frac{K_o f (1 + \eta)}{2} - a \qquad (180)$$

Substituting (180) into (179) gives:

$$q_a = \frac{1}{\dfrac{K_o f (1 + \eta)}{2} - a}$$

$$q_a = \frac{2}{K_o f (1 + \eta) - 2a}$$

This may be written:

$$q_a = \frac{2}{K_o (1 + \eta) \left[f - \dfrac{2a}{K_o (1 + \eta)} \right]} \qquad (181)$$

Let $$f'_a = \frac{2a}{K_o (1 + \eta)} \qquad (182)$$

Substituting (182) into (181) gives:

$$q_a = \frac{2}{K_o (1 + \eta) (f - f'_a)} \qquad (183)$$

5.2.2 Tool Life

Experimental data (section 5.4.1) has shown that there is a linear relationship between the cutting constant and the number of band revolutions in the second wear phase, FIGURE 92.

Hence: $$\frac{dK}{dn} = \frac{K_o}{n_{max}} (1 - \eta) \tag{184}$$

and $$\Delta K = \frac{dK}{dn} \frac{dn}{dT} = \frac{dK}{dn} \phi \tag{185}$$

where $$n_{max} = \phi T \tag{186}$$

Colding's tool life is based upon the time the tool is in contact with the workpiece and being subjected to the conditions which produce wear. In fact for a turning operation there is no difference between this and actual time, but as a bandsaw tooth achieves an intermittent cutting action there is a significant difference between these times, which must be taken into account, thus:

$$T_C = R T \tag{187}$$

where $$R = \frac{B}{L}$$

Combining (184),(185),(186) and (187) gives:

$$T_C = R \frac{K_o}{\Delta K} (1 - \eta) \tag{188}$$

5.2.3 Cutting Velocity

For the bandsaw operation the cutting velocity is given directly by the band speed.

5.2.4 Band Life Equation

Colding's tool life equation is given by (59) and is shown below:

$$\alpha\, T_c\, q^2 = C(V\, T_c\, q)^{b/2}$$

thus $$\alpha = C(V\, T_c\, q)^{b/2}\; T_c^{-1}\; q^{-2}$$

and $$\alpha = C\; V^{b/2}\; T_c^{b/2-1}\; q^{b/2-2} \qquad (189)$$

Substituting (183),(188) and cutting speed into (189) gives:

$$\alpha = C\, V^{b/2} \left[\frac{R\, K_o\,(1-\eta)}{\Delta K}\right]^{b/2-1} \left[\frac{2}{K_o(f-f'_a)(1+\eta)}\right]^{b/2-2}$$

$$\alpha = C\left[\frac{V R K_o(1-\eta)2}{\Delta K\, K_o(f-f'_a)(1+\eta)}\right]^{b/2} \left[\frac{R\, K_o(1-\eta)}{\Delta K}\right]^{-1} \left[\frac{2}{K_o(f-f'_a)(1+\eta)}\right]^{-2}$$

re-arranging gives:

$$\frac{\alpha^{*} R}{\Delta K\, K_o (f - f'_a)^2} = C' \left[\frac{V R}{\Delta K (f - f'_a)} \right]^{b/2} \qquad (190)$$

where $$C' = C \left[\frac{2(1-n)}{(1+n)} \right]^{b/2 - 1} \left[\frac{1+n}{2} \right] \qquad (191)$$

re-arranging (190) gives:

$$\frac{\alpha R}{\Delta K\, K_o (f - f'_a)^2} = C' \frac{V^{b/2}\; R^{b/2}}{\Delta K^{b/2}\; (f - f'_a)^{b/2}}$$

$$\frac{\Delta K^{b/2}}{\Delta K} = C' \frac{V^{b/2}\; R^{b/2}\; K_o (f - f'_a)^2}{(f - f'_a)^{b/2}\; \alpha\; R}$$

$$\Delta K^{b/2 - 1} = C' \frac{V^{b/2}\; R^{b/2 - 1}\; K_o\; (f - f'_a)^{2 - b/2}}{\alpha}$$

* for value of α see page 209

Dividing throughout by $b/2-1$ gives:

$$\Delta K = C'' \frac{R \; V^{\frac{b/2}{b/2-1}} \; K_o^{\frac{1}{b/2-1}} \; (f-f_a')^{\frac{2-b/2}{b/2-1}}}{\alpha^{\frac{1}{b/2-1}}}$$

Substituting the contact time ratio (B/L):

$$\Delta K = C'' \frac{B}{L} \; V^{\frac{b/2}{b/2-1}} \left[\frac{K_o}{\alpha}\right]^{\frac{1}{b/2-1}} (f-f_a')^{\frac{2-b/2}{b/2-1}} \tag{192}$$

where $$C'' = C'^{\frac{1}{b/2-1}} \tag{193}$$

Equation (192) may be written:

$$\Delta K = C'' \frac{B}{L} \; V^{b_1} \left[\frac{K_o}{\alpha}\right]^{b_2} (f-f_a')^{b_3} \tag{194}$$

where $$b_1 = \frac{b/2}{b/2-1} \; ; \; b_2 = \frac{1}{b/2-1} \; ; \; b_3 = \frac{2-b/2}{b/2-1} \tag{195}$$

5.3 EQUIPMENT AND MATERIALS

5.3.1 Workpiece Material

All wear tests were carried out using En44E as the workpiece material, as this material is frequently used by manufacturers of bandsaw blades in their quality control wear tests.

The percentage chemical composition of En44E is:

1.20 C; 0.27 Si; 0.44 Mn; 0.02 S; 0.019 P

All test bars were heat treated by hardening at 880°C followed by oil quenching and tempering at 650°C. This treatment gives a hardness range of 300-320 H.V.30.

The test bars were machined to rectangular cross sections 50mm. deep and breadths in the range 10-50mm.

5.3.2 Bands

All the bands used were standard production issue having 6 and 10 teeth per 25mm. Carbon and high speed steel bi-metal bands were used, with loop lengths of 3.18m. and 3.35m., allowing the contact time ratio (187) to be varied.

5.3.2.1 Carbon Band

The percentage chemical composition of the carbon bands used is:

1.25 C; 0.27 Mn; 0.2 Si; 0.02 S; 0.02 P; 0.25 Ni; 0.2 Cr; 0.1 Mo; 0.1 Cu

The dimensions of this band are:

25.4mm. x 0.9mm. x RAKER SET

They had been given the standard heat treatment under normal production conditions which gave the teeth of the band a hardness of 830-910 H.V.30.

5.3.2.2 High Speed Steel Bi-Metal Band

This band consists of a carbon backing strip which has the following chemical composition:

0.44 C; 0.2 Si; 0.7 Mn; 0.02 S; 0.02 P; 0.55 Ni; 1.1 Cr; 1.0 Mo; 0.07 Va

This carbon backing strip is welded by the electron beam process to an M2 high speed steel cutting edge which has the following percentage chemical composition:

0.85 C; 6.25 W; 4.25 Cr; 2.0 V; 5.0 Mo

The dimensions of this band are:

25.4mm. x 0.9mm. x RAKER SET

Normal production heat treatment gives the carbon backing strip a hardness of approximately 420 H.V.10 and the high speed steel teeth a hardness in the range 860-890 H.V.10.

5.3.3 Cutting Fluid

Most of the tests were carried out dry in the normal atmosphere to create "accelerated" wear conditions. Other tests were carried out using Shell Dromus "B" soluble oil coolant with a water / oil ratio of 30 / 1.

It has been shown (section 5.4.1.1) that the quantity of coolant flowing affected the wear rate. The majority of tests carried out with coolant used a coolant flow rate of 2 litres per minute. The coolant was applied centrally above the workpiece by the standard means provided on the bandsaw machine.

5.3.4 Bandsaw

The bandsaw used is fully described in section 4.

5.4 WEAR TESTING PROCEDURE

At each pre-selected thrust load (section 4.2.5.4) the band is used to cut through the rectangular test bar a number of times. The time taken to cut through the section is recorded, enabling the cutting rate achieved and the number of band revolutions taken to perform the cut, to be calculated. By this procedure the cutting constant can be calculated per section cut using equation (177).

An initial test is performed for each band speed and workpiece geometry so that the intercept in (177) can be obtained; FIGURE 85., shows the form of this test.

Wear tests have been undertaken to determine the variation in the cutting constant with the number of band revolutions performed. The results of all wear tests were recorded on standard test sheets, FIGURE 89.

The initial cutting constant is taken in all cases to be that calculated for the first section cut off, i.e. for an un-worn band.

5.4.1 Test Results

FIGURES 90., and 91., show the cutting constant against the mean number of band revolutions performed e.g. if the band had previously performed 200 revolutions and required a further 30 to cut through the test bar, the corresponding cutting constant would be shown at 215 revolutions.

The cutting constant decreases with the number of band revolutions performed and may be considered to be divided into three distinct phases. These phases correspond to similar phases previously observed when the loss in tooth height was shown against the number of cutting strokes on a power hacksaw [1]. From the similarity of these results it is concluded that the change in the cutting constant can be taken as a measure of band wear. This not only gives a convenient method by which band wear can be measured, but it leads to results which are in a convenient form for cost analysis.

In the first relatively short phase in FIGURE 92., the cutting constant experiences some fluctuations due to initial "running-in".

This phase is followed by one in which the cutting constant falls uniformly with the number of band revolutions performed, and lasts for the majority of the useful life of the band. The third phase is characterised by a very small cutting constant and corresponds to the rapid loss in tooth height observed, [1].

5.4.1.1 Coolant Flow Rate

FIGURES 93., and 94., show the effect of the coolant flow rate on the change in the cutting constant per band revolution and on the initial cutting constant respectively.

The results were obtained by carrying out wear tests under constant machine load and workpiece geometry for various values of coolant flow rate. The flow rate was adjusted via the standard means provided on the bandsaw and calibrated using a measuring flask and stopwatch.

The results are tabulated below:

COOLANT FLOW RATE Litres/minute	INITIAL CUTTING CONSTANT $mm^2 N^{-1} x 10^{-4}$	CHANGE IN CUTTING CONSTANT PER BAND REVOLUTION $mm^2 N^{-1} x 10^{-8}$
0	2.50	22.43
0.4	2.62	13.37
1.0	2.59	8.27
2.0	2.44	5.96
2.2	2.70	9.39
2.6	2.85	6.11

THRUST LOAD = 222N.
BAND SPEED = 23.8m/min.
WORKPIECE BREADTH = 50.8mm.
WORKPIECE DEPTH = 50.8mm.

5.4.1.2 Wear Tests

Using the procedure previously described (section 5.4), a number of wear tests were undertaken under differing conditions of load, speed and workpiece breadth for carbon bands with either 6 or 10 teeth per 25.4mm., and high speed steel bi-metal bands of 6 teeth per 25.4mm. Each set of results were shown on a diagram similar to FIGURE 92., and the change in the cutting constant per band revolution, i.e. the wear rate, determined. The adapted Colding parameters (section 5.2.4), were calculated and the results displayed on a log-log plot based on the dimensionless groups in equation (190). Tests were carried out cutting dry and with coolant flowing at 2 litres per minute.

Results obtained both with and without coolant for the carbon and high speed steel bi-metal bands are shown in FIGURE 95., and TABLES I-IV.

The constant and Colding's wear index shown in equation (190) were determined from FIGURE 95., and are shown below:

BAND MATERIAL	CARBON		HIGH SPEED STEEL BI-METAL	
COOLANT	DRY	SOLUBLE OIL	DRY	SOLUBLE OIL
CONSTANT C'	1.0558 E-10	3.4460 E-11	1.5423 E-16	4.3213 E-15
COLDING'S WEAR INDEX	2.4513	2.3113	2.1885	2.3378
CONSTANT C''	7.2550 E-9	8.8488 E-10	3.5542 E-15	5.1427 E-13
b_1	5.4316	7.4247	11.6101	6.9207
b_2	4.4316	6.4247	10.6101	5.9207
b_3	3.4316	5.4247	9.6101	4.9207

The slope and intercepts of FIGURE 95., were determined using a minimum error routine on a computer. This routine is a standard program which gives the least regression line of Y on X.

The least regression lines are given below:

(a) Carbon / Dry

The line is $Y = 1.225636\ X - 1.836392$

Standard deviation $X = 0.3391192$

Standard deviation $Y = 0.4213648$

(b) Carbon / Coolant

The line is $Y = 1.155631\ X - 1.40889$

Standard deviation $X = 0.3493506$

Standard deviation $Y = 0.4059193$

(c) High Speed Steel Bi-metal / Dry

The line is $Y = 1.09427\ X - 1.362121$

Standard deviation $X = 0.499267$

Standard deviation $Y = 0.5475442$

(d) High Speed Steel Bi-metal / Coolant

The line is $Y = 1.168886\ X - 2.075547$

Standard deviation $X = 0.6436666$

Standard deviation $Y = 0.7583519$

In keeping with Colding's procedure the diffusivity was taken as unity in every case.

The variation in the initial cutting constant against the reciprocal of the number of teeth in contact with the workpiece for both band materials with dry and coolant conditions are shown in FIGURES 96., and 97.

The data relating to FIGURES 96., and 97., is shown in TABLES V and VI.

6 COMPUTER SIMULATION

In order to fully utilize the work shown in section 5, it is necessary to simulate the bandsaw operation on a computer.

The method of simulation is based on the metal removed and blade wear produced, during one revolution of the band. The slot depth produced in the workpiece is determined on the assumption that the cutting constant remains unaltered during one revolution of the band. The decrease in the cutting constant produced during this cycle is determined, and the cutting constant suitably reduced for the next revolution. This cycle of events continues until the cutting constant becomes so small it indicates that the band needs replacing.

In practice the metal removal and blade wear process occur simultaneously. It is considered that for modern bandsaw blades one revolution of the band is such a small unit in the life of the band that this simplification in the model does not lead to significant errors of prediction.

6.1 CUTTING TIME

From equation (176) the cutting time for bandsaw operations may be derived. Assuming that the variation in the cutting constant is negligible during a single revolution of the band then the proportion of the cross sectional area of the workpiece cut through per revolution of the saw is given by multiplying (176) by the time per band revolution.

Thus:

$$A_r = V\left[\frac{KF}{wB} - \frac{a\,t\,p}{w}\right] \cdot Tp \qquad (196)$$

Hence it is possible to determine the proportion of the cross section of the workpiece cut through by each revolution of the band.

The cutting constant in (196) corresponds to the breadth of the workpiece at that position in the section where the band revolution occurs and on the amount of damage the blade has experienced during previous revolutions of the band.

Before the total number of band revolutions needed to cut through the entire section can be determined it is necessary to account for the influence of wear on the cutting efficiency of the band and more precisely the influence of wear on the cutting constant. Once the number of band revolutions has been determined the cutting time is known for a given band speed.

6.2 EFFECT OF WEAR

From the investigations of the factors that influence bandsaw blade wear using dimensional analysis (section 5) it has been established that the cutting constant decreases as a result of damage caused by wear as shown in FIGURE 92., and that the reduction in the cutting constant per revolution of the band is given by (194).

For consecutive revolutions of the band it is possible to write:

$$(K)_{N+1} = (K)_N - \Delta K \tag{197}$$

Combining (194) and (197) with (176) it is possible to determine the time needed to cut through a workpiece section when the cutting efficiency of the blade is reducing due to the effects of wear.

6.3 AVERAGE CUTTING RATE

It is unrealistic to base estimates of the average cutting time on any assumed value of cutting constant. The only true estimate must be based on the gradual decay of the cutting constant over the useful life of the band. Since the rate of decay is a complex function of many parameters (192), the average cutting time is similarly influenced by such parameters.

In addition to the factors influencing the average cutting time, the cutting rate is affected by the time taken to index the workpiece to a position suitable for cutting between operations and by the time needed to change the band. Such times depend on the method of operation and are not affected by the parameters that influence the cutting time. Hence, for the purpose of estimating the average cutting rate these two non-productive times have been considered constant, thus:

$$A = \frac{60}{\left[T_A + T_L + \frac{T_B}{M}\right]} \tag{198}$$

6.4 CUTTING COST

The cost of achieving a cut by using the bandsaw operation may be considered to be made up of the following major sub-costs.

1. time costs, including:
   (i) cutting time costs
   (ii) workpiece index time costs
   (iii) blade replacement time costs

2. the cost of purchasing a new band

3. scrap costs

As the cost analysis is to be used to determine optimum sawing conditions the scrap cost is neglected, because it remains constant for all machine settings; although it is known to be between 5-37 per cent of the total cost of achieving a cut by the bandsaw operation.

6.4.1 Cost Rate

The cost rate is defined as the total cost of operating the bandsaw machine per hour use and is made up of the following components:

(i) labour cost rate
(ii) machine cost rate (including purchase and maintenance costs)

As such the cost rate depends in part, on the percentage utilization of the machine and therefore, on the amount of sawing undertaken and the reliability of the machine. Based on the above, the cost per cut is given by:

$$C_C = C_R\left[\frac{T_A + T_L}{60}\right] + C_R\left[\frac{T_B}{60\,M}\right] + \frac{C_B}{M} \qquad (199)$$

or

$$\omega = \gamma\left[\frac{T_A + T_L}{60}\right] + \frac{1}{M}\left[\frac{T_B\,\gamma}{60} + 1\right] \qquad (200)$$

where ω = Cost Factor = $\dfrac{C_C}{C_B}$

and γ = Cost Ratio = $\dfrac{C_R}{C_B}$

By expressing the cost ratio and cost factor in a dimensionless form the results are to some extent independent of changes due to inflation.

6.4.2 Non-Productive Times And Costs

The following non-productive times are used in the simulation model and are based on standard times accepted in the sawing industry as norms:

(i) time to index workpiece between cuts (T_L) = 0.11minutes

(ii) time to change a band (T_B) = 5.1minutes

The following non-productive costs are used in the simulation model and are based on standard costs accepted in the sawing industry as norms:

(i) cost rate per hour (C_R) = £ 3.25

(ii) band replacement cost (C_B) = £ 2.36 for a carbon band of length 3.35m.

and (C_B) = £ 15.81 for a high speed steel bi-metal band of length 3.35m.

(iii) cost ratio (γ) for carbon band = 1.38

(iv) cost ratio (γ) for high speed steel bi-metal band = 0.21

6.5 ALGORITHM FOR A COMPUTER PROGRAM

FIGURE 98., shows an algorithm suitable for a computer routine to simulate a bandsaw operating with constant feed rate or constant thrust load. The algorithm indicates how the method shown in section 6.2 may be used, taking blade wear into account.

A computer program based on such an algorithm enables the number of sections a band is capable of cutting during its useful life, and the average cutting time for these sections, to be determined. The end of the useful life of the band is indicated by a minimum acceptable cutting constant or by the over-loading of the cutting tool.

From the data obtained from such a simulation the cutting rate and cost of bandsawing can be determined.

6.6 COMPUTER PROGRAMS

Computer programs were written in VSBASIC for use on an IBM 370 / 135 computer, operating on the MUSIC system. The programs were written in conversational form for access via terminals. Use of Batch Job Submission was made to produce the simulation results shown in section (6.7).

The computer programs are shown on the following pages and reference should be made to the algorithm in FIGURE 98.

6.6.1 Program I Constant Thrust Load

```
010 PRINT"BANDSAW WITH CONSTANT THRUST LOAD (F)"
020 PRINT"THE WORKPIECE IS OF RECTANGULAR SECTION"
030 PRINT"WORKPIECE MATERIAL IS EN44E THROUGHOUT"
040 PRINT
050 PRINT
060 PRINT"WHAT IS THE BREADTH OF THE SECTION IN MM."
070 INPUT B
080 PRINT"WHAT IS THE DEPTH OF THE SECTION IN MM."
090 INPUT D
100 PRINT"WHAT IS THE INITIAL CUTTING CONSTANT IN MM**2/N."
110 INPUT K1
120 PRINT"WHAT IS THE SPEED OF THE BAND IN M/MIN."
130 INPUT V
140 PRINT"WHAT IS THE THRUST LOAD SETTING IN NEWTONS."
150 INPUT F
160 PRINT"WHAT IS THE BAND MADE OF,TYPE 1 FOR CARBON BAND,"
170 PRINT"OR 0 FOR HIGH SPEED BI-METAL BAND."
180 INPUT Y
190 IF Y=1 THEN 290
200 PRINT"IF COOLANT IS USED TYPE 1,IF DRY TYPE 0."
210 INPUT Y1
220 IF Y1=1 THEN 260
230 B1=2.1885
240 C=3.5542E-15
250 GO TO 370
260 B1=2.3378
270 C=5.1427E-13
280 GO TO 370
290 PRINT"IF COOLANT IS USED TYPE 1,IF DRY TYPE 0."
300 INPUT Y1
310 IF Y1=1 THEN 350
320 B1=2.4513
330 C=7.255E-9
340 GO TO 370
350 B1=2.3113
360 C=8.8488E-10
370 PRINT"WHAT IS THE VALUE OF'A',THE INTERCEPT CAUSED BY"
380 PRINT"THE PLOUGHING FORCE."
390 INPUT A2
400 E1=0.15
401 PRINT"BREADTH=",B,"MM."
402 PRINT"DEPTH=",D,"MM."
403 PRINT"INITIAL CUTTING CONSTANT=",K1,"MM**2/N."
404 PRINT"THRUST LOAD=",F,"NEWTONS."
405 PRINT"BAND SPEED=",V,"METRES /MINUTE."
406 PRINT"BAND MATERIAL =",Y,"1=CARBON,0=H.S.S."
407 PRINT"COOLANT CONDITIONS=",Y1,"1=WET,0=DRY."
408 PRINT"INTERCEPT'A'=",A2,""
410 A=1.0
420 W=1.6
425 PRINT C,B1
430 P=6
440 T=0.92
450 L=3353
```

```
460 P1=0
470 X=0
480 S1=0
490 D1=0
500 M=0
510 K=K1
520 N1=INT(P*B/25)
530 F1=F/(N1*T)
540 F2=2*A2/K1/(1+E1)
550 C1=(B1/2)/(B1/2-1)
560 C2=1/(B1/2-1)
570 C3=(2-B1/2)/(B1/2-1)
580 V1=V*1000/60
590 V2=(K*F/W/B-A2*T*P/W/25)*V1
600 T1=(L/V1)
610 D1=V2*T1
620 X=X+D1
630 P1=P1+1
640 IF X>=D THEN 690
650 K2=C*(B/L)*(V1**C1)*((K1/A)**C2)*((F1 -F2)**C3)
660 K=K-(K2*T1)
670 IF K<=0 THEN 770
680 GO TO 590
690 M=M+1
700 T2=P1*T1
710 S1=S1+T2
720 IF (K/K1)>=E1 THEN 740
730 GO TO 780
740 X=0
750 P1=0
760 GO TO 650
770 IF M=0 THEN 950
780 T3=S1/M/60
790 P2=60/(T3+0.11+(5.1/M))
800 IF Y=1 THEN 830
810 G1=0.21
820 GO TO 840
830 G1=1.38
840 C4=G1*(((T3+0.11)/60)+(((5.1*G1)/60)+1)/M)
850 F3=M+1
880 PRINT"BAND FAILED TO CUT ON THE",F3,"SECTION."
890 PRINT"BAND COMPLETED",M,"CUTS."
900 PRINT"AVERAGE CUTTING TIME=",T3,"MINUTES."
910 PRINT"AVERAGE CUTTING RATE=",P2,"SECTIONS PER HOUR."
920 PRINT"COST RATIO=",G1,""
930 PRINT"COST FACTOR=",C4,""
940 GO TO 960
950 PRINT"BAND FAILED COMPLETELY ON THE FIRST SECTION."
960 PRINT"TO CONTINUE SESSION TYPE 1,TO END TYPE 0."
970 INPUT R1
980 IF R1=1 THEN 10
990 IF R1<>0 THEN 960
995 END
```

6.6.2 Program II Constant Feed Rate

```
010 PRINT"BANDSAW OPERATION WITH CONSTANT FEED RATE."
020 PRINT"THE WORKPIECE IS OF RECTANGULAR SECTION."
030 PRINT"WORKPIECE IS EN44E THROUGHOUT."
040 PRINT
050 PRINT
060 PRINT"WHAT IS THE BREADTH OF THE SECTION IN MM."
070 INPUT B
080 PRINT"WHAT IS THE DEPTH OF THE SECTION IN MM."
090 INPUT D
100 PRINT"WHAT IS THE INITIAL CUTTING CONSTANT IN MM**2/N."
105 INPUT K1
120 PRINT"WHAT IS THE SPEED OF THE BAND IN M/MIN."
130 INPUT V
140 PRINT"WHAT FEED RATE IS REQUIRED IN MM/S."
150 INPUT V2
160 PRINT"WHAT IS THE BAND MADE OF,TYPE 1 FOR CARBON,"
170 PRINT"OR 0 FOR HIGH SPEED BI-METAL BAND."
180 INPUT Y
190 IF Y=1 THEN 290
200 PRINT"IF COOLANT IS USED TYPE 1,IF DRY TYPE 0."
210 INPUT Y1
220 IF Y1=1 THEN 260
230 B1=2.1885
240 C=3.5542E-15
250 GO TO 370
260 B1=2.3378
270 C=5.1427E-13
280 GO TO 370
290 PRINT"IF COOLANT IS USED TYPE 1,IF DRY TYPE 0."
300 INPUT Y1
310 IF Y1=1 THEN 350
320 B1=2.4513
330 C=7.255E-9
340 GO TO 370
350 B1=2.3113
360 C=8.8488E-10
370 PRINT"WHAT IS THE VALUE OF'A' THE INTERCEPT CAUSED BY"
380 PRINT"THE PLOUGHING FORCE."
390 INPUT A2
400 E1=0.15
401 PRINT"BREADTH=",B,"MM."
402 PRINT"DEPTH=",D,"MM."
403 PRINT"INITIAL CUTTING CONSTANT=",K1,"MM**2/N."
404 PRINT"BAND SPEED=",V,"METRES/MINUTE."
405 PRINT"FEED RATE =",V2,"MM/S."
406 PRINT"BAND MATERIAL=",Y,"1=CARBON,0=H.S.S."
407 PRINT"COOLANT CONDITIONS=",Y1,"1=WET,0=DRY."
408 PRINT"INTERCEPT 'A'=",A2,""
410 A=1.0
420 W=1.6
422 F4=500
425 PRINT C,B1
430 P=6
440 L=3353
450 T=0.92
```

```
460 P1=0
470 X=0
480 S1=0
490 D1=0
500 M=0
510 N1=INT(P*B/25)
520 K=K1
530 C1=(B1/2)/(B1/2-1)
540 C2=1/(B1/2-1)
550 C3=(2-B1/2)/(B1/2-1)
560 V1=V*1000/60
580 F2=2*A2/K1/(1+E1)
590 F3=(V2*W/V1+A2*T*P/25)*B/K
595 IF F3>=F4 THEN 780
600 F1=F3/(N1*T)
610 T1=(L/V1)
620 D1=V2*T1
630 X=X+D1
640 P1=P1+1
650 IF X>=D THEN 700
660 K2=C*(B/L)*(V1**C1)*((K1/A)**C2)*((F1-F2)**C3)
670 K=K-(K2*T1)
680 IF K<=0 THEN 780
690 GO TO 590
700 M=M+1
710 T2=P1*T1
720 S1=S1+T2
730 IF F3<=500 THEN 750
740 GO TO 790
750 X=0
760 P1=0
770 GO TO 660
780 IF M=0 THEN 950
790 T3=S1/M/60
800 P2=60/(T3+0.11+(5.1/M))
810 IF Y=1 THEN 840
820 G1=0.21
830 GO TO 850
840 G1=1.38
850 C4=G1*(((T3+0.11)/60)+(((5.1*G1)/60)+1)/M)
860 F3=M+1
880 PRINT"BAND FAILED TO CUT ON THE ",F3,"SECTION."
890 PRINT"BAND COMPLETED",M,"CUTS."
900 PRINT"AVERAGE CUTTING TIME=",T3,"MINUTES."
910 PRINT"AVERAGE CUTTING RATE=",P2,"SECTIONS PER HOUR."
920 PRINT"COST RATIO=",G1,""
930 PRINT"COST FACTOR=",C4,""
940 GO TO 960
950 PRINT"BAND FAILED COMPLETELY ON THE FIRST SECTION."
960 PRINT"TO CONTINUE SESSION TYPE 1,TO END TYPE 0."
970 INPUT R1
980 IF R1=1 THEN 10
990 IF R1<>0 THEN 960
995 END
```

6.7 SIMULATION RESULTS

The computer programs in section 6.6, based on the algorithm described, have been used to investigate the effects of various machine parameters on the average cutting rate (sections per hour) and cost (cost ratio). Both the constant thrust load and constant feed rate systems of bandsawing are investigated.

In every case the factor η, which specifies the end of the useful life of the band has been taken to be 0.15. The maximum allowable thrust load has been set at 500N for all operations.

6.7.1 Carbon Band - Constant Thrust Load

In these simulation results PROGRAM I was used with various band speeds in the range 10-40m / min. for selected values of thrust load in the range 200-500N for both dry and coolant cutting conditions. The computer print-outs for these tests are shown on the following pages.

FIGURE 99., uses this data, and shows the effects of band speed and thrust load on the average cutting rate and cost factor, for carbon bands both dry and with coolant for constant thrust load.

```
BREADTH=             50              MM.
DEPTH=               50              MM.
INITIAL CUTTING CONSTANT=             2.900001E-04     MM**2/N.
THRUST LOAD=         200             NEWTONS.
BAND SPEED=          10              METRES /MINUTE.
BAND MATERIAL =      1               1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                   0                1=WET,0=DRY.
INTERCEPT'A'=        6.500001E-04
 7.255000E-09        2.4513
BAND FAILED TO CUT ON THE             1099             SECTION.
BAND COMPLETED       1098            CUTS.
AVERAGE CUTTING TIME=                 15.64531         MINUTES.
AVERAGE CUTTING RATE=                 3.807117         SECTIONS PER HOUR.
COST RATIO=          1.38
COST FACTOR=         .3637763
BREADTH=             50              MM.
DEPTH=               50              MM.
INITIAL CUTTING CONSTANT=             2.900001E-04     MM**2/N.
THRUST LOAD=         300             NEWTONS.
BAND SPEED=          10              METRES /MINUTE.
BAND MATERIAL =      1               1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                   0                1=WET,0=DRY.
INTERCEPT'A'=        6.500001E-04
 7.255000E-09        2.4513
BAND FAILED TO CUT ON THE             331              SECTION.
BAND COMPLETED       330             CUTS.
AVERAGE CUTTING TIME=                 9.681787         MINUTES.
AVERAGE CUTTING RATE=                 6.117929         SECTIONS PER HOUR.
COST RATIO=          1.38
COST FACTOR=         .2298833
BREADTH=             50              MM.
DEPTH=               50              MM.
INITIAL CUTTING CONSTANT=             2.900001E-04     MM**2/N.
THRUST LOAD=         400             NEWTONS.
BAND SPEED=          10              METRES /MINUTE.
BAND MATERIAL =      1               1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                   0                1=WET,0=DRY.
INTERCEPT'A'=        6.500001E-04
 7.255000E-09        2.4513
BAND FAILED TO CUT ON THE             148              SECTION.
BAND COMPLETED       147             CUTS.
AVERAGE CUTTING TIME=                 6.970556         MINUTES.
AVERAGE CUTTING RATE=                 8.432592         SECTIONS PER HOUR.
COST RATIO=          1.38
COST FACTOR=         .1733416
BREADTH=             50              MM.
DEPTH=               50              MM.
INITIAL CUTTING CONSTANT=             2.900001E-04     MM**2/N.
THRUST LOAD=         450             NEWTONS.
BAND SPEED=          10              METRES /MINUTE.
BAND MATERIAL =      1               1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                   0                1=WET,0=DRY.
INTERCEPT'A'=        6.500001E-04
 7.255000E-09        2.4513
BAND FAILED TO CUT ON THE             108              SECTION.
BAND COMPLETED       107             CUTS.
AVERAGE CUTTING TIME=                 6.273526         MINUTES.
AVERAGE CUTTING RATE=                 9.329535         SECTIONS PER HOUR.
COST RATIO=          1.38
COST FACTOR=         .161231
```

Carbon Band   Constant Thrust Load   Dry   V=10m/min

```
BREADTH=             50              MM.
DEPTH=               50              MM.
INITIAL CUTTING CONSTANT=             2.900001E-04     MM**2/N.
THRUST LOAD=         500             NEWTONS.
BAND SPEED=          10              METRES /MINUTE.
BAND MATERIAL =      1               1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                   0                1=WET,0=DRY.
INTERCEPT'A'=        6.500001E-04
 7.255000E-09        2.4513
BAND FAILED TO CUT ON THE             82               SECTION.
BAND COMPLETED       81              CUTS.
AVERAGE CUTTING TIME=                 5.766304         MINUTES.
AVERAGE CUTTING RATE=                 10.10226         SECTIONS PER HOUR.
COST RATIO=          1.38
COST FACTOR=         .1541903
```

Carbon Band   Constant Thrust Load   Dry   V=10m/min

```
BREADTH=              50                  MM.
DEPTH=                50                  MM.
INITIAL CUTTING CONSTANT=                  2.900001E-04     MM**2/N.
THRUST LOAD=          100                 NEWTONS.
BAND SPEED=           20                  METRES /MINUTE.
BAND MATERIAL =       1                   1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                        0                1=WET,0=DRY.
INTERCEPT'A'=         6.500001E-04
 7.255000E-09         2.4513
BAND FAILED TO CUT ON THE                  613              SECTION.
BAND COMPLETED        612                 CUTS.
AVERAGE CUTTING TIME=                      18.22384         MINUTES.
AVERAGE CUTTING RATE=                      3.271688         SECTIONS PER HOUR.
COST RATIO=           1.38
COST FACTOR=          .4241284
BREADTH=              50                  MM.
DEPTH=                50                  MM.
INITIAL CUTTING CONSTANT=                  2.900001E-04     MM**2/N.
THRUST LOAD=          200                 NEWTONS.
BAND SPEED=           20                  METRES /MINUTE.
BAND MATERIAL =       1                   1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                        0                1=WET,0=DRY.
INTERCEPT'A'=         6.500001E-04
 7.255000E-09         2.4513
BAND FAILED TO CUT ON THE                  52               SECTION.
BAND COMPLETED        51                  CUTS.
AVERAGE CUTTING TIME=                      7.619836         MINUTES.
AVERAGE CUTTING RATE=                      7.662996         SECTIONS PER HOUR.
COST RATIO=           1.38
COST FACTOR=          .2080189
BREADTH=              50                  MM.
DEPTH=                50                  MM.
INITIAL CUTTING CONSTANT=                  2.900001E-04     MM**2/N.
THRUST LOAD=          300                 NEWTONS.
BAND SPEED=           20                  METRES /MINUTE.
BAND MATERIAL =       1                   1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                        0                1=WET,0=DRY.
INTERCEPT'A'=         6.500001E-04
 7.255000E-09         2.4513
BAND FAILED TO CUT ON THE                  16               SECTION.
BAND COMPLETED        15                  CUTS.
AVERAGE CUTTING TIME=                      4.381249         MINUTES.
AVERAGE CUTTING RATE=                      12.41915         SECTIONS PER HOUR.
COST RATIO=           1.38
COST FACTOR=          .2060902
BREADTH=              50                  MM.
DEPTH=                50                  MM.
INITIAL CUTTING CONSTANT=                  2.900001E-04     MM**2/N.
THRUST LOAD=          400                 NEWTONS.
BAND SPEED=           20                  METRES /MINUTE.
BAND MATERIAL =       1                   1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                        0                1=WET,0=DRY.
INTERCEPT'A'=         6.500001E-04
 7.255000E-09         2.4513
BAND FAILED TO CUT ON THE                  7                SECTION.
BAND COMPLETED        6                   CUTS.
AVERAGE CUTTING TIME=                      2.766223         MINUTES.
AVERAGE CUTTING RATE=                      16.1021          SECTIONS PER HOUR.
COST RATIO=           1.38
COST FACTOR=          .3231319
```

Carbon Band   Constant Thrust Load   Dry   V=20m/min

```
BREADTH=              50                  MM.
DEPTH=                50                  MM.
INITIAL CUTTING CONSTANT=                  2.900001E-04     MM**2/N.
THRUST LOAD=          450                 NEWTONS.
BAND SPEED=           20                  METRES /MINUTE.
BAND MATERIAL =       1                   1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                        0                1=WET,0=DRY.
INTERCEPT'A'=         6.500001E-04
 7.255000E-09         2.4513
BAND FAILED TO CUT ON THE                  6                SECTION.
BAND COMPLETED        5                   CUTS.
AVERAGE CUTTING TIME=                      3.017698         MINUTES.
AVERAGE CUTTING RATE=                      14.46586         SECTIONS PER HOUR.
COST RATIO=           1.38
COST FACTOR=          .3803115
BREADTH=              50                  MM.
DEPTH=                50                  MM.
INITIAL CUTTING CONSTANT=                  2.900001E-04     MM**2/N.
THRUST LOAD=          500                 NEWTONS.
BAND SPEED=           20                  METRES /MINUTE.
BAND MATERIAL =       1                   1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                        0                1=WET,0=DRY.
INTERCEPT'A'=         6.500001E-04
 7.255000E-09         2.4513
BAND FAILED TO CUT ON THE                  4                SECTION.
BAND COMPLETED        3                   CUTS.
AVERAGE CUTTING TIME=                      2.123566         MINUTES.
AVERAGE CUTTING RATE=                      15.25334         SECTIONS PER HOUR.
COST RATIO=           1.38
COST FACTOR=          .5653296
```

Carbon Band   Constant Thrust Load   Dry   V=20m/min

```
BREADTH=              50                MM.
DEPTH=                50                MM.
INITIAL CUTTING CONSTANT=                2.900001E-04     MM**2/N.
THRUST LOAD=          100               NEWTONS.
BAND SPEED=           30                METRES /MINUTE.
BAND MATERIAL =       1                 1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                      0                1=WET,0=DRY.
INTERCEPT'A'=         6.500001E-04
 7.255000E-09         2.4513
BAND FAILED TO CUT ON THE                102              SECTION.
BAND COMPLETED        101               CUTS.
AVERAGE CUTTING TIME=                    11.26405         MINUTES.
AVERAGE CUTTING RATE=                    5.251852         SECTIONS PER HOUR.
COST RATIO=           1.38
COST FACTOR=          .276869

BREADTH=              50                MM.
DEPTH=                50                MM.
INITIAL CUTTING CONSTANT=                2.900001E-04     MM**2/N.
THRUST LOAD=          200               NEWTONS.
BAND SPEED=           30                METRES /MINUTE.
BAND MATERIAL =       1                 1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                      0                1=WET,0=DRY.
INTERCEPT'A'=         6.500001E-04
 7.255000E-09         2.4513
BAND FAILED TO CUT ON THE                9                SECTION.
BAND COMPLETED        8                 CUTS.
AVERAGE CUTTING TIME=                    4.261101         MINUTES.
AVERAGE CUTTING RATE=                    11.97939         SECTIONS PER HOUR.
COST RATIO=           1.38
COST FACTOR=          .2932694

BREADTH=              50                MM.
DEPTH=                50                MM.
INITIAL CUTTING CONSTANT=                2.900001E-04     MM**2/N.
THRUST LOAD=          300               NEWTONS.
BAND SPEED=           30                METRES /MINUTE.
BAND MATERIAL =       1                 1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                      0                1=WET,0=DRY.
INTERCEPT'A'=         6.500001E-04
 7.255000E-09         2.4513
BAND FAILED TO CUT ON THE                3                SECTION.
BAND COMPLETED        2                 CUTS.
AVERAGE CUTTING TIME=                    2.291215         MINUTES.
AVERAGE CUTTING RATE=                    12.11824         SECTIONS PER HOUR.
COST RATIO=           1.38
COST FACTOR=          .8261643

BREADTH=              50                MM.
DEPTH=                50                MM.
INITIAL CUTTING CONSTANT=                2.900001E-04     MM**2/N.
THRUST LOAD=          400               NEWTONS.
BAND SPEED=           30                METRES /MINUTE.
BAND MATERIAL =       1                 1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                      0                1=WET,0=DRY.
INTERCEPT'A'=         6.500001E-04
 7.255000E-09         2.4513
BAND FAILED TO CUT ON THE                2                SECTION.
BAND COMPLETED        1                 CUTS.
AVERAGE CUTTING TIME=                    1.788266         MINUTES.
AVERAGE CUTTING RATE=                    8.573551         SECTIONS PER HOUR.
COST RATIO=           1.38
COST FACTOR=          1.585531
```

Carbon Band   Constant Thrust Load   Dry   V=30m/min

```
BREADTH=              50              MM.
DEPTH=                50              MM.
INITIAL CUTTING CONSTANT=              2.900001E-04      MM**2/N.
THRUST LOAD=          300             NEWTONS.
BAND SPEED=           10              METRES /MINUTE.
BAND MATERIAL =       1               1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                    1                 1=WET,0=DRY.
INTERCEPT'A'=         6.500001E-04
 8.848799E-10         2.3113
BAND FAILED TO CUT ON THE              2113              SECTION.
BAND COMPLETED        2112            CUTS.
AVERAGE CUTTING TIME=                  9.599723          MINUTES.
AVERAGE CUTTING RATE=                  6.177836          SECTIONS PER HOUR.
COST RATIO=           1.38
COST FACTOR=          .2240536

BREADTH=              50              MM.
DEPTH=                50              MM.
INITIAL CUTTING CONSTANT=              2.900001E-04      MM**2/N.
THRUST LOAD=          400             NEWTONS.
BAND SPEED=           10              METRES /MINUTE.
BAND MATERIAL =       1               1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                    1                 1=WET,0=DRY.
INTERCEPT'A'=         6.500001E-04
 8.848799E-10         2.3113
BAND FAILED TO CUT ON THE              496               SECTION.
BAND COMPLETED        495             CUTS.
AVERAGE CUTTING TIME=                  6.978003          MINUTES.
AVERAGE CUTTING RATE=                  8.452722          SECTIONS PER HOUR.
COST RATIO=           1.38
COST FACTOR=          .1661389
```

Carbon Band   Constant Thrust Load   Coolant   V=10m/min

```
BREADTH=             50               MM.
DEPTH=               50               MM.
INITIAL CUTTING CONSTANT=              2.900001E-04     MM**2/N.
THRUST LOAD=         200              NEWTONS.
BAND SPEED=          20               METRES /MINUTE.
BAND MATERIAL =      1                1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                    1                1=WET,0=DRY.
INTERCEPT'A'=        6.500001E-04
 8.848799E-10        2.3113
BAND FAILED TO CUT ON THE              222              SECTION.
BAND COMPLETED       221              CUTS.
AVERAGE CUTTING TIME=                  7.545671         MINUTES.
AVERAGE CUTTING RATE=                  7.813775         SECTIONS PER HOUR.
COST RATIO=          1.38
COST FACTOR=         .1830571

BREADTH=             50               MM.
DEPTH=               50               MM.
INITIAL CUTTING CONSTANT=              2.900001E-04     MM**2/N.
THRUST LOAD=         300              NEWTONS.
BAND SPEED=          20               METRES /MINUTE.
BAND MATERIAL =      1                1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                    1                1=WET,0=DRY.
INTERCEPT'A'=        6.500001E-04
 8.848799E-10        2.3113
BAND FAILED TO CUT ON THE              26               SECTION.
BAND COMPLETED       25               CUTS.
AVERAGE CUTTING TIME=                  5.022786         MINUTES.
AVERAGE CUTTING RATE=                  11.24272         SECTIONS PER HOUR.
COST RATIO=          1.38
COST FACTOR=         .1797288

BREADTH=             50               MM.
DEPTH=               50               MM.
INITIAL CUTTING CONSTANT=              2.900001E-04     MM**2/N.
THRUST LOAD=         400              NEWTONS.
BAND SPEED=          20               METRES /MINUTE.
BAND MATERIAL =      1                1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                    1                1=WET,0=DRY.
INTERCEPT'A'=        6.500001E-04
 8.848799E-10        2.3113
BAND FAILED TO CUT ON THE              6                SECTION.
BAND COMPLETED       5                CUTS.
AVERAGE CUTTING TIME=                  2.749459         MINUTES.
AVERAGE CUTTING RATE=                  15.46608         SECTIONS PER HOUR.
COST RATIO=          1.38
COST FACTOR=         .374142

BREADTH=             50               MM.
DEPTH=               50               MM.
INITIAL CUTTING CONSTANT=              2.900001E-04     MM**2/N.
THRUST LOAD=         450              NEWTONS.
BAND SPEED=          20               METRES /MINUTE.
BAND MATERIAL =      1                1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                    1                1=WET,0=DRY.
INTERCEPT'A'=        6.500001E-04
 8.848799E-10        2.3113
BAND FAILED TO CUT ON THE              4                SECTION.
BAND COMPLETED       3                CUTS.
AVERAGE CUTTING TIME=                  2.570632         MINUTES.
AVERAGE CUTTING RATE=                  13.69666         SECTIONS PER HOUR.
COST RATIO=          1.38
COST FACTOR=         .575612
```

Carbon Band   Constant Thrust Load   Coolant   V=20m/min

```
BREADTH=               50               MM.
DEPTH=                 50               MM.
INITIAL CUTTING CONSTANT=                2.900001E-04      MM**2/N.
THRUST LOAD=           150              NEWTONS.
BAND SPEED=            30               METRES /MINUTE.
BAND MATERIAL =        1                1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                      1                 1=WET,0=DRY.
INTERCEPT'A'=          6.500001E-04
 8.848799E-10          2.3113
BAND FAILED TO CUT ON THE                90                SECTION.
BAND COMPLETED         89               CUTS.
AVERAGE CUTTING TIME=                    6.733598          MINUTES.
AVERAGE CUTTING RATE=                    8.694518          SECTIONS PER HOUR.
COST RATIO=            1.38
COST FACTOR=           .174727

BREADTH=               50               MM.
DEPTH=                 50               MM.
INITIAL CUTTING CONSTANT=                2.900001E-04      MM**2/N.
THRUST LOAD=           160              NEWTONS.
BAND SPEED=            30               METRES /MINUTE.
BAND MATERIAL =        1                1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                      1                 1=WET,0=DRY.
INTERCEPT'A'=          6.500001E-04
 8.848799E-10          2.3113
BAND FAILED TO CUT ON THE                61                SECTION.
BAND COMPLETED         60               CUTS.
AVERAGE CUTTING TIME=                    6.268221          MINUTES.
AVERAGE CUTTING RATE=                    9.283298          SECTIONS PER HOUR.
COST RATIO=            1.38
COST FACTOR=           .1723968

BREADTH=               50               MM.
DEPTH=                 50               MM.
INITIAL CUTTING CONSTANT=                2.900001E-04      MM**2/N.
THRUST LOAD=           180              NEWTONS.
BAND SPEED=            30               METRES /MINUTE.
BAND MATERIAL =        1                1=CARBON,C=H.S.S.
COOLANT CONDITIONS=                      1                 1=WET,0=DRY.
INTERCEPT'A'=          6.500001E-04
 8.848799E-10          2.3113
BAND FAILED TO CUT ON THE                31                SECTION.
BAND COMPLETED         30               CUTS.
AVERAGE CUTTING TIME=                    5.688904          MINUTES.
AVERAGE CUTTING RATE=                    10.0521           SECTIONS PER HOUR.
COST RATIO=            1.38
COST FACTOR=           .1847703

BREADTH=               50               MM.
DEPTH=                 50               MM.
INITIAL CUTTING CONSTANT=                2.900001E-04      MM**2/N.
THRUST LOAD=           200              NEWTONS.
BAND SPEED=            30               METRES /MINUTE.
BAND MATERIAL =        1                1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                      1                 1=WET,0=DRY.
INTERCEPT'A'=          6.500001E-04
 8.848799E-10          2.3113
BAND FAILED TO CUT ON THE                17                SECTION.
BAND COMPLETED         16               CUTS.
AVERAGE CUTTING TIME=                    4.533532          MINUTES.
AVERAGE CUTTING RATE=                    12.09121          SECTIONS PER HOUR.
COST RATIO=            1.38
COST FACTOR=           .2031682
```

Carbon Band   Constant Thrust Load   Coolant   V=30m/min

```
BREADTH=               50               MM.
DEPTH=                 50               MM.
INITIAL CUTTING CONSTANT=                2.900001E-04      MM**2/N.
THRUST LOAD=           300              NEWTONS.
BAND SPEED=            30               METRES /MINUTE.
BAND MATERIAL =        1                1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                      1                 1=WET,0=DRY.
INTERCEPT'A'=          6.500001E-04
 8.848799E-10          2.3113
BAND FAILED TO CUT ON THE                2                 SECTION.
BAND COMPLETED         1                CUTS.
AVERAGE CUTTING TIME=                    2.011799          MINUTES.
AVERAGE CUTTING RATE=                    8.308179          SECTIONS PER HOUR.
COST RATIO=            1.38
COST FACTOR=           1.590673

BREADTH=               50               MM.
DEPTH=                 50               MM.
INITIAL CUTTING CONSTANT=                2.900001E-04      MM**2/N.
THRUST LOAD=           400              NEWTONS.
BAND SPEED=            30               METRES /MINUTE.
BAND MATERIAL =        1                1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                      1                 1=WET,0=DRY.
INTERCEPT'A'=          6.500001E-04
 8.848799E-10          2.3113
BAND FAILED COMPLETELY ON THE FIRST SECTION.
```

Carbon Band   Constant Thrust Load   Coolant   V=30m/min

```
BREADTH=             50              MM.
DEPTH=               50              MM.
INITIAL CUTTING CONSTANT=             2.500000E-04     MM**2/N.
THRUST LOAD=         150             NEWTONS.
BAND SPEED=          40              METRES /MINUTE.
BAND MATERIAL =      1               1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                   1                1=WET,0=DRY.
INTERCEPT'A'=        6.500001E-04
 8.848799E-10        2.3113
BAND FAILED TO CUT ON THE             37               SECTION.
BAND COMPLETED       36              CUTS.
AVERAGE CUTTING TIME=                 5.786238         MINUTES.
AVERAGE CUTTING RATE=                 9.937223         SECTIONS PER HOUR.
COST RATIO=          1.38
COST FACTOR=         .1784432

BREADTH=             50              MM.
DEPTH=               50              MM.
INITIAL CUTTING CONSTANT=             2.500000E-04     MM**2/N.
THRUST LOAD=         200             NEWTONS.
BAND SPEED=          40              METRES /MINUTE.
BAND MATERIAL =      1               1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                   1                1=WET,0=DRY.
INTERCEPT'A'=        6.500001E-04
 8.848799E-10        2.3113
BAND FAILED TO CUT ON THE             7                SECTION.
BAND COMPLETED       6               CUTS.
AVERAGE CUTTING TIME=                 4.205218         MINUTES.
AVERAGE CUTTING RATE=                 11.61616         SECTIONS PER HOUR.
COST RATIO=          1.38
COST FACTOR=         .3562287

BREADTH=             50              MM.
DEPTH=               50              MM.
INITIAL CUTTING CONSTANT=             2.500000E-04     MM**2/N.
THRUST LOAD=         250             NEWTONS.
BAND SPEED=          40              METRES /MINUTE.
BAND MATERIAL =      1               1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                   1                1=WET,0=DRY.
INTERCEPT'A'=        6.500001E-04
 8.848799E-10        2.3113
BAND FAILED TO CUT ON THE             2                SECTION.
BAND COMPLETED       1               CUTS.
AVERAGE CUTTING TIME=                 2.17945          MINUTES.
AVERAGE CUTTING RATE=                 8.119683         SECTIONS PER HOUR.
COST RATIO=          1.38
COST FACTOR=         1.59453
```

Carbon Band   Constant Thrust Load   Coolant   V=40m/min

6.7.2 Carbon Band - Constant Feed Rate

In these simulation tests, PROGRAM II was used with various band speeds in the range 10-40m./ min. for selected values of feed rate in the range 0.1-0.6mm / s., for both dry and coolant cutting conditions. The computer print-outs for these tests are shown on the following pages.

FIGURE 100., uses this data and shows the effects of band speed and feed rate on the average cutting rate and cost factor for carbon bands both dry and with coolant for constant feed rate.

```
BREADTH=                50              MM.
DEPTH=                  50              MM.
INITIAL CUTTING CONSTANT=                2.900001E-04    MM**2/N.
BAND SPEED=             10              METRES/MINUTE.
FEED RATE =             .1              MM/S.
BAND MATERIAL=          1               1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                      0               1=WET,0=DRY.
INTERCEPT 'A'=          6.500001E-04
 7.255000E-09           2.4513
BAND FAILED TO CUT ON THE                559             SECTION.
BAND COMPLETED          558             CUTS.
AVERAGE CUTTING TIME=                    8.382336        MINUTES.
AVERAGE CUTTING RATE=                    7.057599        SECTIONS PER HOUR.
COST RATIO=             1.38
COST FACTOR=            .1980869

BREADTH=                50              MM.
DEPTH=                  50              MM.
INITIAL CUTTING CONSTANT=                2.900001E-04    MM**2/N.
BAND SPEED=             10              METRES/MINUTE.
FEED RATE =             .2              MM/S.
BAND MATERIAL=          1               1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                      0               1=WET,0=DRY.
INTERCEPT 'A'=          6.500001E-04
 7.255000E-09           2.4513
BAND FAILED TO CUT ON THE                73              SECTION.
BAND COMPLETED          72              CUTS.
AVERAGE CUTTING TIME=                    4.358862        MINUTES.
AVERAGE CUTTING RATE=                    13.21675        SECTIONS PER HOUR.
COST RATIO=             1.38
COST FACTOR=            .1241986

BREADTH=                50              MM.
DEPTH=                  50              MM.
INITIAL CUTTING CONSTANT=                2.900001E-04    MM**2/N.
BAND SPEED=             10              METRES/MINUTE.
FEED RATE =             .22             MM/S.
BAND MATERIAL=          1               1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                      0               1=WET,0=DRY.
INTERCEPT 'A'=          6.500001E-04
 7.255000E-09           2.4513
BAND FAILED TO CUT ON THE                49              SECTION.
BAND COMPLETED          48              CUTS.
AVERAGE CUTTING TIME=                    4.023577        MINUTES.
AVERAGE CUTTING RATE=                    14.15152        SECTIONS PER HOUR.
COST RATIO=             1.38
COST FACTOR=            .1271945

BREADTH=                50              MM.
DEPTH=                  50              MM.
INITIAL CUTTING CONSTANT=                2.900001E-04    MM**2/N.
BAND SPEED=             10              METRES/MINUTE.
FEED RATE =             .24             MM/S.
BAND MATERIAL=          1               1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                      0               1=WET,0=DRY.
INTERCEPT 'A'=          6.500001E-04
 7.255000E-09           2.4513
BAND FAILED TO CUT ON THE                31              SECTION.
BAND COMPLETED          30              CUTS.
AVERAGE CUTTING TIME=                    3.68829         MINUTES.
AVERAGE CUTTING RATE=                    15.11987        SECTIONS PER HOUR.
COST RATIO=             1.38
COST FACTOR=            .1357563
```

Carbon Band   Constant Feed Rate   Dry   V=10m/min

```
BREADTH=                50              MM.
DEPTH=                  50              MM.
INITIAL CUTTING CONSTANT=                2.900001E-04    MM**2/N.
BAND SPEED=             10              METRES/MINUTE.
FEED RATE =             .26             MM/S.
BAND MATERIAL=          1               1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                      0               1=WET,0=DRY.
INTERCEPT 'A'=          6.500001E-04
 7.255000E-09           2.4513
BAND FAILED TO CUT ON THE                17              SECTION.
BAND COMPLETED          16              CUTS.
AVERAGE CUTTING TIME=                    3.352999        MINUTES.
AVERAGE CUTTING RATE=                    15.86568        SECTIONS PER HOUR.
COST RATIO=             1.38
COST FACTOR=            .176016

BREADTH=                50              MM.
DEPTH=                  50              MM.
INITIAL CUTTING CONSTANT=                2.900001E-04    MM**2/N.
BAND SPEED=             10              METRES/MINUTE.
FEED RATE =             .28             MM/S.
BAND MATERIAL=          1               1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                      0               1=WET,0=DRY.
INTERCEPT 'A'=          6.500001E-04
 7.255000E-09           2.4513
BAND FAILED TO CUT ON THE                5               SECTION.
BAND COMPLETED          4               CUTS.
AVERAGE CUTTING TIME=                    3.017696        MINUTES.
AVERAGE CUTTING RATE=                    13.62801        SECTIONS PER HOUR.
COST RATIO=             1.38
COST FACTOR=            .4574052

BREADTH=                50              MM.
DEPTH=                  50              MM.
INITIAL CUTTING CONSTANT=                2.900001E-04    MM**2/N.
BAND SPEED=             10              METRES/MINUTE.
FEED RATE =             .3              MM/S.
BAND MATERIAL=          1               1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                      0               1=WET,0=DRY.
INTERCEPT 'A'=          6.500001E-04
 7.255000E-09           2.4513
BAND FAILED COMPLETELY ON THE FIRST SECTION.
```

Carbon Band   Constant Feed Rate   Dry   V=10m/min

```
BREADTH=              50              MM.
DEPTH=                50              MM.
INITIAL CUTTING CONSTANT=              2.900001E-04     MM**2/N.
BAND SPEED=           20              METRES/MINUTE.
FEED RATE =           .1              MM/S.
BAND MATERIAL=        1               1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                    0                1=WET,0=DRY.
INTERCEPT 'A'=        6.500001E-04
 7.255000E-09         2.4513
BAND FAILED TO CUT ON THE              187              SECTION.
BAND COMPLETED        186             CUTS.
AVERAGE CUTTING TIME=                  8.382425         MINUTES.
AVERAGE CUTTING RATE=                  7.042382         SECTIONS PER HOUR.
COST RATIO=           1.38
COST FACTOR=          .2036154

BREADTH=              50              MM.
DEPTH=                50              MM.
INITIAL CUTTING CONSTANT=              2.900001E-04     MM**2/N.
BAND SPEED=           20              METRES/MINUTE.
FEED RATE =           .15             MM/S.
BAND MATERIAL=        1               1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                    0                1=WET,0=DRY.
INTERCEPT 'A'=        6.500001E-04
 7.255000E-09         2.4513
BAND FAILED TO CUT ON THE              57               SECTION.
BAND COMPLETED        56              CUTS.
AVERAGE CUTTING TIME=                  5.700068         MINUTES.
AVERAGE CUTTING RATE=                  10.16753         SECTIONS PER HOUR.
COST RATIO=           1.38
COST FACTOR=          .1611649

BREADTH=              50              MM.
DEPTH=                50              MM.
INITIAL CUTTING CONSTANT=              2.900001E-04     MM**2/N.
BAND SPEED=           20              METRES/MINUTE.
FEED RATE =           .2              MM/S.
BAND MATERIAL=        1               1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                    0                1=WET,0=DRY.
INTERCEPT 'A'=        6.500001E-04
 7.255000E-09         2.4513
BAND FAILED TO CUT ON THE              27               SECTION.
BAND COMPLETED        26              CUTS.
AVERAGE CUTTING TIME=                  4.191233         MINUTES.
AVERAGE CUTTING RATE=                  13.34108         SECTIONS PER HOUR.
COST RATIO=           1.38
COST FACTOR=          .1582311

BREADTH=              50              MM.
DEPTH=                50              MM.
INITIAL CUTTING CONSTANT=              2.900001E-04     MM**2/N.
BAND SPEED=           20              METRES/MINUTE.
FEED RATE =           .3              MM/S.
BAND MATERIAL=        1               1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                    0                1=WET,0=DRY.
INTERCEPT 'A'=        6.500001E-04
 7.255000E-09         2.4513
BAND FAILED TO CUT ON THE              9                SECTION.
BAND COMPLETED        8               CUTS.
AVERAGE CUTTING TIME=                  2.850048         MINUTES.
AVERAGE CUTTING RATE=                  16.67802         SECTIONS PER HOUR.
COST RATIO=           1.38
COST FACTOR=          .2608151
```

Carbon Band   Constant Feed Rate   Dry   V=20m/min

```
BREADTH=              50              MM.
DEPTH=                50              MM.
INITIAL CUTTING CONSTANT=              2.900001E-04     MM**2/N.
BAND SPEED=           20              METRES/MINUTE.
FEED RATE =           .4              MM/S.
BAND MATERIAL=        1               1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                    0                1=WET,0=DRY.
INTERCEPT 'A'=        6.500001E-04
 7.255000E-09         2.4513
BAND FAILED TO CUT ON THE              4                SECTION.
BAND COMPLETED        3               CUTS.
AVERAGE CUTTING TIME=                  2.179448         MINUTES.
AVERAGE CUTTING RATE=                  15.03968         SECTIONS PER HOUR.
COST RATIO=           1.38
COST FACTOR=          .5666149

BREADTH=              50              MM.
DEPTH=                50              MM.
INITIAL CUTTING CONSTANT=              2.900001E-04     MM**2/N.
BAND SPEED=           20              METRES/MINUTE.
FEED RATE =           .5              MM/S.
BAND MATERIAL=        1               1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                    0                1=WET,0=DRY.
INTERCEPT 'A'=        6.500001E-04
 7.255000E-09         2.4513
BAND FAILED TO CUT ON THE              2                SECTION.
BAND COMPLETED        1               CUTS.
AVERAGE CUTTING TIME=                  1.676499         MINUTES.
AVERAGE CUTTING RATE=                  8.712699         SECTIONS PER HOUR.
COST RATIO=           1.38
COST FACTOR=          1.582961

BREADTH=              50              MM.
DEPTH=                50              MM.
INITIAL CUTTING CONSTANT=              2.900001E-04     MM**2/N.
BAND SPEED=           20              METRES/MINUTE.
FEED RATE =           .6              MM/S.
BAND MATERIAL=        1               1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                    0                1=WET,0=DRY.
INTERCEPT 'A'=        6.500001E-04
 7.255000E-09         2.4513
BAND FAILED COMPLETELY ON THE FIRST SECTION.
```

Carbon Blade   Constant Feed Rate   Dry   V=20m/min

```
BREADTH=                 50          MM.
DEPTH=                   50          MM.
INITIAL CUTTING CONSTANT=             2.900001E-04      MM**2/N.
BAND SPEED=              30          METRES/MINUTE.
FEED RATE =              .1          MM/S.
BAND MATERIAL=           1           1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                   0                 1=WET,0=DRY.
INTERCEPT 'A'=           6.500001E-04
 7.255000E-09            2.4513
BAND FAILED TO CUT ON THE             116               SECTION.
BAND COMPLETED           115         CUTS.
AVERAGE CUTTING TIME=                 8.382486          MINUTES.
AVERAGE CUTTING RATE=                 7.028366          SECTIONS PER HOUR.
COST RATIO=              1.38
COST FACTOR=             .2087347
BREADTH=                 50          MM.
DEPTH=                   50          MM.
INITIAL CUTTING CONSTANT=             2.900001E-04      MM**2/N.
BAND SPEED=              30          METRES/MINUTE.
FEED RATE =              .15         MM/S.
BAND MATERIAL=           1           1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                   0                 1=WET,0=DRY.
INTERCEPT 'A'=           6.500001E-04
 7.255000E-09            2.4513
BAND FAILED TO CUT ON THE             32                SECTION.
BAND COMPLETED           31          CUTS.
AVERAGE CUTTING TIME=                 5.588297          MINUTES.
AVERAGE CUTTING RATE=                 10.234            SECTIONS PER HOUR.
COST RATIO=              1.38
COST FACTOR=             .1807985
BREADTH=                 50          MM.
DEPTH=                   50          MM.
INITIAL CUTTING CONSTANT=             2.900001E-04      MM**2/N.
BAND SPEED=              30          METRES/MINUTE.
FEED RATE =              .2          MM/S.
BAND MATERIAL=           1           1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                   0                 1=WET,0=DRY.
INTERCEPT 'A'=           6.500001E-04
 7.255000E-09            2.4513
BAND FAILED TO CUT ON THE             14                SECTION.
BAND COMPLETED           13          CUTS.
AVERAGE CUTTING TIME=                 4.247131          MINUTES.
AVERAGE CUTTING RATE=                 12.63307          SECTIONS PER HOUR.
COST RATIO=              1.38
COST FACTOR=             .2188196
BREADTH=                 50          MM.
DEPTH=                   50          MM.
INITIAL CUTTING CONSTANT=             2.900001E-04      MM**2/N.
BAND SPEED=              30          METRES/MINUTE.
FEED RATE =              .3          MM/S.
BAND MATERIAL=           1           1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                   0                 1=WET,0=DRY.
INTERCEPT 'A'=           6.500001E-04
 7.255000E-09            2.4513
BAND FAILED TO CUT ON THE             5                 SECTION.
BAND COMPLETED           4           CUTS.
AVERAGE CUTTING TIME=                 2.794165          MINUTES.
AVERAGE CUTTING RATE=                 14.35694          SECTIONS PER HOUR.
COST RATIO=              1.38
COST FACTOR=             .452264
```

Carbon Band   Constant Feed Rate   Dry   V=30m/min

```
BREADTH=                 50          MM.
DEPTH=                   50          MM.
INITIAL CUTTING CONSTANT=             2.900001E-04      MM**2/N.
BAND SPEED=              30          METRES/MINUTE.
FEED RATE =              .4          MM/S.
BAND MATERIAL=           1           1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                   0                 1=WET,0=DRY.
INTERCEPT 'A'=           6.500001E-04
 7.255000E-09            2.4513
BAND FAILED TO CUT ON THE             3                 SECTION.
BAND COMPLETED           2           CUTS.
AVERAGE CUTTING TIME=                 2.123566          MINUTES.
AVERAGE CUTTING RATE=                 12.54294          SECTIONS PER HOUR.
COST RATIO=              1.38
COST FACTOR=             .8223084
BREADTH=                 50          MM.
DEPTH=                   50          MM.
INITIAL CUTTING CONSTANT=             2.900001E-04      MM**2/N.
BAND SPEED=              30          METRES/MINUTE.
FEED RATE =              .5          MM/S.
BAND MATERIAL=           1           1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                   0                 1=WET,0=DRY.
INTERCEPT 'A'=           6.500001E-04
 7.255000E-09            2.4513
BAND FAILED TO CUT ON THE             2                 SECTION.
BAND COMPLETED           1           CUTS.
AVERAGE CUTTING TIME=                 1.676499          MINUTES.
AVERAGE CUTTING RATE=                 8.712699          SECTIONS PER HOUR.
COST RATIO=              1.38
COST FACTOR=             1.582961
BREADTH=                 50          MM.
DEPTH=                   50          MM.
INITIAL CUTTING CONSTANT=             2.900001E-04      MM**2/N.
BAND SPEED=              30          METRES/MINUTE.
FEED RATE =              .6          MM/S.
BAND MATERIAL=           1           1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                   0                 1=WET,0=DRY.
INTERCEPT 'A'=           6.500001E-04
 7.255000E-09            2.4513
BAND FAILED COMPLETELY ON THE FIRST SECTION.
```

Carbon Band   Constant Feed Rate   Dry   V=30m/min

```
BREADTH=              50              MM.
DEPTH=                50              MM.
INITIAL CUTTING CONSTANT=              2.900001E-04     MM**2/N.
BAND SPEED=           20              METRES/MINUTE.
FEED RATE =           .15             MM/S.
BAND MATERIAL=        1               1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                    1               1=WET,0=DRY.
INTERCEPT 'A'=        6.500001E-04
 8.848799E-10         2.3113
BAND FAILED TO CUT ON THE              357             SECTION.
BAND COMPLETED        356             CUTS.
AVERAGE CUTTING TIME=                  5.700032        MINUTES.
AVERAGE CUTTING RATE=                  10.30157        SECTIONS PER HOUR.
COST RATIO=           1.38
COST FACTOR=          .1379617

BREADTH=              50              MM.
DEPTH=                50              MM.
INITIAL CUTTING CONSTANT=              2.900001E-04     MM**2/N.
BAND SPEED=           20              METRES/MINUTE.
FEED RATE =           .2              MM/S.
BAND MATERIAL=        1               1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                    1               1=WET,0=DRY.
INTERCEPT 'A'=        6.500001E-04
 8.848799E-10         2.3113
BAND FAILED TO CUT ON THE              88              SECTION.
BAND COMPLETED        87              CUTS.
AVERAGE CUTTING TIME=                  4.191217        MINUTES.
AVERAGE CUTTING RATE=                  13.76198        SECTIONS PER HOUR.
COST RATIO=           1.38
COST FACTOR=          .1166506

BREADTH=              50              MM.
DEPTH=                50              MM.
INITIAL CUTTING CONSTANT=              2.900001E-04     MM**2/N.
BAND SPEED=           20              METRES/MINUTE.
FEED RATE =           .3              MM/S.
BAND MATERIAL=        1               1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                    1               1=WET,0=DRY.
INTERCEPT 'A'=        6.500001E-04
 8.848799E-10         2.3113
BAND FAILED TO CUT ON THE              13              SECTION.
BAND COMPLETED        12              CUTS.
AVERAGE CUTTING TIME=                  2.850048        MINUTES.
AVERAGE CUTTING RATE=                  17.72501        SECTIONS PER HOUR.
COST RATIO=           1.38
COST FACTOR=          .1965704

BREADTH=              50              MM.
DEPTH=                50              MM.
INITIAL CUTTING CONSTANT=              2.900001E-04     MM**2/N.
BAND SPEED=           20              METRES/MINUTE.
FEED RATE =           .4              MM/S.
BAND MATERIAL=        1               1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                    1               1=WET,0=DRY.
INTERCEPT 'A'=        6.500001E-04
 8.848799E-10         2.3113
BAND FAILED TO CUT ON THE              3               SECTION.
BAND COMPLETED        2               CUTS.
AVERAGE CUTTING TIME=                  2.179449        MINUTES.
AVERAGE CUTTING RATE=                  12.39811        SECTIONS PER HOUR.
COST RATIO=           1.38
COST FACTOR=          .8235937
```

Carbon Band   Constant Feed Rate   Coolant   V=20m/min

```
BREADTH=              50              MM.
DEPTH=                50              MM.
INITIAL CUTTING CONSTANT=              2.900001E-04     MM**2/N.
BAND SPEED=           20              METRES/MINUTE.
FEED RATE =           .5              MM/S.
BAND MATERIAL=        1               1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                    1               1=WET,0=DRY.
INTERCEPT 'A'=        6.500001E-04
 8.848799E-10         2.3113
BAND FAILED COMPLETELY ON THE FIRST SECTION.
```

Carbon Band   Constant Feed Rate   Coolant   V=20m/min

```
BREADTH=              50              MM.
DEPTH=                50              MM.
INITIAL CUTTING CONSTANT=              2.900001E-04    MM**2/N.
BAND SPEED=           30              METRES/MINUTE.
FEED RATE =           .15             MM/S.
BAND MATERIAL=        1               1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                    1               1=WET,0=DRY.
INTERCEPT 'A'=        6.500001E-04
 8.848799E-10         2.3113
BAND FAILED TO CUT ON THE              231             SECTION.
BAND COMPLETED        230             CUTS.
AVERAGE CUTTING TIME=                  5.588162        MINUTES.
AVERAGE CUTTING RATE=                  10.48889        SECTIONS PER HOUR.
COST RATIO=           1.38
COST FACTOR=          .1377614

BREADTH=              50              MM.
DEPTH=                50              MM.
INITIAL CUTTING CONSTANT=              2.900001E-04    MM**2/N.
BAND SPEED=           30              METRES/MINUTE.
FEED RATE =           .2              MM/S.
BAND MATERIAL=        1               1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                    1               1=WET,0=DRY.
INTERCEPT 'A'=        6.500001E-04
 8.848799E-10         2.3113
BAND FAILED TO CUT ON THE              50              SECTION.
BAND COMPLETED        49              CUTS.
AVERAGE CUTTING TIME=                  4.247389        MINUTES.
AVERAGE CUTTING RATE=                  13.44939        SECTIONS PER HOUR.
COST RATIO=           1.38
COST FACTOR=          .1316798

BREADTH=              50              MM.
DEPTH=                50              MM.
INITIAL CUTTING CONSTANT=              2.900001E-04    MM**2/N.
BAND SPEED=           30              METRES/MINUTE.
FEED RATE =           .3              MM/S.
BAND MATERIAL=        1               1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                    1               1=WET,0=DRY.
INTERCEPT 'A'=        6.500001E-04
 8.848799E-10         2.3113
BAND FAILED TO CUT ON THE              7               SECTION.
BAND COMPLETED        6               CUTS.
AVERAGE CUTTING TIME=                  2.794165        MINUTES.
AVERAGE CUTTING RATE=                  15.98225        SECTIONS PER HOUR.
COST RATIO=           1.38
COST FACTOR=          .3237745

BREADTH=              50              MM.
DEPTH=                50              MM.
INITIAL CUTTING CONSTANT=              2.900001E-04    MM**2/N.
BAND SPEED=           30              METRES/MINUTE.
FEED RATE =           .4              MM/S.
BAND MATERIAL=        1               1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                    1               1=WET,0=DRY.
INTERCEPT 'A'=        6.500001E-04
 8.848799E-10         2.3113
BAND FAILED TO CUT ON THE              2               SECTION.
BAND COMPLETED        1               CUTS.
AVERAGE CUTTING TIME=                  2.123566        MINUTES.
AVERAGE CUTTING RATE=                  8.181559        SECTIONS PER HOUR.
COST RATIO=           1.38
COST FACTOR=          1.593244
```

Carbon Band   Constant Feed Rate   Coolant   V=30m/min

```
BREADTH=              50              MM.
DEPTH=                50              MM.
INITIAL CUTTING CONSTANT=              2.900001E-04    MM**2/N.
BAND SPEED=           30              METRES/MINUTE.
FEED RATE =           .5              MM/S.
BAND MATERIAL=        1               1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                    1               1=WET,0=DRY.
INTERCEPT 'A'=        6.500001E-04
 8.848799E-10         2.3113
BAND FAILED COMPLETELY ON THE FIRST SECTION.
```

Carbon Band   Constant Feed Rate   Coolant   V=30m/min

```
BREADTH=               50                MM.
DEPTH=                 50                MM.
INITIAL CUTTING CONSTANT=                 2.900001E-04     MM**2/N.
BAND SPEED=            40                METRES/MINUTE.
FEED RATE =            .15               MM/S.
BAND MATERIAL=         1                 1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                       1                1=WET,0=DRY.
INTERCEPT 'A'=         6.500001E-04
 6.848799E-10          2.3113
BAND FAILED TO CUT ON THE                 191              SECTION.
BAND COMPLETED         190               CUTS.
AVERAGE CUTTING TIME=                     5.616276         MINUTES.
AVERAGE CUTTING RATE=                     10.42913         SECTIONS PER HOUR.
COST RATIO=            1.38
COST FACTOR=           .1398193

BREADTH=               50                MM.
DEPTH=                 50                MM.
INITIAL CUTTING CONSTANT=                 2.900001E-04     MM**2/N.
BAND SPEED=            40                METRES/MINUTE.
FEED RATE =            .2                MM/S.
BAND MATERIAL=         1                 1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                       1                1=WET,0=DRY.
INTERCEPT 'A'=         6.500001E-04
 6.848799E-10          2.3113
BAND FAILED TO CUT ON THE                 37               SECTION.
BAND COMPLETED         36                CUTS.
AVERAGE CUTTING TIME=                     4.191227         MINUTES.
AVERAGE CUTTING RATE=                     13.50471         SECTIONS PER HOUR.
COST RATIO=            1.38
COST FACTOR=           .141758

BREADTH=               50                MM.
DEPTH=                 50                MM.
INITIAL CUTTING CONSTANT=                 2.900001E-04     MM**2/N.
BAND SPEED=            40                METRES/MINUTE.
FEED RATE =            .3                MM/S.
BAND MATERIAL=         1                 1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                       1                1=WET,0=DRY.
INTERCEPT 'A'=         6.500001E-04
 6.848799E-10          2.3113
BAND FAILED TO CUT ON THE                 5                SECTION.
BAND COMPLETED         4                 CUTS.
AVERAGE CUTTING TIME=                     2.850048         MINUTES.
AVERAGE CUTTING RATE=                     14.16749         SECTIONS PER HOUR.
COST RATIO=            1.38
COST FACTOR=           .4535493

BREADTH=               50                MM.
DEPTH=                 50                MM.
INITIAL CUTTING CONSTANT=                 2.900001E-04     MM**2/N.
BAND SPEED=            40                METRES/MINUTE.
FEED RATE =            .4                MM/S.
BAND MATERIAL=         1                 1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                       1                1=WET,0=DRY.
INTERCEPT 'A'=         6.500001E-04
 6.848799E-10          2.3113
BAND FAILED TO CUT ON THE                 2                SECTION.
BAND COMPLETED         1                 CUTS.
AVERAGE CUTTING TIME=                     2.095625         MINUTES.
AVERAGE CUTTING RATE=                     8.21285          SECTIONS PER HOUR.
COST RATIO=            1.38
COST FACTOR=           1.592632
```

Carbon Band   Constant Feed Rate   Coolant   V=40m/min

```
BREADTH=               50                MM.
DEPTH=                 50                MM.
INITIAL CUTTING CONSTANT=                 2.900001E-04     MM**2/N.
BAND SPEED=            40                METRES/MINUTE.
FEED RATE =            .5                MM/S.
BAND MATERIAL=         1                 1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                       1                1=WET,0=DRY.
INTERCEPT 'A'=         6.500001E-04
 6.848799E-10          2.3113
BAND FAILED COMPLETELY ON THE FIRST SECTION.
```

Carbon Band   Constant Feed Rate   Coolant   V=40m/min

6.7.3 High Speed Steel Bi-Metal Band - Constant Thrust Load

In these simulation tests, PROGRAM I was used with various band speeds in the range 40-120m / min. for selected values of thrust load in the range 250-500N, for both dry and coolant cutting conditions. The computer print-outs for these tests are shown on the following pages.

FIGURE 101., uses this data and shows the effects of band speed and thrust load on the average cutting rate and cost factor, for high speed steel bi-metal bands both dry and with coolant for constant thrust load.

```
BREADTH=              50            MM.
DEPTH=                50            MM.
INITIAL CUTTING CONSTANT=            2.599999E-04     MM**2/N.
THRUST LOAD=          250           NEWTONS.
BAND SPEED=           40            METRES /MINUTE.
BAND MATERIAL =       0             1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                  0                1=WET,0=DRY.
INTERCEPT'A'=         4.400001E-04
 3.554201E-15         2.1885
BAND FAILED TO CUT ON THE            1437             SECTION.
BAND COMPLETED        1436          CUTS.
AVERAGE CUTTING TIME=                3.137402         MINUTES.
AVERAGE CUTTING RATE=                18.45612         SECTIONS PER HOUR.
COST RATIO=           .21
COST FACTOR=          1.151475E-02
BREADTH=              50            MM.
DEPTH=                50            MM.
INITIAL CUTTING CONSTANT=            2.599999E-04     MM**2/N.
THRUST LOAD=          300           NEWTONS.
BAND SPEED=           40            METRES /MINUTE.
BAND MATERIAL =       0             1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                  0                1=WET,0=DRY.
INTERCEPT'A'=         4.400001E-04
 3.554201E-15         2.1885
BAND FAILED TO CUT ON THE            243              SECTION.
BAND COMPLETED        242           CUTS.
AVERAGE CUTTING TIME=                2.593701         MINUTES.
AVERAGE CUTTING RATE=                22.02016         SECTIONS PER HOUR.
COST RATIO=           .21
COST FACTOR=          1.034621E-02
BREADTH=              50            MM.
DEPTH=                50            MM.
INITIAL CUTTING CONSTANT=            2.599999E-04     MM**2/N.
THRUST LOAD=          350           NEWTONS.
BAND SPEED=           40            METRES /MINUTE.
BAND MATERIAL =       0             1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                  0                1=WET,0=DRY.
INTERCEPT'A'=         4.400001E-04
 3.554201E-15         2.1885
BAND FAILED TO CUT ON THE            56               SECTION.
BAND COMPLETED        55            CUTS.
AVERAGE CUTTING TIME=                2.142862         MINUTES.
AVERAGE CUTTING RATE=                25.57993         SECTIONS PER HOUR.
COST RATIO=           .21
COST FACTOR=          1.177135E-02
BREADTH=              50            MM.
DEPTH=                50            MM.
INITIAL CUTTING CONSTANT=            2.599999E-04     MM**2/N.
THRUST LOAD=          400           NEWTONS.
BAND SPEED=           40            METRES /MINUTE.
BAND MATERIAL =       0             1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                  0                1=WET,0=DRY.
INTERCEPT'A'=         4.400001E-04
 3.554201E-15         2.1885
BAND FAILED TO CUT ON THE            16               SECTION.
BAND COMPLETED        15            CUTS.
AVERAGE CUTTING TIME=                1.687675         MINUTES.
AVERAGE CUTTING RATE=                28.06787         SECTIONS PER HOUR.
COST RATIO=           .21
COST FACTOR=          2.054174E-02
```

HSS Bi-metal Band   Constant Thrust Load   Dry   V=40m/min

```
BREADTH=              50            MM.
DEPTH=                50            MM.
INITIAL CUTTING CONSTANT=            2.599999E-04     MM**2/N.
THRUST LOAD=          450           NEWTONS.
BAND SPEED=           40            METRES /MINUTE.
BAND MATERIAL =       0             1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                  0                1=WET,0=DRY.
INTERCEPT'A'=         4.400001E-04
 3.554201E-15         2.1885
BAND FAILED TO CUT ON THE            6                SECTION.
BAND COMPLETED        5             CUTS.
AVERAGE CUTTING TIME=                1.492085         MINUTES.
AVERAGE CUTTING RATE=                22.88255         SECTIONS PER HOUR.
COST RATIO=           .21
COST FACTOR=          4.835697E-02
BREADTH=              50            MM.
DEPTH=                50            MM.
INITIAL CUTTING CONSTANT=            2.599999E-04     MM**2/N.
THRUST LOAD=          500           NEWTONS.
BAND SPEED=           40            METRES /MINUTE.
BAND MATERIAL =       0             1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                  0                1=WET,0=DRY.
INTERCEPT'A'=         4.400001E-04
 3.554201E-15         2.1885
BAND FAILED TO CUT ON THE            3                SECTION.
BAND COMPLETED        2             CUTS.
AVERAGE CUTTING TIME=                1.3412           MINUTES.
AVERAGE CUTTING RATE=                14.9955          SECTIONS PER HOUR.
COST RATIO=           .21
COST FACTOR=          .1119534
```

HSS Bi-metal Band   Constant Thrust Load   Dry   V=40m/min

```
BREADTH=                50            MM.
DEPTH=                  50            MM.
INITIAL CUTTING CONSTANT=              1.800000E-04    MM**2/N.
THRUST LOAD=            250           NEWTONS.
BAND SPEED=             60            METRES /MINUTE.
BAND MATERIAL =         0             1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                    0               1=WET,0=DRY.
INTERCEPT'A'=           2.900001E-04
 3.554201E-15           2.1885
BAND FAILED TO CUT ON THE              438             SECTION.
BAND COMPLETED          437           CUTS.
AVERAGE CUTTING TIME=                  3.00588         MINUTES.
AVERAGE CUTTING RATE=                  19.18434        SECTIONS PER HOUR.
COST RATIO=             .21
COST FACTOR=            1.139476E-02
BREADTH=                50            MM.
DEPTH=                  50            MM.
INITIAL CUTTING CONSTANT=              1.800000E-04    MM**2/N.
THRUST LOAD=            275           NEWTONS.
BAND SPEED=             60            METRES /MINUTE.
BAND MATERIAL =         0             1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                    0               1=WET,0=DRY.
INTERCEPT'A'=           2.900001E-04
 3.554201E-15           2.1885
BAND FAILED TO CUT ON THE              173             SECTION.
BAND COMPLETED          172           CUTS.
AVERAGE CUTTING TIME=                  2.678799        MINUTES.
AVERAGE CUTTING RATE=                  21.2883         SECTIONS PER HOUR.
COST RATIO=             .21
COST FACTOR=            1.100351E-02
BREADTH=                50            MM.
DEPTH=                  50            MM.
INITIAL CUTTING CONSTANT=              1.800000E-04    MM**2/N.
THRUST LOAD=            300           NEWTONS.
BAND SPEED=             60            METRES /MINUTE.
BAND MATERIAL =         0             1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                    0               1=WET,0=DRY.
INTERCEPT'A'=           2.900001E-04
 3.554201E-15           2.1885
BAND FAILED TO CUT ON THE              75              SECTION.
BAND COMPLETED          74            CUTS.
AVERAGE CUTTING TIME=                  2.395416        MINUTES.
AVERAGE CUTTING RATE=                  23.30699        SECTIONS PER HOUR.
COST RATIO=             .21
COST FACTOR=            1.165745E-02
BREADTH=                50            MM.
DEPTH=                  50            MM.
INITIAL CUTTING CONSTANT=              1.800000E-04    MM**2/N.
THRUST LOAD=            350           NEWTONS.
BAND SPEED=             60            METRES /MINUTE.
BAND MATERIAL =         0             1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                    0               1=WET,0=DRY.
INTERCEPT'A'=           2.900001E-04
 3.554201E-15           2.1885
BAND FAILED TO CUT ON THE              18              SECTION.
BAND COMPLETED          17            CUTS.
AVERAGE CUTTING TIME=                  2.018373        MINUTES.
AVERAGE CUTTING RATE=                  24.70792        SECTIONS PER HOUR.
COST RATIO=             .21
COST FACTOR=            [illegible]2274E-02
```

HSS Bi-metal Band   Constant Thrust Load   Dry   V=60m/min

```
BREADTH=                50            MM.
DEPTH=                  50            MM.
INITIAL CUTTING CONSTANT=              1.800000E-04    MM**2/N.
THRUST LOAD=            400           NEWTONS.
BAND SPEED=             60            METRES /MINUTE.
BAND MATERIAL =         0             1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                    0               1=WET,0=DRY.
INTERCEPT'A'=           2.900001E-04
 3.554201E-15           2.1885
BAND FAILED TO CUT ON THE              5               SECTION.
BAND COMPLETED          4             CUTS.
AVERAGE CUTTING TIME=                  1.369141        MINUTES.
AVERAGE CUTTING RATE=                  21.78539        SECTIONS PER HOUR.
COST RATIO=             .21
COST FACTOR=            5.861410E-02
BREADTH=                50            MM.
DEPTH=                  50            MM.
INITIAL CUTTING CONSTANT=              1.800000E-04    MM**2/N.
THRUST LOAD=            450           NEWTONS.
BAND SPEED=             60            METRES /MINUTE.
BAND MATERIAL =         0             1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                    0               1=WET,0=DRY.
INTERCEPT'A'=           2.900001E-04
 3.554201E-15           2.1885
BAND FAILED TO CUT ON THE              2               SECTION.
BAND COMPLETED          1             CUTS.
AVERAGE CUTTING TIME=                  1.061783        MINUTES.
AVERAGE CUTTING RATE=                  9.566657        SECTIONS PER HOUR.
COST RATIO=             .21
COST FACTOR=            .2178496
BREADTH=                50            MM.
DEPTH=                  50            MM.
INITIAL CUTTING CONSTANT=              1.800000E-04    MM**2/N.
THRUST LOAD=            500           NEWTONS.
BAND SPEED=             60            METRES /MINUTE.
BAND MATERIAL =         0             1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                    0               1=WET,0=DRY.
INTERCEPT'A'=           2.900001E-04
 3.554201E-15           2.1885
BAND FAILED COMPLETELY ON THE FIRST SECTION.
```

HSS Bi-metal Band   Constant Thrust Load   Dry   V=60m/min

```
BREADTH=                 50           MM.
DEPTH=                   50           MM.
INITIAL CUTTING CONSTANT=              1.000000E-04     MM**2/N.
THRUST LOAD=             300          NEWTONS.
BAND SPEED=              80           METRES /MINUTE.
BAND MATERIAL =          0            1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                    0                1=WET,0=DRY.
INTERCEPT'A'=            2.200000E-04
 3.554201E-15            2.1885
BAND FAILED TO CUT ON THE              802              SECTION.
BAND COMPLETED           801          CUTS.
AVERAGE CUTTING TIME=                  3.422577         MINUTES.
AVERAGE CUTTING RATE=                  16.95421         SECTIONS PER HOUR.
COST RATIO=              .21
COST FACTOR=             1.263086E-02
BREADTH=                 50           MM.
DEPTH=                   50           MM.
INITIAL CUTTING CONSTANT=              1.000000E-04     MM**2/N.
THRUST LOAD=             350          NEWTONS.
BAND SPEED=              80           METRES /MINUTE.
BAND MATERIAL =          0            1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                    0                1=WET,0=DRY.
INTERCEPT'A'=            2.200000E-04
 3.554201E-15            2.1885
BAND FAILED TO CUT ON THE              176              SECTION.
BAND COMPLETED           175          CUTS.
AVERAGE CUTTING TIME=                  2.895529         MINUTES.
AVERAGE CUTTING RATE=                  19.7715          SECTIONS PER HOUR.
COST RATIO=              .21
COST FACTOR=             1.174077E-02
BREADTH=                 50           MM.
DEPTH=                   50           MM.
INITIAL CUTTING CONSTANT=              1.000000E-04     MM**2/N.
THRUST LOAD=             400          NEWTONS.
BAND SPEED=              80           METRES /MINUTE.
BAND MATERIAL =          0            1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                    0                1=WET,0=DRY.
INTERCEPT'A'=            2.200000E-04
 3.554201E-15            2.1885
BAND FAILED TO CUT ON THE              49               SECTION.
BAND COMPLETED           48           CUTS.
AVERAGE CUTTING TIME=                  2.504264         MINUTES.
AVERAGE CUTTING RATE=                  22.05466         SECTIONS PER HOUR.
COST RATIO=              .21
COST FACTOR=             1.360301E-02
BREADTH=                 50           MM.
DEPTH=                   50           MM.
INITIAL CUTTING CONSTANT=              1.000000E-04     MM**2/N.
THRUST LOAD=             450          NEWTONS.
BAND SPEED=              80           METRES /MINUTE.
BAND MATERIAL =          0            1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                    0                1=WET,0=DRY.
INTERCEPT'A'=            2.200000E-04
 3.554201E-15            2.1885
BAND FAILED TO CUT ON THE              16               SECTION.
BAND COMPLETED           15           CUTS.
AVERAGE CUTTING TIME=                  1.961503         MINUTES.
AVERAGE CUTTING RATE=                  24.88075         SECTIONS PER HOUR.
COST RATIO=              .21
COST FACTOR=             2.15[illegible]14E-02
```

HSS Bi-metal Band   Constant Thrust Load   Dry   V=80m/min

```
BREADTH=                 50           MM.
DEPTH=                   50           MM.
INITIAL CUTTING CONSTANT=              1.000000E-04     MM**2/N.
THRUST LOAD=             500          NEWTONS.
BAND SPEED=              80           METRES /MINUTE.
BAND MATERIAL =          0            1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                    0                1=WET,0=DRY.
INTERCEPT'A'=            2.200000E-04
 3.554201E-15            2.1885
BAND FAILED TO CUT ON THE              6                SECTION.
BAND COMPLETED           5            CUTS.
AVERAGE CUTTING TIME=                  1.567526         MINUTES.
AVERAGE CUTTING RATE=                  22.2426          SECTIONS PER HOUR.
COST RATIO=              .21
COST FACTOR=             4.862102E-02
```

HSS Bi-metal Band   Constant Thrust Load   Dry   V=80m/min

```
BREATH=              50                 MM.
DEPTH=               50                 MM.
INITIAL CUTTING CONSTANT=                6.999999E-05      MM**2/N.
THRUST LOAD=         350                NEWTONS.
BAND SPEED=          100                METRES /MINUTE.
BAND MATERIAL =      0                  1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                      0                 1=WET,0=DRY.
INTERCEPT'A'=        1.800000E-04
 3.554201E-15        2.1885
BAND FAILED TO CUT ON THE                431               SECTION.
BAND COMPLETED       430                CUTS.
AVERAGE CUTTING TIME=                    3.363144          MINUTES.
AVERAGE CUTTING RATE=                    17.21661          SECTIONS PER HOUR.
COST RATIO=          .21
COST FACTOR=         1.265309E-02
BREADTH=             50                 MM.
DEPTH=               50                 MM.
INITIAL CUTTING CONSTANT=                6.999999E-05      MM**2/N.
THRUST LOAD=         400                NEWTONS.
BAND SPEED=          100                METRES /MINUTE.
BAND MATERIAL =      0                  1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                      0                 1=WET,0=DRY.
INTERCEPT'A'=        1.800000E-04
 3.554201E-15        2.1885
BAND FAILED TO CUT ON THE                116               SECTION.
BAND COMPLETED       115                CUTS.
AVERAGE CUTTING TIME=                    2.868689          MINUTES.
AVERAGE CUTTING RATE=                    19.8476           SECTIONS PER HOUR.
COST RATIO=          .21
COST FACTOR=         1.228409E-02
BREADTH=             50                 MM.
DEPTH=               50                 MM.
INITIAL CUTTING CONSTANT=                6.999999E-05      MM**2/N.
THRUST LOAD=         450                NEWTONS.
BAND SPEED=          100                METRES /MINUTE.
BAND MATERIAL =      0                  1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                      0                 1=WET,0=DRY.
INTERCEPT'A'=        1.800000E-04
 3.554201E-15        2.1885
BAND FAILED TO CUT ON THE                37                SECTION.
BAND COMPLETED       36                 CUTS.
AVERAGE CUTTING TIME=                    2.365723          MINUTES.
AVERAGE CUTTING RATE=                    22.9236           SECTIONS PER HOUR.
COST RATIO=          .21
COST FACTOR=         1.460247E-02
BREADTH=             50                 MM.
DEPTH=               50                 MM.
INITIAL CUTTING CONSTANT=                6.999999E-05      MM**2/N.
THRUST LOAD=         500                NEWTONS.
BAND SPEED=          100                METRES /MINUTE.
BAND MATERIAL =      0                  1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                      0                 1=WET,0=DRY.
INTERCEPT'A'=        1.800000E-04
 3.554201E-15        2.1885
BAND FAILED TO CUT ON THE                14                SECTION.
BAND COMPLETED       13                 CUTS.
AVERAGE CUTTING TIME=                    2.599491          MINUTES.
AVERAGE CUTTING RATE=                    23.06097          SECTIONS PER HOUR.
COST RATIO=          .21
COST FACTOR=         2.417539E-02
```

HSS Bi-metal Band   Constant Thrust Load   Dry   V=100m/min

```
BREADTH=                 50             MM.
DEPTH=                   50             MM.
INITIAL CUTTING CONSTANT=                5.000000E-05      MM**2/N.
THRUST LOAD=             390            NEWTONS.
BAND SPEED=              120            METRES /MINUTE.
BAND MATERIAL =          0              1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                      0                 1=WET,0=DRY.
INTERCEPT'A'=            1.500000E-04
 3.554201E-15            2.1885
BAND FAILED TO CUT ON THE                477               SECTION.
BAND COMPLETED           476            CUTS.
AVERAGE CUTTING TIME=                    3.545373          MINUTES.
AVERAGE CUTTING RATE=                    16.36623          SECTIONS PER HOUR.
COST RATIO=              .21
COST FACTOR=             1.324284E-02
BREADTH=                 50             MM.
DEPTH=                   50             MM.
INITIAL CUTTING CONSTANT=                5.000000E-05      MM**2/N.
THRUST LOAD=             400            NEWTONS.
BAND SPEED=              120            METRES /MINUTE.
BAND MATERIAL =          0              1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                      0                 1=WET,0=DRY.
INTERCEPT'A'=            1.500000E-04
 3.554201E-15            2.1885
BAND FAILED TO CUT ON THE                370               SECTION.
BAND COMPLETED           369            CUTS.
AVERAGE CUTTING TIME=                    3.406642          MINUTES.
AVERAGE CUTTING RATE=                    16.99493          SECTIONS PER HOUR.
COST RATIO=              .21
COST FACTOR=             1.288751E-02
BREADTH=                 50             MM.
DEPTH=                   50             MM.
INITIAL CUTTING CONSTANT=                5.000000E-05      MM**2/N.
THRUST LOAD=             425            NEWTONS.
BAND SPEED=              120            METRES /MINUTE.
BAND MATERIAL =          0              1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                      0                 1=WET,0=DRY.
INTERCEPT'A'=            1.500000E-04
 3.554201E-15            2.1885
BAND FAILED TO CUT ON THE                202               SECTION.
BAND COMPLETED           201            CUTS.
AVERAGE CUTTING TIME=                    3.180873          MINUTES.
AVERAGE CUTTING RATE=                    18.09274          SECTIONS PER HOUR.
COST RATIO=              .21
COST FACTOR=             1.258148E-02
BREADTH=                 50             MM.
DEPTH=                   50             MM.
INITIAL CUTTING CONSTANT=                5.000000E-05      MM**2/N.
THRUST LOAD=             450            NEWTONS.
BAND SPEED=              120            METRES /MINUTE.
BAND MATERIAL =          0              1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                      0                 1=WET,0=DRY.
INTERCEPT'A'=            1.500000E-04
 3.554201E-15            2.1885
BAND FAILED TO CUT ON THE                116               SECTION.
BAND COMPLETED           115            CUTS.
AVERAGE CUTTING TIME=                    3.084736          MINUTES.
AVERAGE CUTTING RATE=                    18.52376          SECTIONS PER HOUR.
COST RATIO=              .21
COST FACTOR=             1.304025E-02
```

HSS Bi-metal Band   Constant Thrust Load   Dry   V=120m/min

```
BREADTH=                 50             MM.
DEPTH=                   50             MM.
INITIAL CUTTING CONSTANT=                5.000000E-05      MM**2/N.
THRUST LOAD=             500            NEWTONS.
BAND SPEED=              120            METRES /MINUTE.
BAND MATERIAL =          0              1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                      0                 1=WET,0=DRY.
INTERCEPT'A'=            1.500000E-04
 3.554201E-15            2.1885
BAND FAILED TO CUT ON THE                42                SECTION.
BAND COMPLETED           41             CUTS.
AVERAGE CUTTING TIME=                    2.768943          MINUTES.
AVERAGE CUTTING RATE=                    19.9778           SECTIONS PER HOUR.
COST RATIO=              .21
COST FACTOR=             1.528967E-02
```

HSS Bi-metal Band   Constant Thrust Load   Dry   V=120m/min

```
BREADTH=                 50            MM.
DEPTH=                   50            MM.
INITIAL CUTTING CONSTANT=               3.000000E-04     MM**2/N.
THRUST LOAD=             250           NEWTONS.
BAND SPEED=              40            METRES /MINUTE.
BAND MATERIAL =          0             1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                     1                1=WET,0=DRY.
INTERCEPT'A'=            4.400001E-04
 5.142700E-13            2.3378
BAND FAILED TO CUT ON THE               1654             SECTION.
BAND COMPLETED           1653          CUTS.
AVERAGE CUTTING TIME=                   2.672123         MINUTES.
AVERAGE CUTTING RATE=                   21.54237         SECTIONS PER HOUR.
COST RATIO=              .21
COST FACTOR=             9.866733E-03
BREADTH=                 50            MM.
DEPTH=                   50            MM.
INITIAL CUTTING CONSTANT=               3.000000E-04     MM**2/N.
THRUST LOAD=             300           NEWTONS.
BAND SPEED=              40            METRES /MINUTE.
BAND MATERIAL =          0             1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                     1                1=WET,0=DRY.
INTERCEPT'A'=            4.400001E-04
 5.142700E-13            2.3378
BAND FAILED TO CUT ON THE               744              SECTION.
BAND COMPLETED           743           CUTS.
AVERAGE CUTTING TIME=                   2.194457         MINUTES.
AVERAGE CUTTING RATE=                   25.95918         SECTIONS PER HOUR.
COST RATIO=              .21
COST FACTOR=             8.353278E-03
BREADTH=                 50            MM.
DEPTH=                   50            MM.
INITIAL CUTTING CONSTANT=               3.000000E-04     MM**2/N.
THRUST LOAD=             350           NEWTONS.
BAND SPEED=              40            METRES /MINUTE.
BAND MATERIAL =          0             1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                     1                1=WET,0=DRY.
INTERCEPT'A'=            4.400001E-04
 5.142700E-13            2.3378
BAND FAILED TO CUT ON THE               384              SECTION.
BAND COMPLETED           383           CUTS.
AVERAGE CUTTING TIME=                   1.867319         MINUTES.
AVERAGE CUTTING RATE=                   30.14114         SECTIONS PER HOUR.
COST RATIO=              .21
COST FACTOR=             7.478703E-03
BREADTH=                 50            MM.
DEPTH=                   50            MM.
INITIAL CUTTING CONSTANT=               3.000000E-04     MM**2/N.
THRUST LOAD=             400           NEWTONS.
BAND SPEED=              40            METRES /MINUTE.
BAND MATERIAL =          0             1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                     1                1=WET,0=DRY.
INTERCEPT'A'=            4.400001E-04
 5.142700E-13            2.3378
BAND FAILED TO CUT ON THE               218              SECTION.
BAND COMPLETED           217           CUTS.
AVERAGE CUTTING TIME=                   1.620851         MINUTES.
AVERAGE CUTTING RATE=                   34.20067         SECTIONS PER HOUR.
COST RATIO=              .21
COST FACTOR=             7.042989E-03
```

HSS Bi-metal Band   Constant Thrust Load   Coolant   V=40m/min

```
BREADTH=                 50            MM.
DEPTH=                   50            MM.
INITIAL CUTTING CONSTANT=               3.000000E-04     MM**2/N.
THRUST LOAD=             450           NEWTONS.
BAND SPEED=              40            METRES /MINUTE.
BAND MATERIAL =          0             1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                     1                1=WET,0=DRY.
INTERCEPT'A'=            4.400001E-04
 5.142700E-13            2.3378
BAND FAILED TO CUT ON THE               133              SECTION.
BAND COMPLETED           132           CUTS.
AVERAGE CUTTING TIME=                   1.438344         MINUTES.
AVERAGE CUTTING RATE=                   37.80766         SECTIONS PER HOUR.
COST RATIO=              .21
COST FACTOR=             7.038508E-03
BREADTH=                 50            MM.
DEPTH=                   50            MM.
INITIAL CUTTING CONSTANT=               3.000000E-04     MM**2/N.
THRUST LOAD=             500           NEWTONS.
BAND SPEED=              40            METRES /MINUTE.
BAND MATERIAL =          0             1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                     1                1=WET,0=DRY.
INTERCEPT'A'=            4.400001E-04
 5.142700E-13            2.3378
BAND FAILED TO CUT ON THE               86               SECTION.
BAND COMPLETED           85            CUTS.
AVERAGE CUTTING TIME=                   1.301746         MINUTES.
AVERAGE CUTTING RATE=                   40.76791         SECTIONS PER HOUR.
COST RATIO=              .21
COST FACTOR=             7.455796E-03
```

HSS Bi-metal Band   Constant Thrust Load   Coolant   V=40m/min

```
BREADTH=                50              MM.
DEPTH=                  50              MM.
INITIAL CUTTING CONSTANT=               2.200000E-04     MM**2/N.
THRUST LOAD=            250             NEWTONS.
BAND SPEED=             60              METRES /MINUTE.
BAND MATERIAL =         0               1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                      1               1=WET,0=DRY.
INTERCEPT'A'=           2.900001E-04
 5.142700E-13           2.3378
BAND FAILED TO CUT ON THE                487             SECTION.
BAND COMPLETED          486             CUTS.
AVERAGE CUTTING TIME=                    2.399266        MINUTES.
AVERAGE CUTTING RATE=                    23.8118         SECTIONS PER HOUR.
COST RATIO=             .21
COST FACTOR=            9.222239E-03
BREADTH=                50              MM.
DEPTH=                  50              MM.
INITIAL CUTTING CONSTANT=               2.200000E-04     MM**2/N.
THRUST LOAD=            300             NEWTONS.
BAND SPEED=             60              METRES /MINUTE.
BAND MATERIAL =         0               1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                      1               1=WET,0=DRY.
INTERCEPT'A'=           2.900001E-04
 5.142700E-13           2.3378
BAND FAILED TO CUT ON THE                222             SECTION.
BAND COMPLETED          221             CUTS.
AVERAGE CUTTING TIME=                    1.981176        MINUTES.
AVERAGE CUTTING RATE=                    28.37881        SECTIONS PER HOUR.
COST RATIO=             .21
COST FACTOR=            8.286301E-03
BREADTH=                50              MM.
DEPTH=                  50              MM.
INITIAL CUTTING CONSTANT=               2.200000E-04     MM**2/N.
THRUST LOAD=            350             NEWTONS.
BAND SPEED=             60              METRES /MINUTE.
BAND MATERIAL =         0               1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                      1               1=WET,0=DRY.
INTERCEPT'A'=           2.900001E-04
 5.142700E-13           2.3378
BAND FAILED TO CUT ON THE                116             SECTION.
BAND COMPLETED          115             CUTS.
AVERAGE CUTTING TIME=                    1.719246        MINUTES.
AVERAGE CUTTING RATE=                    32.02402        SECTIONS PER HOUR.
COST RATIO=             .21
COST FACTOR=            8.261040E-03
BREADTH=                50              MM.
DEPTH=                  50              MM.
INITIAL CUTTING CONSTANT=               2.200000E-04     MM**2/N.
THRUST LOAD=            400             NEWTONS.
BAND SPEED=             60              METRES /MINUTE.
BAND MATERIAL =         0               1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                      1               1=WET,0=DRY.
INTERCEPT'A'=           2.900001E-04
 5.142700E-13           2.3378
BAND FAILED TO CUT ON THE                66              SECTION.
BAND COMPLETED          65              CUTS.
AVERAGE CUTTING TIME=                    1.44694         MINUTES.
AVERAGE CUTTING RATE=                    36.68625        SECTIONS PER HOUR.
COST RATIO=             .21
COST FACTOR=            8.737724E-03
```

HSS Bi-metal Band   Constant Thrust Load   Coolant   V=60m/min

```
BREADTH=                50              MM.
DEPTH=                  50              MM.
INITIAL CUTTING CONSTANT=               2.200000E-04     MM**2/N.
THRUST LOAD=            450             NEWTONS.
BAND SPEED=             60              METRES /MINUTE.
BAND MATERIAL =.        0               1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                      1               1=WET,0=DRY.
INTERCEPT'A'=           2.900001E-04
 5.142700E-13           2.3378
BAND FAILED TO CUT ON THE                41              SECTION.
BAND COMPLETED          40              CUTS.
AVERAGE CUTTING TIME=                    1.346786        MINUTES.
AVERAGE CUTTING RATE=                    37.87195        SECTIONS PER HOUR.
COST RATIO=             .21
COST FACTOR=            1.044246E-02
BREADTH=                50              MM.
DEPTH=                  50              MM.
INITIAL CUTTING CONSTANT=               2.200000E-04     MM**2/N.
THRUST LOAD=            500             NEWTONS.
BAND SPEED=             60              METRES /MINUTE.
BAND MATERIAL =         0               1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                      1               1=WET,0=DRY.
INTERCEPT'A'=           2.900001E-04
 5.142700E-13           2.3378
BAND FAILED TO CUT ON THE                26              SECTION.
BAND COMPLETED          25              CUTS.
AVERAGE CUTTING TIME=                    1.088605        MINUTES.
AVERAGE CUTTING RATE=                    42.77757        SECTIONS PER HOUR.
COST RATIO=             .21
COST FACTOR=            1.2745[illegible]5E-02
```

HSS Bi-metal Band   Constant Thrust Load   Coolant   V=60m/min

```
BREADTH=               50               MM.
DEPTH=                 50               MM.
INITIAL CUTTING CONSTANT=                1.500000E-04      MM**2/N.
THRUST LOAD=           250              NEWTONS.
BAND SPEED=            80               METRES /MINUTE.
BAND MATERIAL =        0                1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                      1                 1=WET,0=DRY.
INTERCEPT'A'=          2.200000E-04
 5.142700E-13          2.3378
BAND FAILED TO CUT ON THE                421               SECTION.
BAND COMPLETED         420              CUTS.
AVERAGE CUTTING TIME=                    2.668697          MINUTES.
AVERAGE CUTTING RATE=                    21.4989           SECTIONS PER HOUR.
COST RATIO=            .21
COST FACTOR=           1.023436E-02

BREADTH=               50               MM.
DEPTH=                 50               MM.
INITIAL CUTTING CONSTANT=                1.500000E-04      MM**2/N.
THRUST LOAD=           300              NEWTONS.
BAND SPEED=            80               METRES /MINUTE.
BAND MATERIAL =        0                1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                      1                 1=WET,0=DRY.
INTERCEPT'A'=          2.200000E-04
 5.142700E-13          2.3378
BAND FAILED TO CUT ON THE                190               SECTION.
BAND COMPLETED         189              CUTS.
AVERAGE CUTTING TIME=                    2.175878          MINUTES.
AVERAGE CUTTING RATE=                    25.94189          SECTIONS PER HOUR.
COST RATIO=            .21
COST FACTOR=           9.131510E-03

BREADTH=               50               MM.
DEPTH=                 50               MM.
INITIAL CUTTING CONSTANT=                1.500000E-04      MM**2/N.
THRUST LOAD=           350              NEWTONS.
BAND SPEED=            80               METRES /MINUTE.
BAND MATERIAL =        0                1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                      1                 1=WET,0=DRY.
INTERCEPT'A'=          2.200000E-04
 5.142700E-13          2.3378
BAND FAILED TO CUT ON THE                99                SECTION.
BAND COMPLETED         98               CUTS.
AVERAGE CUTTING TIME=                    1.920688          MINUTES.
AVERAGE CUTTING RATE=                    28.80836          SECTIONS PER HOUR.
COST RATIO=            .21
COST FACTOR=           9.288508E-03

BREADTH=               50               MM.
DEPTH=                 50               MM.
INITIAL CUTTING CONSTANT=                1.500000E-04      MM**2/N.
THRUST LOAD=           400              NEWTONS.
BAND SPEED=            80               METRES /MINUTE.
BAND MATERIAL =        0                1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                      1                 1=WET,0=DRY.
INTERCEPT'A'=          2.200000E-04
 5.142700E-13          2.3378
BAND FAILED TO CUT ON THE                56                SECTION.
BAND COMPLETED         55               CUTS.
AVERAGE CUTTING TIME=                    1.385048          MINUTES.
AVERAGE CUTTING RATE=                    33.56128          SECTIONS PER HOUR.
COST RATIO=            .21
COST FACTOR=           4.813997E-03
```

HSS Bi-metal Band   Constant Thrust Load   Coolant   V=80m/min

```
BREADTH=               50               MM.
DEPTH=                 50               MM.
INITIAL CUTTING CONSTANT=                1.500000E-04      MM**2/N.
THRUST LOAD=           450              NEWTONS.
BAND SPEED=            80               METRES /MINUTE.
BAND MATERIAL =        0                1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                      1                 1=WET,0=DRY.
INTERCEPT'A'=          2.200000E-04
 5.142700E-13          2.3378
BAND FAILED TO CUT ON THE                34                SECTION.
BAND COMPLETED         33               CUTS.
AVERAGE CUTTING TIME=                    1.347548          MINUTES.
AVERAGE CUTTING RATE=                    37.2187           SECTIONS PER HOUR.
COST RATIO=            .21
COST FACTOR=           1.157864E-02

BREADTH=               50               MM.
DEPTH=                 50               MM.
INITIAL CUTTING CONSTANT=                1.500000E-04      MM**2/N.
THRUST LOAD=           500              NEWTONS.
BAND SPEED=            80               METRES /MINUTE.
BAND MATERIAL =        0                1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                      1                 1=WET,0=DRY.
INTERCEPT'A'=          2.200000E-04
 5.142700E-13          2.3378
BAND FAILED TO CUT ON THE                22                SECTION.
BAND COMPLETED         21               CUTS.
AVERAGE CUTTING TIME=                    1.171552          MINUTES.
AVERAGE CUTTING RATE=                    39.35953          SECTIONS PER HOUR.
COST RATIO=            .21
COST FACTOR=           1.466392E-02
```

HSS Bi-metal Band   Constant Thrust Load   Coolant   V=80m/min

```
BREADTH=                 50                MM.
DEPTH=                   50                MM.
INITIAL CUTTING CONSTANT=                  1.200000E-04     MM**2/N.
THRUST LOAD=             250               NEWTONS.
BAND SPEED=              100               METRES /MINUTE.
BAND MATERIAL =          0                 1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                        1                1=WET,0=DRY.
INTERCEPT'A'=            1.800000E-04
 5.142700E-13            2.3378
BAND FAILED TO CUT ON THE                  273              SECTION.
BAND COMPLETED           272               CUTS.
AVERAGE CUTTING TIME=                      2.674858         MINUTES.
AVERAGE CUTTING RATE=                      21.401           SECTIONS PER HOUR.
COST RATIO=              .21
COST FACTOR=             1.053284E-02
```

```
BREADTH=                 50                MM.
DEPTH=                   50                MM.
INITIAL CUTTING CONSTANT=                  1.200000E-04     MM**2/N.
THRUST LOAD=             300               NEWTONS.
BAND SPEED=              100               METRES /MINUTE.
BAND MATERIAL =          0                 1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                        1                1=WET,0=DRY.
INTERCEPT'A'=            1.800000E-04
 5.142700E-13            2.3378
BAND FAILED TO CUT ON THE                  124              SECTION.
BAND COMPLETED           123               CUTS.
AVERAGE CUTTING TIME=                      2.272934         MINUTES.
AVERAGE CUTTING RATE=                      24.74841         SECTIONS PER HOUR.
COST RATIO=              .21
COST FACTOR=             1.007806E-02
```

```
BREADTH=                 50                MM.
DEPTH=                   50                MM.
INITIAL CUTTING CONSTANT=                  1.200000E-04     MM**2/N.
THRUST LOAD=             350               NEWTONS.
BAND SPEED=              100               METRES /MINUTE.
BAND MATERIAL =          0                 1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                        1                1=WET,0=DRY.
INTERCEPT'A'=            1.800000E-04
 5.142700E-13            2.3378
BAND FAILED TO CUT ON THE                  64               SECTION.
BAND COMPLETED           63                CUTS.
AVERAGE CUTTING TIME=                      1.847865         MINUTES.
AVERAGE CUTTING RATE=                      29.42883         SECTIONS PER HOUR.
COST RATIO=              .21
COST FACTOR=             1.024536E-02
```

```
BREADTH=                 50                MM.
DEPTH=                   50                MM.
INITIAL CUTTING CONSTANT=                  1.200000E-04     MM**2/N.
THRUST LOAD=             400               NEWTONS.
BAND SPEED=              100               METRES /MINUTE.
BAND MATERIAL =          0                 1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                        1                1=WET,0=DRY.
INTERCEPT'A'=            1.800000E-04
 5.142700E-13            2.3378
BAND FAILED TO CUT ON THE                  37               SECTION.
BAND COMPLETED           36                CUTS.
AVERAGE CUTTING TIME=                      1.714684         MINUTES.
AVERAGE CUTTING RATE=                      30.51338         SECTIONS PER HOUR.
COST RATIO=              .21
COST FACTOR=             1.232385E-02
```

HSS Bi-metal Band   Constant Thrust Load   Coolant   V=100m/min

```
BREADTH=                 50                MM.
DEPTH=                   50                MM.
INITIAL CUTTING CONSTANT=                  1.200000E-04     MM**2/N.
THRUST LOAD=             450               NEWTONS.
BAND SPEED=              100               METRES /MINUTE.
BAND MATERIAL =          0                 1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                        1                1=WET,0=DRY.
INTERCEPT'A'=            1.800000E-04
 5.142700E-13            2.3378
BAND FAILED TO CUT ON THE                  22               SECTION.
BAND COMPLETED           21                CUTS.
AVERAGE CUTTING TIME=                      1.299685         MINUTES.
AVERAGE CUTTING RATE=                      36.30771         SECTIONS PER HOUR.
COST RATIO=              .21
COST FACTOR=             1.511238E-02
```

```
BREADTH=                 50                MM.
DEPTH=                   50                MM.
INITIAL CUTTING CONSTANT=                  1.200000E-04     MM**2/N.
THRUST LOAD=             500               NEWTONS.
BAND SPEED=              100               METRES /MINUTE.
BAND MATERIAL =          0                 1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                        1                1=WET,0=DRY.
INTERCEPT'A'=            1.800000E-04
 5.142700E-13            2.3378
BAND FAILED TO CUT ON THE                  15               SECTION.
BAND COMPLETED           14                CUTS.
AVERAGE CUTTING TIME=                      1.238213         MINUTES.
AVERAGE CUTTING RATE=                      35.03653         SECTIONS PER HOUR.
COST RATIO=              .21
COST FACTOR=             1.998648E-02
```

HSS Bi-metal Band   Constant Thrust Load   Coolant   V=100m/min

```
BREADTH=               50           MM.
DEPTH=                 50           MM.
INITIAL CUTTING CONSTANT=            1.000000E-04     MM**2/N.
THRUST LOAD=           250          NEWTONS.
BAND SPEED=            120          METRES /MINUTE.
BAND MATERIAL =        0            1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                  1                1=WET,0=DRY.
INTERCEPT'A'=          1.500000E-04
 5.142700E-13          2.3378
BAND FAILED TO CUT ON THE            190              SECTION.
BAND COMPLETED         189          CUTS.
AVERAGE CUTTING TIME=                2.66892          MINUTES.
AVERAGE CUTTING RATE=                21.38348         SECTIONS PER HOUR.
COST RATIO=            .21
COST FACTOR=           1.085716E-02

BREADTH=               50           MM.
DEPTH=                 50           MM.
INITIAL CUTTING CONSTANT=            1.000000E-04     MM**2/N.
THRUST LOAD=           300          NEWTONS.
BAND SPEED=            120          METRES /MINUTE.
BAND MATERIAL =        0            1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                  1                1=WET,0=DRY.
INTERCEPT'A'=          1.500000E-04
 5.142700E-13          2.3378
BAND FAILED TO CUT ON THE            86               SECTION.
BAND COMPLETED         85           CUTS.
AVERAGE CUTTING TIME=                2.156094         MINUTES.
AVERAGE CUTTING RATE=                25.79433         SECTIONS PER HOUR.
COST RATIO=            .21
COST FACTOR=           1.044601E-02

BREADTH=               50           MM.
DEPTH=                 50           MM.
INITIAL CUTTING CONSTANT=            1.000000E-04     MM**2/N.
THRUST LOAD=           350          NEWTONS.
BAND SPEED=            120          METRES /MINUTE.
BAND MATERIAL =        0            1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                  1                1=WET,0=DRY.
INTERCEPT'A'=          1.500000E-04
 5.142700E-13          2.3378
BAND FAILED TO CUT ON THE            45               SECTION.
BAND COMPLETED         44           CUTS.
AVERAGE CUTTING TIME=                1.875896         MINUTES.
AVERAGE CUTTING RATE=                28.54689         SECTIONS PER HOUR.
COST RATIO=            .21
COST FACTOR=           1.180855E-02

BREADTH=               50           MM.
DEPTH=                 50           MM.
INITIAL CUTTING CONSTANT=            1.000000E-04     MM**2/N.
THRUST LOAD=           400          NEWTONS.
BAND SPEED=            120          METRES /MINUTE.
BAND MATERIAL =                     1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                  1                1=WET,0=DRY.
INTERCEPT'A'=          1.500000E-04
 5.142700E-13          2.3378
BAND FAILED TO CUT ON THE            26               SECTION.
BAND COMPLETED         25           CUTS.
AVERAGE CUTTING TIME=                1.688791         MINUTES.
AVERAGE CUTTING RATE=                29.95819         SECTIONS PER HOUR.
COST RATIO=            .21
COST FACTOR=           1.484569E-02
```

HSS Bi-metal Band   Constant Thrust Load   Coolant   V=120m/min

```
BREADTH=               50           MM.
DEPTH=                 50           MM.
INITIAL CUTTING CONSTANT=            1.000000E-04     MM**2/N.
THRUST LOAD=           450          NEWTONS.
BAND SPEED=            120          METRES /MINUTE.
BAND MATERIAL =        0            1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                  1                1=WET,0=DRY.
INTERCEPT'A'=          1.500000E-04
 5.142700E-13          2.3378
BAND FAILED TO CUT ON THE            16               SECTION.
BAND COMPLETED         15           CUTS.
AVERAGE CUTTING TIME=                1.36355          MINUTES.
AVERAGE CUTTING RATE=                33.08429         SECTIONS PER HOUR.
COST RATIO=            .21
COST FACTOR=           1.940730E-02

BREADTH=               50           MM.
DEPTH=                 50           MM.
INITIAL CUTTING CONSTANT=            1.000000E-04     MM**2/N.
THRUST LOAD=           500          NEWTONS.
BAND SPEED=            120          METRES /MINUTE.
BAND MATERIAL =        0            1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                  1                1=WET,0=DRY.
INTERCEPT'A'=          1.500000E-04
 5.142700E-13          2.3378
BAND FAILED TO CUT ON THE            10               SECTION.
BAND COMPLETED         9            CUTS.
AVERAGE CUTTING TIME=                1.077305         MINUTES.
AVERAGE CUTTING RATE=                34.20808         SECTIONS PER HOUR.
COST RATIO=            .21
COST FACTOR=           2.790538E-02
```

HSS Bi-metal Band   Constant Thrust Load   Coolant   V=120m/min

6.7.4 High Speed Steel Bi-Metal Bands - Constant Feed Rate

In these simulation tests, PROGRAM II was used with various band speeds in the range 40-120m / min., for selected values of feed rate in the range 0.3-1.0mm / s. for both dry and coolant cutting conditions. The computer print-outs for these tests are shown on the following pages.

FIGURE 102., uses this data and shows the effects of band speed and feed rate on the average cutting rate and cost factor, for high speed steel bi-metal bands both dry and with coolant for constant feed rate.

```
BREADTH=                50          MM.
DEPTH=                  50          MM.
INITIAL CUTTING CONSTANT=            2.599999E-04      MM**2/N.
BAND SPEED=             40          METRES/MINUTE.
FEED RATE =             .4          MM/S.
BAND MATERIAL=          0           1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                  0                 1=WET,0=DRY.
INTERCEPT 'A'=          4.400001E-04
 3.554201E-15           2.1885
BAND FAILED TO CUT ON THE            1946              SECTION.
BAND COMPLETED          1945        CUTS.
AVERAGE CUTTING TIME=                2.095001          MINUTES.
AVERAGE CUTTING RATE=                27.17856          SECTIONS PER HOUR.
COST RATIO=             .21
COST FACTOR=            7.827397E-03
```

```
BREADTH=                50          MM.
DEPTH=                  50          MM.
INITIAL CUTTING CONSTANT=            2.599999E-04      MM**2/N.
BAND SPEED=             40          METRES/MINUTE.
FEED RATE =             .45         MM/S.
BAND MATERIAL=          0           1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                  0                 1=WET,0=DRY.
INTERCEPT 'A'=          4.400001E-04
 3.554201E-15           2.1885
BAND FAILED TO CUT ON THE            668               SECTION.
BAND COMPLETED          667         CUTS.
AVERAGE CUTTING TIME=                1.927804          MINUTES.
AVERAGE CUTTING RATE=                29.3334           SECTIONS PER HOUR.
COST RATIO=             .21
COST FACTOR=            7.452771E-03
```

```
BREADTH=                50          MM.
DEPTH=                  50          MM.
INITIAL CUTTING CONSTANT=            2.599999E-04      MM**2/N.
BAND SPEED=             40          METRES/MINUTE.
FEED RATE =             .5          MM/S.
BAND MATERIAL=          0           1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                  0                 1=WET,0=DRY.
INTERCEPT 'A'=          4.400001E-04
 3.554201E-15           2.1885
BAND FAILED TO CUT ON THE            269               SECTION.
BAND COMPLETED          268         CUTS.
AVERAGE CUTTING TIME=                1.676497          MINUTES.
AVERAGE CUTTING RATE=                33.23131          SECTIONS PER HOUR.
COST RATIO=             .21
COST FACTOR=            7.550332E-03
```

```
BREADTH=                50          MM.
DEPTH=                  50          MM.
INITIAL CUTTING CONSTANT=            2.599999E-04      MM**2/N.
BAND SPEED=             40          METRES/MINUTE.
FEED RATE =             .55         MM/S.
BAND MATERIAL=          0           1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                  0                 1=WET,0=DRY.
INTERCEPT 'A'=          4.400001E-04
 3.554201E-15           2.1885
BAND FAILED TO CUT ON THE            109               SECTION.
BAND COMPLETED          108         CUTS.
AVERAGE CUTTING TIME=                1.592653          MINUTES.
AVERAGE CUTTING RATE=                34.28815          SECTIONS PER HOUR.
COST RATIO=             .21
COST FACTOR=            7.933433E-03
```

HSS Bi-metal Band   Constant Feed Rate   Dry   V=40m/min

```
BREADTH=                50          MM.
DEPTH=                  50          MM.
INITIAL CUTTING CONSTANT=            2.599999E-04      MM**2/N.
BAND SPEED=             40          METRES/MINUTE.
FEED RATE =             .6          MM/S.
BAND MATERIAL=          0           1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                  0                 1=WET,0=DRY.
INTERCEPT 'A'=          4.400001E-04
 3.554201E-15           2.1885
BAND FAILED TO CUT ON THE            52                SECTION.
BAND COMPLETED          51          CUTS.
AVERAGE CUTTING TIME=                1.425022          MINUTES.
AVERAGE CUTTING RATE=                36.69676          SECTIONS PER HOUR.
COST RATIO=             .21
COST FACTOR=            9.563718E-03
```

```
BREADTH=                50          MM.
DEPTH=                  50          MM.
INITIAL CUTTING CONSTANT=            2.599999E-04      MM**2/N.
BAND SPEED=             40          METRES/MINUTE.
FEED RATE =             .7          MM/S.
BAND MATERIAL=          0           1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                  0                 1=WET,0=DRY.
INTERCEPT 'A'=          4.400001E-04
 3.554201E-15           2.1885
BAND FAILED TO CUT ON THE            13                SECTION.
BAND COMPLETED          12          CUTS.
AVERAGE CUTTING TIME=                1.257373          MINUTES.
AVERAGE CUTTING RATE=                33.47519          SECTIONS PER HOUR.
COST RATIO=             .21
COST FACTOR=            2.259817E-02
```

HSS Bi-metal Band   Constant Feed Rate   Dry   V=40m/min

```
BREADTH=                50             MM.
DEPTH=                  50             MM.
INITIAL CUTTING CONSTANT=               1.800000E-04    MM**2/N.
BAND SPEED=             60             METRES/MINUTE.
FEED RATE =             .37            MM/S.
BAND MATERIAL=          0              1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                     0               1=WET,0=DRY.
INTERCEPT 'A'=          2.900001E-04
 3.554201E-15           2.1885
BAND FAILED TO CUT ON THE               1855            SECTION.
BAND COMPLETED          1854           CUTS.
AVERAGE CUTTING TIME=                   2.290775        MINUTES.
AVERAGE CUTTING RATE=                   24.96332        SECTIONS PER HOUR.
COST RATIO=             .21
COST FACTOR=            8.517999E-03

BREADTH=                50             MM.
DEPTH=                  50             MM.
INITIAL CUTTING CONSTANT=               1.800000E-04    MM**2/N.
BAND SPEED=             60             METRES/MINUTE.
FEED RATE =             .4             MM/S.
BAND MATERIAL=          0              1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                     0               1=WET,0=DRY.
INTERCEPT 'A'=          2.900001E-04
 3.554201E-15           2.1885
BAND FAILED TO CUT ON THE               908             SECTION.
BAND COMPLETED          907            CUTS.
AVERAGE CUTTING TIME=                   2.12325         MINUTES.
AVERAGE CUTTING RATE=                   26.79919        SECTIONS PER HOUR.
COST RATIO=             .21
COST FACTOR=            8.052036E-03

BREADTH=                50             MM.
DEPTH=                  50             MM.
INITIAL CUTTING CONSTANT=               1.800000E-04    MM**2/N.
BAND SPEED=             60             METRES/MINUTE.
FEED RATE =             .45            MM/S.
BAND MATERIAL=          0              1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                     0               1=WET,0=DRY.
INTERCEPT 'A'=          2.900001E-04
 3.554201E-15           2.1885
BAND FAILED TO CUT ON THE               308             SECTION.
BAND COMPLETED          307            CUTS.
AVERAGE CUTTING TIME=                   1.900003        MINUTES.
AVERAGE CUTTING RATE=                   29.606          SECTIONS PER HOUR.
COST RATIO=             .21
COST FACTOR=            7.731255E-03

BREADTH=                50             MM.
DEPTH=                  50             MM.
INITIAL CUTTING CONSTANT=               1.800000E-04    MM**2/N.
BAND SPEED=             60             METRES/MINUTE.
FEED RATE =             .5             MM/S.
BAND MATERIAL=          0              1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                     0               1=WET,0=DRY.
INTERCEPT 'A'=          2.900001E-04
 3.554201E-15           2.1885
BAND FAILED TO CUT ON THE               120             SECTION.
BAND COMPLETED          119            CUTS.
AVERAGE CUTTING TIME=                   1.676497        MINUTES.
AVERAGE CUTTING RATE=                   32.79848        SECTIONS PER HOUR.
COST RATIO=             .21
COST FACTOR=            8.148940E-03
```

HSS Bi-metal Band   Constant Feed Rate   Dry   V=60m/min

```
BREADTH=                50             MM.
DEPTH=                  50             MM.
INITIAL CUTTING CONSTANT=               1.800000E-04    MM**2/N.
BAND SPEED=             60             METRES/MINUTE.
FEED RATE =             .55            MM/S.
BAND MATERIAL=          0              1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                     0               1=WET,0=DRY.
INTERCEPT 'A'=          2.900001E-04
 3.554201E-15           2.1885
BAND FAILED TO CUT ON THE               50              SECTION.
BAND COMPLETED          49             CUTS.
AVERAGE CUTTING TIME=                   1.564728        MINUTES.
AVERAGE CUTTING RATE=                   33.73044        SECTIONS PER HOUR.
COST RATIO=             .21
COST FACTOR=            1.022376E-02

BREADTH=                50             MM.
DEPTH=                  50             MM.
INITIAL CUTTING CONSTANT=               1.800000E-04    MM**2/N.
BAND SPEED=             60             METRES/MINUTE.
FEED RATE =             .6             MM/S.
BAND MATERIAL=          0              1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                     0               1=WET,0=DRY.
INTERCEPT 'A'=          2.900001E-04
 3.554201E-15           2.1885
BAND FAILED TO CUT ON THE               24              SECTION.
BAND COMPLETED          23             CUTS.
AVERAGE CUTTING TIME=                   1.397082        MINUTES.
AVERAGE CUTTING RATE=                   34.70573        SECTIONS PER HOUR.
COST RATIO=             .21
COST FACTOR=            1.456819E-02

BREADTH=                50             MM.
DEPTH=                  50             MM.
INITIAL CUTTING CONSTANT=               1.800000E-04    MM**2/N.
BAND SPEED=             60             METRES/MINUTE.
FEED RATE =             .7             MM/S.
BAND MATERIAL=          0              1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                     0               1=WET,0=DRY.
INTERCEPT 'A'=          2.900001E-04
 3.554201E-15           2.1885
BAND FAILED TO CUT ON THE               6               SECTION.
BAND COMPLETED          5              CUTS.
AVERAGE CUTTING TIME=                   1.229432        MINUTES.
AVERAGE CUTTING RATE=                   25.42986        SECTIONS PER HOUR.
COST RATIO=             .21
COST FACTOR=            4.743769E-02
```

HSS Bi-metal Band   Constant Feed Rate   Dry   V=60m/min

```
BREADTH=                 50                  MM.
DEPTH=                   50                  MM.
INITIAL CUTTING CONSTANT=                     1.000000E-04      MM**2/N.
BAND SPEED=              80                  METRES/MINUTE.
FEED RATE =              .35                 MM/S.
BAND MATERIAL=           0                   1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                           0                 1=WET,0=DRY.
INTERCEPT 'A'=           2.200000E-04
 3.554201E-15            2.1885
BAND FAILED TO CUT ON THE                     1747              SECTION.
BAND COMPLETED           1746                CUTS.
AVERAGE CUTTING TIME=                         2.38866           MINUTES.
AVERAGE CUTTING RATE=                         23.93483          SECTIONS PER HOUR.
COST RATIO=              .21
COST FACTOR=             [illegible].567729E-03
BREADTH=                 50                  MM.
DEPTH=                   50                  MM.
INITIAL CUTTING CONSTANT=                     1.000000E-04      MM**2/N.
BAND SPEED=              80                  METRES/MINUTE.
FEED RATE =              .4                  MM/S.
BAND MATERIAL=           0                   1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                           0                 1=WET,0=DRY.
INTERCEPT 'A'=           2.200000E-04
 3.554201E-15            2.1885
BAND FAILED TO CUT ON THE                     520               SECTION.
BAND COMPLETED           519                 CUTS.
AVERAGE CUTTING TIME=                         2.095575          MINUTES.
AVERAGE CUTTING RATE=                         27.08313          SECTIONS PER HOUR.
COST RATIO=              .21
COST FACTOR=             6.131355E-03
BREADTH=                 50                  MM.
DEPTH=                   50                  MM.
INITIAL CUTTING CONSTANT=                     1.000000E-04      MM**2/N.
BAND SPEED=              80                  METRES/MINUTE.
FEED RATE =              .45                 MM/S.
BAND MATERIAL=           0                   1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                           0                 1=WET,0=DRY.
INTERCEPT 'A'=           2.200000E-04
 3.554201E-15            2.1885
BAND FAILED TO CUT ON THE                     175               SECTION.
BAND COMPLETED           174                 CUTS.
AVERAGE CUTTING TIME=                         1.886014          MINUTES.
AVERAGE CUTTING RATE=                         29.62488          SECTIONS PER HOUR.
COST RATIO=              .21
COST FACTOR=             [illegible].214485E-03
BREADTH=                 50                  MM.
DEPTH=                   50                  MM.
INITIAL CUTTING CONSTANT=                     1.000000E-04      MM**2/N.
BAND SPEED=              80                  METRES/MINUTE.
FEED RATE =              .5                  MM/S.
BAND MATERIAL=           0                   1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                           0                 1=WET,0=DRY.
INTERCEPT 'A'=           2.200000E-04
 3.554201E-15            2.1885
BAND FAILED TO CUT ON THE                     68                SECTION.
BAND COMPLETED           67                  CUTS.
AVERAGE CUTTING TIME=                         1.676497          MINUTES.
AVERAGE CUTTING RATE=                         32.21277          SECTIONS PER HOUR.
COST RATIO=              .21
COST FACTOR=             9.44307[illegible]E-03
```

HSS Bi-metal Band   Constant Feed Rate   Dry   V=80m/min

```
BREADTH=                 50                  MM.
DEPTH=                   50                  MM.
INITIAL CUTTING CONSTANT=                     1.000000E-04      MM**2/N.
BAND SPEED=              80                  METRES/MINUTE.
FEED RATE =              .6                  MM/S.
BAND MATERIAL=           0                   1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                           0                 1=WET,0=DRY.
INTERCEPT 'A'=           2.200000E-04
 3.554201E-15            2.1885
BAND FAILED TO CUT ON THE                     13                SECTION.
BAND COMPLETED           12                  CUTS.
AVERAGE CUTTING TIME=                         1.425024          MINUTES.
AVERAGE CUTTING RATE=                         30.61188          SECTIONS PER HOUR.
COST RATIO=              .21
COST FACTOR=             2.318494E-02
BREADTH=                 50                  MM.
DEPTH=                   50                  MM.
INITIAL CUTTING CONSTANT=                     1.000000E-04      MM**2/N.
BAND SPEED=              80                  METRES/MINUTE.
FEED RATE =              .7                  MM/S.
BAND MATERIAL=           0                   1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                           0                 1=WET,0=DRY.
INTERCEPT 'A'=           2.200000E-04
 3.554201E-15            2.1885
BAND FAILED TO CUT ON THE                     3                 SECTION.
BAND COMPLETED           2                   CUTS.
AVERAGE CUTTING TIME=                         1.215462          MINUTES.
AVERAGE CUTTING RATE=                         15.46203          SECTIONS PER HOUR.
COST RATIO=              .21
COST FACTOR=             .1115133
```

HSS Bi-metal Band   Constant Feed Rate   Dry   V=80m/min

```
BREADTH=                 50               MM.
DEPTH=                   50               MM.
INITIAL CUTTING CONSTANT=                  6.999999E-05        MM**2/N.
BAND SPEED=              100              METRES/MINUTE.
FEED RATE =              .35              MM/S.
BAND MATERIAL=           0                1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                        0                   1=WET,0=DRY.
INTERCEPT 'A'=           1.800000E-04
 3.554201E-15            2.1885
BAND FAILED TO CUT ON THE                  1120                SECTION.
BAND COMPLETED           1119             CUTS.
AVERAGE CUTTING TIME=                      2.413778            MINUTES.
AVERAGE CUTTING RATE=                      23.73102            SECTIONS PER HOUR.
COST RATIO=              .21
COST FACTOR=             9.[illegible]24236E-03

BREADTH=                 50               MM.
DEPTH=                   50               MM.
INITIAL CUTTING CONSTANT=                  6.999999E-05        MM**2/N.
BAND SPEED=              100              METRES/MINUTE.
FEED RATE =              .4               MM/S.
BAND MATERIAL=           0                1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                        0                   1=WET,0=DRY.
INTERCEPT 'A'=           1.800000E-04
 3.554201E-15            2.1885
BAND FAILED TO CUT ON THE                  334                 SECTION.
BAND COMPLETED           333              CUTS.
AVERAGE CUTTING TIME=                      2.11237             MINUTES.
AVERAGE CUTTING RATE=                      26.81342            SECTIONS PER HOUR.
COST RATIO=              .21
COST FACTOR=             8.420181E-03

BREADTH=                 50               MM.
DEPTH=                   50               MM.
INITIAL CUTTING CONSTANT=                  6.999999E-05        MM**2/N.
BAND SPEED=              100              METRES/MINUTE.
FEED RATE =              .45              MM/S.
BAND MATERIAL=           0                1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                        0                   1=WET,0=DRY.
INTERCEPT 'A'=           1.800000E-04
 3.554201E-15            2.1885
BAND FAILED TO CUT ON THE                  113                 SECTION.
BAND COMPLETED           112              CUTS.
AVERAGE CUTTING TIME=                      1.877671            MINUTES.
AVERAGE CUTTING RATE=                      29.51004            SECTIONS PER HOUR.
COST RATIO=              .21
COST FACTOR=             8.865312E-03

BREADTH=                 50               MM.
DEPTH=                   50               MM.
INITIAL CUTTING CONSTANT=                  6.999999E-05        MM**2/N.
BAND SPEED=              100              METRES/MINUTE.
FEED RATE =              .5               MM/S.
BAND MATERIAL=           0                1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                        0                   1=WET,0=DRY.
INTERCEPT 'A'=           1.800000E-04
 3.554201E-15            2.1885
BAND FAILED TO CUT ON THE                  43                  SECTION.
BAND COMPLETED           42               CUTS.
AVERAGE CUTTING TIME=                      1.676497            MINUTES.
AVERAGE CUTTING RATE=                      31.44777            SECTIONS PER HOUR.
COST RATIO=              .21
COST FACTOR=             1.134198E-02
```

HSS Bi-metal Band   Constant Feed Rate   Dry   V=100m/min

```
BREADTH=                 50               MM.
DEPTH=                   50               MM.
INITIAL CUTTING CONSTANT=                  6.999999E-05        MM**2/N.
BAND SPEED=              100              METRES/MINUTE.
FEED RATE =              .6               MM/S.
BAND MATERIAL=           0                1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                        0                   1=WET,0=DRY.
INTERCEPT 'A'=           1.800000E-04
 3.554201E-15            2.1885
BAND FAILED TO CUT ON THE                  7                   SECTION.
BAND COMPLETED           6                CUTS.
AVERAGE CUTTING TIME=                      1.408257            MINUTES.
AVERAGE CUTTING RATE=                      25.33508            SECTIONS PER HOUR.
COST RATIO=              .21
COST FACTOR=             4.093863E-02
```

HSS Bi-metal Band   Constant Feed Rate   Dry   V=100m/min

```
BREADTH=            50              MM.
DEPTH=              50              MM.
INITIAL CUTTING CONSTANT=            5.000000E-05    MM**2/N.
BAND SPEED=         120             METRES/MINUTE.
FEED RATE =         .35             MM/S.
BAND MATERIAL=      0               1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                  0               1=WET,0=DRY.
INTERCEPT 'A'=      1.500000E-04
 3.554201E-15       2.1885
BAND FAILED TO CUT ON THE            772             SECTION.
BAND COMPLETED      771             CUTS.
AVERAGE CUTTING TIME=                2.402584        MINUTES.
AVERAGE CUTTING RATE=                23.81709        SECTIONS PER HOUR.
COST RATIO=         .21
COST FACTOR=        9. 71276E-03

BREADTH=            50              MM.
DEPTH=              50              MM.
INITIAL CUTTING CONSTANT=            5.000000E-05    MM**2/N.
BAND SPEED=         120             METRES/MINUTE.
FEED RATE =         .4              MM/S.
BAND MATERIAL=      0               1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                  0               1=WET,0=DRY.
INTERCEPT 'A'=      1.500000E-04
 3.554201E-15       2.1885
BAND FAILED TO CUT ON THE            230             SECTION.
BAND COMPLETED      229             CUTS.
AVERAGE CUTTING TIME=                2.095579        MINUTES.
AVERAGE CUTTING RATE=                26.93179        SECTIONS PER HOUR.
COST RATIO=         .21
COST FACTOR=        8.652922E-03

BREADTH=            50              MM.
DEPTH=              50              MM.
INITIAL CUTTING CONSTANT=            5.000000E-05    MM**2/N.
BAND SPEED=         120             METRES/MINUTE.
FEED RATE =         .45             MM/S.
BAND MATERIAL=      0               1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                  0               1=WET,0=DRY.
INTERCEPT 'A'=      1.500000E-04
 3.554201E-15       2.1885
BAND FAILED TO CUT ON THE            75              SECTION.
BAND COMPLETED      74              CUTS.
AVERAGE CUTTING TIME=                1.87208         MINUTES.
AVERAGE CUTTING RATE=                29.25404        SECTIONS PER HOUR.
COST RATIO=         .21
COST FACTOR=        9.625766E-03

BREADTH=            50              MM.
DEPTH=              50              MM.
INITIAL CUTTING CONSTANT=            5.000000E-05    MM**2/N.
BAND SPEED=         120             METRES/MINUTE.
FEED RATE =         .5              MM/S.
BAND MATERIAL=      0               1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                  0               1=WET,0=DRY.
INTERCEPT 'A'=      1.500000E-04
 3.554201E-15       2.1885
BAND FAILED TO CUT ON THE            25              SECTION.
BAND COMPLETED      24              CUTS.
AVERAGE CUTTING TIME=                1.676497        MINUTES.
AVERAGE CUTTING RATE=                30.01506        SECTIONS PER HOUR.
COST RATIO=         .21
COST FACTOR=        1.515892E-02
```

ESS Bi-metal Band   Constant Feed Rate   Dry   V=120m/min

```
BREADTH=              50              MM.
DEPTH=                50              MM.
INITIAL CUTTING CONSTANT=              3.000000E-04     MM**2/N.
BAND SPEED=           40              METRES/MINUTE.
FEED RATE =           .55             MM/S.
BAND MATERIAL=        0               1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                    1                1=WET,0=DRY.
INTERCEPT 'A'=        4.400001E-04
 5.142700E-13         2.3378
BAND FAILED TO CUT ON THE              676              SECTION.
BAND COMPLETED        675             CUTS.
AVERAGE CUTTING TIME=                  1.592645         MINUTES.
AVERAGE CUTTING RATE=                  35.08362         SECTIONS PER HOUR.
COST RATIO=           .21
COST FACTOR=          6.275915E-03
BREADTH=              50              MM.
DEPTH=                50              MM.
INITIAL CUTTING CONSTANT=              3.000000E-04     MM**2/N.
BAND SPEED=           40              METRES/MINUTE.
FEED RATE =           .6              MM/S.
BAND MATERIAL=        0               1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                    1                1=WET,0=DRY.
INTERCEPT 'A'=        4.400001E-04
 5.142700E-13         2.3378
BAND FAILED TO CUT ON THE              485              SECTION.
BAND COMPLETED        484             CUTS.
AVERAGE CUTTING TIME=                  1.425002         MINUTES.
AVERAGE CUTTING RATE=                  38.8214          SECTIONS PER HOUR.
COST RATIO=           .21
COST FACTOR=          5.814131E-03
BREADTH=              50              MM.
DEPTH=                50              MM.
INITIAL CUTTING CONSTANT=              3.000000E-04     MM**2/N.
BAND SPEED=           40              METRES/MINUTE.
FEED RATE =           .7              MM/S.
BAND MATERIAL=        0               1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                    1                1=WET,0=DRY.
INTERCEPT 'A'=        4.400001E-04
 5.142700E-13         2.3378
BAND FAILED TO CUT ON THE              247              SECTION.
BAND COMPLETED        246             CUTS.
AVERAGE CUTTING TIME=                  1.25736          MINUTES.
AVERAGE CUTTING RATE=                  43.22485         SECTIONS PER HOUR.
COST RATIO=           .21
COST FACTOR=          5.654652E-03
BREADTH=              50              MM.
DEPTH=                50              MM.
INITIAL CUTTING CONSTANT=              3.000000E-04     MM**2/N.
BAND SPEED=           40              METRES/MINUTE.
FEED RATE =           .8              MM/S.
BAND MATERIAL=        0               1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                    1                1=WET,0=DRY.
INTERCEPT 'A'=        4.400001E-04
 5.142700E-13         2.3378
BAND FAILED TO CUT ON THE              138              SECTION.
BAND COMPLETED        137             CUTS.
AVERAGE CUTTING TIME=                  1.089717         MINUTES.
AVERAGE CUTTING RATE=                  48.5067          SECTIONS PER HOUR.
COST RATIO=           .21
COST FACTOR=          5.759213E-03
```

HSS Bi-metal Band   Constant Feed Rate   Coolant   V=40m/min

```
BREADTH=              50              MM.
DEPTH=                50              MM.
INITIAL CUTTING CONSTANT=              3.000000E-04     MM**2/N.
BAND SPEED=           40              METRES/MINUTE.
FEED RATE =           .9              MM/S.
BAND MATERIAL=        0               1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                    1                1=WET,0=DRY.
INTERCEPT 'A'=        4.400001E-04
 5.142700E-13         2.3378
BAND FAILED TO CUT ON THE              75               SECTION.
BAND COMPLETED        74              CUTS.
AVERAGE CUTTING TIME=                  1.005896         MINUTES.
AVERAGE CUTTING RATE=                  50.64087         SECTIONS PER HOUR.
COST RATIO=           .21
COST FACTOR=          6.794121E-03
BREADTH=              50              MM.
DEPTH=                50              MM.
INITIAL CUTTING CONSTANT=              3.000000E-04     MM**2/N.
BAND SPEED=           40              METRES/MINUTE.
FEED RATE =           1               MM/S.
BAND MATERIAL=        0               1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                    1                1=WET,0=DRY.
INTERCEPT 'A'=        4.400001E-04
 5.142700E-13         2.3378
BAND FAILED TO CUT ON THE              44               SECTION.
BAND COMPLETED        43              CUTS.
AVERAGE CUTTING TIME=                  .8382487         MINUTES.
AVERAGE CUTTING RATE=                  56.24019         SECTIONS PER HOUR.
COST RATIO=           .21
COST FACTOR=          8.289762E-03
```

HSS Bi-metal Band   Constant Feed Rate   Coolant   V=40m/min

```
BREADTH=              50                   MM.
DEPTH=                50                   MM.
INITIAL CUTTING CONSTANT=                   2.200000E-04      MM**2/N.
BAND SPEED=           60                   METRES/MINUTE.
FEED RATE =           .5                   MM/S.
BAND MATERIAL=        0                    1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                         1                 1=WET,0=DRY.
INTERCEPT 'A'=        2.900001E-04
 5.142700E-13         2.3378
BAND FAILED TO CUT ON THE                   473               SECTION.
BAND COMPLETED        472                  CUTS.
AVERAGE CUTTING TIME=                       1.676497          MINUTES.
AVERAGE CUTTING RATE=                       33.38339          SECTIONS PER HOUR.
COST RATIO=           .21
COST FACTOR=          6.725590E-03
BREADTH=              50                   MM.
DEPTH=                50                   MM.
INITIAL CUTTING CONSTANT=                   2.200000E-04      MM**2/N.
BAND SPEED=           60                   METRES/MINUTE.
FEED RATE =           .55                  MM/S.
BAND MATERIAL=        0                    1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                         1                 1=WET,0=DRY.
INTERCEPT 'A'=        2.900001E-04
 5.142700E-13         2.3378
BAND FAILED TO CUT ON THE                   311               SECTION.
BAND COMPLETED        310                  CUTS.
AVERAGE CUTTING TIME=                       1.564715          MINUTES.
AVERAGE CUTTING RATE=                       35.47847          SECTIONS PER HOUR.
COST RATIO=           .21
COST FACTOR=          6.551012E-03
BREADTH=              50                   MM.
DEPTH=                50                   MM.
INITIAL CUTTING CONSTANT=                   2.200000E-04      MM**2/N.
BAND SPEED=           60                   METRES/MINUTE.
FEED RATE =           .6                   MM/S.
BAND MATERIAL=        0                    1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                         1                 1=WET,0=DRY.
INTERCEPT 'A'=        2.900001E-04
 5.142700E-13         2.3378
BAND FAILED TO CUT ON THE                   223               SECTION.
BAND COMPLETED        222                  CUTS.
AVERAGE CUTTING TIME=                       1.397073          MINUTES.
AVERAGE CUTTING RATE=                       39.21454          SECTIONS PER HOUR.
COST RATIO=           .21
COST FACTOR=          6.237581E-03
BREADTH=              50                   MM.
DEPTH=                50                   MM.
INITIAL CUTTING CONSTANT=                   2.200000E-04      MM**2/N.
BAND SPEED=           60                   METRES/MINUTE.
FEED RATE =           .7                   MM/S.
BAND MATERIAL=        0                    1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                         1                 1=WET,0=DRY.
INTERCEPT 'A'=        2.900001E-04
 5.142700E-13         2.3378
BAND FAILED TO CUT ON THE                   115               SECTION.
BAND COMPLETED        114                  CUTS.
AVERAGE CUTTING TIME=                       1.229428          MINUTES.
AVERAGE CUTTING RATE=                       43.34746          SECTIONS PER HOUR.
COST RATIO=           .21
COST FACTOR=          6.562982E-03
```

HSS Bi-metal Band   Constant Feed Rate   Coolant   V=60m/min

```
BREADTH=              50                   MM.
DEPTH=                50                   MM.
INITIAL CUTTING CONSTANT=                   2.200000E-04      MM**2/N.
BAND SPEED=           60                   METRES/MINUTE.
FEED RATE =           .8                   MM/S.
BAND MATERIAL=        0                    1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                         1                 1=WET,0=DRY.
INTERCEPT 'A'=        2.900001E-04
 5.142700E-13         2.3378
BAND FAILED TO CUT ON THE                   66                SECTION.
BAND COMPLETED        65                   CUTS.
AVERAGE CUTTING TIME=                       1.061779          MINUTES.
AVERAGE CUTTING RATE=                       47.9908           SECTIONS PER HOUR.
COST RATIO=           .21
COST FACTOR=          7.389661E-03
BREADTH=              50                   MM.
DEPTH=                50                   MM.
INITIAL CUTTING CONSTANT=                   2.200000E-04      MM**2/N.
BAND SPEED=           60                   METRES/MINUTE.
FEED RATE =           .9                   MM/S.
BAND MATERIAL=        0                    1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                         1                 1=WET,0=DRY.
INTERCEPT 'A'=        2.900001E-04
 5.142700E-13         2.3378
BAND FAILED TO CUT ON THE                   39                SECTION.
BAND COMPLETED        38                   CUTS.
AVERAGE CUTTING TIME=                       .9500163          MINUTES.
AVERAGE CUTTING RATE=                       50.24176          SECTIONS PER HOUR.
COST RATIO=           .21
COST FACTOR=          9.335011E-03
BREADTH=              50                   MM.
DEPTH=                50                   MM.
INITIAL CUTTING CONSTANT=                   2.200000E-04      MM**2/N.
BAND SPEED=           60                   METRES/MINUTE.
FEED RATE =           1                    MM/S.
BAND MATERIAL=        0                    1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                         1                 1=WET,0=DRY.
INTERCEPT 'A'=        2.900001E-04
 5.142700E-13         2.3378
BAND FAILED TO CUT ON THE                   24                SECTION.
BAND COMPLETED        23                   CUTS.
AVERAGE CUTTING TIME=                       .8382487          MINUTES.
AVERAGE CUTTING RATE=                       51.28258          SECTIONS PER HOUR.
COST RATIO=           .21
COST FACTOR=          1.261228E-02
```

HSS Bi-metal Band   Constant Feed Rate   Coolant   V=60m/min

```
BREADTH=               50               MM.
DEPTH=                 50               MM.
INITIAL CUTTING CONSTANT=                1.500000E-04      MM**2/N.
BAND SPEED=            80               METRES/MINUTE.
FEED RATE =            .5               MM/S.
BAND MATERIAL=         0                1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                      1                 1=WET,0=DRY.
INTERCEPT 'A'=         2.200000E-04
 5.142700E-13          2.3378
BAND FAILED TO CUT ON THE                266               SECTION.
BAND COMPLETED         265              CUTS.
AVERAGE CUTTING TIME=                    1.676497          MINUTES.
AVERAGE CUTTING RATE=                    33.22734          SECTIONS PER HOUR.
COST RATIO=            .21
COST FACTOR=           7.059332E-03

BREADTH=               50               MM.
DEPTH=                 50               MM.
INITIAL CUTTING CONSTANT=                1.500000E-04      MM**2/N.
BAND SPEED=            80               METRES/MINUTE.
FEED RATE =            .55              MM/S.
BAND MATERIAL=         0                1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                      1                 1=WET,0=DRY.
INTERCEPT 'A'=         2.200000E-04
 5.142700E-13          2.3378
BAND FAILED TO CUT ON THE                176               SECTION.
BAND COMPLETED         175              CUTS.
AVERAGE CUTTING TIME=                    1.550727          MINUTES.
AVERAGE CUTTING RATE=                    35.50571          SECTIONS PER HOUR.
COST RATIO=            .21
COST FACTOR=           7.033959E-03

BREADTH=               50               MM.
DEPTH=                 50               MM.
INITIAL CUTTING CONSTANT=                1.500000E-04      MM**2/N.
BAND SPEED=            80               METRES/MINUTE.
FEED RATE =            .6               MM/S.
BAND MATERIAL=         0                1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                      1                 1=WET,0=DRY.
INTERCEPT 'A'=         2.200000E-04
 5.142700E-13          2.3378
BAND FAILED TO CUT ON THE                123               SECTION.
BAND COMPLETED         122              CUTS.
AVERAGE CUTTING TIME=                    1.425009          MINUTES.
AVERAGE CUTTING RATE=                    38.05148          SECTIONS PER HOUR.
COST RATIO=            .21
COST FACTOR=           7.124562E-03

BREADTH=               50               MM.
DEPTH=                 50               MM.
INITIAL CUTTING CONSTANT=                1.500000E-04      MM**2/N.
BAND SPEED=            80               METRES/MINUTE.
FEED RATE =            .7               MM/S.
BAND MATERIAL=         0                1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                      1                 1=WET,0=DRY.
INTERCEPT 'A'=         2.200000E-04
 5.142700E-13          2.3378
BAND FAILED TO CUT ON THE                64                SECTION.
BAND COMPLETED         63               CUTS.
AVERAGE CUTTING TIME=                    1.215458          MINUTES.
AVERAGE CUTTING RATE=                    42.66183          SECTIONS PER HOUR.
COST RATIO=            .21
COST FACTOR=           8.031931E-03
```

HSS Bi-metal Band   Constant Feed Rate   Coolant   V=80m/min

```
BREADTH=               50               MM.
DEPTH=                 50               MM.
INITIAL CUTTING CONSTANT=                1.500000E-04      MM**2/N.
BAND SPEED=            80               METRES/MINUTE.
FEED RATE =            .8               MM/S.
BAND MATERIAL=         0                1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                      1                 1=WET,0=DRY.
INTERCEPT 'A'=         2.200000E-04
 5.142700E-13          2.3378
BAND FAILED TO CUT ON THE                36                SECTION.
BAND COMPLETED         35               CUTS.
AVERAGE CUTTING TIME=                    1.047811          MINUTES.
AVERAGE CUTTING RATE=                    46.02907          SECTIONS PER HOUR.
COST RATIO=            .21
COST FACTOR=           1.015943E-02

BREADTH=               50               MM.
DEPTH=                 50               MM.
INITIAL CUTTING CONSTANT=                1.500000E-04      MM**2/N.
BAND SPEED=            80               METRES/MINUTE.
FEED RATE =            .9               MM/S.
BAND MATERIAL=         0                1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                      1                 1=WET,0=DRY.
INTERCEPT 'A'=         2.200000E-04
 5.142700E-13          2.3378
BAND FAILED TO CUT ON THE                20                SECTION.
BAND COMPLETED         19               CUTS.
AVERAGE CUTTING TIME=                    .9639854          MINUTES.
AVERAGE CUTTING RATE=                    44.69588          SECTIONS PER HOUR.
COST RATIO=            .21
COST FACTOR=           1.500886E-02

BREADTH=               50               MM.
DEPTH=                 50               MM.
INITIAL CUTTING CONSTANT=                1.500000E-04      MM**2/N.
BAND SPEED=            80               METRES/MINUTE.
FEED RATE =            1                MM/S.
BAND MATERIAL=         0                1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                      1                 1=WET,0=DRY.
INTERCEPT 'A'=         2.200000E-04
 5.142700E-13          2.3378
BAND FAILED TO CUT ON THE                11                SECTION.
BAND COMPLETED         10               CUTS.
AVERAGE CUTTING TIME=                    .8382489          MINUTES.
AVERAGE CUTTING RATE=                    41.14525          SECTIONS PER HOUR.
COST RATIO=            .21
COST FACTOR=           2.469370E-02
```

HSS Bi-metal Band   Constant Feed Rate   Coolant   V=80m/min

```
BREADTH=                 50               MM.
DEPTH=                   50               MM.
INITIAL CUTTING CONSTANT=                  1.200000E-04     MM**2/N.
BAND SPEED=              100              METRES/MINUTE.
FEED RATE =              .4               MM/S.
BAND MATERIAL=           0                1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                        1                1=WET,0=DRY.
INTERCEPT 'A'=           1.800000E-04
 5.142700E-13            2.3378
BAND FAILED TO CUT ON THE                  430              SECTION.
BAND COMPLETED           429              CUTS.
AVERAGE CUTTING TIME=                      2.11237          MINUTES.
AVERAGE CUTTING RATE=                      26.85455         SECTIONS PER HOUR.
COST RATIO=              .21
COST FACTOR=             8.276541E-03
BREADTH=                 50               MM.
DEPTH=                   50               MM.
INITIAL CUTTING CONSTANT=                  1.200000E-04     MM**2/N.
BAND SPEED=              100              METRES/MINUTE.
FEED RATE =              .5               MM/S.
BAND MATERIAL=           0                1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                        1                1=WET,0=DRY.
INTERCEPT 'A'=           1.800000E-04
 5.142700E-13            2.3378
BAND FAILED TO CUT ON THE                  172              SECTION.
BAND COMPLETED           171              CUTS.
AVERAGE CUTTING TIME=                      1.676497         MINUTES.
AVERAGE CUTTING RATE=                      33.03381         SECTIONS PER HOUR.
COST RATIO=              .21
COST FACTOR=             7.502723E-03
BREADTH=                 50               MM.
DEPTH=                   50               MM.
INITIAL CUTTING CONSTANT=                  1.200000E-04     MM**2/N.
BAND SPEED=              100              METRES/MINUTE.
FEED RATE =              .6               MM/S.
BAND MATERIAL=           0                1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                        1                1=WET,0=DRY.
INTERCEPT 'A'=           1.800000E-04
 5.142700E-13            2.3378
BAND FAILED TO CUT ON THE                  80               SECTION.
BAND COMPLETED           79               CUTS.
AVERAGE CUTTING TIME=                      1.408236         MINUTES.
AVERAGE CUTTING RATE=                      37.9077          SECTIONS PER HOUR.
COST RATIO=              .21
COST FACTOR=             8.019496E-03
BREADTH=                 50               MM.
DEPTH=                   50               MM.
INITIAL CUTTING CONSTANT=                  1.200000E-04     MM**2/N.
BAND SPEED=              100              METRES/MINUTE.
FEED RATE =              .7               MM/S.
BAND MATERIAL=           0                1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                        1                1=WET,0=DRY.
INTERCEPT 'A'=           1.800000E-04
 5.142700E-13            2.3378
BAND FAILED TO CUT ON THE                  42               SECTION.
BAND COMPLETED           41               CUTS.
AVERAGE CUTTING TIME=                      1.207076         MINUTES.
AVERAGE CUTTING RATE=                      41.6243          SECTIONS PER HOUR.
COST RATIO=              .21
COST FACTOR=             9.823140E-03
```

HSS Bi-metal Band   Constant Feed Rate   Coolant   V=100m/min

```
BREADTH=                 50               MM.
DEPTH=                   50               MM.
INITIAL CUTTING CONSTANT=                  1.200000E-04     MM**2/N.
BAND SPEED=              100              METRES/MINUTE.
FEED RATE =              .8               MM/S.
BAND MATERIAL=           0                1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                        1                1=WET,0=DRY.
INTERCEPT 'A'=           1.800000E-04
 5.142700E-13            2.3378
BAND FAILED TO CUT ON THE                  23               SECTION.
BAND COMPLETED           22               CUTS.
AVERAGE CUTTING TIME=                      1.072957         MINUTES.
AVERAGE CUTTING RATE=                      42.40956         SECTIONS PER HOUR.
COST RATIO=              .21
COST FACTOR=             1.385618E-02
BREADTH=                 50               MM.
DEPTH=                   50               MM.
INITIAL CUTTING CONSTANT=                  1.200000E-04     MM**2/N.
BAND SPEED=              100              METRES/MINUTE.
FEED RATE =              .9               MM/S.
BAND MATERIAL=           0                1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                        1                1=WET,0=DRY.
INTERCEPT 'A'=           1.800000E-04
 5.142700E-13            2.3378
BAND FAILED TO CUT ON THE                  13               SECTION.
BAND COMPLETED           12               CUTS.
AVERAGE CUTTING TIME=                      .938839          MINUTES.
AVERAGE CUTTING RATE=                      40.71004         SECTIONS PER HOUR.
COST RATIO=              .21
COST FACTOR=             2.148329E-02
BREADTH=                 50               MM.
DEPTH=                   50               MM.
INITIAL CUTTING CONSTANT=                  1.200000E-04     MM**2/N.
BAND SPEED=              100              METRES/MINUTE.
FEED RATE =              1                MM/S.
BAND MATERIAL=           0                1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                        1                1=WET,0=DRY.
INTERCEPT 'A'=           1.800000E-04
 5.142700E-13            2.3378
BAND FAILED TO CUT ON THE                  7                SECTION.
BAND COMPLETED           6                CUTS.
AVERAGE CUTTING TIME=                      .8382492         MINUTES.
AVERAGE CUTTING RATE=                      33.36578         SECTIONS PER HOUR.
COST RATIO=              .21
COST FACTOR=             3.894360E-02
```

HSS Bi-metal Band   Constant Feed Rate   Coolant   V=100m/min

```
BREADTH=              50              MM.
DEPTH=                50              MM.
INITIAL CUTTING CONSTANT=              1.000000E-04     MM**2/N.
BAND SPEED=           120             METRES/MINUTE.
FEED RATE =           .4              MM/S.
BAND MATERIAL=        0               1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                    1                1=WET,0=DRY.
INTERCEPT 'A'=        1.500000E-04
 5.142700E-13         2.3378
BAND FAILED TO CUT ON THE              301              SECTION.
BAND COMPLETED        300             CUTS.
AVERAGE CUTTING TIME=                  2.095577         MINUTES.
AVERAGE CUTTING RATE=                  26.9957          SECTIONS PER HOUR.
COST RATIO=           .21
COST FACTOR=          8.432012E-03
BREADTH=              50              MM.
DEPTH=                50              MM.
INITIAL CUTTING CONSTANT=              1.000000E-04     MM**2/N.
BAND SPEED=           120             METRES/MINUTE.
FEED RATE =           .5              MM/S.
BAND MATERIAL=        0               1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                    1                1=WET,0=DRY.
INTERCEPT 'A'=        1.500000E-04
 5.142700E-13         2.3378
BAND FAILED TO CUT ON THE              119              SECTION.
BAND COMPLETED        118             CUTS.
AVERAGE CUTTING TIME=                  1.676497         MINUTES.
AVERAGE CUTTING RATE=                  32.79198         SECTIONS PER HOUR.
COST RATIO=           .21
COST FACTOR=          8.064162E-03
BREADTH=              50              MM.
DEPTH=                50              MM.
INITIAL CUTTING CONSTANT=              1.000000E-04     MM**2/N.
BAND SPEED=           120             METRES/MINUTE.
FEED RATE =           .6              MM/S.
BAND MATERIAL=        0               1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                    1                1=WET,0=DRY.
INTERCEPT 'A'=        1.500000E-04
 5.142700E-13         2.3378
BAND FAILED TO CUT ON THE              56               SECTION.
BAND COMPLETED        55              CUTS.
AVERAGE CUTTING TIME=                  1.39708          MINUTES.
AVERAGE CUTTING RATE=                  37.50452         SECTIONS PER HOUR.
COST RATIO=           .21
COST FACTOR=          9.161111E-03
BREADTH=              50              MM.
DEPTH=                50              MM.
INITIAL CUTTING CONSTANT=              1.000000E-04     MM**2/N.
BAND SPEED=           120             METRES/MINUTE.
FEED RATE =           .7              MM/S.
BAND MATERIAL=        0               1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                    1                1=WET,0=DRY.
INTERCEPT 'A'=        1.500000E-04
 5.142700E-13         2.3378
BAND FAILED TO CUT ON THE              29               SECTION.
BAND COMPLETED        28              CUTS.
AVERAGE CUTTING TIME=                  1.201488         MINUTES.
AVERAGE CUTTING RATE=                  40.17058         SECTIONS PER HOUR.
COST RATIO=           .21
COST FACTOR=          1.222408E-02
```

HSS Bi-metal Band   Constant Feed Rate   Coolant   V=120m/min

```
BREADTH=              50              MM.
DEPTH=                50              MM.
INITIAL CUTTING CONSTANT=              1.000000E-04     MM**2/N.
BAND SPEED=           120             METRES/MINUTE.
FEED RATE =           .8              MM/S.
BAND MATERIAL=        0               1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                    1                1=WET,0=DRY.
INTERCEPT 'A'=        1.500000E-04
 5.142700E-13         2.3378
BAND FAILED TO CUT ON THE              16               SECTION.
BAND COMPLETED        15              CUTS.
AVERAGE CUTTING TIME=                  1.06178          MINUTES.
AVERAGE CUTTING RATE=                  39.68834         SECTIONS PER HOUR.
COST RATIO=           .21
COST FACTOR=          1.835111E-02
BREADTH=              50              MM.
DEPTH=                50              MM.
INITIAL CUTTING CONSTANT=              1.000000E-04     MM**2/N.
BAND SPEED=           120             METRES/MINUTE.
FEED RATE =           .9              MM/S.
BAND MATERIAL=        0               1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                    1                1=WET,0=DRY.
INTERCEPT 'A'=        1.500000E-04
 5.142700E-13         2.3378
BAND FAILED TO CUT ON THE              9                SECTION.
BAND COMPLETED        8               CUTS.
AVERAGE CUTTING TIME=                  .9500163         MINUTES.
AVERAGE CUTTING RATE=                  35.34576         SECTIONS PER HOUR.
COST RATIO=           .21
COST FACTOR=          3.042860E-02
BREADTH=              50              MM.
DEPTH=                50              MM.
INITIAL CUTTING CONSTANT=              1.000000E-04     MM**2/N.
BAND SPEED=           120             METRES/MINUTE.
FEED RATE =           1               MM/S.
BAND MATERIAL=        0               1=CARBON,0=H.S.S.
COOLANT CONDITIONS=                    1                1=WET,0=DRY.
INTERCEPT 'A'=        1.500000E-04
 5.142700E-13         2.3378
BAND FAILED TO CUT ON THE              5                SECTION.
BAND COMPLETED        4               CUTS.
AVERAGE CUTTING TIME=                  .8382494         MINUTES.
AVERAGE CUTTING RATE=                  26.98753         SECTIONS PER HOUR.
COST RATIO=           .21
COST FACTOR=          5.675598E-02
```

HSS Bi-metal Band   Constant Feed Rate   Coolant   V=120m/min

7 DISCUSSION

7.1 PROCESS CHARACTERISTICS

Some factors and relationships which govern the metal removal rate of a bandsaw blade have been outlined.

A bandsaw blade may be considered a blunt cutting tool [1] whose metal removal rate is controlled, for a given workpiece by the band speed, the pitch of the teeth and the load applied to it by the machine.

The investigation has shown a linear relationship between the depth of cut per tooth and the thrust load per tooth per unit blade thickness, for a given workpiece material, workpiece size and band speed. The ratio of these parameters has been defined as a cutting constant and is shown to depend on the number of teeth in contact with the workpiece. For a given workpiece material and band speed the cutting constant has been found to increase as the number of teeth in contact with the workpiece decreases.

7.2 BAND WEAR TESTING

Adapting Colding's three dimensional tool life equation for the bandsaw operation has been succesful.

It has enabled many of the engineering parameters associated with the bandsaw operation to be related to the wear rate of the band.

The following are discussions on the influences of the major bandsaw parameters on band wear. The significance and use that this wear testing method has to both users of the bandsaw operation and bandsaw equipment manufacturers are also discussed.

Throughout these discussions the wear rate is taken as the change in the cutting constant per revolution of the band, since this is a measure of the loss in cutting efficiency per band revolution.

7.2.1 Band Speed

The band speed governs the amount of heat that may be transferred from the cutting edge either through the band material itself or into the workpiece.

Each tooth on the band experiences a temperature rise as it cuts through the workpiece and then undergoes a cooling down period as it travels around the band machine until it comes into contact with the workpiece again. Each tooth experiences a thermal cycle every band revolution. The cutting action of each tooth can be considered to be of a repeated interrupted nature. At slow band speeds a tooth on the band has more time to cool down between periods of workpiece contact than at fast band speeds. Thermal cycling has been shown to have considerable influence on tool life in a metal cutting process of a repeated interrupted nature [69].

Band speed will therefore have a significant influence on the temperature of the cutting edges, and hence on wear rate.

Equation (192) shows the relationship of band speed to band wear rate and indicates that:

$$\text{wear rate} \propto V^{b_1}$$

For the test conditions the indice varies from 5.43-11.61. The implication of this is that if the band speed is doubled the wear rate is increased more than 360 fold.

7.2.2 Thrust Load

The actual thrust load developed by the bandsaw is not the prime factor controlling the wear rate, but it is the thrust load per tooth per unit thickness. Hence, the effect of a given thrust load on the wear rate depends on the number of teeth engaged with the workpiece, i.e. the teeth pitch and workpiece breadth, and the thickness of the blade.

Equation (192) shows the relationship of thrust load per tooth per unit thickness to wear rate and is given by:

$$\text{wear rate} \propto (f - f_a')^{b_3}$$

where $f = \dfrac{F}{Bpt}$ and $f_a' = \dfrac{2a}{K_o(1+\eta)}$.

For the test conditions the indice varies from 3.43-9.61 implying that if the thrust load is doubled the wear rate increases more than 90 fold.

7.2.3 Initial Cutting Constant

The initial cutting constant is that cutting constant calculated for the first section to be cut off i.e. for an unworn band.

It has been shown (192) that the relationship between the initial cutting constant and the wear rate of the band is given by:

$$\text{wear rate} \propto K_o^{b_2}$$

For the test conditions the indice varies from 4.43-10.61. This implies that if the initial cutting constant is doubled the wear rate increases more than 180 fold.

7.2.4 Breadth Of Workpiece

In addition to the influence of workpiece breadth on the thrust load per tooth per unit thickness (section 7.1.2) it has a direct effect on the wear rate and also governs the initial cutting constant.

FIGURES 96., and 97., show that typically the initial cutting constant increases when the breadth of the workpiece is small. Therefore its total influence on the wear rate is very complex and for a given thrust load per tooth per unit thickness, may be separated into two different effects.

As the workpiece breadth increases, the time an individual tooth is exposed to the conditions causing wear also increases (i.e. the contact time ratio increases).

As a result of this effect the wear rate is increased when the breadth of the workpiece is large. However, the breadth of the workpiece is one of the parameters controlling the initial cutting constant, which is shown by equation (194), to be related to the wear rate.

As a result of this effect the wear rate and the initial cutting constant both increase when the breadth of the workpiece is small. This illustrates that the total influence of the workpiece breadth consists of two opposing effects. FIGURE 103., shows the combined effects of these influences and is based on equation (194).

The total effect is such that the wear rate is increased when the breadth of the workpiece is small, illustrating that the second of the effects described is dominant.

7.2.5 Cutting Efficiency Of A Band

For a band to be efficient it must have a large initial cutting constant and be resistant to wear.

The results indicate that the initial cutting constant does have considerable effect on the wear rate, i.e. the decline in cutting efficiency with use, FIGURE 104.

This effect implies that any developments which improve the cutting performance of a band will reduce blade life i.e. high cutting rates can only be achieved at the expense of blade life.

7.2.6 Coolant

The only type of coolant used throughout this investigation was soluble oil coolant, as used in industrial applications.

The results indicate that the coolant has two different effects on the performance of bandsaw blades.

The first effect achieved with small coolant flow rates leads to a slight increase in the initial cutting constant which gradually increases again with flow rate, and is most probably produced by an improvement in lubrication, FIGURES 94., 96., and 97.

The second effect leads to a significant fall in the wear rate and is dependant on the coolant flow rate, FIGURE 93. This reduction in wear rate is caused by a reduction in the temperature achieved at the blade tooth. Large flow rates of coolant are required to carry away enough of the heat generated to sufficiently reduce the temperature and cause an improvement in the wear rate. A coolant flow rate of between 1.5-2 litres per minute is considered sufficient for the test conditions used to achieve the necessary cooling effect.

Similar effects have been reported for the power hacksaw operation. Thompson and Taylor [5] used a coolant flow rate of 2 litre per minute when investigating the factors influencing the wear rate of power hacksaw blades.

7.2.7 Band Wear Testing - Its Applications

The wear testing method developed has some significant applications for both manufacturers of bandsaw equipment and their users. Four main applications are listed below:

(i) tests to validate improvements and developments in materials, band design and machine performance.

(ii) quality control tests to determine the performance of an individual band against accepted standards.

(iii) tests to compare the performance of coolants and lubricants.

(iv) tests to compare the performance of bands and machines when cutting different workpiece materials.

The following discussions cover these four objectives.

7.2.7.1 Tests To Validate Improvements And Developments In Materials, Band Design And Machine Performance

The procedure outlined in section 5.4 including the assessment of band performance based on the modified Colding's tool life equation is ideal for this application.

Since the method is based on a number of tests using a quantity of similar bands under a variety of test conditions such as varying band speed, machine load and workpiece geometry, it leads directly to the average performance level for material and equipment combination selected.

New band materials can be investigated and results compared. In this investigation we have compared carbon bands with high speed steel bi-metal. Radical changes in tooth geometry can easily be assessed using the same procedure. Bandsaw machine developments can be tested against standard machine configurations to evaluate any improvements in cutting performance achieved.

When the results are combined with the simulation model discussed in section 6.5, indications of the appropriate production rate and cost per cut achieved for specific test combinations can be compared making the method developed a very powerful design / development tool.

7.2.7.2 Quality Control Tests To Determine The Performance Of An Individual Band Against Accepted Standards

The procedure based on the modified Colding's equation is not relevant to a quality control test as it is the particular performance of an individual band that is needed and not the average performance of a number of bands.

The wear testing procedure discussed in section 5.4 leads to data relevant to a quality control test and is illustrated in FIGURES 90., and 91.

To convert this procedure to an acceptable quality control test it would be necessary to standardize on band speed, thrust load, test bar material and geometry, and coolant flow rate.

This test requires that the change in the cutting constant with the number of band revolutions performed be determined and assumes a knowledge of the thrust load developed between the band and test bar.

This investigation has shown that a bandsaw machine can be succesfully adapted to a gravity feed system. This system can be calibrated with sufficient accuracy to make continuous load measurements and expensive dynamometers unnecessary. This makes the procedure more economical and simplified in use.

The wear test results indicate that there are two important qualities which are determined by the wear test procedure described, both of which are related to cutting performance.

The first is the initial cutting constant which although not directly associated with band wear, can vary considerably and is related to the wear rate.

The second is the decrease in the cutting constant per band revolution; a direct measure of the wear rate.

Both these parameters have implications on the total cutting performance and depend on different variables. Any manufacturer using these methods as a standard wear test procedure should recognise and separate these parameters when relating them to physical features of the band.

A single parameter which indicates the total band performance can be obtained by dividing the initial cutting constant by the change in the cutting constant per band revolution. This parameter is a measure of the total number of revolutions the band can make when $\eta = 0$.

7.2.7.3 Tests To Compare The Performance Of Coolants And Lubricants

The full procedure of an assessment of performance based on the modified Colding's approach can be used to test the effectiveness of various coolants and lubricants. The simulation model can be used to investigate the effects of coolant on the productivity rate, cost per cut and tool life for various material and equipment combinations.

However, it is felt that such a rigorous routine is probably too involved for this purpose. FIGURES 93., and 94., show the results of a shortened series of tests which yield adequate information on coolant performance.

To produce a set of results as shown, it is only necessary to carry out wear tests using one combination of band speed and thrust load, and for a single test bar geometry. The flow rate of the coolant under test would be the only parameter to be varied. Results of such a test carried out for various coolants and lubricants would yield information on both the lubricating (FIGURE 94.) and cooling effect (FIGURE 93.) achieved and would indicate the coolant flow rate required to satisfy a particular set of conditions.

7.2.7.4 Tests To Compare The Performance Of Bands When Cutting Different Workpiece Materials

The information on band machining En44E shown in FIGURES 99-102., shows the output per hour and cost per cut for various combinations of band material, band speed, feed rate and thrust load. This information is of great significance to any user of the bandsaw operation who cuts En44E.

The procedure outlined in section 5.4, including the assessment of band performance based on the modified Colding's tool life equation, combined with simulation model discussed in section 6.5, can be used to indicate the appropriate productivity rate and cost per cut achieved, for specific workpiece material / bandsaw equipment combinations.

This method can be used as the basic tool for compiling a bandsawing data bank facility. Thus enabling manufacturers of bandsaw equipment to supply their customers with an accurate information service on the technology of the bandsaw process.

Manufacturers of bands would then be in a position to recommend the optimum sawing conditions, and supply other related data, such as costs and machining times for sawing various workpiece materials to their customers, [70-74].

7.3 SIMULATION METHOD

It has been shown that the effects of band wear can be taken into account when determining cutting rates for bandsaw operations.

A flow chart for a computer simulation has been described and used to demonstrate the influence of certain parameters on the performance of bandsaw operations when either the thrust load or feed rate are constant. This method, together with the wear method described (section 5.4) enabled laboratory test data to be converted to cutting rates and costs. This provides the assessment of a particular combination of sawing parameters to be made in terms of realistic criteria which can be readily understood by bandsaw users.

The computer method has been used in conjunction with data relating to rather unusual or difficult to cut material. Many of the trends obtained are believed to be typical of those that would be obtained with the more common workpiece materials.

The following are discussions of the trends and their significance to both user and manufacturer of bandsaw equipment.

7.3.1 Band Speed, Thrust Load And Feed Rate

The cost per cut can be lowered by decreasing the cutting time;

increasing the cutting speed reduces the cutting time, but also reduces the tool life at a faster rate. Thus increasing the cutting speed has opposing effects on the cost per cut, since the cost of machining time decreases while the total tool cost (tool changing time cost + tool cost per section) increases.

The effect of speed on the cost per cut is shown in FIGURES 99-102. It is interesting to note that an optimum cost occurs due to the increasing tool cost (an ideal band which does not wear would give an ever decreasing cost per cut as the speed increases). Although it is unlikely that such an ideal tool will ever be discovered, tool materials which can resist high speeds i.e. when changing from carbon to high speed steel bi-metal bands, giving longer tool life values, will cause the optimum speed to occur at higher values. This means that greater demands on the machine capabilities will result from improved tool materials.

The production rate or output per hour is inversely proportional to the production time per component, and is dependent on the cutting conditions and the tool life. Decreases in the non-productive time and the time to change the band, will increase the production rate. Increases in the cutting speed will reduce the cutting time per section and increase the tool changing time per component; a minimum time per component (or maximum production rate) will therefore result, as seen in FIGURES 99-102. The speed for maximum production rate is always higher than the speed for minimum cost per component.

FIGURES 99-102., show that the most economical thrust load or feed rate for a given band speed is much smaller than the value that produces the greatest cutting rate.

When choosing the optimum conditions for a bandsaw operation, a choice must be made as to whether cost or cutting rate is to be optimised.

7.3.2 Constant Thrust Load v. Constant Feed Rate

Comparisons between FIGURES 101., and 102., show that within the ranges considered for high speed steel bi-metal bands, the constant feed rate system is more economical and productive for a given band speed than the constant thrust load system. When using carbon blades the advantage of the constant feed rate system is less pronounced.

Typically, modern bandsaw machines do not operate on pure constant thrust load or pure constant feed rate systems; they are usually somewhere between the two. These results demonstrate that bandsaw manufacturers should look towards a constant feed rate system of operation.

7.3.3 Cutting Fluid

FIGURES 99., and 100., give an estimate of the effects of cutting fluid on the performance criteria for carbon blades. The use of soluble oil coolant with carbon bands gives little increase in cutting rate but leads to a reduction in the cost per section cut, when compared with results obtained in the normal atmosphere at a given band speed. If we consider the constant feed rate situation with a band speed of 20m / minute under optimised conditions, the use of a coolant increases the output per hour by one unit and the cost per section cut off is reduced from 38 to 28pence.

For some of the high band speeds available on production bandsaws, the wear rate induced in carbon blades is so excessive that their use is impractical. However, when soluble oil coolant is used, a greater range of band speed is made possible than when cutting in the normal atmosphere.

FIGURES 101., and 102., show the effects of cutting fluid on the performance criteria for high speed steel bi-metal bands. The use of a soluble oil coolant leads to reduction in cost and increases the output rate per hour compared with those obtained when cutting dry in the normal atmosphere.

If we consider the constant feed rate situation for a band speed of 80m / minute under optimised conditions, the use of a coolant increases the output rate per hour from 33 to 46 sections per hour and reduces the cost per section cut from 12.6 to 11pence.

However, it should be noted that the data was obtained with a coolant flow rate of 2 litres per minute and that FIGURE 93., indicates that some of the benefits obtained would be reduced at smaller flow rates.

The introduction of soluble oil coolant with high speed steel bi-metal bands has little effect on the range of speeds which may be used.

7.3.4 Band Material

Comparisons between carbon bands, FIGURES 99., and 100., and high speed steel bi-metal bands, FIGURES 101., and 102., show that the high speed steel bi-metal band is superior in performance to a carbon band, both with respect to output per hour and cost per cut.

Comparisons show that high speed steel bi-metal bands are superior to carbon bands when used on the constant thrust load system or on the constant feed rate system, under dry cutting conditions or with coolant flowing.

Whether or not high speed steel bi-metal bands are adopted by machine users is another matter; part of the problem seems to be a lack of awareness. The bandsaw may be one of the only machine tools still using carbon-steel tooling.

It is often considered by users that the cost of the band is the dominant factor in the total cutting cost. Perhaps this is the reason some users still employ carbon steel bands, when one considers that a high speed steel bi-metal band costs seven times that of a carbon band of the same dimensions.

This investigation has shown that the band cost represents a small proportion of the total cutting cost. The results show that the increase in band cost, when changing to high speed steel bi-metal bands, is more than offset by better cutting rates and longer blade life, which combine to reduce the total cost per cut.

When replacing carbon bands with high speed steel bi-metal and using the constant feed rate method of operation with soluble oil coolant and a band speed of 40m / minute; the results indicate that the lowest cost per section is reduced from 40pence at a cutting rate of 13 sections per hour, to 8pence, at a cutting rate of 45 sections per hour. The cost per cut is found by multiplying the cost factor in FIGURES 100., and 102., by the current purchase price of the band, (see section 6.4.2).

If the same procedure is repeated for a system operating with constant thrust load at a band speed of 40m / minute with coolant flowing, the lowest cost per section is reduced from 40pence at a cutting rate of 10 sections per hour, to 11pence at a cutting rate of 36 sections per hour.

These results show that the lowest cost per cut can be reduced by a factor of 5 or 4 times, depending on which system of operation is adopted, even though the cost of tooling has been increased 7 fold by replacing carbon bands with high speed steel bi-metal.

Since most production bandsaws operate on a system somewhere between these two, then it can be seen that users could reduce the cost per cut by approximately 4.5 times if carbon bands were replaced by high speed steel bi-metal bands.

7.3.5 Machine Parameters

The results obtained show that the choice of machine parameters play a major part in determining the performance of bandsaw operations.

The results show that for high speed steel bi-metal bands, the highest optimum output in sections per hour is not obtained at high band speeds; a result that is perhaps surprising. FIGURE 101., shows that for the constant thrust load system, lower band speeds can give from 4-8 more sections per hour output while reducing the cost per cut. FIGURE 102., shows that band speeds with a feed rate in the range 0.5-0.65mm / second give good performance both with respect to output per hour and total cost per cut.

This shows how savings on the total cost of bandsawing operations can be made when it is realized that by adjusting cutting rates to more efficient levels the cost per cut is reduced, even though the wear rate of the band may be increased. The resulting cost reduction arises because of the high cost rate for modern production bandsaw machines which is typically £ 3.25 per hour.

The idea of operating a bandsaw with small feed rates in order to improve band life does not result in a reduction in cutting cost because of the excessive cutting times produced.

7.3.6 Power Hacksaw v. Bandsaw

It is very interesting to undertake a similar comparison with a power hacksaw operation (see section 3.7), which, with high speed steel blades, gives a lowest cost per section cut, of 10pence, at a cutting rate of 20 sections per hour, when cutting the same material and section under similar conditions to those in section 7.3.4.

The results are shown on the next page, with those in section 7.3.4 for comparison.

OPERATION	LOWEST COST PER SECTION CUT	SECTIONS CUT PER HOUR
Bandsaw operation with constant feed rate:		
Carbon Band	40 pence	13
High Speed Steel Bi-Metal Band	8 pence	45
Bandsaw operation with constant thrust load:		
Carbon Band	40 pence	10
High Speed Steel Bi-Metal Band	11 pence	36
Power hacksaw operation:		
High Speed Steel Blade	10 pence	20

7.3.7 Conclusions

The main conclusions are listed below:

(i) the bandsaw operation may be a low cost, high cutting rate operation when high speed steel bi-metal bands are used with a coolant supply under optimised operating conditions.

(ii) for all bandsaw operations high speed steel bi-metal bands are preferred to carbon bands; the increased blade cost being more than offset by better cutting rates and longer band life, which combine to reduce the cost per cut.

(iii) a bandsaw machine operating with the constant feed rate system is superior to one operating with a constant thrust load system.

(iv) a reduction in the total cost per cut can usually be obtained by optimising feed rates at the expense of band life.

(v) the bandsaw operation can be as economical as the power hacksaw operation whilst achieving a higher cutting rate.

7.3.8 Suggestions For Further Work

It is suggested that the present work provides a basis for the following investigations:

(i) to establish the cutting constant and wear index for a wide selection of workpiece materials. Build up of computer simulation results for the bandsaw operation and form a bandsaw data centre to recommend the optimum and standard sawing conditions for various workpiece / machine combinations, and to supply other related data such as cost and machining time.

(ii) to render a consulting service to solve the troubles experienced by users of the bandsaw operation.

(iii) to establish a standard test method for the evaluation of the performance of modern bandsaw blades and machines.

(iv) the development of an adaptive control device which would automatically determine the labour cost per cut, the band cost per cut, and the total cost per cut; enabling the optimum feed rate to be reached via a control system.

This could be achieved by using the equations developed in this investigation and the method of adaptive control developed by D. A. Gall [75] for the abrasive cut-off operation.

DETAILS OF FURTHER STUDY AND COURSES ATTENDED

Attended the 16th International Machine Tool Design and Research Conference held in September 1975 at the University of Machester Institute of Science and Technology. Two papers were presented at this conference, see [5,6].

A paper entitled A Computer Simulation Of The Power Hacksaw Operation And Its Use In Estimating Blade Life, Cutting Rate And Cost, was published in the Production Engineer [7].

Attended a computer programming course on FORTRAN IV at Sheffield City Polytechnic Department of Computer Studies.

APPENDIX

The author presented a paper at the Seventeenth International Machine Tool Design and Research Conference (17th M.T.D.R.) held at Birmingham University on the 20-24th September 1976.

The title of the paper presented is:

A STUDY OF BANDSAW BLADE WEAR AND ITS EFFECTS ON CUTTING RATES AND ECONOMICS

This paper is reproduced on the following pages.

The author was awarded a Hatfield / Sorby Memorial Prize for the work presented in this thesis and was also awarded the Sykes Cup.

The Hatfield / Sorby Memorial Prizes are awarded by the Sheffield Metallurgical and Engineering Association (SMEA) to encourage Post Graduate Students studying for Masters Degrees. The prizes are for metallurgical or engineering work, preferably having an industrial bias, and are awarded annually to Sheffield University and Sheffield City Polytechnic. A condition of the award is that the prize winners shall present an account of their work to an association meeting. The Sykes Cup, originally presented by Sir Charles Sykes FRS, is awarded to the Hatfield / Sorby prize winner who, in the opinion of the SMEA Council, gives the best presentation of his work.

A STUDY OF BANDSAW BLADE WEAR AND ITS EFFECTS ON CUTTING RATES AND ECONOMICS

R. W. TAYLOR and P. J. THOMPSON
Department of Mechanical and Production Engineering
Sheffield City Polytechnic

SUMMARY

Relationships between the wear rate of the band and relevant parameters such as band speed, machine load and geometry of the workpiece have been obtained. Wear rate and cutting rate have been expressed in terms of a cutting constant, which defines the penetration of the teeth, and its decay with use. A computer based simulation of the bandsaw operation is used to investigate the influences of relevant engineering parameters on productivity and cutting economics. The data obtained from the simulation model has been used to determine cutting rates and costs of horizontal bandsaw operations carried out on workpiece material classified as difficult to cut. The results show that the cutting rate reaches a maxima, the cutting cost a minima and blade life decreases, when the thrust load, feed rate and band speed increase. Trends obtained are believed to be typical of those that would be obtained when cutting the more common materials.

INTRODUCTION

This study investigates how cutting rates and costs of horizontal bandsaw operations are influenced by wear rate, machine load and workpiece geometry.

A review of recent work carried out within the Department of Mechanical and Production Engineering, Sheffield City Polytechnic, [1-7], suggests that this paper is a natural extension of sawing research.

The horizontal bandsaw is perhaps the most versatile of all cutting-off machines used in modern production plants. The majority are hydraulic and may be classified as either constant feed rate or constant thrust load machines. As a result of wear, the band is replaced when it either becomes overloaded or the feed rate becomes unacceptable, depending on which type of machine is used. Cutting rates, in terms of the number of sections cut per hour and cost per cut, depend on the rate of wear of the blade over its effective life.

The following is based on a study of the factors influencing band wear and on an approach using dimensional analysis, first proposed by Colding [8], in a study of lathe tool wear; modified by Thompson and Taylor [5], in a study of power hacksaw blade wear, and further modified by Taylor [9], in a study of bandsaw blade wear.

Relationships between wear rate of the blade and engineering parameters such as band speed, machine load, and geometry of the band and workpiece are shown. Both the wear rate and cutting rate have been expressed in terms of a cutting constant and its decay with use.

A method of simulating the horizontal bandsaw operation is shown which utilizes the above relationships. The computer simulation is based on the metal removal and blade wear produced, during one revolution of the band. The slot depth produced in the workpiece is determined on the assumption that the cutting constant remains unaltered during one revolution of the band. The decrease in the cutting constant produced during this cycle is determined, and the cutting constant suitably reduced for the next revolution. This cycle of events continues until the cutting constant becomes so small that it indicates that the blade needs replacing. In practice the metal removal and blade wear process occur simultaneously. However, it is considered that for modern bandsaw blades one revolution of the blade is such a small unit in the life of a blade that the simplification in our model does not lead to significant errors in predictions.

The use of the simulation model is demonstrated by a study of the influence of machine parameters on productivity and costs, for both constant thrust load and constant feed rate horizontal bandsaw operations. The workpiece material in each case being considered of a difficult to cut nature by the sawing trade. Results for Carbon alloy and High Speed Steel Bi-metal blades both with, and without coolant are shown.

Perhaps the most significant outcome of this investigation is how the cost per cut is reduced, the tool life increased, and the cutting rate increased by using High Speed Steel Bi-metal blades with an adequate flow of coolant.

Naturally, as the quality of the band tool improves, its purchase cost rises. This study shows that the increased cost is more than offset by better cutting rates and longer tool life, which combine to reduce the cost per cut despite the increased blade cost.

BLADE WEAR TESTING

Colding [8], has used dimensional analysis to obtain a three dimensional, tool-life equation, which is aimed at a generalization of Taylor's equation [10]. As there seems to be general agreement that tool life is a direct function of temperature in the region where Taylor's equation is valid, Colding has not included temperature in his analysis, but instead substituted the thermal properties of the workpiece. To take into account the specific energy Colding has used the chip equivalent. The third parameter considered by Colding is the cutting speed. Colding's three dimensional, tool-life equation has proved useful in interpreting lathe tool-life data.

The physical conditions controlling the wear of bandsaw blades are quite different from those controlling the wear of lathe tools. Specifically the chip formation mechanism is very different and an individual tooth on the blade performs an intermittent cutting action whilst a lathe tool does not. However, since the three parameters considered by Colding to influence the tool life are so basic it was considered that his tool-life equation may be valid for bandsaw operations.

Before Colding's equation can be applied to this operation it is necessary to express the tool life, chip equivalent and cutting speed in terms of parameters that can be measured during a bandsaw blade wear test. The actual method of modification is set out in [9] and the modified equation is given by equation (5) Appendix II.

Wear tests have been carried out to determine the variation in the cutting constant (see Appendix I) with the number of band revolutions performed. The procedure adopted for obtaining this data is as follows. At each thrust load and cutting rate the blade is used to cut through a rectangular test bar a number of times. Relevant measurements [9] are taken so that by using equation (4) Appendix I, the cutting constant can be determined for a particular cut. This process is repeated many times and the change in the cutting constant per revolution of the band is determined.

Workpiece Material

All wear tests were carried out using En44E as the workpiece material. En44E is frequently used by manufacturers of bandsaw blades in their quality control wear tests, and is the reason why it was used.

The percentage chemical composition of En44E is:

1.20 C; 0.27 Si; 0.44 Mn; 0.02 S; 0.019 P

All test bars were heat treated by hardening at 880°C and oil quenching followed by tempering at 650°C. This treatment gives a hardness range of 300-320 H.V.30.

The test bars were machined to rectangular cross sections 50 mm. deep by breadths in the range 10-50 mm.

Blades

All the blades used were standard production issue having 6 and 10 teeth per 25mm. Both Carbon and High Speed Steel Bi-metal blades were used. Blade lengths of 3.18m. and 3.35m. were used so as to vary the contact time ratio.

(i) Carbon Blade

The percentage chemical composition is:

1.25 C; 0.27 Mn: 0.2 Si; 0.02 S; 0.02 P; 0.25 Ni; 0.2 Cr; 0.1 Mo; 0.1 Cu

Blade dimensions:
25.4mm. x 0.9mm. x Raker Set
They had been given, under normal production conditions the standard heat treatment which gave the teeth of the blade a hardness of 830-910 H.V.30.

(ii) High Speed Steel Bi-metal Blade

This blade consists of a Carbon backing strip which has the following chemical composition:

0.44 C; 0.2 Si; 0.7 Mn; 0.02 S; 0.02 P; 0.55 Ni; 1.1 Cr; 1.0 Mo; 0.07 Va

This Carbon backing strip is welded by the Electron Beam process to an M2 High Speed Steel cutting edge which has the following percentage chemical composition:

0.85 C; 6.25 W; 4.25 Cr; 2.0 V; 5.0 Mo

Blade dimensions:
25.4mm. x 0.9mm. x Raker Set
Normal production heat treatment gives the Carbon backing strip a hardness of approximately 420 H.V.10 and the High Speed Steel teeth a hardness in the range 860-890 H.V. 10.

Cutting Fluid

Most of the tests were carried out dry in the normal atmosphere to create "accelerated" wear conditions. Other tests were carried out using Shell Dromus "B" soluble oil coolant with a water/oil ratio of 30/1.

It has been shown [9] that the quantity of coolant flowing affected the wear rate. The majority of tests were carried out with a coolant flow rate of 2 litres/minute. The coolant was applied centrally above the workpiece by the standard means provided on the bandsaw machine.

Horizontal Bandsaw

The machine used was a standard production model in which the cutting band is carried horizontally on a swing arm assembly, pivotted at one end. The saw was modified [9] so that the thrust load develops by virtue of the gravity force acting on a massive swing arm assembly, rather than by the action of a hydraulic device.

Experimental Results

Using the procedure previously described, a number of wear tests were carried out under differing conditions of load, cutting speed, and workpiece breadths for blades of different tooth pitch. The adapted Colding parameters were calculated and the results displayed on a Log-Log plot based on the dimensionless groups shown in equation (5)

The results obtained with the Carbon and High Speed Steel Bi-metal blades both with and without coolant are shown in Fig.1.

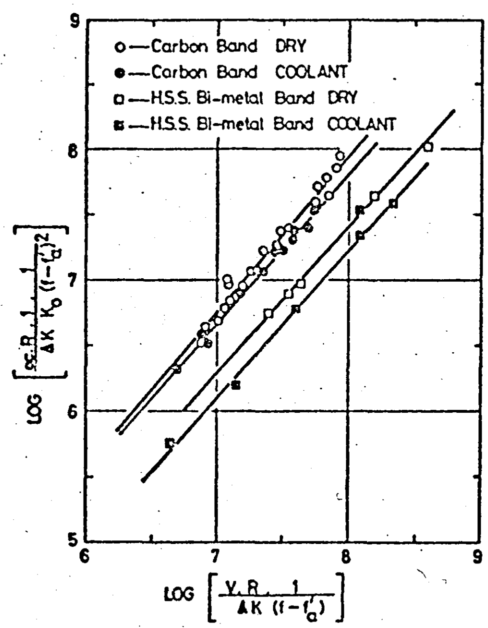


Fig.1 Log-Log dimensionless plot for Carbon blades with and without coolant and for High Speed Steel Bi-metal blades with and without coolant, showing the wear parameters.

From this figure the constants and Colding's Wear Index given in equation (5) were determined, these are shown in TABLE I. The slope and intercept of these lines were determined using a minimum error routine on a computer.

TABLE I

BAND MATERIAL	CARBON		HIGH SPEED STEEL Bi-metal	
COOLANT	DRY	SOLUBLE OIL	DRY	SOLUBLE OIL
CONSTANT C	1.0558 E-10	3.4460 E-11	1.5423 E-16	4.3213 E-15
COLDING'S WEAR INDEX	2.4513	2.3113	2.1885	2.3378
CONSTANT C"	7.2550 E-9	8.8488 E-10	3.5542 E-15	5.1427 E-13
b_1	5.4316	7.4247	11.6101	6.9207
b_2	4.4316	6.4247	10.6101	5.9207
b_3	3.4316	5.4247	9.6101	4.9207

SIMULATION MODEL

Fig.2. shows a flow chart for a computer routine to simulate both the constant thrust load and constant feed rate bandsaw operations.

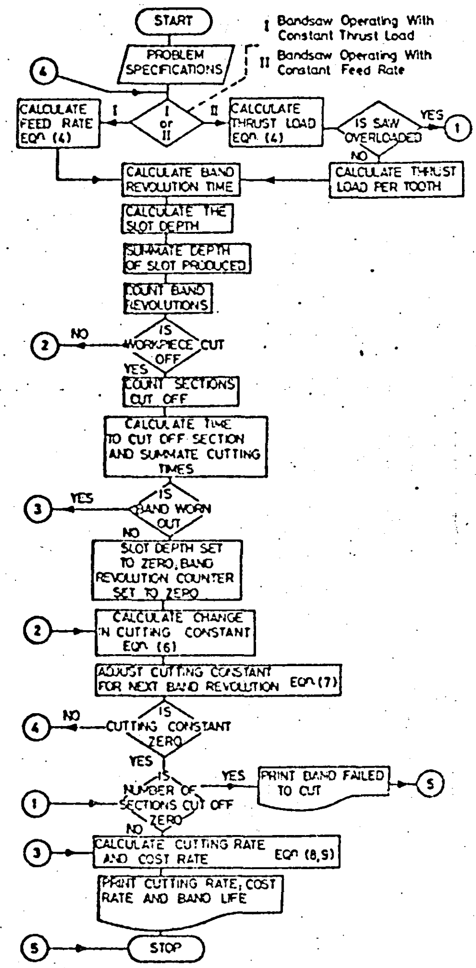


Fig.2 A flow chart suitable for a computer routine to simulate both the constant thrust load and the constant feed rate horizontal bandsaw operation.

The flow chart indicates how blade wear is accounted for. A computer program based on such a flow chart enables the number of sections a blade is capable of cutting during its useful life, and the average cutting time to produce these sections, to be determined. The end of the useful life of the blade is indicated by a minimum acceptable cutting constant or by the overloading of the cutting tool. From the data obtained from such a simulation the cutting rate and cost of horizontal bandsawing can be determined.

Non-productive Times and Costs

The following non-productive times are used in the simulation model and are based on standard times accepted in the sawing trade as norms:

(a) time to index the workpiece between cuts (T_L) = 0.11 minutes

(b) time to change the blade (T_B) = 5.1 minutes

The following non-productive costs are used in the simulation model:

Cost Ratio (C_R/C_B) = 1.5 for Carbon blades.

Cost Ratio (C_R/C_B) = 0.22 for High Speed Steel Bi-metal blades.

By expressing both the cost ratio and cost factor (APPENDIX III) in a dimensionless form the results are to some extent independant of changes due to inflation.

SIMULATION RESULTS

A computer program based on the flow chart described has been used to investigate the effects of various machine parameters on the average cutting rate (sections per hour) and cost (cost ratio). Both the constant thrust load and constant feed rate method of bandsawing are investigated. Fig.3, shows the effects of band speed and thrust load on the average cutting rate and cost factor, for Carbon blades with constant thrust load operation both dry and with coolant.

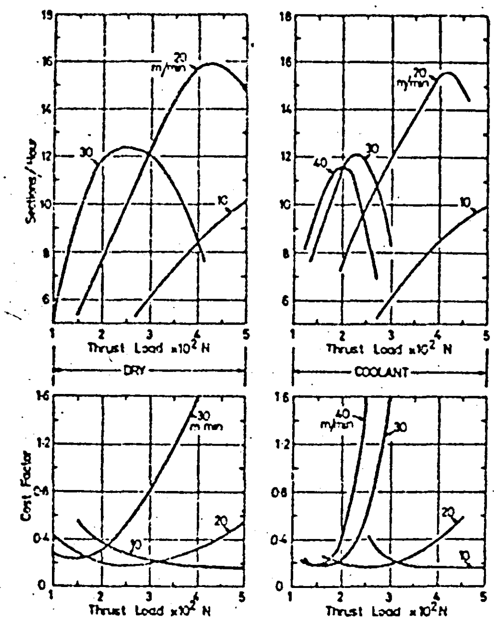


Fig.3 The effects of band speed and thrust load on the average cutting rate and cost factor, for a bandsaw operating with constant thrust load and Carbon blades, with and without coolant: Breadth of workpiece = 50mm; Depth of workpiece = 50mm; Teeth per 25mm. = 6.

Fig.4, shows the effects of band speed and feed rate on the average cutting rate and cost factor for Carbon blades with constant feed rate operation, both dry and with coolant.

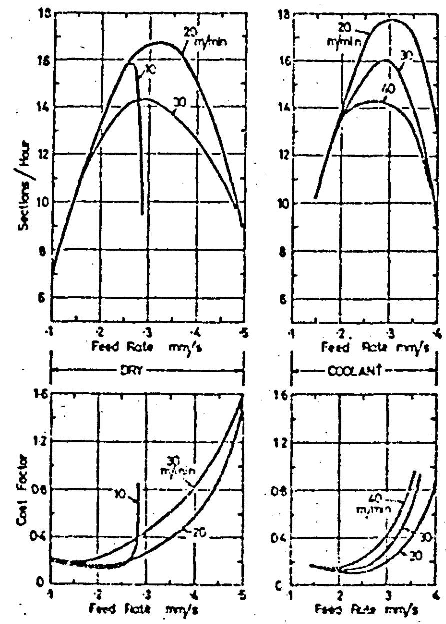


Fig.4 The effects of band speed and feed rate on the average cutting rate and cost factor, for a bandsaw operating with constant feed rate and Carbon blades, with and without coolant: Breadth of workpiece = 50mm; Depth of workpiece = 50mm; Teeth per 25mm. = 6.

Fig.5, shows the effects of band speed and thrust load on the average cutting rate and cost factor for High Speed Steel Bi-metal blades with constant thrust load operation, both dry and with coolant. Fig.6, shows the effects of band speed and feed rate on the average cutting rate and cost factor for High Speed Steel Bi-metal blades with constant feed rate operation, both dry and with coolant.

In every case the factor η, that specifies the end of the useful life of the blade has been taken to be 0.15. The maximum allowable thrust load has been set at 500N for all operations.

DISCUSSION

It has been shown how the effects of bandsaw blade wear can be taken into account when determining cutting rates for bandsaw operations.

A flow chart for a computer simulation when either the thrust load or feed rate are constant, has been described and used to demonstrate the influences of certain parameters on the performance of bandsaw

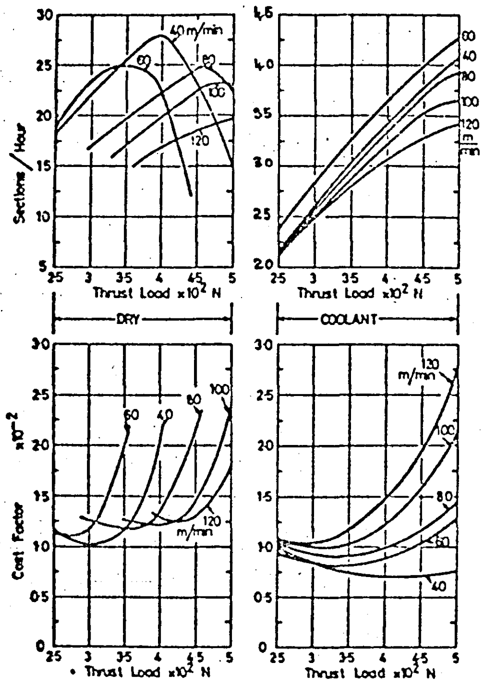


Fig.5 The effects of band speed and thrust load on the average cutting rate and cost factor, for a bandsaw operating with constant thrust load and High Speed Steel Bi-metal blades, with and without coolant: Breadth of workpiece = 50mm; Depth of workpiece = 50mm; Teeth per 25mm. = 6.

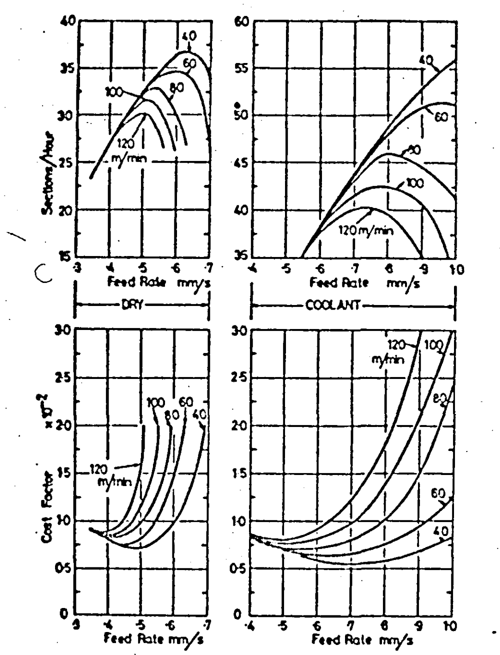


Fig.6 The effects of band speed and feed rate on the average cutting rate and cost factor, for a bandsaw operation with constant feed rate and High Speed Steel Bi-metal blades, with and without coolant: Breadth of workpiece = 50mm; Depth of workpiece = 50mm; Teeth per 25mm. = 6.

operations. This method, together with the wear methods described briefly, and in more detail by Taylor [9], enable laboratory test data to be converted to cutting rates and cost. Thus providing an assessment of a particular combination of sawing parameters to be made in terms of realistic criteria which can be readily understood by those wishing to use bandsaw operations.

The computer method has been used in conjunction with readily available data; this data relates to rather unusual and difficult to cut material. However, many of the trends obtained are believed to be typical of those that would be obtained with the more common workpiece materials.

The following are discussions of the trends and their significances to both user and producer of bandsaw equipment.

Band Speed; Thrust Load and Feed Rate

Figs.3 to 6, show that within the ranges of thrust load and feed rate considered the cutting cost reaches a minimum value and the cutting rate reaches a maximum value at all band speeds. It is seen that the most economical thrust load or feed rate for given band speed, is much smaller than the value that produces the greatest average cutting rate. Hence when choosing the optimum conditions for a bandsaw operation a choice must be made as to whether cost or cutting rate is to be optimised.

Constant Thrust Load or Constant Feed Rate

Comparison between Figs.5 and 6, show that within the ranges considered for High Speed Steel Bi-metal blades, the constant feed rate system is both more economical and productive for a given band speed than the constant thrust load system. When using Carbon blades the advantage of the constant feed rate system is less pronounced.

Cutting Fluid

Figs.3 and 4, give an estimate of the effects of cutting fluid on the performance criteria for Carbon blades. The use of soluble oil coolant with Carbon blades gives little reduction in both cost and cutting rate when compared with results obtained in the normal atmosphere at a given band speed. At some of the high band speeds available on production bandsaws the wear rate induced in Carbon blades is so excessive that their use is impractical. However, when soluble oil is used, a greater range of band speeds is possible than in the normal atmosphere.

Figs.5 and 6, show the effects of cutting fluid on the performance criteria for High Speed Steel Bi-metal blades. The use of a soluble oil coolant leads to a reduction in cost and an increase in the average cutting rate compared with those obtained when cutting dry in the normal atmosphere. However it should be noted that the data was obtained with a coolant flow rate of 2 litres per minute and that current work [9], indicates that some of the benefits obtained would be reduced at smaller flow rates. The introduction of soluble oil coolant with High Speed Steel Bi-metal blades has little effect on the range of band speed which may be used.

Band Material

Comparisons between Carbon blades, figs.3 and 4, and High Speed Steel Bi-metal blades, Figs.5 and 6, show that the High Speed Steel Bi-metal blade is superior in performance to a Carbon blade; both with and without coolant and for both types of machine. It is often considered by users that the cost of the blade is the dominant factor in the total cutting cost; this investigation has shown that the blade cost represents a small proportion of the total. The cost of a High Speed Steel Bi-metal blade is approximately seven times larger than that for a Carbon blade.

The results show that this increase in blade cost is more than offset by better cutting rates and longer blade life, which combine to reduce the total cost per cut. When replacing Carbon blades with High Speed Steel Bi-metal and using the constant feed rate method of operation with soluble oil coolant and a band speed of 40m/minute; results indicate that the lowest cost per section is reduced from £0.4, at a cutting rate of 13 sections per hour, to £0.08, at a cutting rate of 45 sections per hour. The cost per cut is found by multiplying the cost factor by the current purchase price of the blade. It is very interesting to undertake a similar comparison with a power hacksaw operation [7] which, with High Speed Steel blades gives a lowest cost per section cut, of £0.1, at a cutting rate of 20 sections per hour, when cutting the same material and section under similar conditions. Showing the bandsaw operation can be as economical as the power hacksaw operation whilst achieving a higher cutting rate.

Machine Parameters

The results obtained show that the choice of machine parameters play a major part in determining the performance of bandsaw operations. The results show that for High Speed Steel Bi-metal blades, the optimum output in sections per hour is not obtained at high band speeds; a result that is perhaps surprising. Slow band speeds with a feed rate in the range 0.5 to 0.65 mm/second gives good performance both with regard to output per hour and total cost per cut. This shows how big savings on the total cost of bandsawing operations can be made when it is realized that by adjusting cutting rates to more efficient levels the cost per cut is reduced even though the wear rate of the blade is increased. The reason for the resulting cost reduction is because of the high cost rate for modern production bandsaw machines which is currently £3.25 per hour. The idea of operating a bandsaw with small feed rates in order to improve blade life does not result in a reduction in cutting cost because of the excessive cutting times produced.

CONCLUSIONS

1. The bandsaw operation may be a low cost, high cutting rate operation when High Speed Steel Bi-metal blades are used with a coolant supply under optimised operating conditions.

2. For all bandsaw operations High Speed Steel Bi-metal blades should be preferred, rather than Carbon blades, the increased blade cost being more than offset by better cutting rates and longer blade life, which combine to reduce the cost per cut.

3. A bandsaw machine operating with the constant feed rate system is superior to one operating with a constant thrust load system.

4. A reduction in the total cost per cut can usually be obtained by optimising feed rates at the expense of blade life.

5. The bandsaw operation can be as economical as the power hacksaw operation whilst achieving a higher cutting rate.

ACKNOWLEDGEMENTS

The authors would like to thank James Neill (Services) Ltd., for sponsoring this work and the authorities at Sheffield City Polytechnic for permission to undertake the work. Particular thanks are due to Mr. D. Taylor, Manager of Technical Services, James Neill (Services) Ltd., and to his staff for their assistance and helpful advice.

REFERENCES

1. P.J. THOMPSON and M. SARWAR (1974) Power Hacksawing, 15th. I.M.T.D.R. Conf., September.

2. M. SARWAR and P.J. THOMPSON (1974) Simulation of the Cutting Action of a Single Hacksaw Blade Tooth, Production Engineer, June.

3. P.J. THOMPSON (1974) A Theoretical Study of the Cutting Action of Power Hacksaw Blades, J. Mach. Tool Des. and Res., Vol. 14, pp 199-209.

4. P.J. THOMPSON (1974) Factors Influencing the Sawing Rate of Hard Ductile Metals by Power Hacksawing and Bandsawing Operations, Metals Technology, October.

5. P.J. THOMPSON and R.W. TAYLOR (1975) An Investigation into Factors Influencing the Wear Rate of Power Hacksaw Blades using Dimensional Analysis-Blade Wear Testing,

Presented to the Metal Cutting Seminar, 16th. I.M.T.D.R. Conf., September.

6. P.J. THOMPSON and R.W. TAYLOR (1975) An Analysis of the Lateral Displacement of a Power Hacksaw Blade and its Influence on the Quality of the Cut, Presented to the Metal Cutting Seminar, 16th. I.M.T.D.R. Conf., September.

7. P.J. THOMPSON and R.W. TAYLOR (1976) A Computer Simulation of the Power Hacksaw Operation and its Use in Estimating Blade Life, Cutting Rate and Cost, Production Engineer, January.

8. B.N. COLDING (1959) A Three-Dimensional, Tool-Life Equation-Machining Economics, Journal of Engineering of Industry, pp 239-250, August.

9. R.W. TAYLOR (1976) An Investigation into the Wear Characteristics of Bandsaw Blades and Their Influence on the Sawing Rates and Costs of the Bandsaw Operation, M.Phil. Thesis, Sheffield City Polytechnic.

10. J. TAYLOR (1962) The Tool Wear-Time Relationship in Metal Cutting, Int. J. Mach., Tool Des. and Res., Vol. 2, pp 119-152.

VARIABLES

- A average cutting rate
- a intercept
- B breadth of the workpiece
- b Colding's wear index
- C cost
- C', C'' Colding constants
- F total instantaneous thrust load acting between the workpiece and the blade
- f instantaneous thrust load acting per tooth per unit blade thickness
- f' the component of the thrust force per tooth due solely to the cutting edge radius
- K cutting constant
- ΔK change in the cutting constant per revolution of the blade
- L length of the blade loop
- M number of sections cut off during the useful life of the blade
- N number of blade revolutions needed to cut through a workpiece
- p number of teeth per unit length of the blade
- R contact time ratio = B/L
- T time (minutes)
- t blade thickness
- V cutting speed of the blade
- $v\delta l$ rate of volume removed
- w slot width
- α thermal diffusivity of work material
- δ instantaneous depth of cut per blade tooth
- η fractional reduction in K_o at the end of the useful life of the blade
- v cutting rate

SUFFICES

- A cutting average
- a average value
- B blade replacement
- c per section cut
- L to index the workpiece between consecutive cuts
- o initial value
- R rate per hour
- 1,2,3 specific values

APPENDIX I

Definition of the Cutting Constant and Relationships with Cutting Rate

Cutting tests [9] with un-worn blades have shown a linear relationship between the depth of cut per tooth and the thrust load per tooth per unit blade thickness. The slope has been defined as a cutting constant, thus

$$\delta = K.f - a \qquad (1)$$

where $F = f.B.p.t$

Tests have shown that the cutting constant decreases with wear and that

$$a = K.f'$$

The rate at which metal is removed by the blade is.

$$v\delta l = \delta.t.B.p.V \qquad (2)$$

The rate at which metal is removed from the workpiece may be written

$$v\delta l = v.w.B \qquad (3)$$

Combining and using the concept of volume constancy gives

$$v = V\left[\frac{K.F}{w.B} - \frac{a.t.p}{w}\right] \qquad (4)$$

This equation is used in the simulation to calculate the cutting rate when the thrust load is constant. In the simulation of band-saw machines which employ a constant feed rate (4) may be used to determine the thrust load between the blade and the workpiece.

APPENDIX II

Wear Rate Relationships

From an investigation [9] of the factors influencing bandsaw blade wear using dimensional analysis it has been established that the reduction in the cutting constant per revolution of the blade can be found from the modified Colding equation given below

$$\frac{\alpha.R}{\Delta K} \cdot \frac{1}{K_o} \cdot \frac{1}{(f-f'_a)^2} = C'\left[\frac{V.R}{\Delta K} \cdot \frac{1}{(f-f'_a)}\right]^{b/2} \qquad (5)$$

and is given by

$$\Delta K = C''. \frac{B}{L} . V^{b_1} . \left[\frac{K_o}{\alpha}\right]^{b_2} .(f-f'_a)^{b_3} \qquad (6)$$

where $f'_a = 2a/K_o(1+\eta)$

For consecutive revolutions of the blade it is possible to write

$$(K)_{N+1} = (K)_N - \Delta K \qquad (7)$$

and combining these expressions with (4) it is possible to determine the time needed to cut through a workpiece section when the cutting efficiency of the blade is reducing due to the effects of wear.

APPENDIX III

Average Cutting Rate and Cost Rate

a) Average Cutting Rate

The average cutting rate in terms of the number of sections cut per hour is affected by the time taken to index the workpiece to a position suitable for cutting between operations and by the time needed to change the blade. Such times depend on the method of operation and are not affected by the parameters that influence the cutting time. Hence, for the purpose of estimating the average cutting rate these two non-productive times have been considered constant, thus

$$A = \frac{60}{\left[T_A + T_L + \frac{T_B}{M}\right]} \qquad (8)$$

b) Cutting Cost

The cost of achieving a cut by using the bandsaw operation may be considered to be made up of the following major sub-costs

1. time costs, including:
   i) cutting time cost
   ii) workpiece index time cost
   iii) blade replacement time cost

2. blade replacement cost; and

3. scrap costs

As the cost analyses that follow are to be used to determine optimum sawing conditions the scrap cost is neglected, because it remains constant for all machine settings; although it is known to be between 5-37 per cent of the total cost of achieving a cut by the bandsaw operation.

c) Cost Rate

The cost rate is defined as the total cost of operating the bandsaw machine per hour of use and is made up of the following components:

labour cost rate, and
machine cost rate (including purchase and maintenance costs)

As such the cost rate depends in part, on the percentage utilization of the machine and therefore, on the amount of sawing undertaken and the reliability of the machine. Based on the above, the cost per cut is given by:

$$C_c = C_R\left[\frac{T_A + T_L}{60}\right] + C_R\left[\frac{T_B}{60.M}\right] + \frac{C_B}{M}$$

$$\text{or } \omega = \gamma\left[\frac{T_A + T_L}{60}\right] + \frac{1}{M}\left[\frac{T_B\gamma}{60} + 1\right] \qquad (9)$$

where ω = cost factor = C_c/C_B

and γ = cost ratio = C_R/C_B

PLATES

I	The horizontal bandsaw, showing the swing arm assembly and front pan.
II	A surface cut by a power hacksaw operation showing the region roughened by the ploughing action of the teeth. The direction of cutting is from right to left.
III	The horizontal bandsaw showing the major modifications. The lead counterbalance is shown along with the sliding jockey weight and fabricated outrigger. The hydraulic cylinder can be seen after it had been disconnected.
IV	The load measuring system; comprising the piezoelectric transducer, charge amplifier, galvo-amplifier and ultra-violet oscillograph.
V	The cutting arc through which the band swings.
VI	The spring system showing the lever welded to the hinge pin of the saw.
VII	The test arrangement showing the method of workpiece clamping.

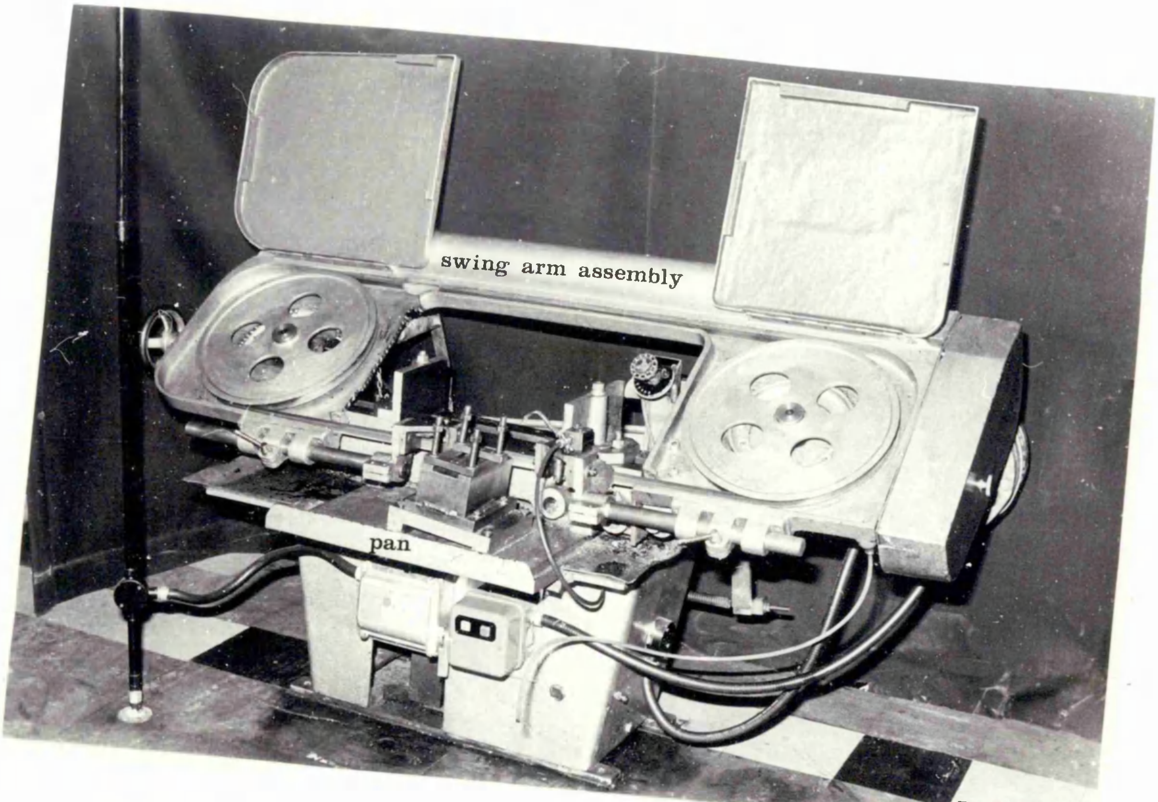


PLATE I

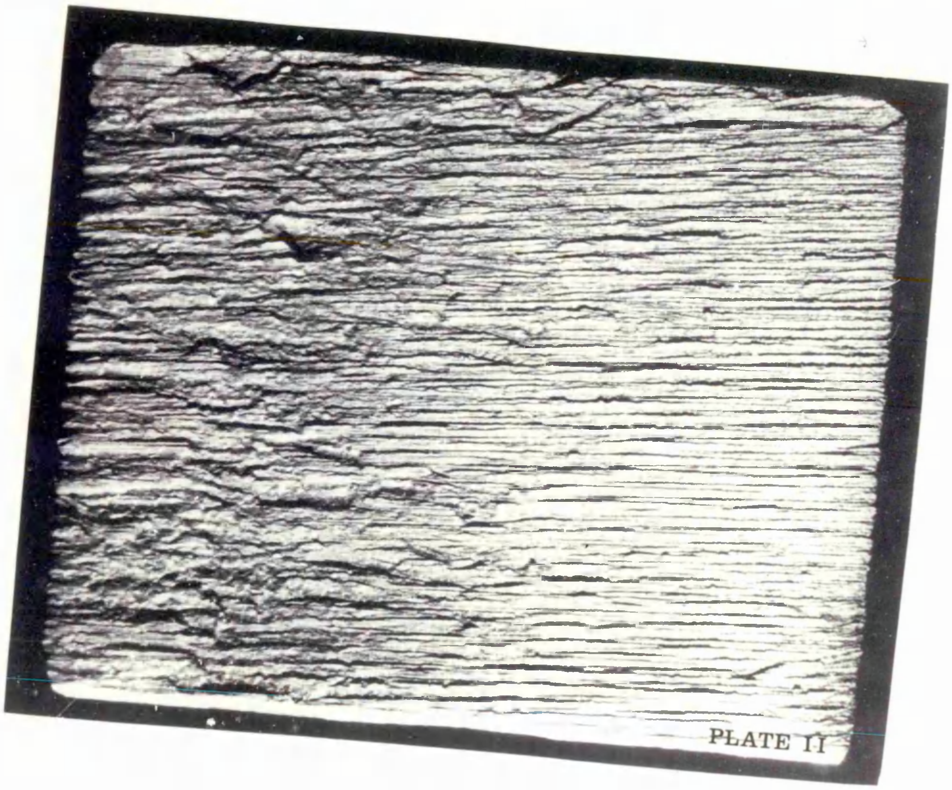


PLATE II

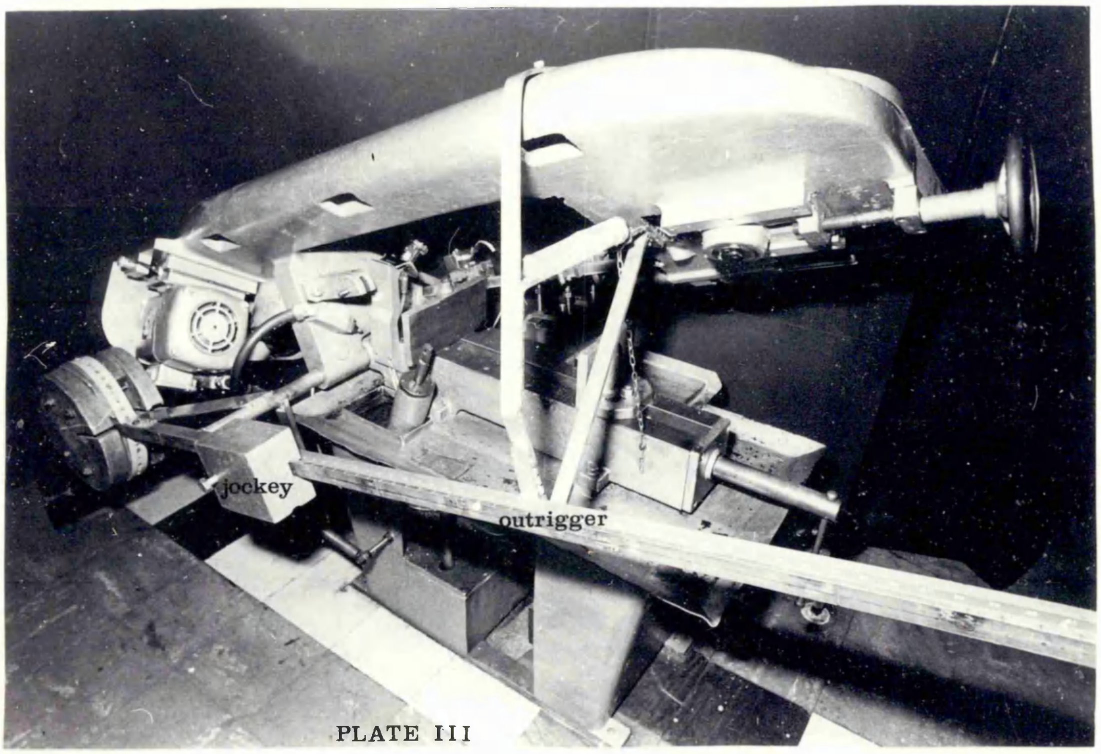


PLATE III

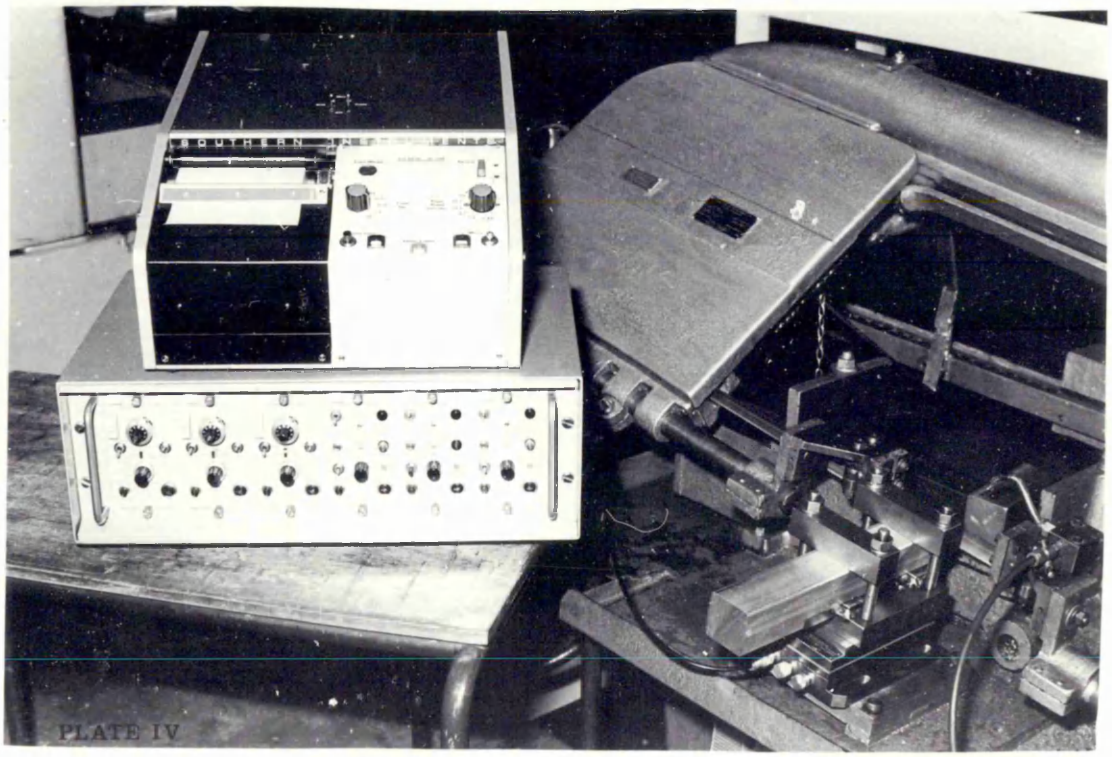


PLATE IV

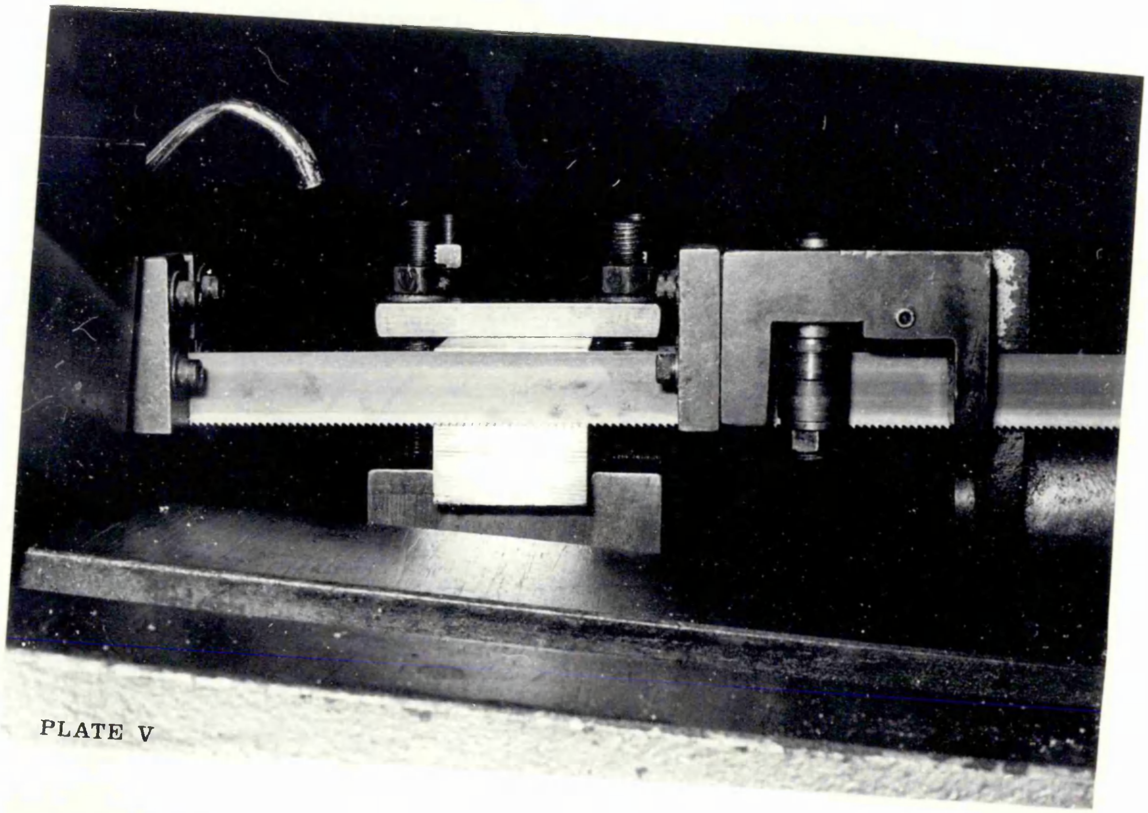


PLATE V

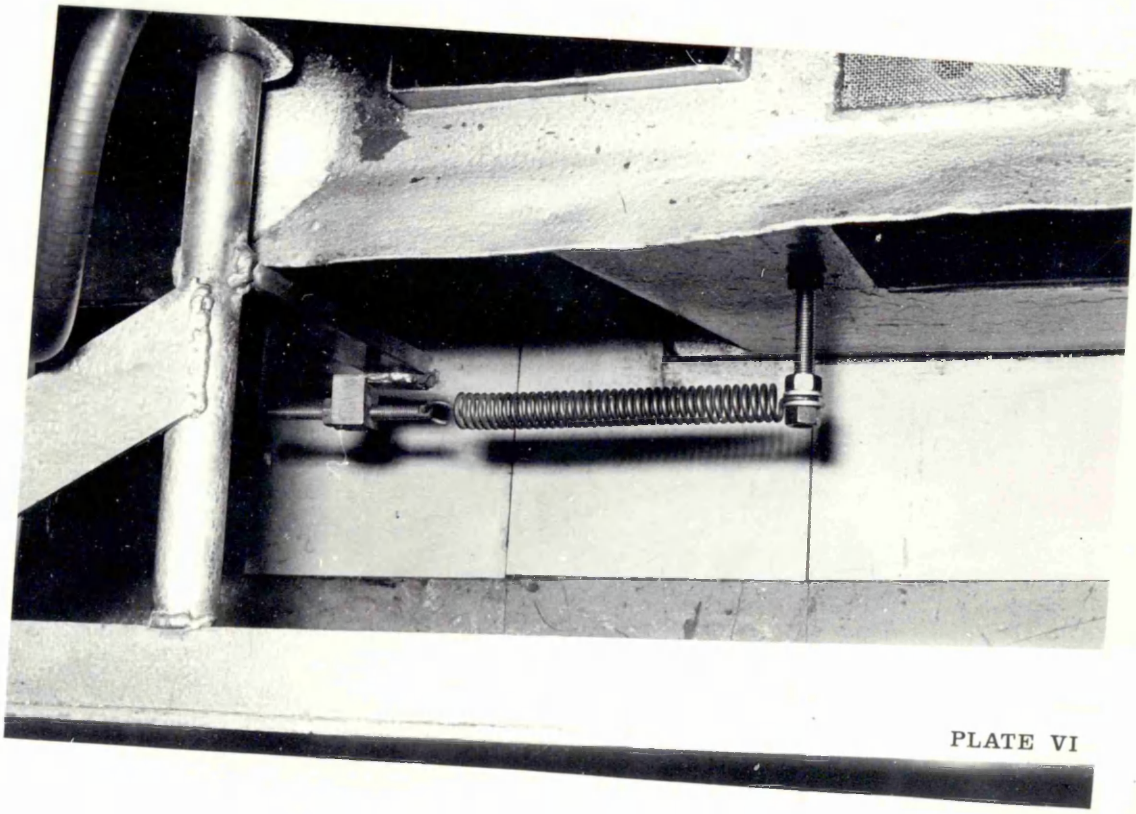


PLATE VI

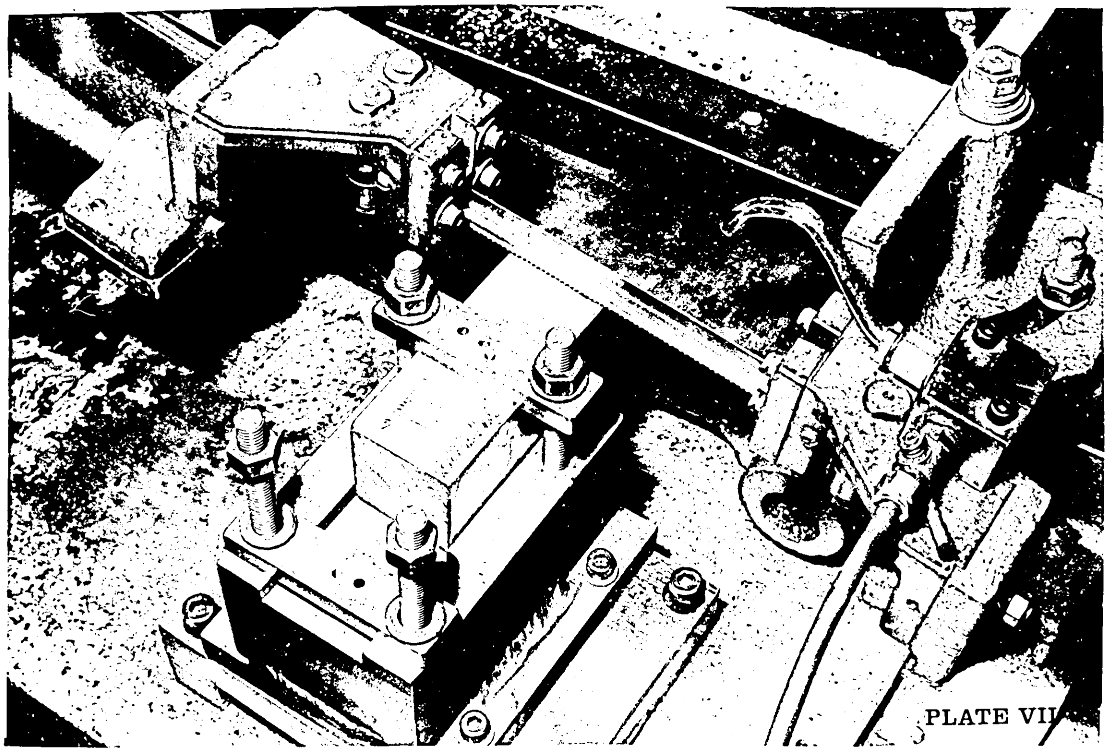


PLATE VII

TABLES

TABLE I Carbon Band —— Dry

F N	$(f-f'_a)$ Nmm^{-1}	V $mmin^{-1}$	B mm	p	L m	R	$K_o.10^{-4}$ mm^2N^{-1}	$\Delta K.10^{-8}$ mm^2N^{-1}	□	◇
194	14.8	23.8	50.8	6	3.35	.01515	2.564	11.98	6.5280	6.3475
194	9.2	23.8	50.8	10	3.35	.01515	2.538	6.46	7.0043	7.0362
166	16.4	23.8	40	6	3.35	.01193	2.613	20.42	6.1479	5.9143
138	11.7	23.8	25	10	3.35	.00746	2.640	7.08	6.5516	6.4609
194	14.9	23.8	50.8	6	3.35	.01515	2.141	25.70	6.1939	6.0892
208	16.2	23.8	50.8	6	3.35	.01515	2.820	24.34	6.1824	5.9222
138	13.2	23.8	40	6	3.35	.01193	2.462	13.53	6.4211	6.3079
299	15	23.8	50.8	10	3.35	.01515	2.396	5.87	6.8330	6.6767
222	22.9	23.8	40	6	3.35	.01193	2.620	21.82	5.9760	5.5977
194	19.7	23.8	40	6	3.35	.01193	2.670	19.78	6.0842	5.7642
111	10.1	23.8	40	6	3.35	.01193	2.690	5.79	6.9055	6.8692
200	15.5	23.8	50.8	6	3.35	.01515	2.722	15.93	6.3861	6.1617
111	10.1	23.8	40	6	3.35	.01193	2.700	6.60	6.8486	6.8109
194	14.9	23.8	50.8	6	3.35	.01515	2.843	16.75	6.3801	6.1519
208	16.2	23.8	50.8	6	3.35	.01515	2.751	19.14	6.2867	6.0374
215	16.8	23.8	50.8	6	3.35	.01515	2.747	25.99	6.1370	5.8722
222	17.5	23.8	50.8	6	3.35	.01515	2.660	35.59	5.9846	5.7177
222	10.7	23.8	50.8	10	3.35	.01515	2.588	5.87	6.9784	6.9340
307	15.4	23.8	50.8	10	3.35	.01515	2.591	4.57	6.9291	6.7259
166	13.2	23.8	50.8	6	3.35	.01515	2.279	31.44	6.1602	6.0820
208	16.2	23.8	50.8	6	3.18	.016	2.372	16.34	6.3791	6.1945
200	16.2	23.8	50.8	6	3.18	.016	2.183	8.85	6.6454	6.4969

□	◇
$LOG\left[\dfrac{V\,R}{\Delta K\,(f-f'_a)}\right]$	$LOG\left[\dfrac{\alpha R}{\Delta K\ K_o\,(f-f'_a)^2}\right]$

TABLE II Carbon Band —— Coolant

F N	$(f-f'_a)$ Nmm^{-1}	V $mmin^{-1}$	B mm	p	L m	R	$K_o 10^{-4}$ mm^2N^{-1}	$\Delta K 10^{-8}$ mm^2N^{-1}	□	◇
208	15.7	23.8	50.8	6	3.35	.01515	2.442	5.96	6.8069	6.6232
194	14.4	23.8	50.8	6	3.35	.01515	2.764	12.95	6.5065	6.3056
194	14.4	40	50.8	6	3.35	.01515	2.493	69.61	6.0013	5.6191
138	9.4	40	50.8	6	3.35	.01515	2.428	14.00	6.8853	6.7027
166	11.9	40	50.8	6	3.35	.01515	2.444	54.96	6.1875	5.8982
153	10.7	40	50.8	6	3.35	.01515	2.444	12.63	6.8714	6.6274
166	11.9	40	50.8	6	3.35	.01515	2.410	18.63	6.6574	6.3744
194	14.4	40	50.8	6	3.35	.01515	2.500	40.78	6.2335	5.8506
222	17.0	23.8	50.8	6	3.35	.01515	2.852	6.11	6.7624	6.4771
222	17.0	23.8	50.8	6	3.35	.01515	2.701	9.39	6.5759	6.3139
222	17.0	23.8	50.8	6	3.35	.01515	2.738	19.62	6.2558	5.9886

TABLE III High Speed Steel Bi-Metal Band —— Dry

248	21.2	66	50.8	6	3.35	.01515	1.648	0.59	8.1229	7.5366
300	25.9	66	50.8	6	3.35	.01515	1.619	7.47	6.9337	6.2672
235	20.1	55	50.8	6	3.35	.01515	1.840	1.63	7.6271	7.0966
274	23.6	66	50.8	6	3.35	.01515	1.741	4.90	7.1580	6.5011
288	24.9	66	50.8	6	3.35	.01515	1.668	5.57	7.0796	6.4183

TABLE IV High Speed Steel Bi-Metal Band —— Coolant

389	34.0	66	50.8	6	3.35	.01515	2.112	32.16	6.1821	5.2837
384	33.6	66	50.8	6	3.35	.01515	2.216	10.59	6.6706	5.7189
208	15.7	55	50.8	6	3.35	.01515	2.420	2.64	7.5241	6.9809
300	25.9	66	50.8	6	3.35	.01515	2.337	4.76	7.1294	6.3032
262	22.5	66	50.8	6	3.35	.01515	2.154	1.85	7.6016	6.8733
288	24.9	66	50.8	6	3.35	.01515	2.195	0.93	7.8569	7.0773

□	◇
$\mathrm{LOG}\left[\dfrac{VR}{\Delta K(f-f'_a)}\right]$	$\mathrm{LOG}\left[\dfrac{\propto R}{\Delta K\, K_o (f-f'_a)^2}\right]$

TABLE V

B mm	n_c	$1/n_c$	$K_o\,10^{-4}$ mm^2N^{-1}	
50.8	12	.083	2.86	Coolant V=23·8 m/min
50.8	12	.083	3.13	
16	4	.25	2.8	
16	4	.25	2.9	
12.5	3	.333	2.74	

Carbon Band

50.8	12	.083	2.45	Coolant V=40 m/min
50.8	12	.083	2.57	
28	7	.143	2.6	
16	4	.25	2.5	
12.5	3	.333	2.17	
12.5	3	.333	2.2	

50.8	12	.083	2.79	Dry V=23-8 m/min
50.8	12	.083	3.01	
16.	4	.25	3.26	
12.5	3	.333	3.38	

TABLE VI

High Speed Steel Bi-Metal Band

50.8	12	.083	2.58	Dry V=23·8 m/min
16.	4	.25	3.73	
12.5	3	.333	3.99	

50.8	12	.083	2.61	Dry V=40 m/min
16	4	.25	3.57	
12.5	3	.333	3.56	

50.8	12	.083	1.66	Dry V=55 m/min
16.	4	.25	2.01	
12.5	3	.333	2.52	

cont.

B mm	n_c	$1/n_c$	$K_o\ 10^{-4}$ $mm^2 N^{-1}$	
50.8	12	.083	1.96	Dry
16	4	.25	2.26	V=66 m/min

TABLE VI cont.

High Speed Steel Bi-Metal Band

50.8	12	.083	3.19	Coolant
16	4	.25	3.77	V=23·8 m/min
12.5	3	.333	3.88	
50.8	12	.083	2.99	
26	6	.166	3.44	Coolant
20.5	5	.20	3.47	V=40 m/min
16	4	.25	3.49	
12.5	3	.333	3.28	
12.5	3	.333	3.38	
50.8	12	.083	2.69	Coolant
16.	4	.25	3.31	V=55 m/min
12.5	3	.333	3.16	
50.8	12	.083	2.15	
50.8	12	.083	2.10	Coolant
50.8	12	.083	2.18	V=66 m/min
16.	4	.25	2.72	
12.5	3	.333	2.98	

FIGURES

102 The effects of band speed and feed rate on the average cutting rate and cost factor, for a bandsaw operating with constant feed rate and high speed steel bi-metal blades, with and without coolant.

103 The variation in the cutting constant per band revolution against the breadth of the workpiece, for En44E with coolant and high speed steel bi-metal band.

104 The effect of the initial cutting constant on the wear rate, i.e. the decline in the cutting constant per band revolution.

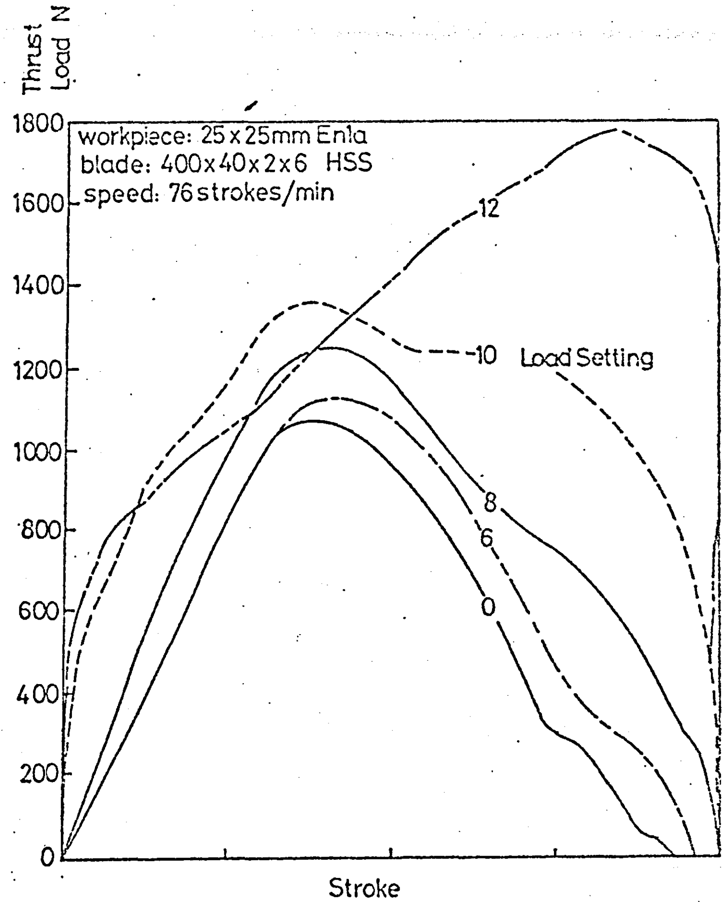


FIGURE 1.
Thrust load variation developed by a hydraulic power hacksaw machine.

[1]

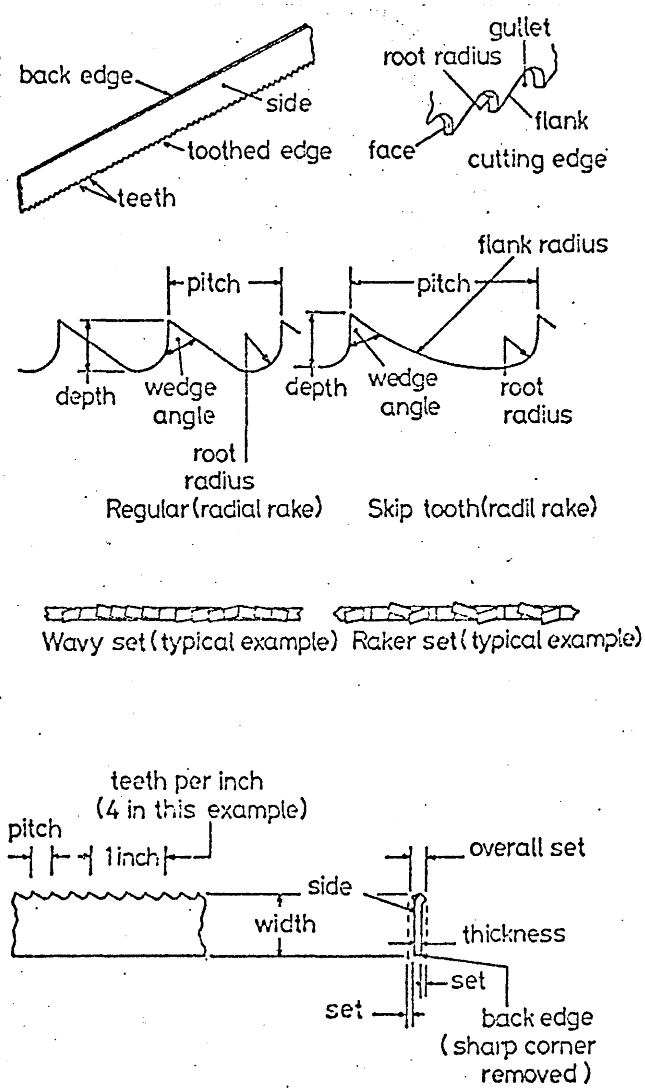


FIGURE 2.
Nomenclature of metal-cutting hacksaw and bandsaw blades.

[3]

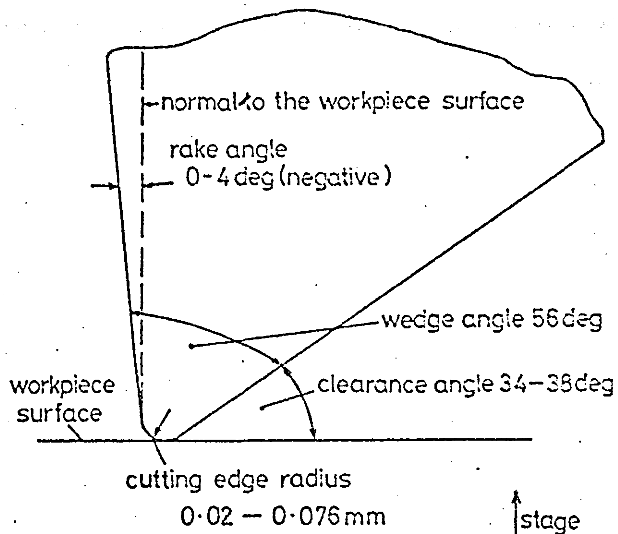


FIGURE 3.
Typical tooth profile showing principal angles and cutting edge radius.

[4]

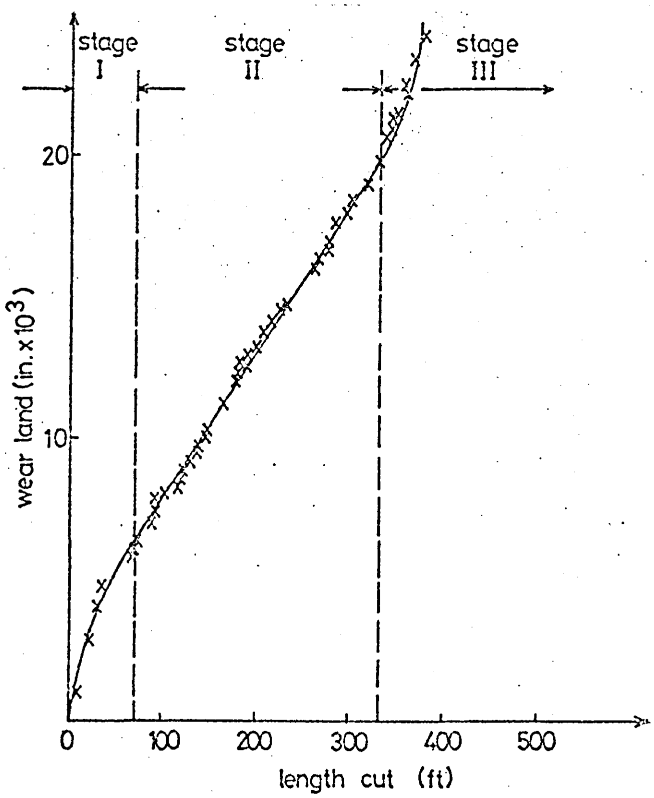


FIGURE 4.
The growth of wear land with length cut for a fine depth of cut fly-milling operation.

[15]

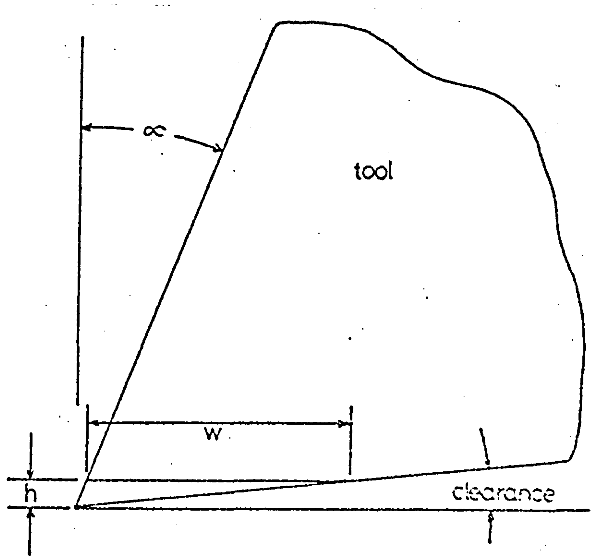


FIGURE 5.
Shape of wear scar on clearance face.

[57]

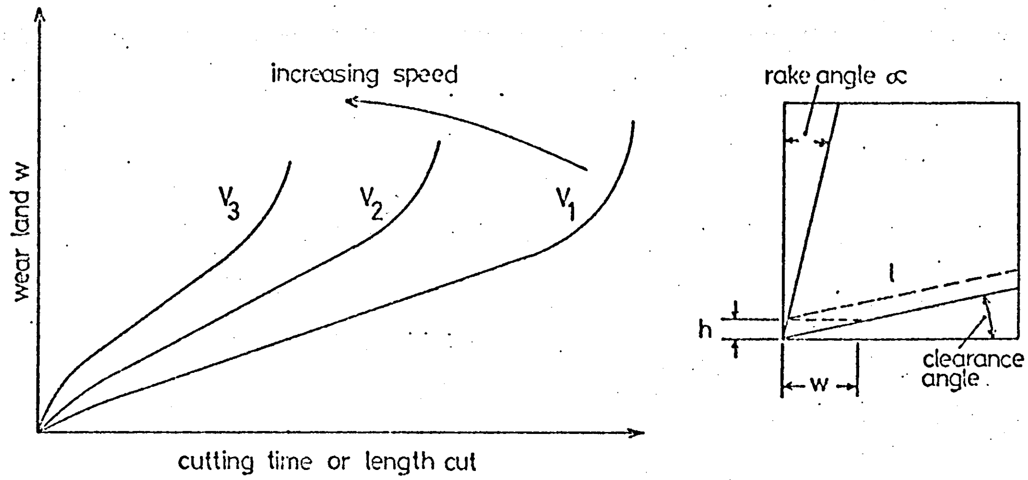


FIGURE 6.
Wear land growth and simplified geometry of worn tool (flank wear).

[51]

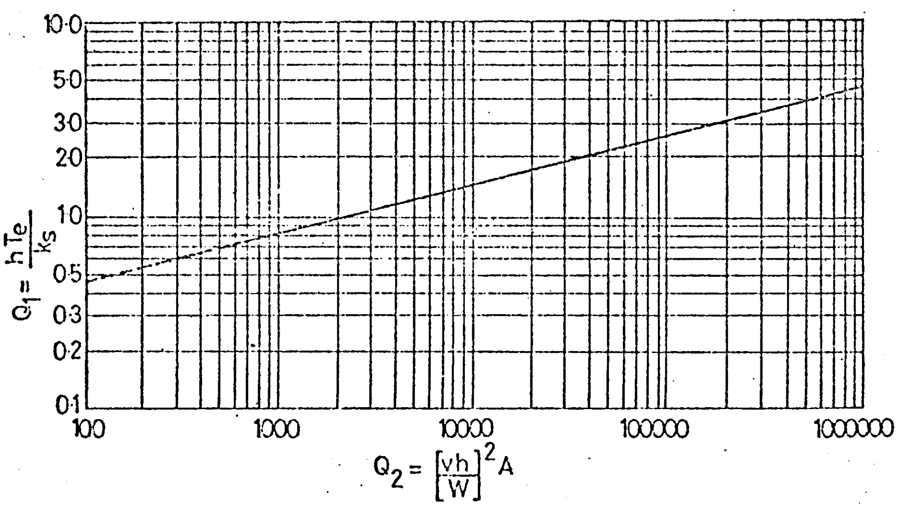


FIGURE 7.
Master curve for cutting temperature.

[26]

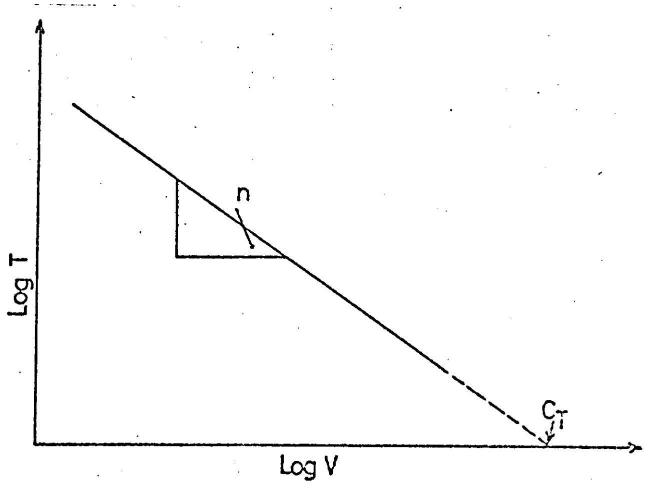


FIGURE 8.
The Taylor relationship.

[38]

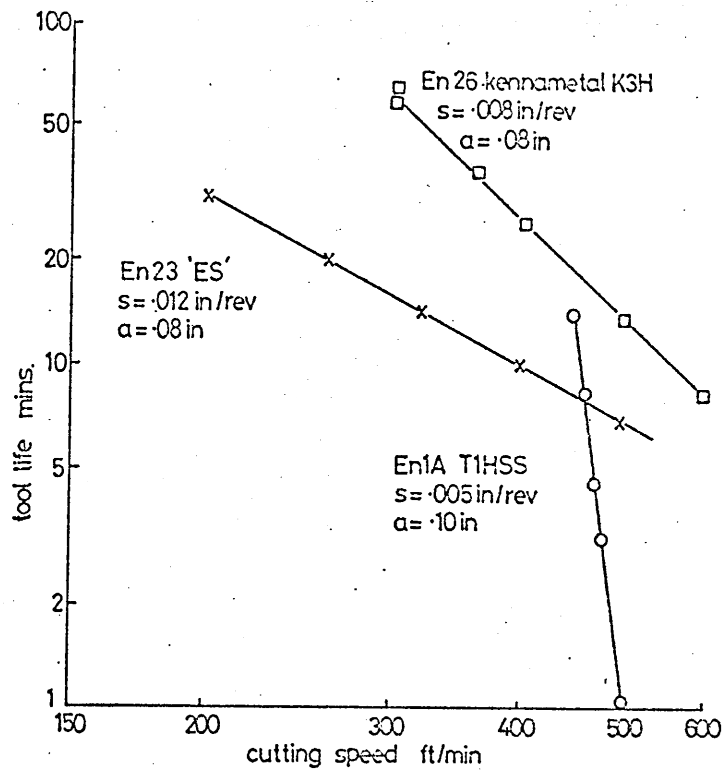


FIGURE 9.
Tool life for various tool and workpiece combinations.

[38]

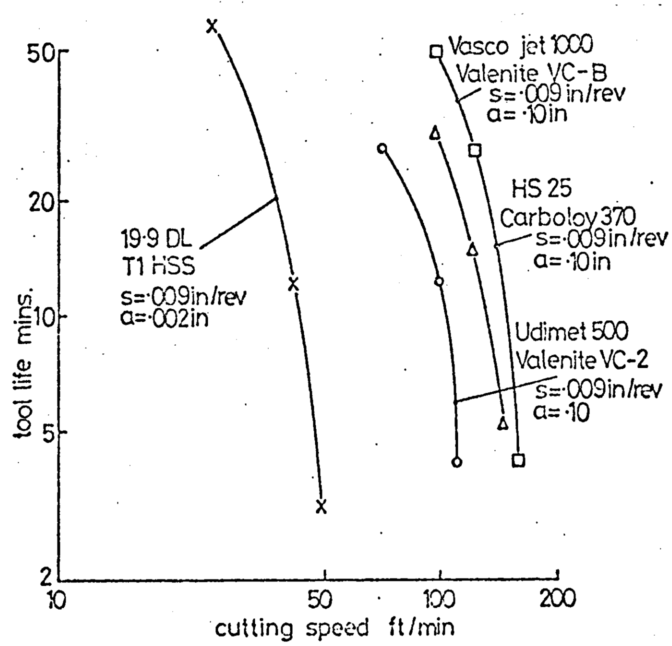


FIGURE 10.
Tool life curves for high strength thermal resistant materials.

[39]

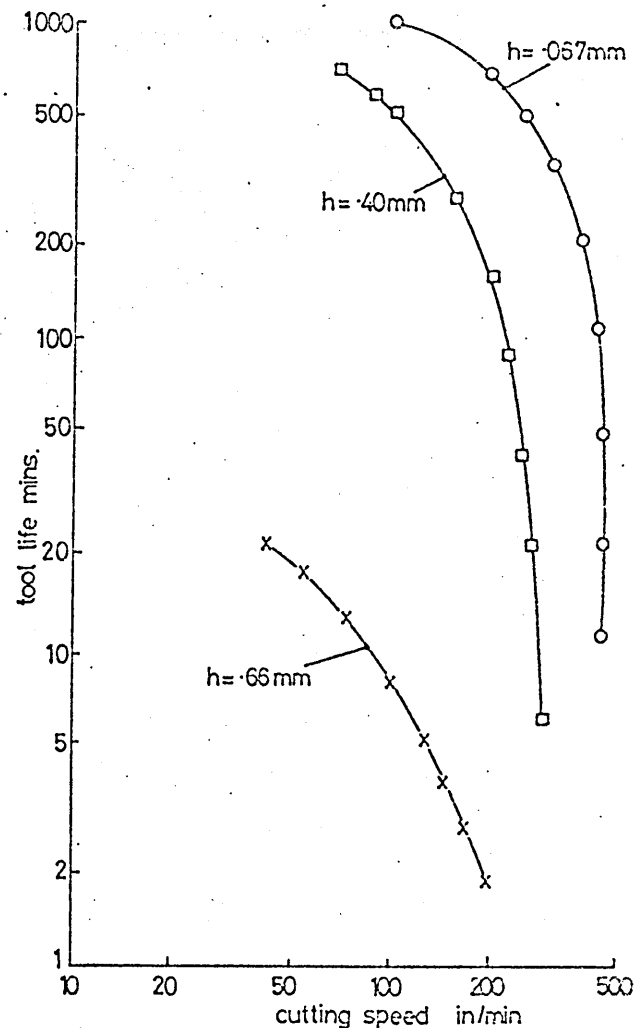


FIGURE 11.
Tool life curves when
machining a carbon steel
with carbide tools.

[40]

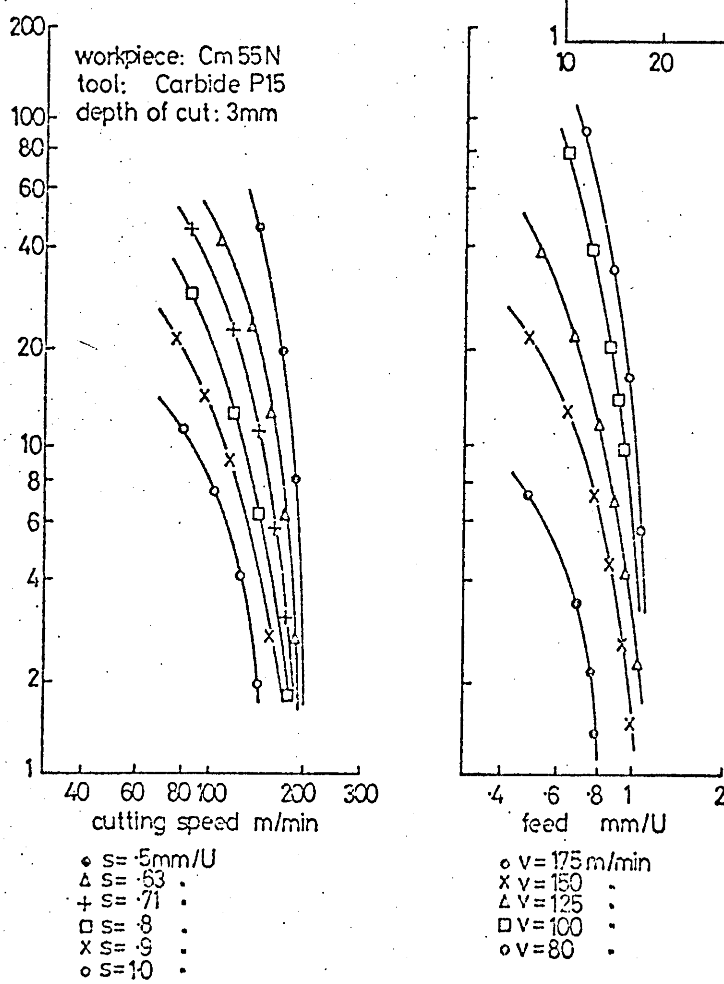


FIGURE 12.
Typical tool life
curves with varying
slopes.

[41]

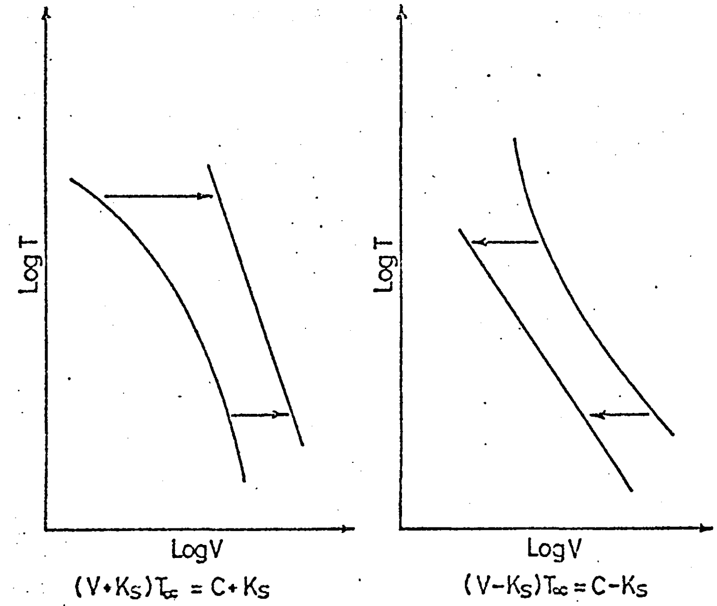


FIGURE 13.
Kronenberg's method of modifying a curved Taylor plot.

[42]

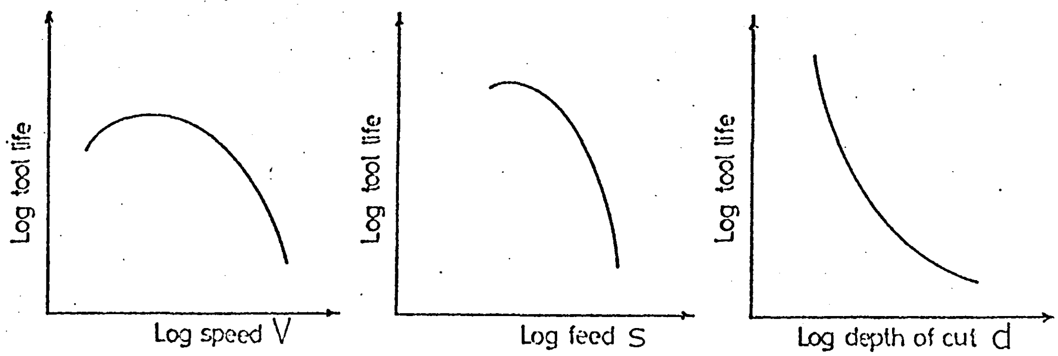
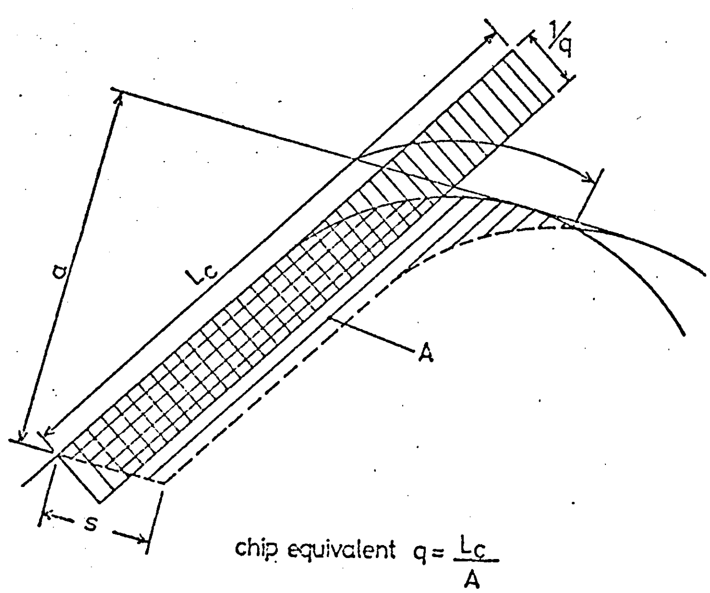


FIGURE 14.
General trend of tool life with speed (V), feed (s), and depth of cut (d).

[44]

FIGURE 15.
Definition of chip equivalent.

[45]



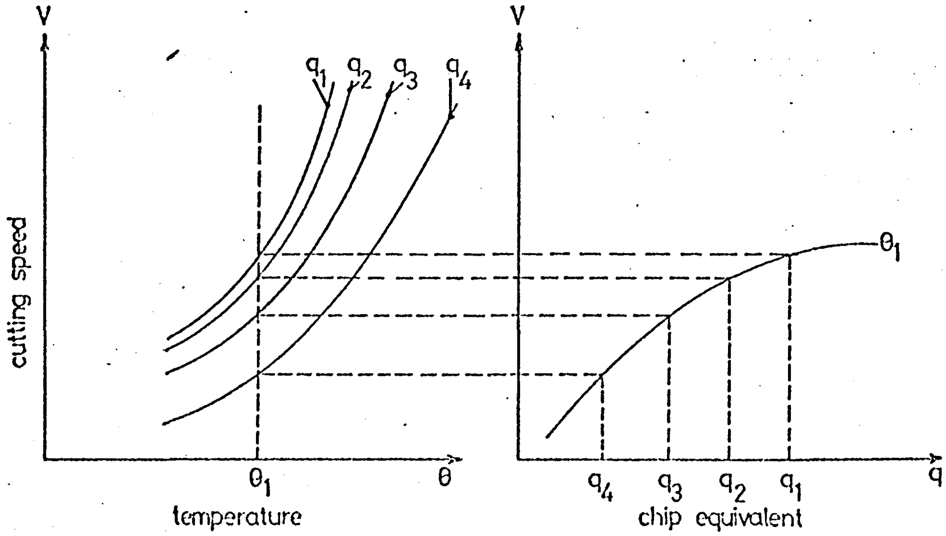
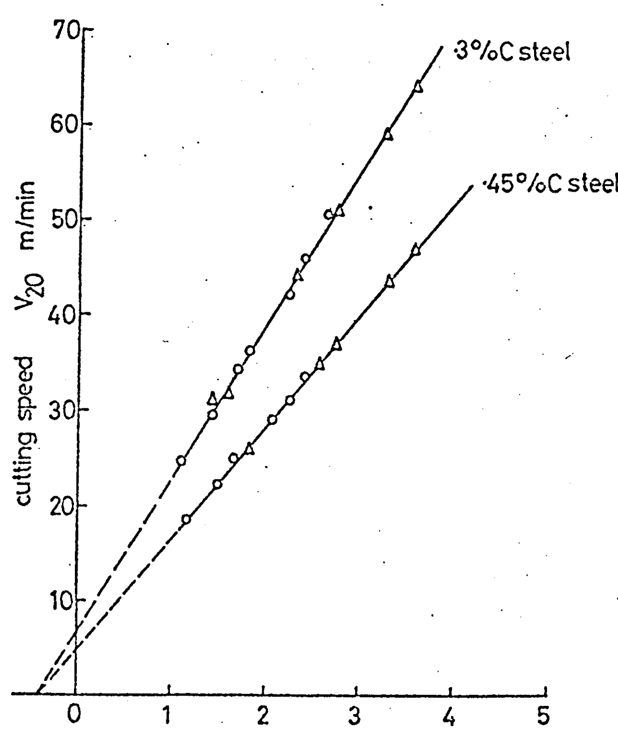


FIGURE 16.
Influence of chip equivalent on cutting temperature.
[46]

FIGURE 17.
Influence of chip equivalent on tool life.
[46]



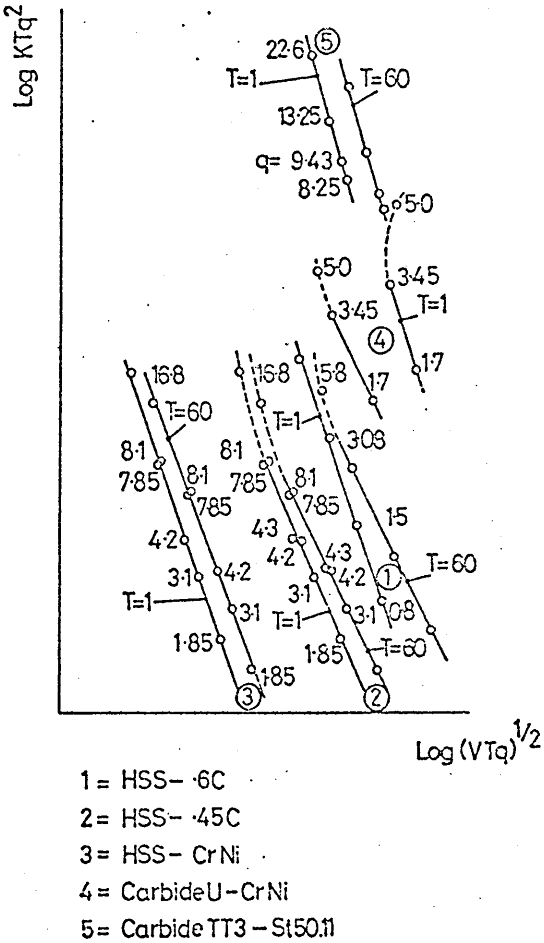


FIGURE 18.
Relations between dimensionless quantities.

[35]

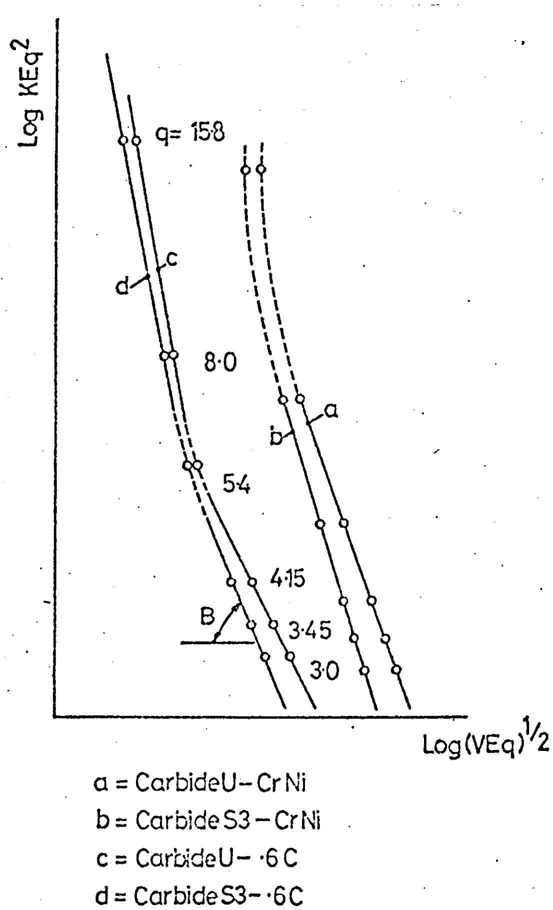


FIGURE 19.
Relations between dimensionless quantities.

[35]

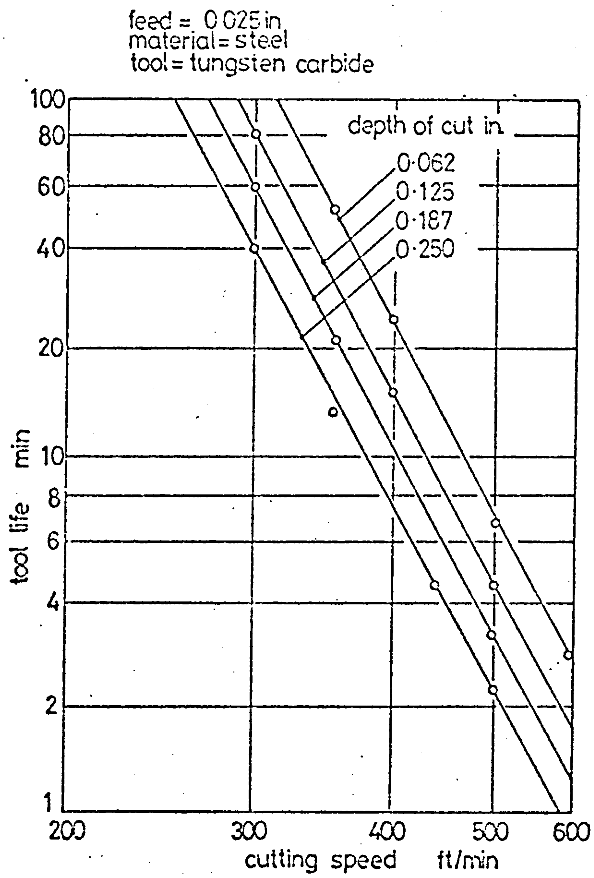


FIGURE 20.
Effect of cutting speed on tool life for various depths of cut.

[51]

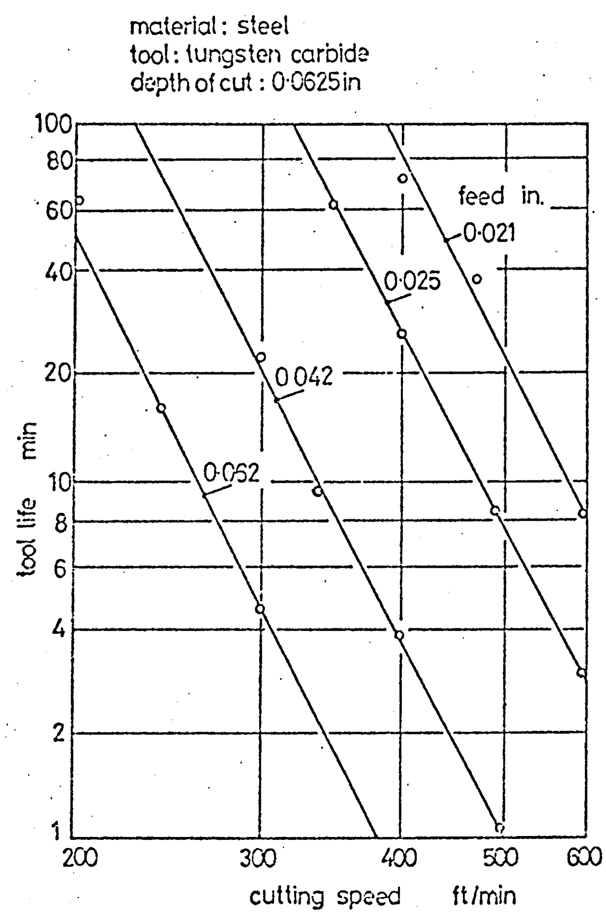


FIGURE 21.
Effect of cutting speed on tool life for various feeds.

[51]

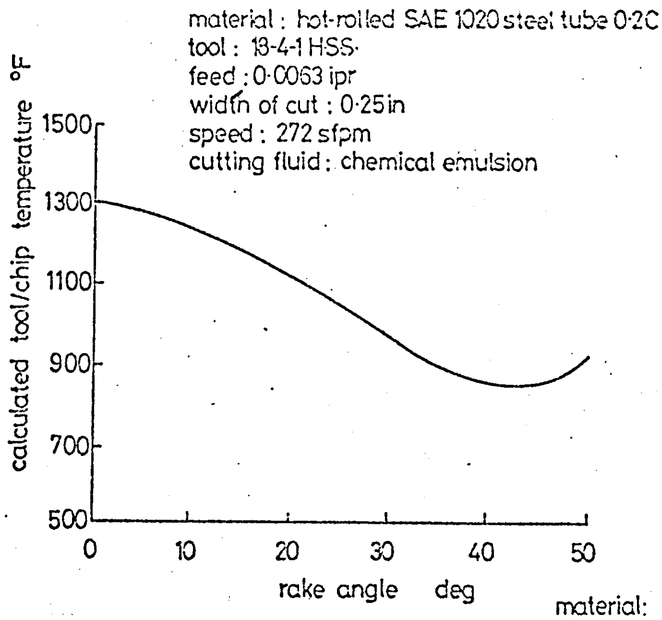


FIGURE 22.
Effect of rake angle on the calculated tool-chip interface temperature in orthogonal cutting.

[52]

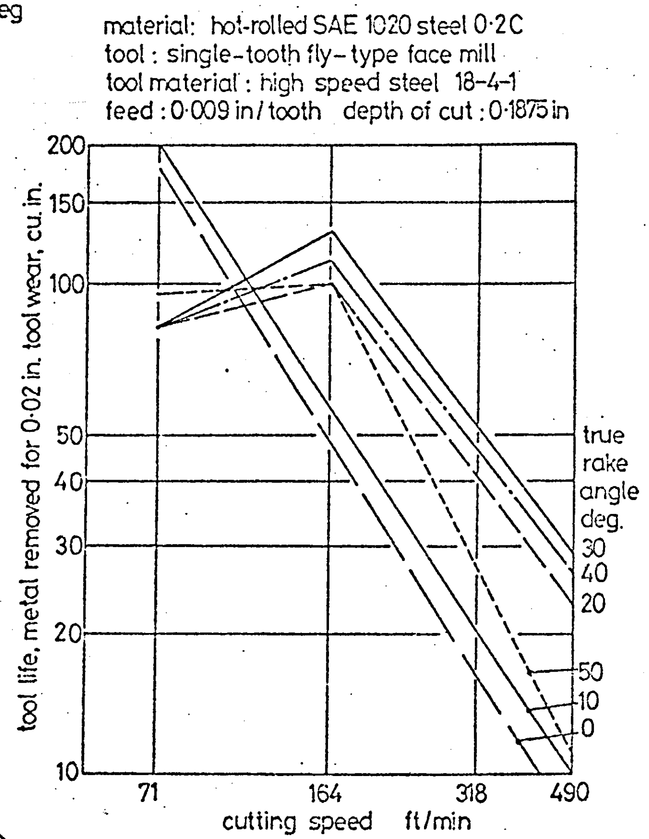


FIGURE 23.
Effect of cutting speed on tool life for different rake angles when face milling steel with a single tooth fly-cutter.

[52]

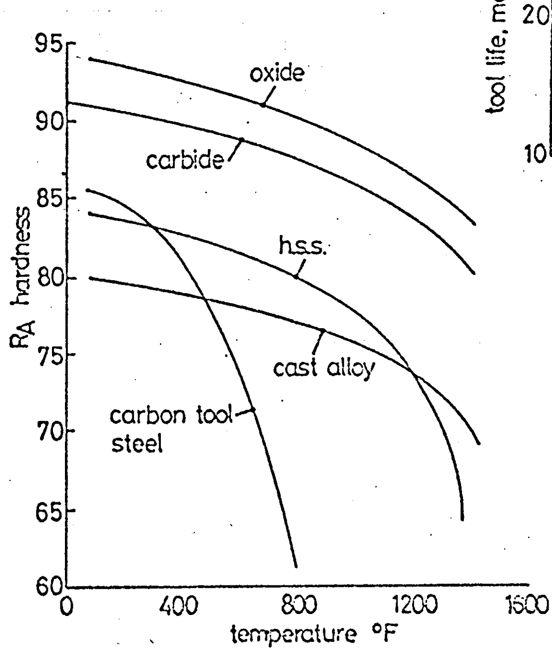


FIGURE 24.
Effect of temperature on the hardness of various tool materials.

[54]

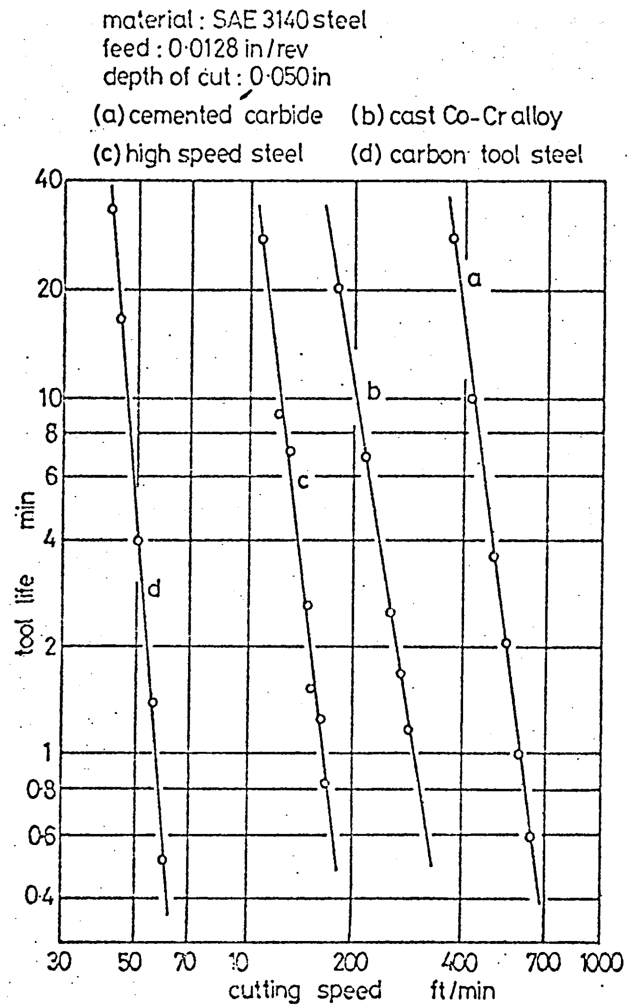


FIGURE 25.
Effect of cutting speed on tool life for the common tool materials.

[55]

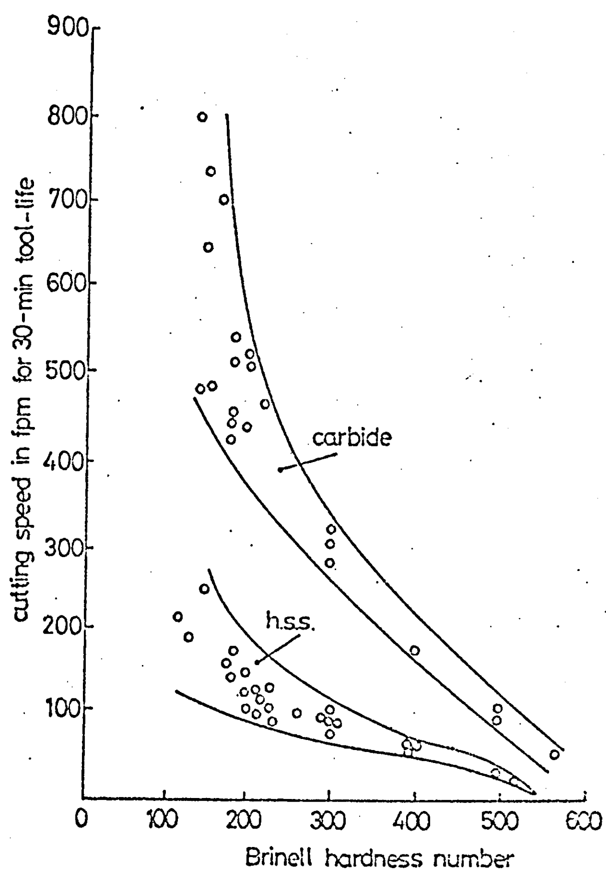


FIGURE 26.
Relation between cutting speed for a fixed tool life and Brinell hardness.

[56]

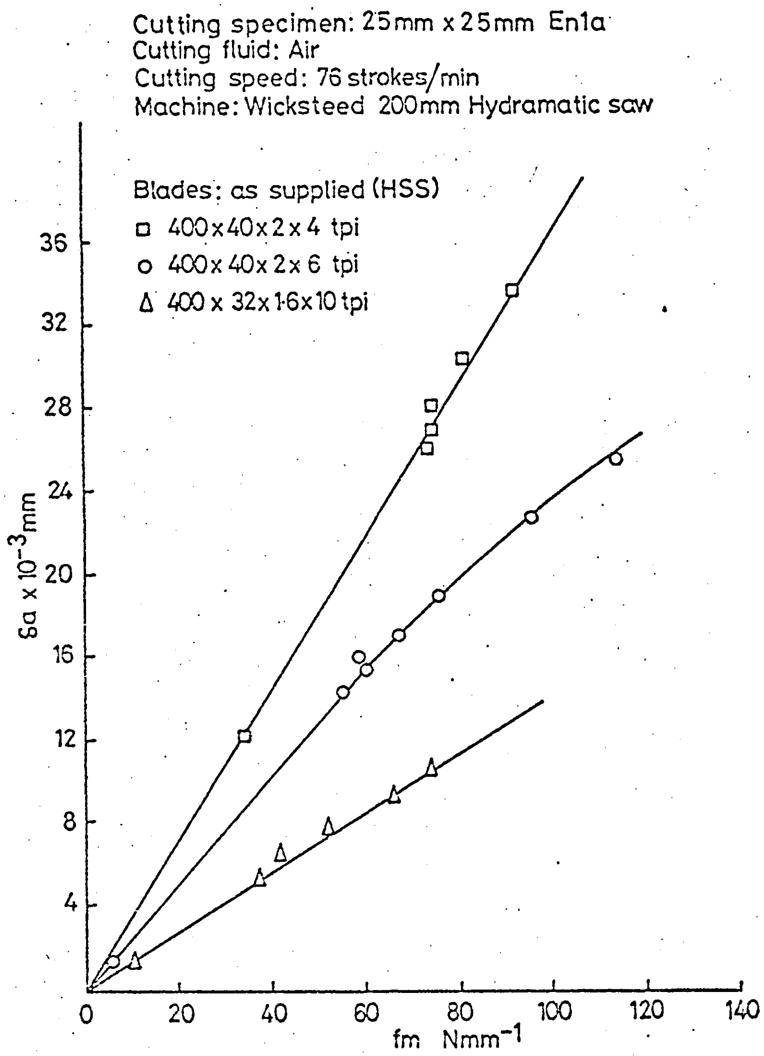


FIGURE 27.
The average depth of cut per tooth against the thrust load per tooth per unit thickness for blades having different teeth pitch.

[1]

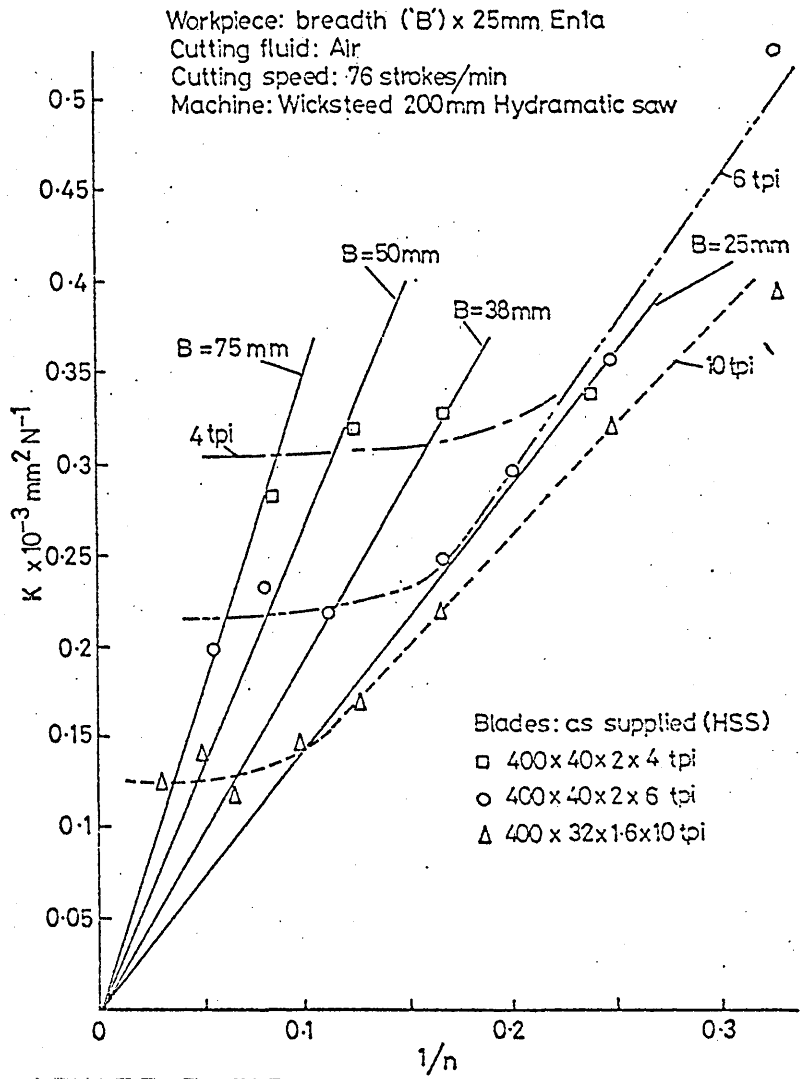


FIGURE 28.
The cutting constant against the reciprocal of the number of teeth in contact with the workpiece.

[1]

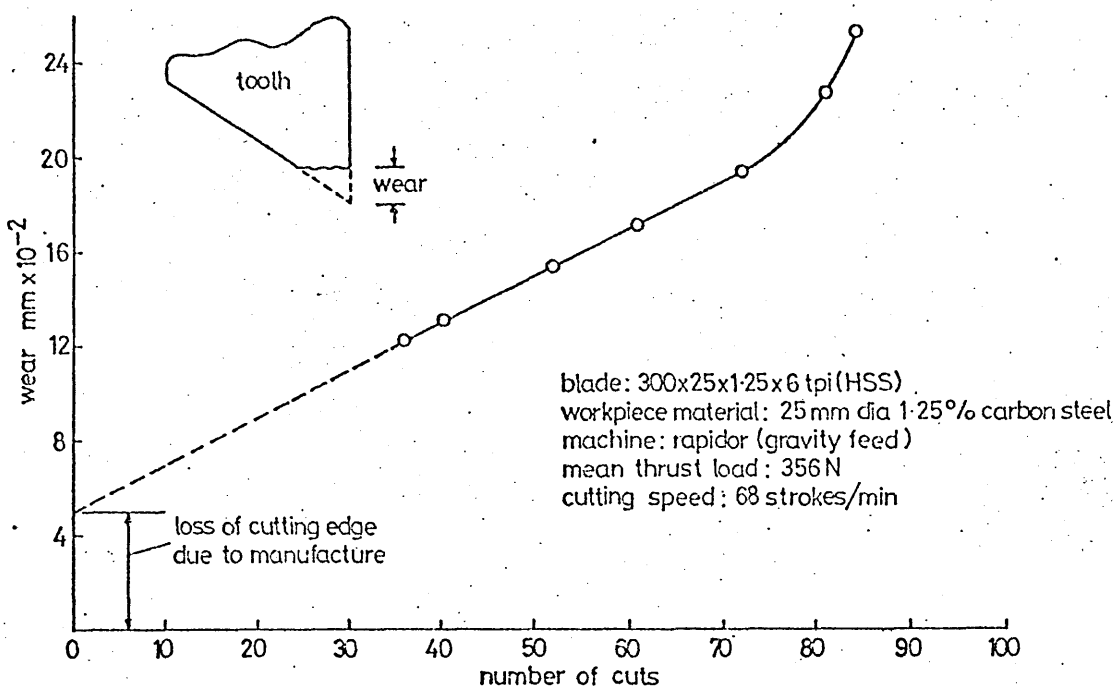


FIGURE 29.
The tooth wear against the number of cuts achieved.

[1]

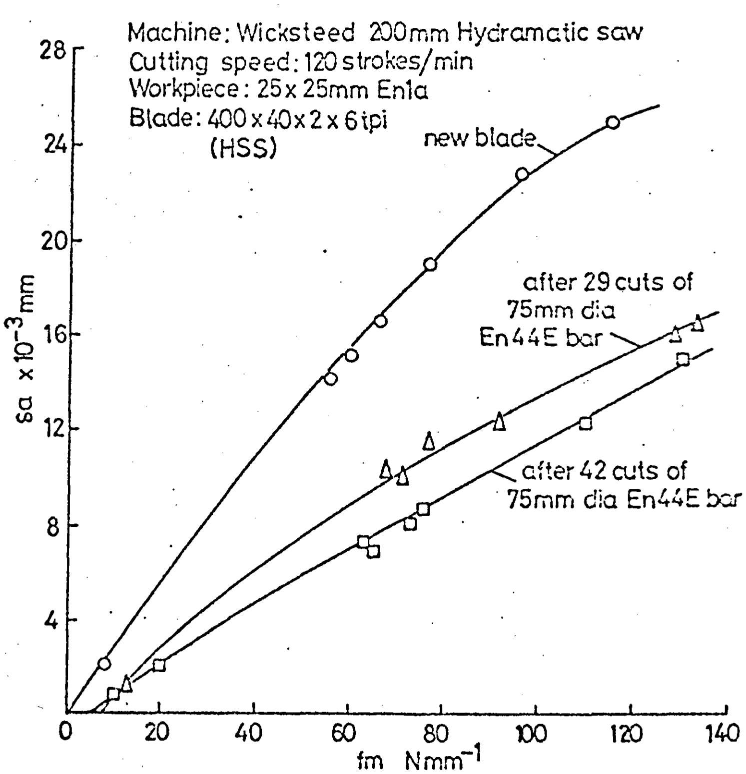


FIGURE 30.
The average depth of cut per tooth against the mean thrust load per tooth per unit thickness for a blade in three states of wear.

[1]

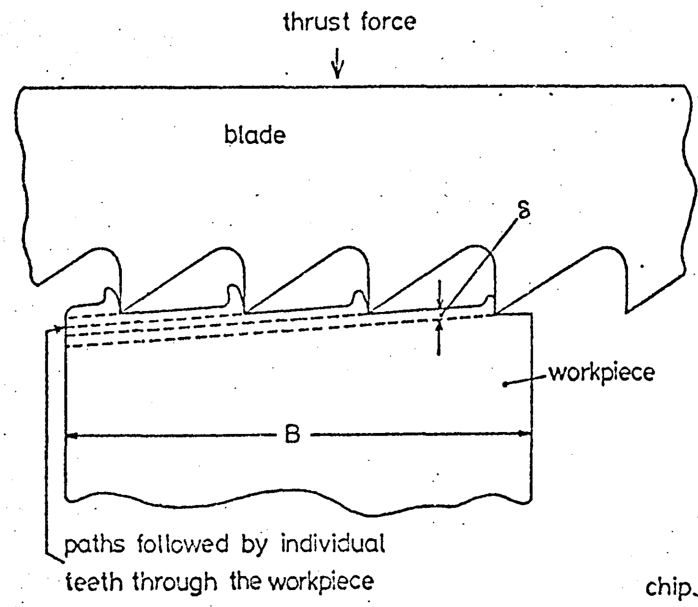


FIGURE 31.
Cutting action of a hacksaw blade showing the method of material removal.

[1]

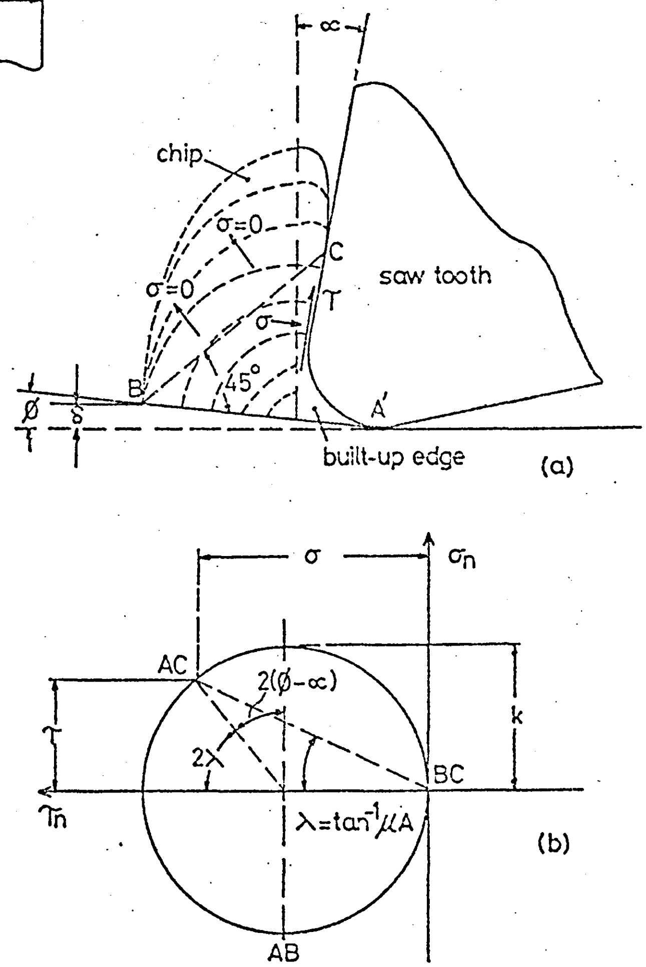


FIGURE 32.
a) A fully established deformation zone based on the Lee-Shaffer model.
b) Mohr's stress diagram for all points in the deformation zone.

[65]

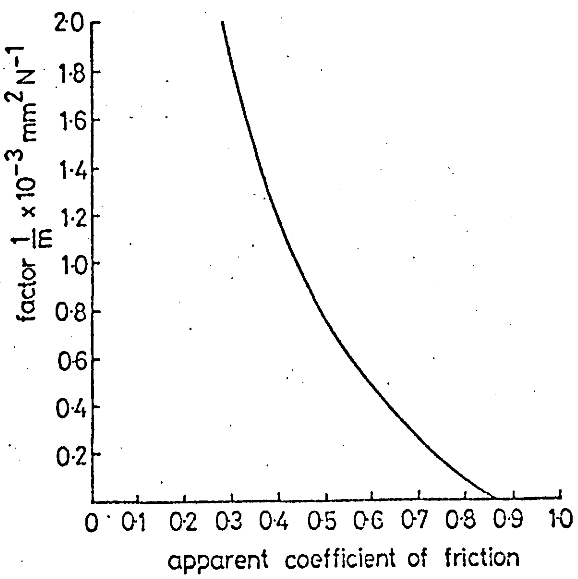


FIGURE 33.
Predicted variation in the cutting constant for a fully developed deformation zone against the apparent coefficient of friction.

[65]

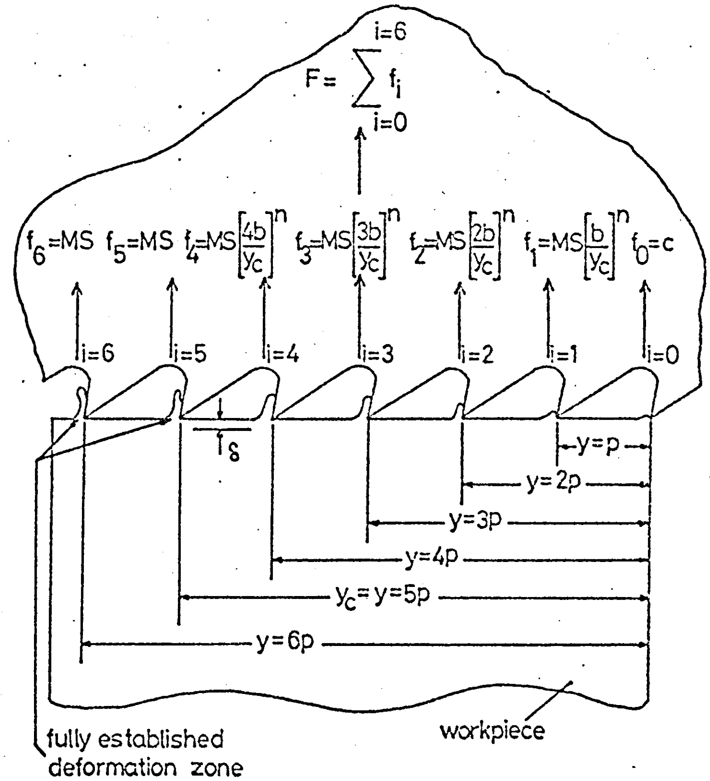


FIGURE 34.
Tooth thrust loads according to the proposed model.

[65]

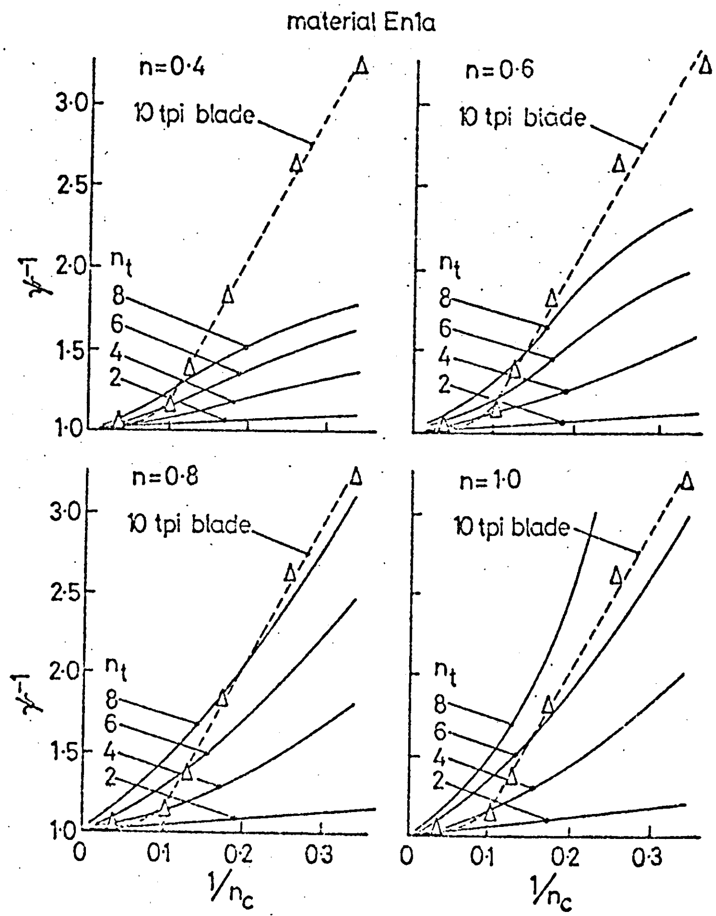


FIGURE 35.
Comparisons between the computed values of the reciprocal of the chip factor for various values of the cutting force index and experimental values.

[65]

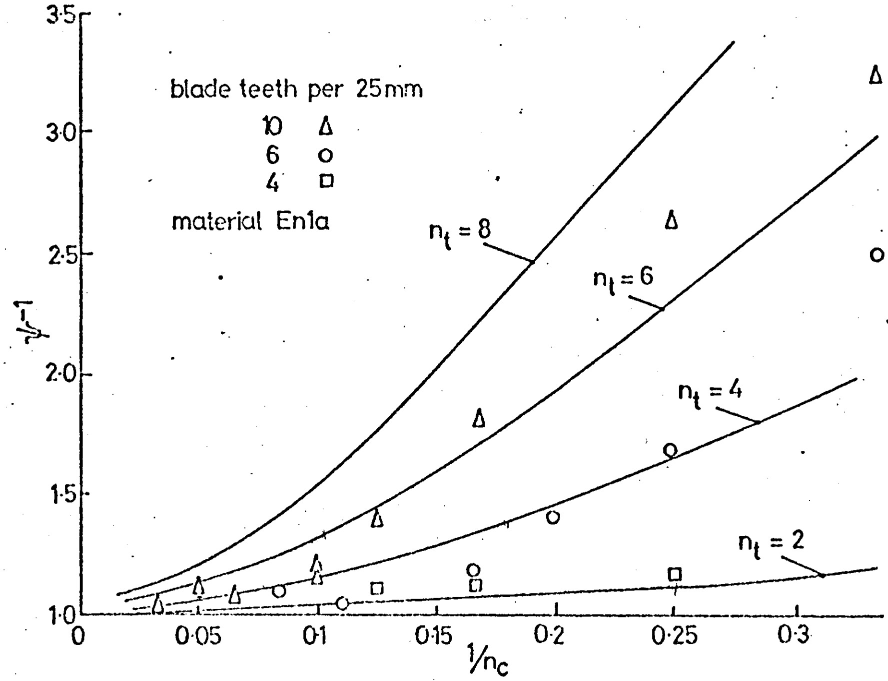


FIGURE 36.
Comparisons between the computed values of the reciprocal of the chip factor for a cutting force index of unity and experimental data obtained with blades of various pitch.

[65]

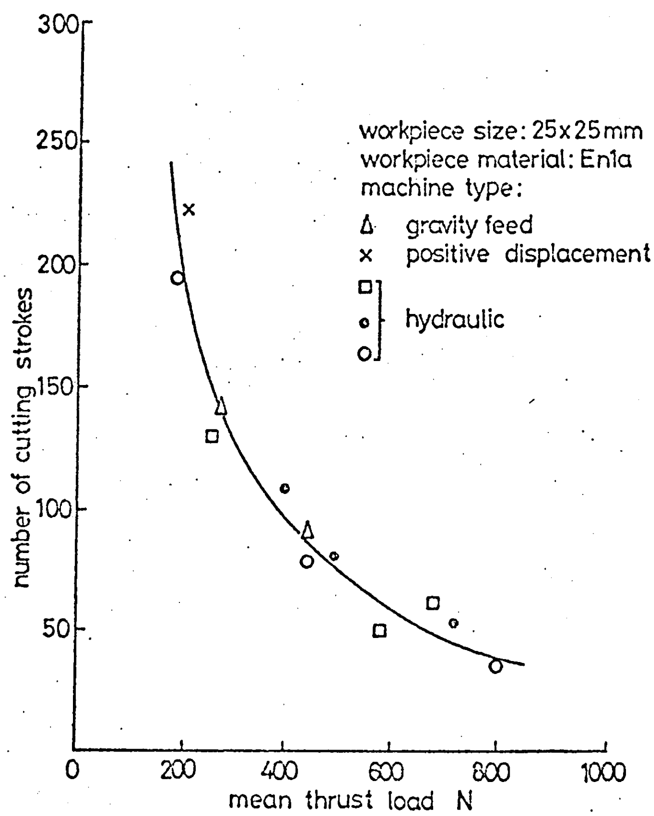


FIGURE 37.
Variation in number of cutting strokes needed to cut through an En1A workpiece against mean thrust load for a 6t.p.i. blade.

[67]

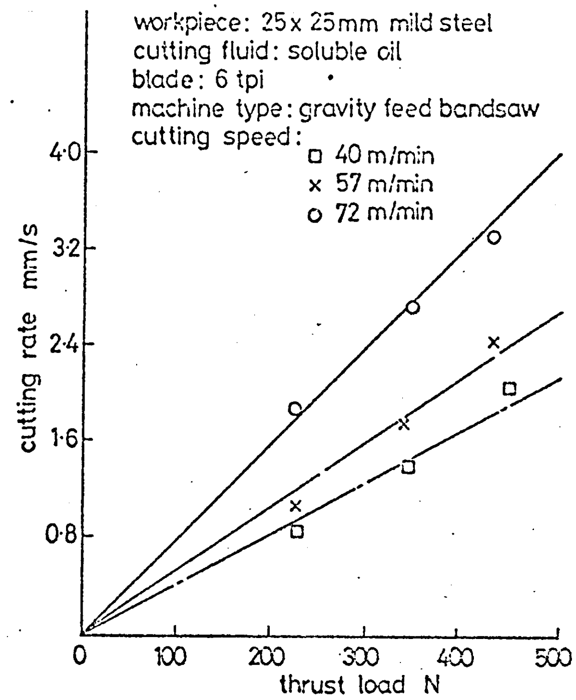


FIGURE 38.
Cutting rate against thrust load achieved at various band speeds on a gravity feed bandsaw.

[67]

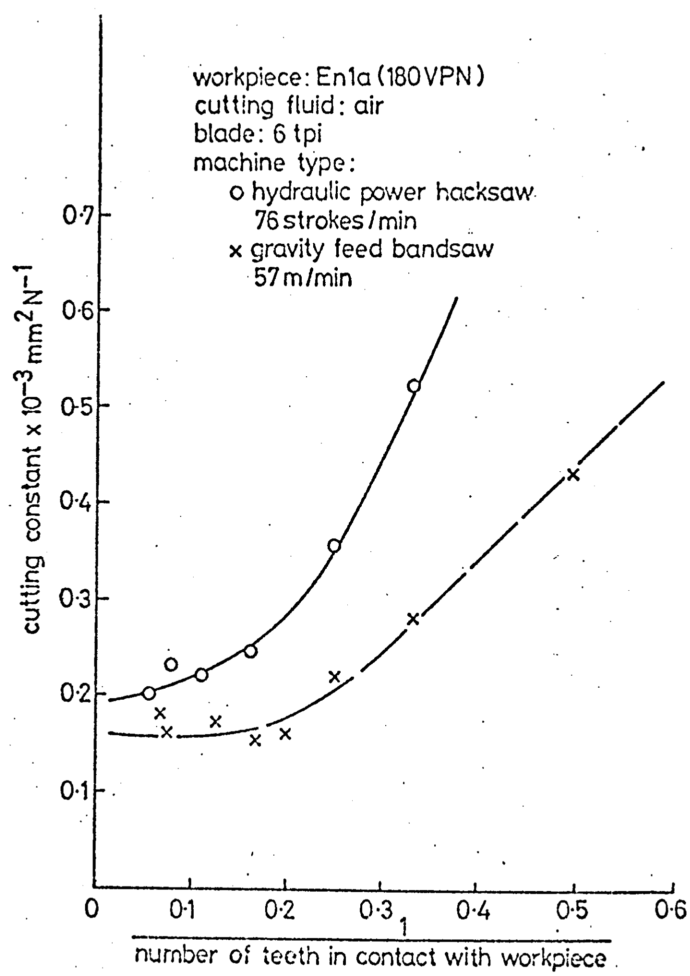


FIGURE 39.
Comparison of variation in cutting constant achieved by power hacksaw and bandsaw machines.

[67]

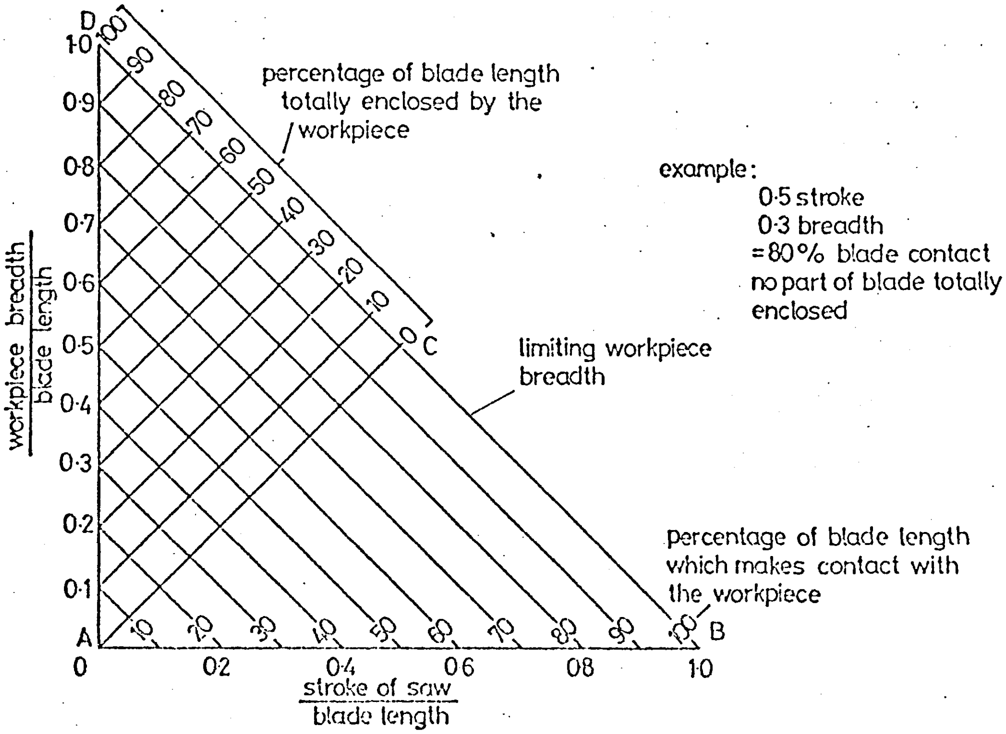


FIGURE 40.
Geometric relationships between blade length, workpiece breadth, and stroke of the saw for power hacksaw operations.

[67]

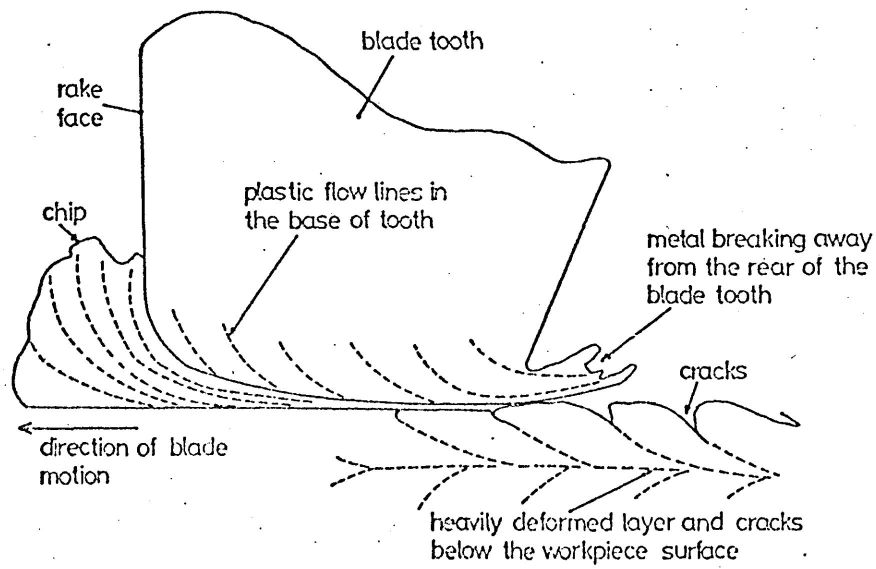


FIGURE 41.
Deformation occurring in both the blade tooth and workpiece compiled from microscopic observations during wear tests on En44E in phase II wear.

[5]

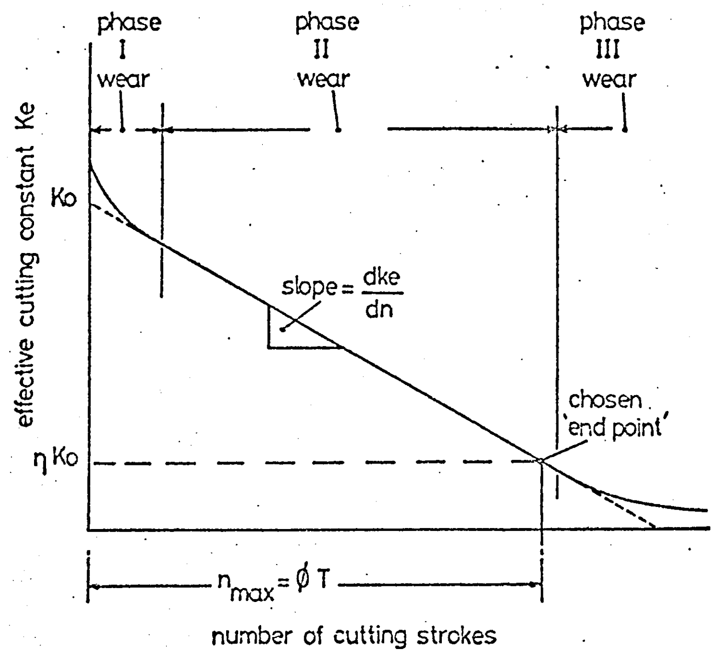


FIGURE 42.
Variation in the effective cutting constant against the number of cutting strokes, showing some of the terms used.

[5]

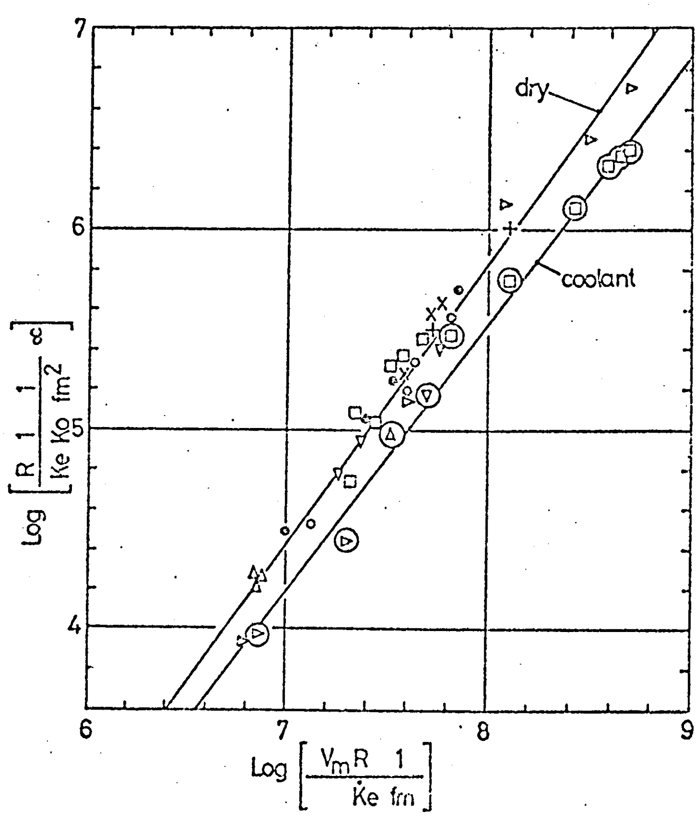


FIGURE 43.
Log-Log dimensionless plot for En44E, with and without coolant.

[5]

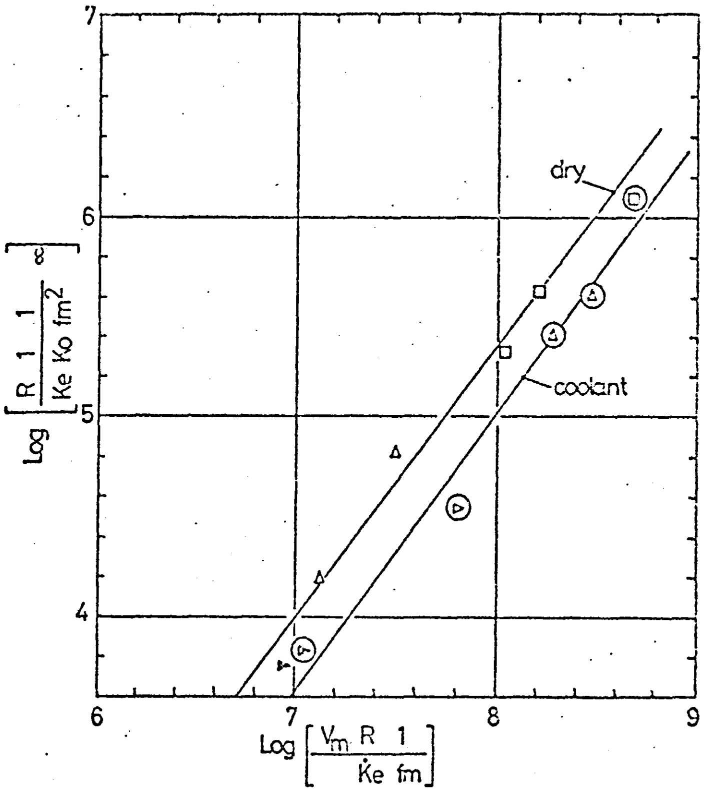


FIGURE 44.
Log-Log plot for 0.6% Carbon steel, with and without coolant.

[5]

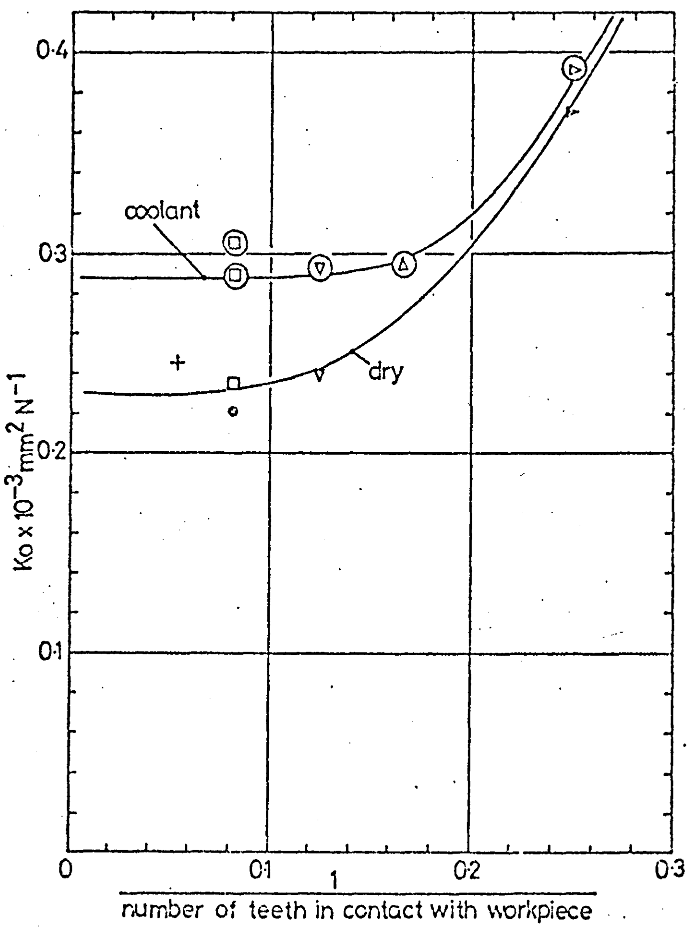


FIGURE 45.
Variation in the initial cutting constant against the reciprocal of the number of teeth in contact with the workpiece for En44E, with and without coolant.

[5]

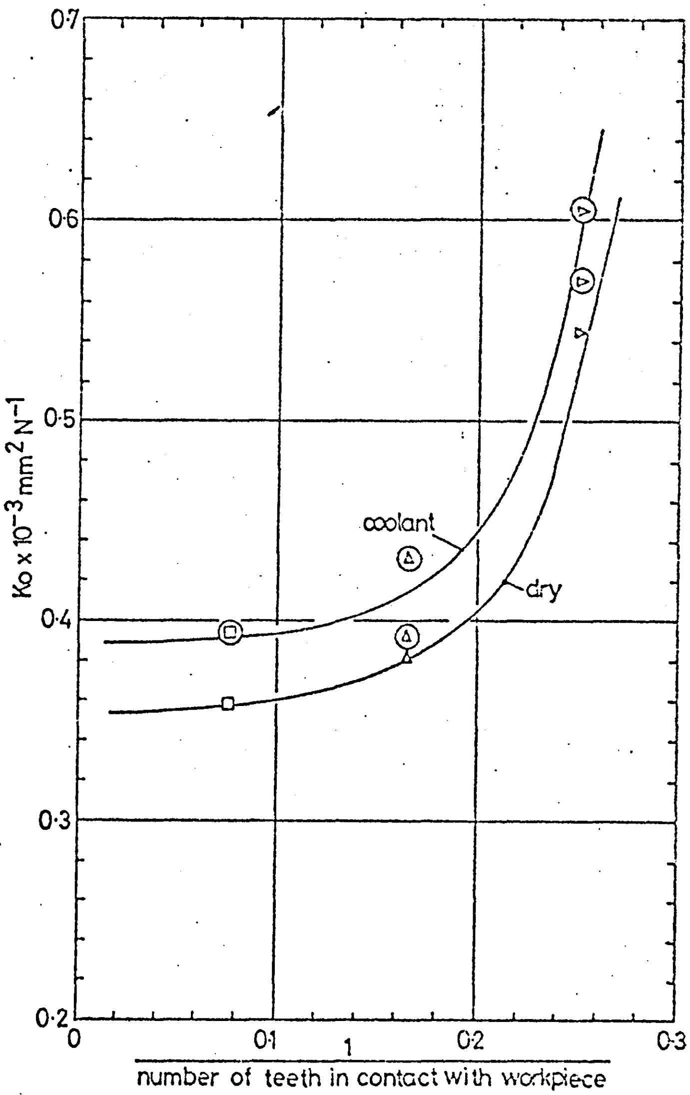


FIGURE 46.
Variation in the initial cutting constant against the reciprocal of the number of teeth in contact with the workpiece for 0.6% carbon steel, with and without coolant.

[5]

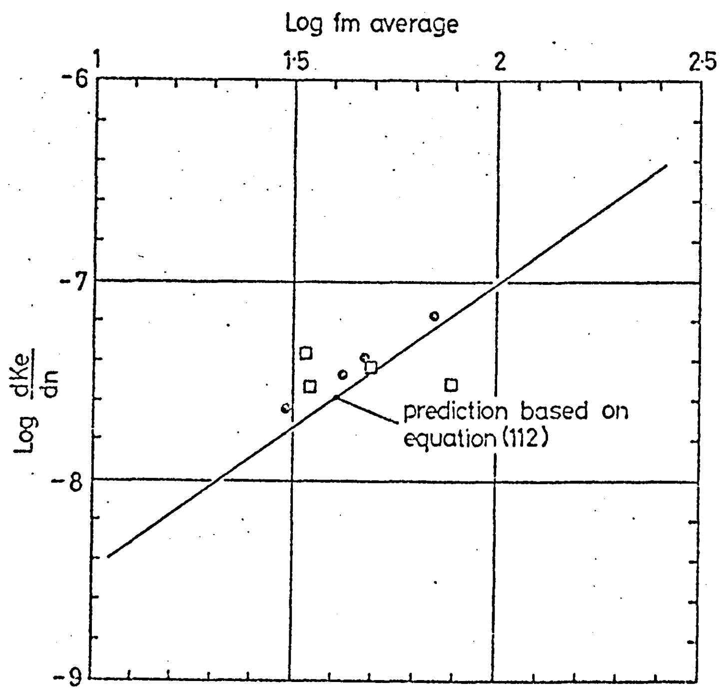
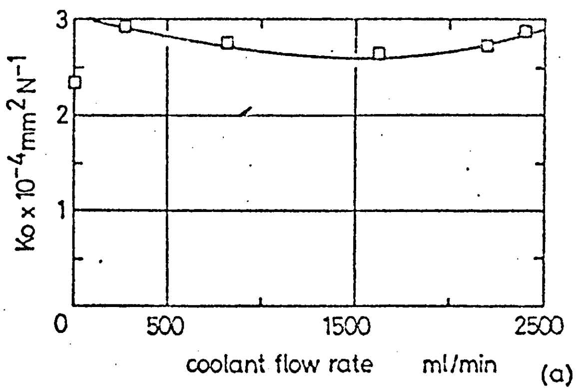


FIGURE 47.
Log-Log plot of the variation in the effective cutting constant per cutting stroke against the thrust load per tooth per unit thickness for En44E cut dry.

[5]



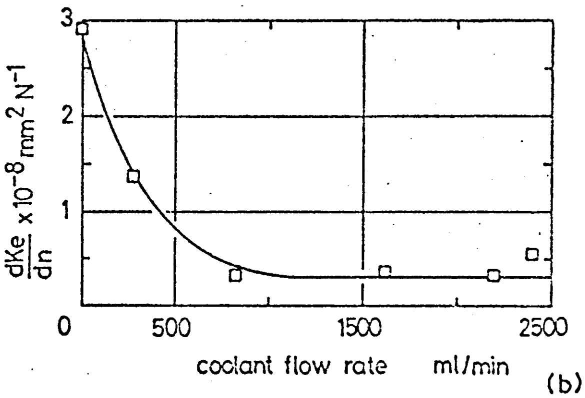
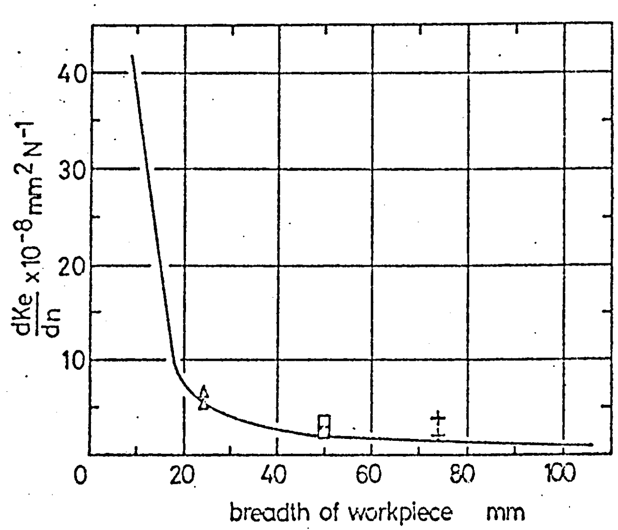


FIGURE 48.
The effect of the coolant flow rate on (a) the initial cutting constant (b) the change in the effective cutting constant per cutting stroke for En44E.

[5]

FIGURE 49.
The variation in the effective cutting constant per cutting stroke against the breadth of the workpiece, for En44E cut dry.

[5]



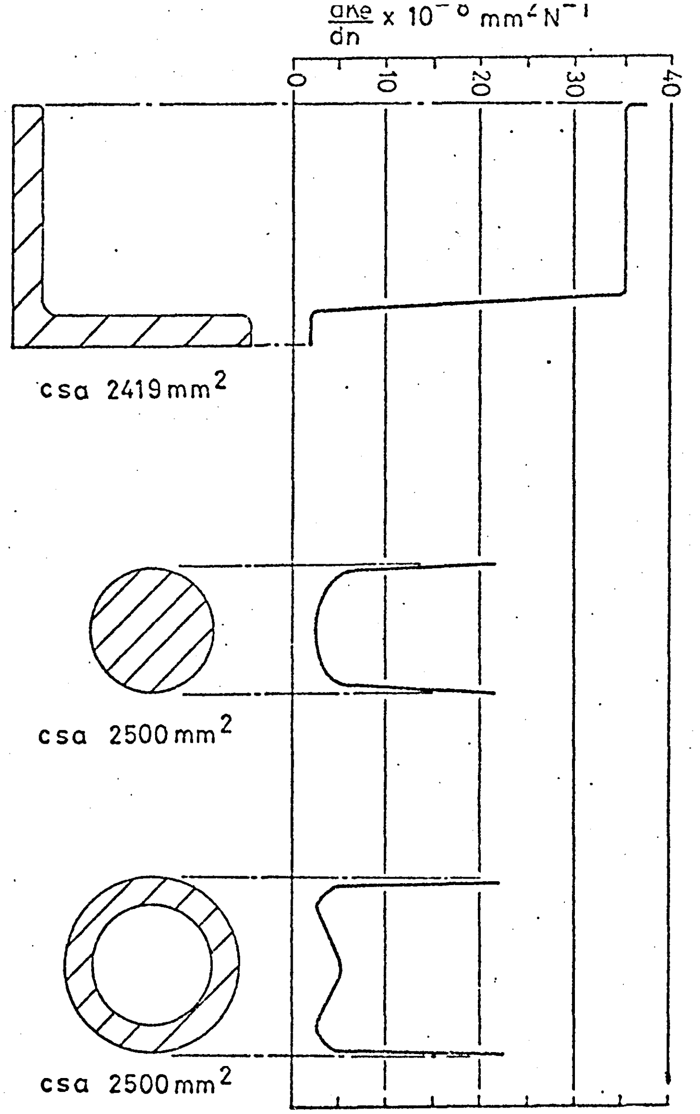


FIGURE 50.
The effect of workpiece shape on the wear rate for En44E cut dry.

[5]

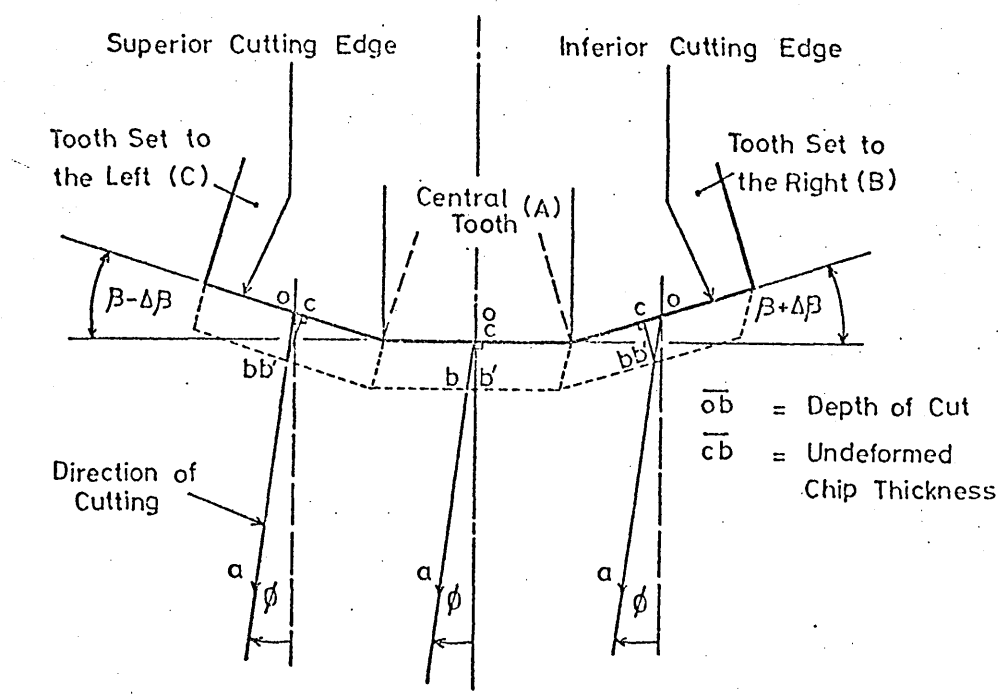


FIGURE 51.
Three cutting edges of a blade having Raker set, for clarity the three cutting edges are shown side by side. [6]

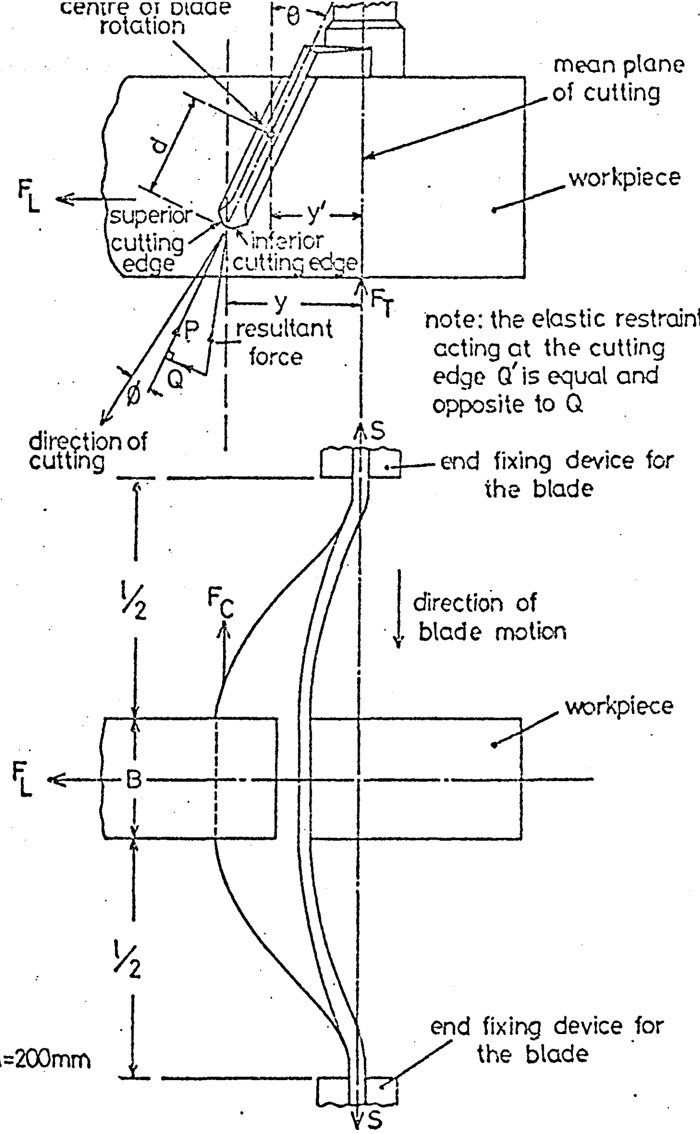


FIGURE 52.
Blade distortion occurring as the cutting edge is displaced from the mean plane of cutting.

[6]

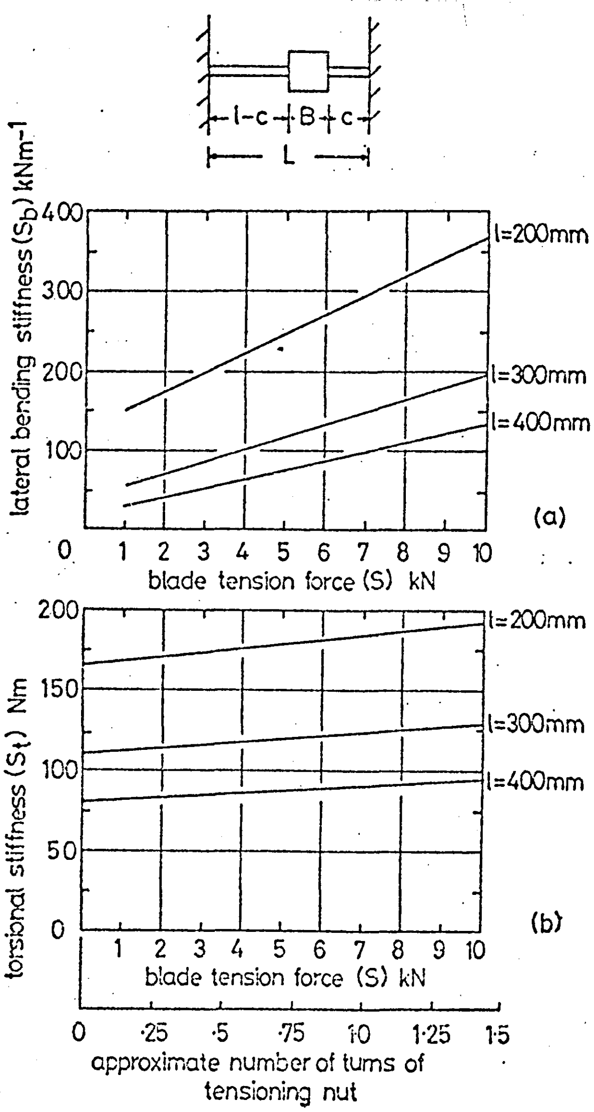


FIGURE 53.
The stiffness of a standard power hacksaw blade against blade tension force for various free blade lengths when the workpiece is at the centre of the blade (a)lateral bending stiffness (b)torsional stiffness.

[6]

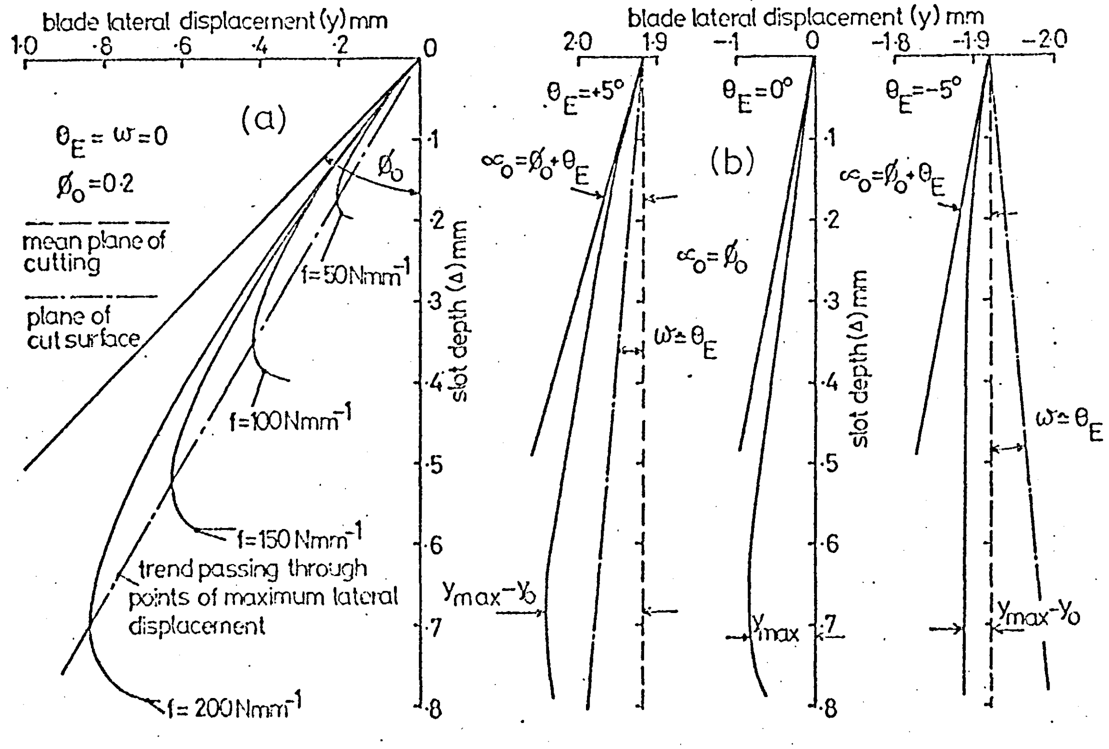


FIGURE 54.
Theoretical predictions of the lateral displacement of the cutting edge against depth of cut (a) for various thrust loads per tooth per unit thickness (b) for various clamping errors.

[6]

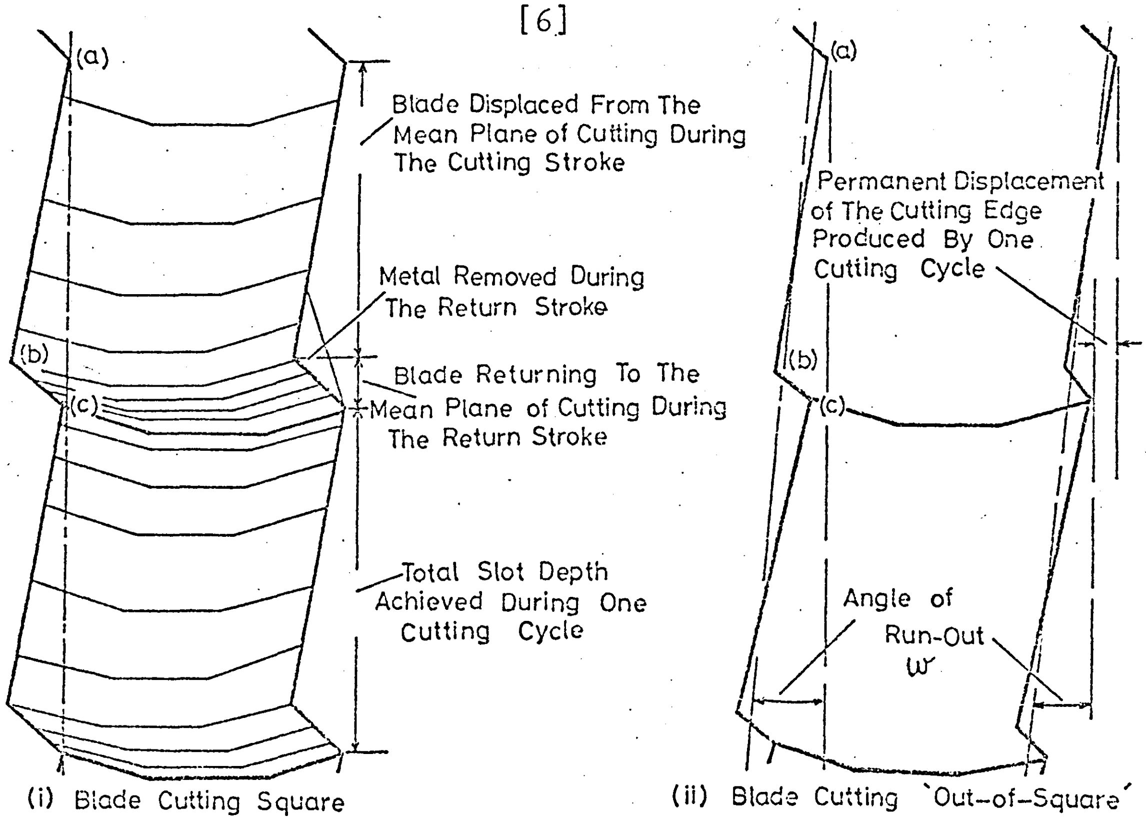


FIGURE 55.
Sections through the slot produced as the cutting edge of the blade wanders from the mean plane of cutting (i) blade cutting square (ii) blade cutting out-of-square. [6]

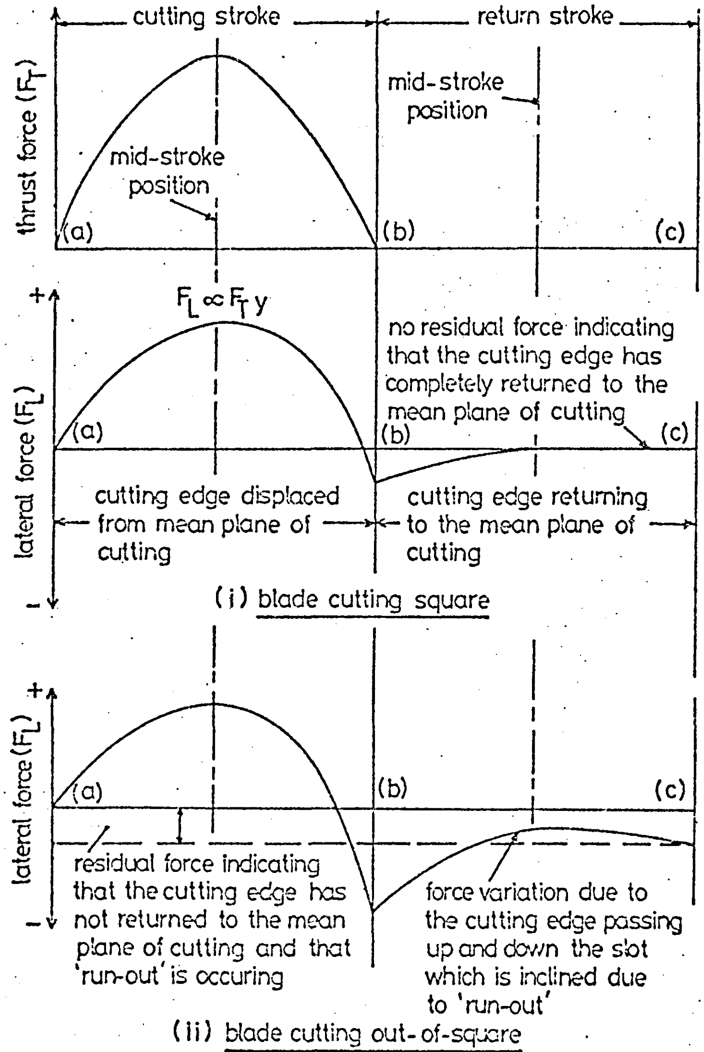


FIGURE 56.
Trends in the thrust and lateral components of the force acting on the workpiece
(i) blade cutting square
(ii) blade cutting out-of-square.

[6]

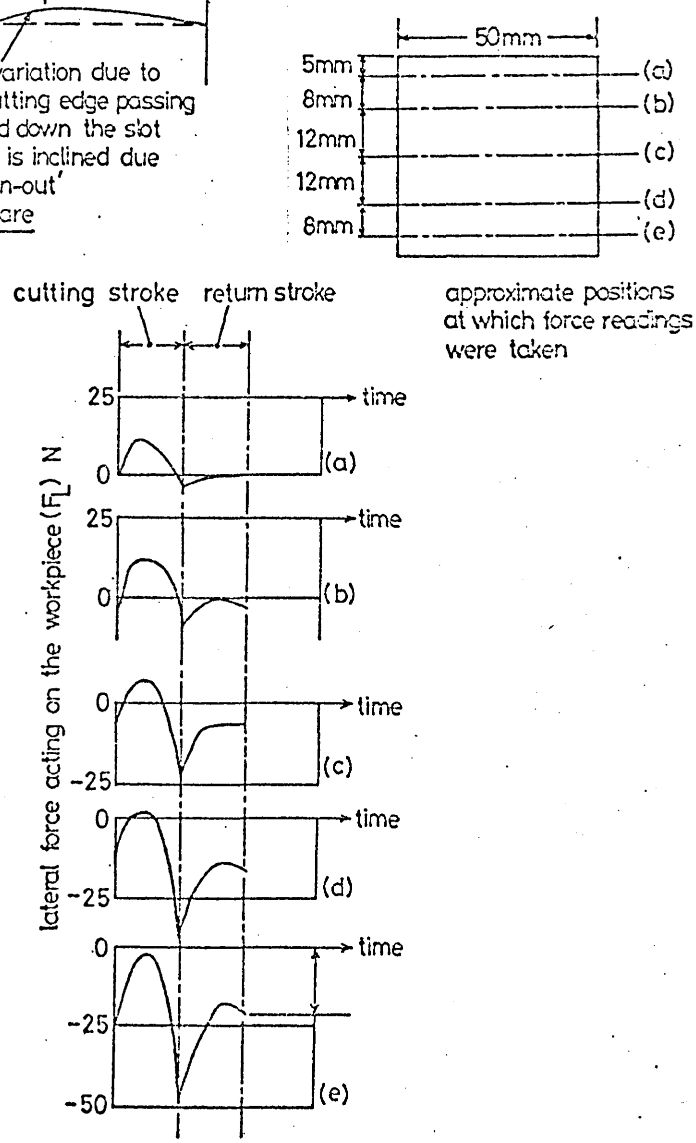


FIGURE 57.
Experimentally determined variations in the lateral components of the force acting on the workpiece at various slot depths as the blade cuts out-of-square.

[6]

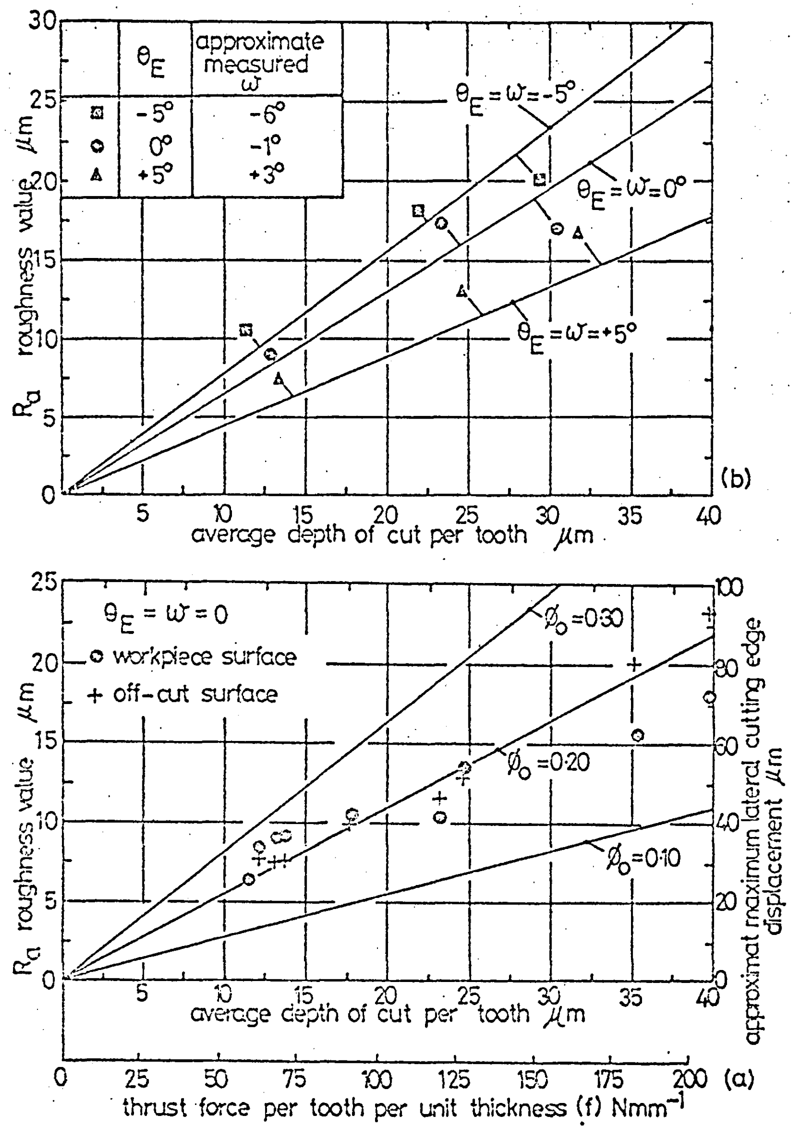


FIGURE 58. Roughness against average depth of cut (a)experimental and theoretical predictions (b)showing the effects of clamping error. [6]

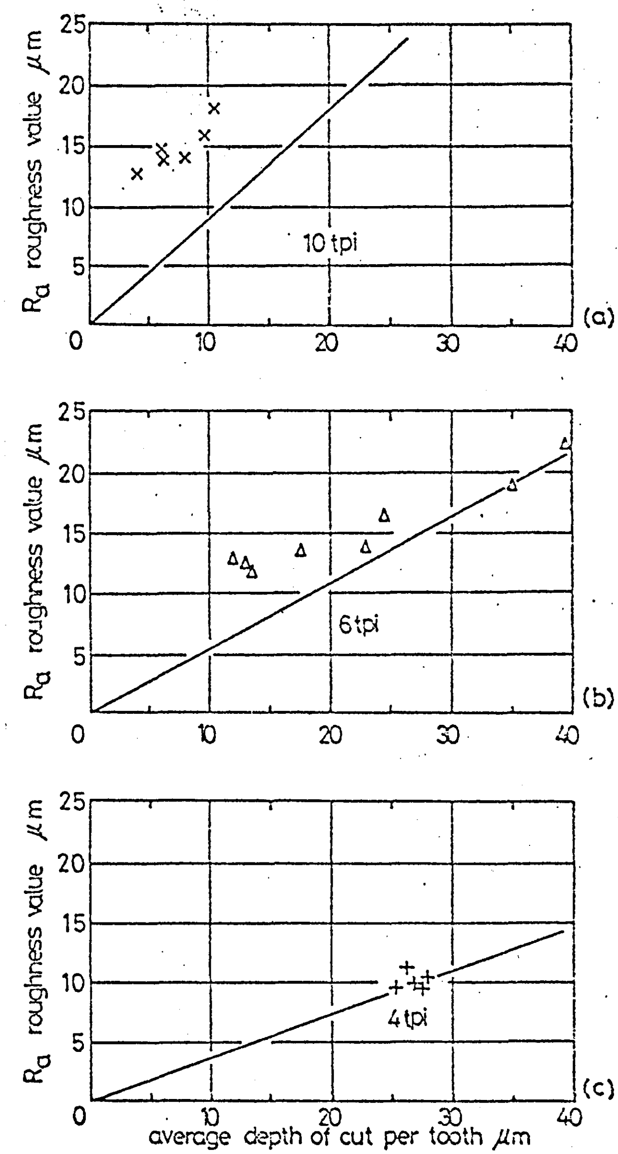


FIGURE 59. Roughness against average depth of cut in regions affected by ploughing (a)10t.p.i. (b) 6t.p.i. (c) 4t.p.i. [6]

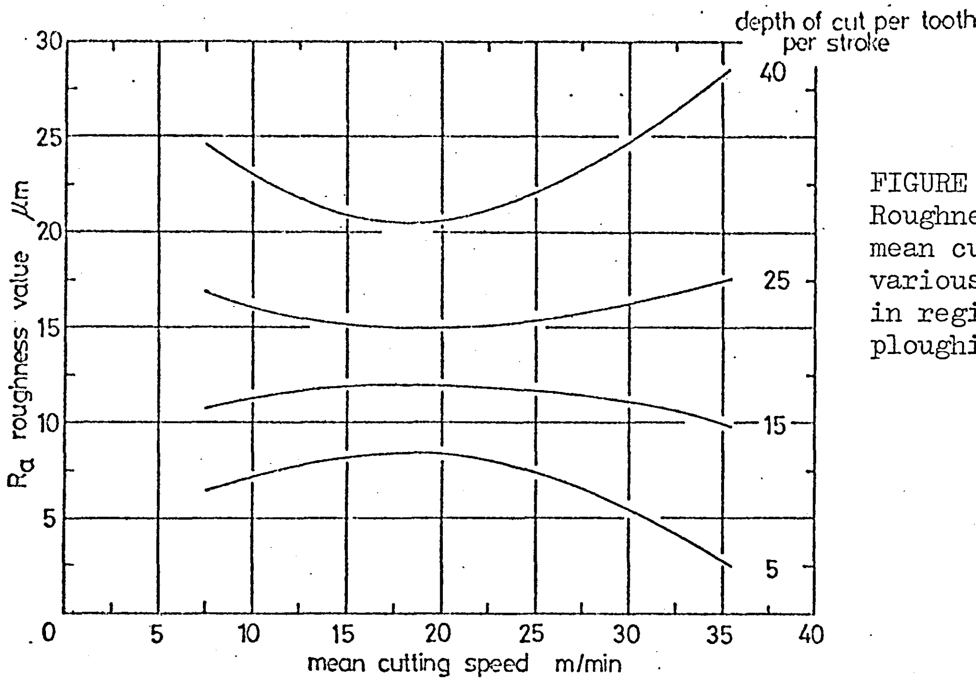


FIGURE 60.
Roughness against the mean cutting speed for various depths of cut in regions affected by ploughing.

[6]

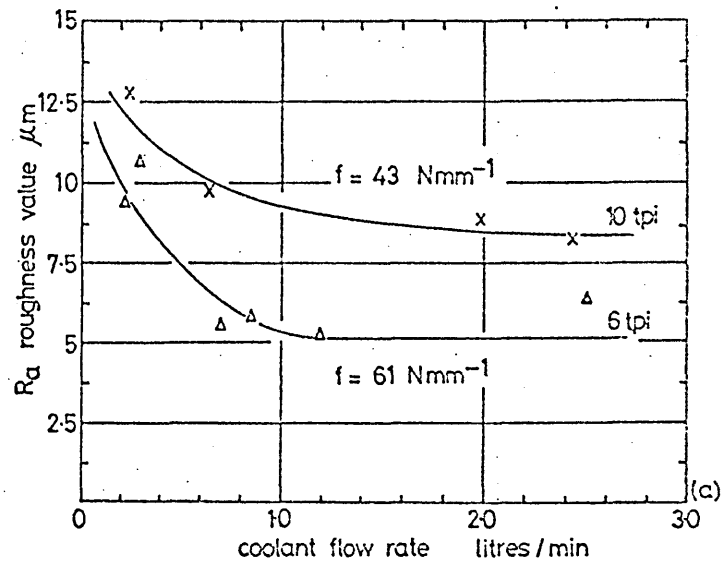
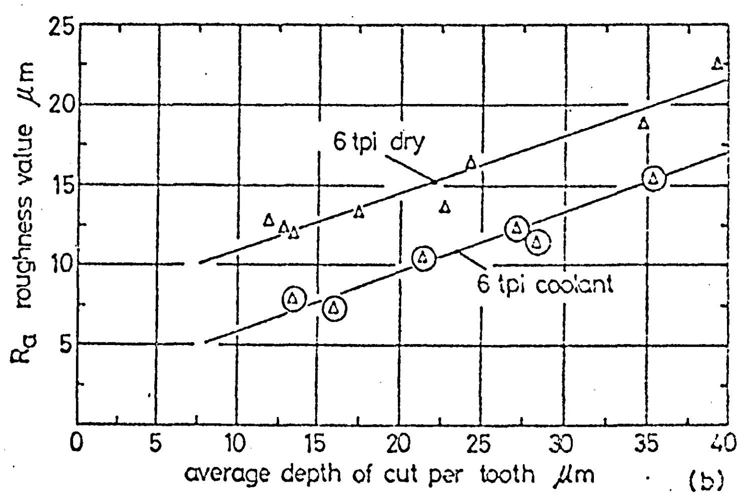


FIGURE 61.
(a) effect of coolant flow rate on roughness at a constant load for regions affected by ploughing (b) roughness against average depth of cut for regions affected by ploughing with and without coolant.

[6]



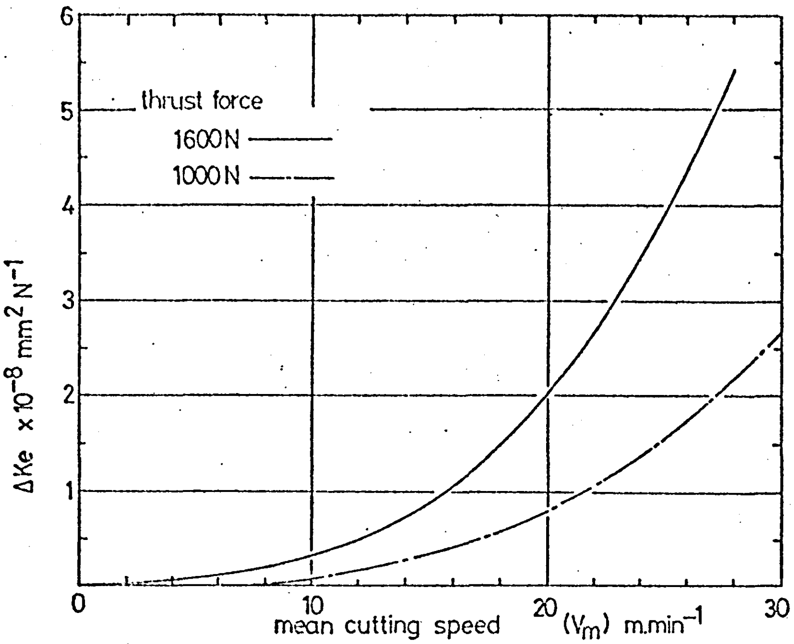


FIGURE 62.
Change in the effective cutting constant per stroke of the saw against the mean cutting speed.

[7]

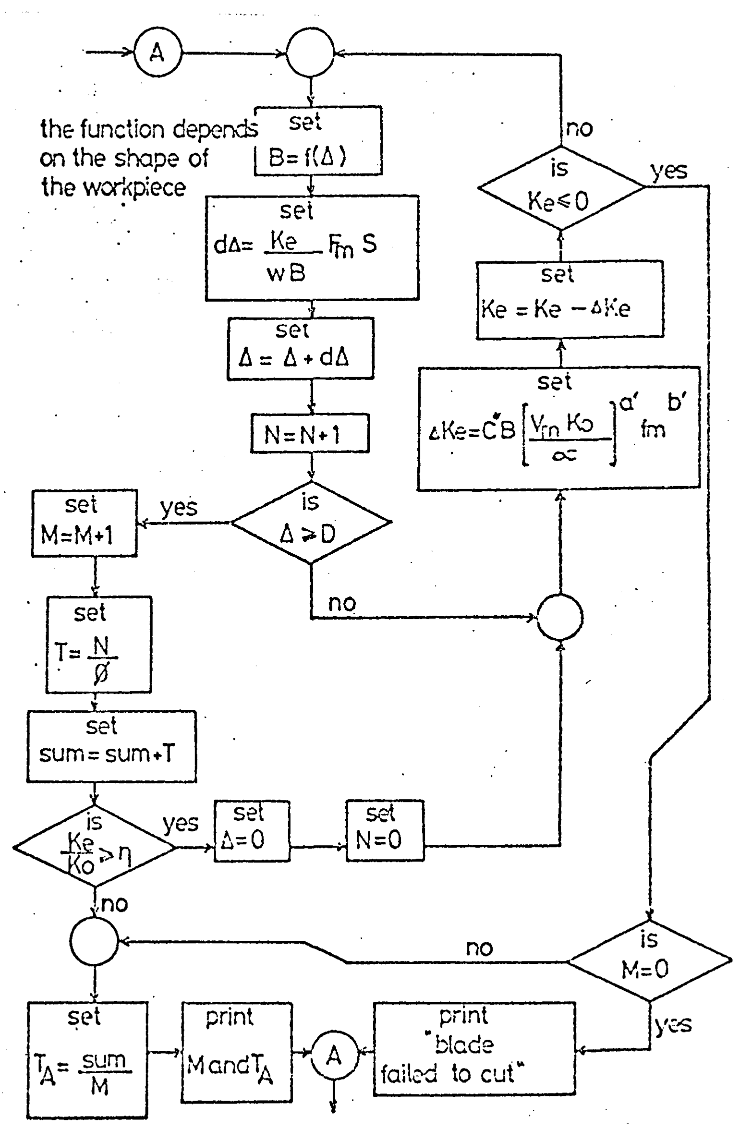


FIGURE 63.
An algorithm suitable for a computer routine to simulate a power hacksaw operation.

[7]

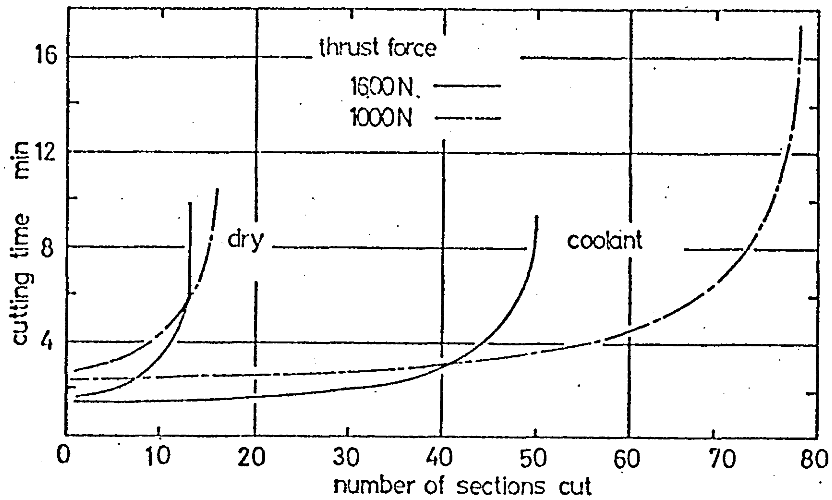


FIGURE 64.
Variation in the cutting time against the number of sections cut.
[7]

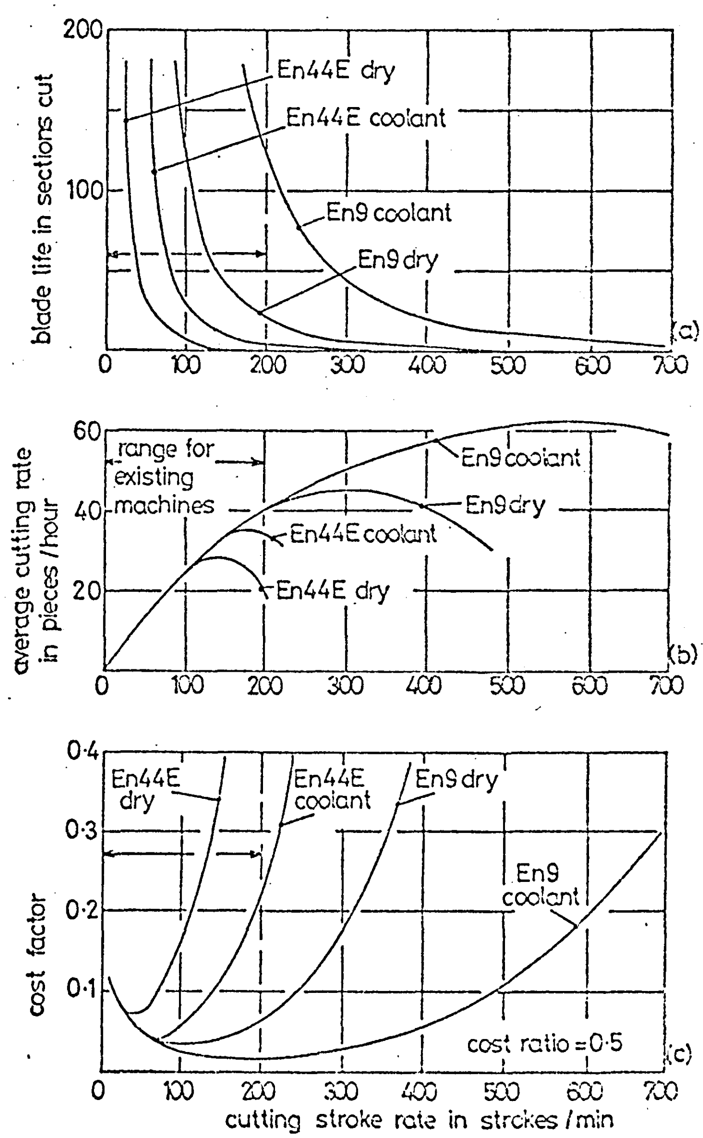


FIGURE 65.
The effects of the cutting stroke rate on (a) blade life in sections cut (b) average cutting rate (c) the cost factor.
[7]

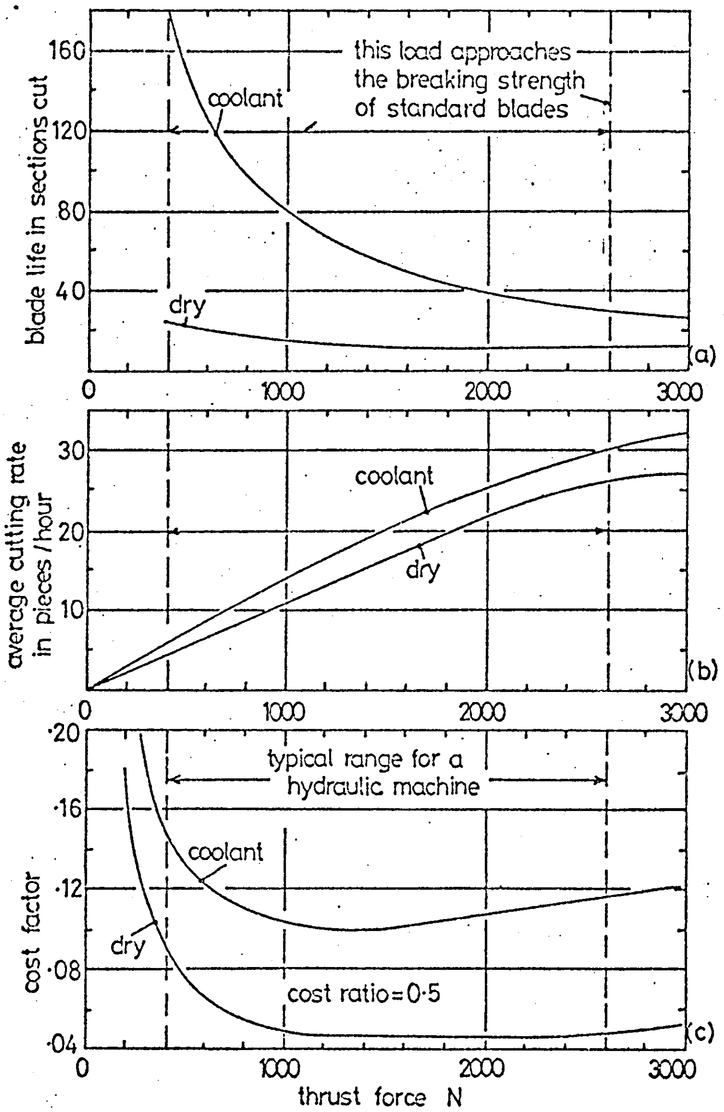
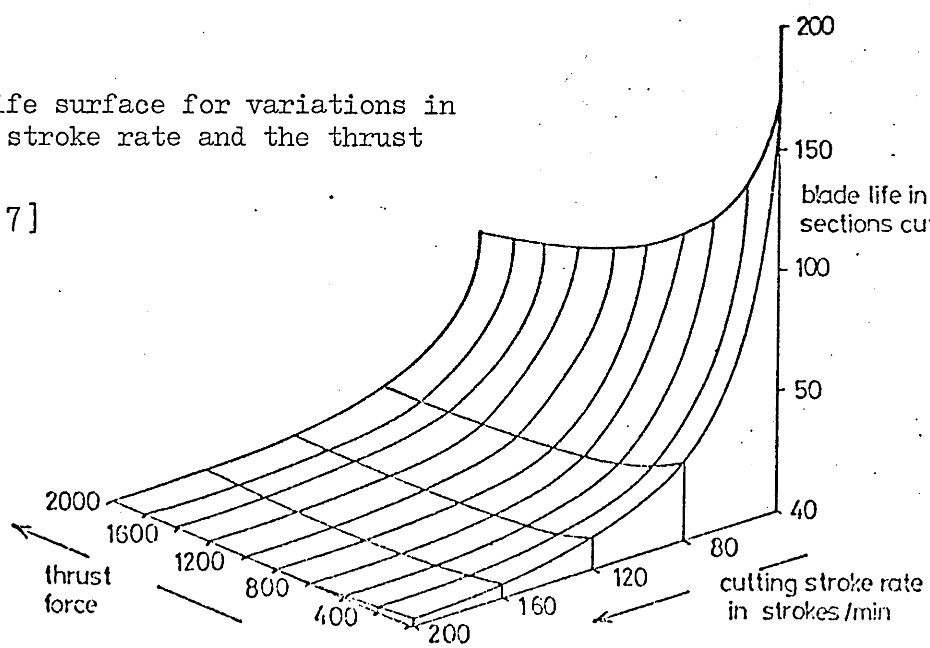


FIGURE 66.
The effects of the thrust load on (a) blade life in sections cut (b) average cutting rate (c) cost factor.

[7]

FIGURE 67.
The blade life surface for variations in the cutting stroke rate and the thrust force.

[7]



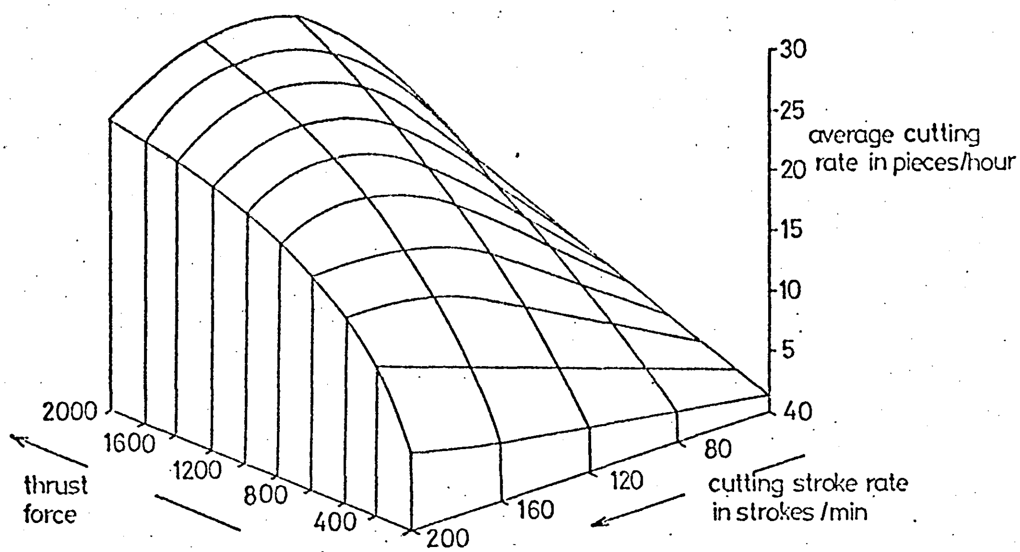


FIGURE 68.
The average cutting rate surface for variations in the cutting stroke rate and the thrust force.

[7]

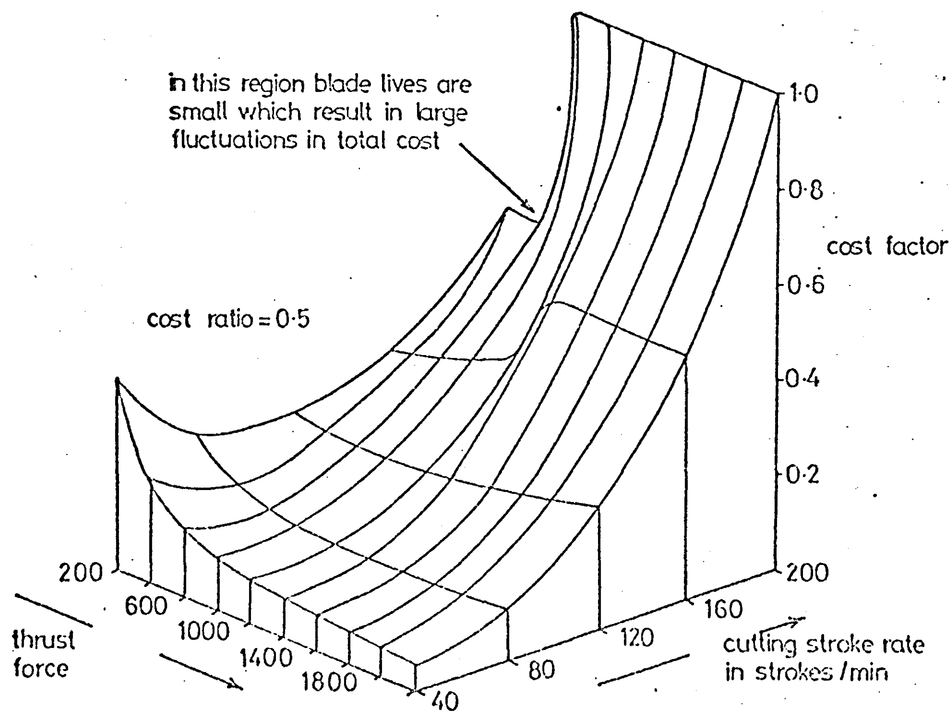


FIGURE 69.
The cost factor surface for variations in the cutting stroke rate and the thrust force.

[7]

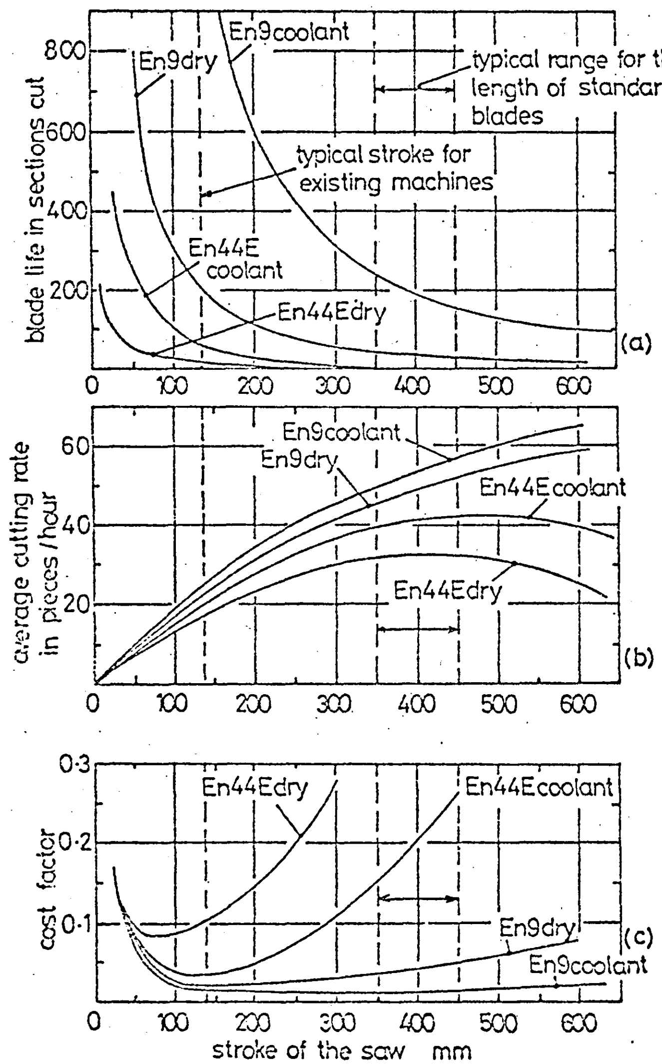


FIGURE 70.
The effects of the stroke of the saw on (a) blade life in sections cut (b) average cutting rate (c) cost factor. [7]

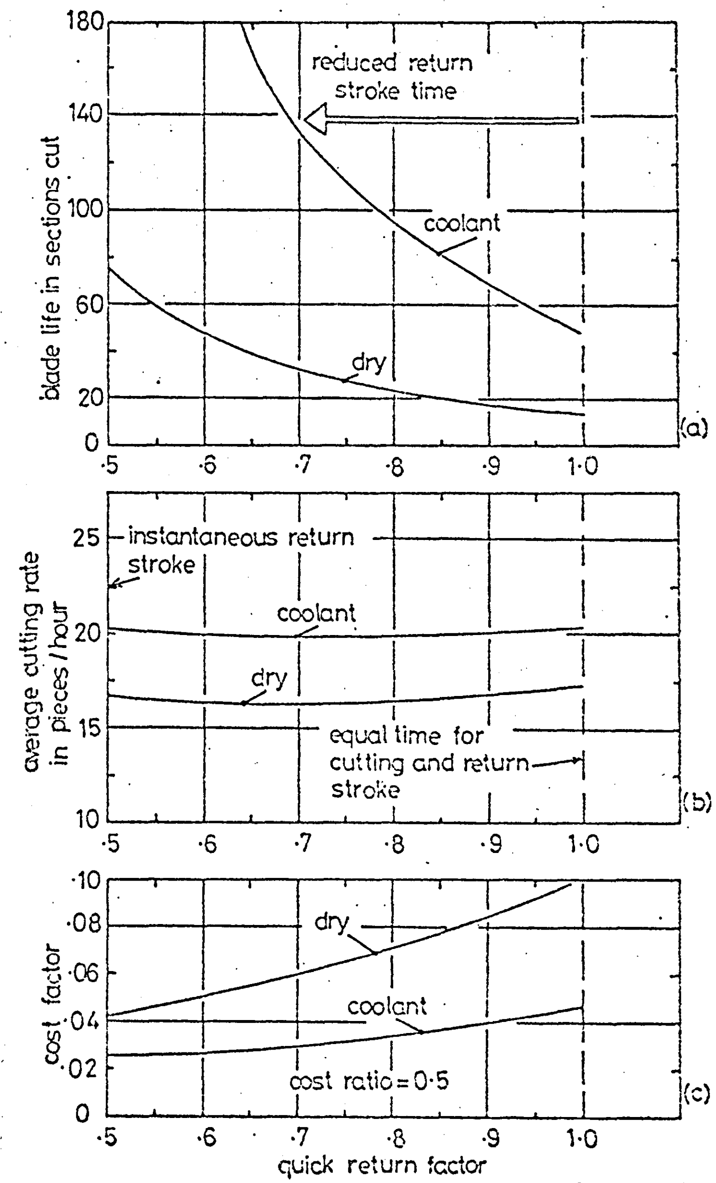


FIGURE 71.
The effects of quick return on (a) blade life in sections cut (b) average cutting rate (c) cost factor. [7]

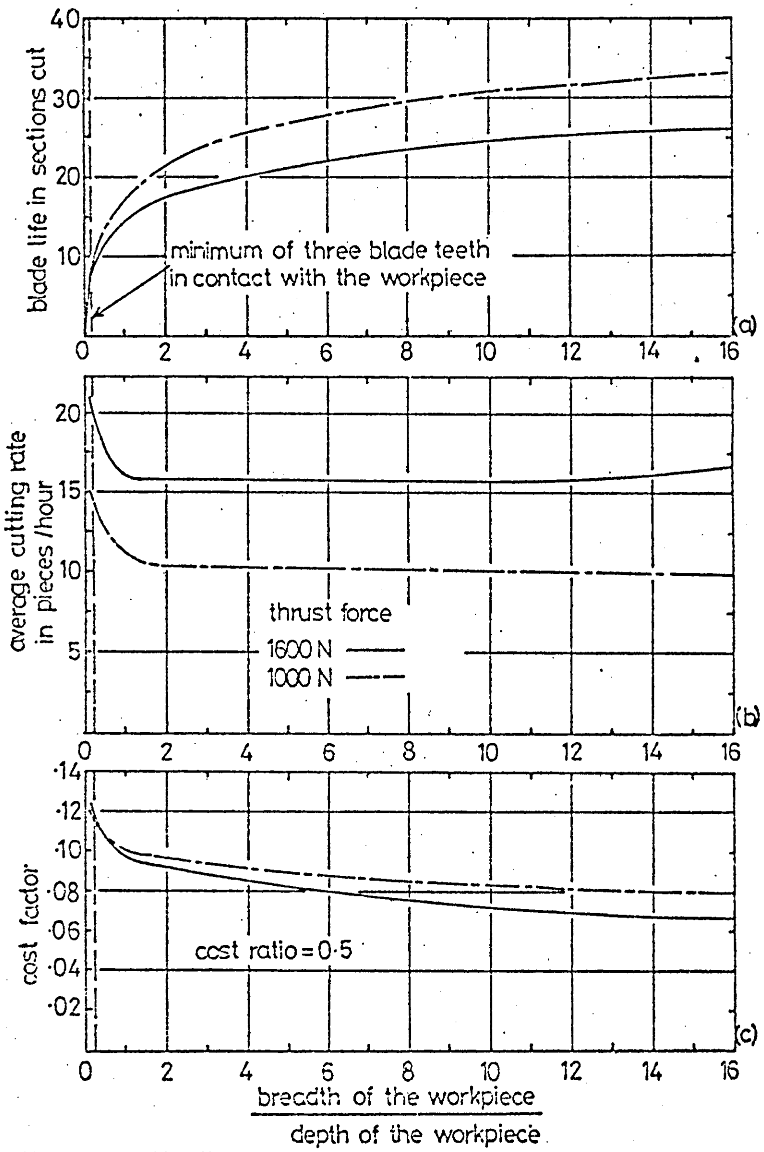


FIGURE 72.
The effects of breadth/depth ratio of rectangular workpieces with a cross sectional area of 2500 mm^2 on (a) blade life in sections cut (b) average cutting rate (c) cost factor. [7]

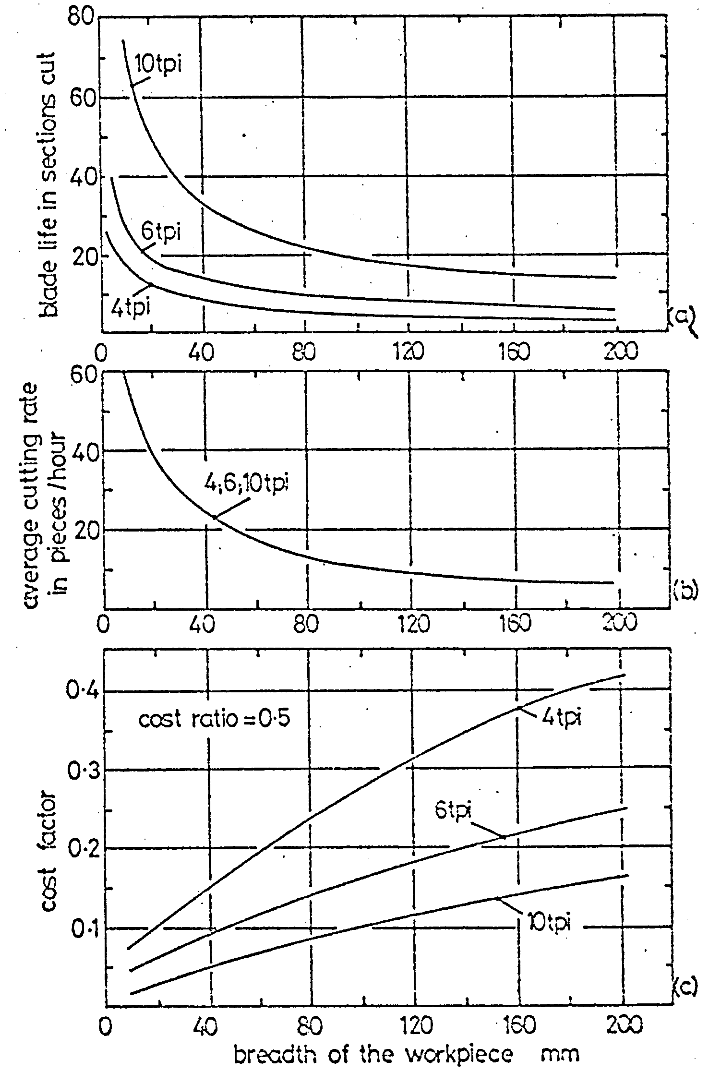


FIGURE 73.
The effects of blade teeth pitch and breadth of the workpiece on (a) blade life in sections cut (b) average cutting rate (c) cost factor. [7]

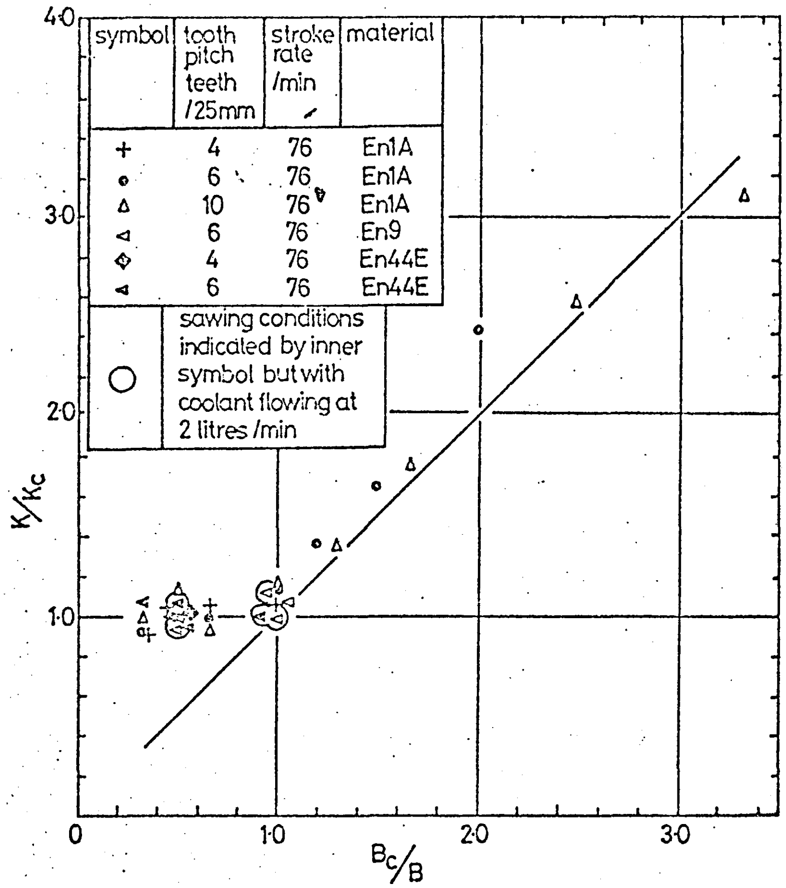


FIGURE 74.
Variation in the cutting constant against breadth of cut in dimensionless form for a number of ductile metals and blade teeth pitch.

[68]

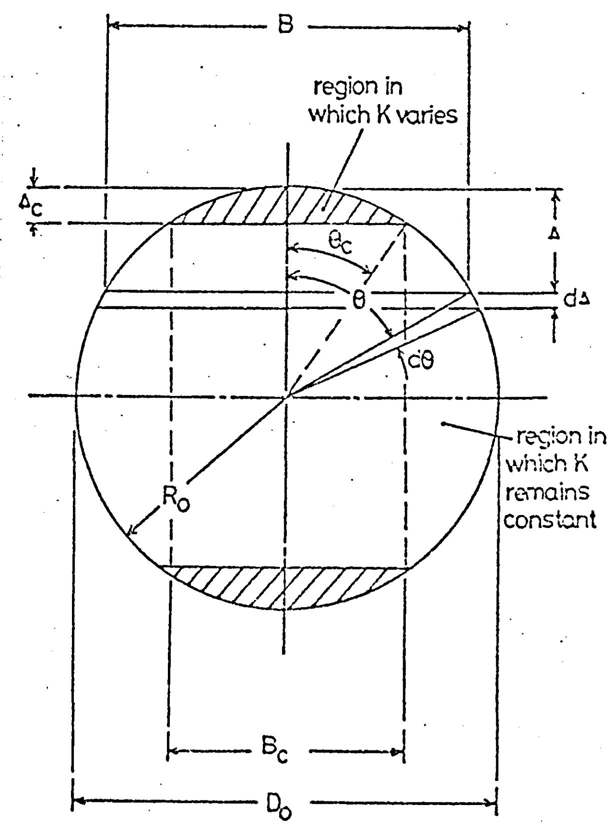


FIGURE 75.
Relationships between various geometric parameters.

[68]

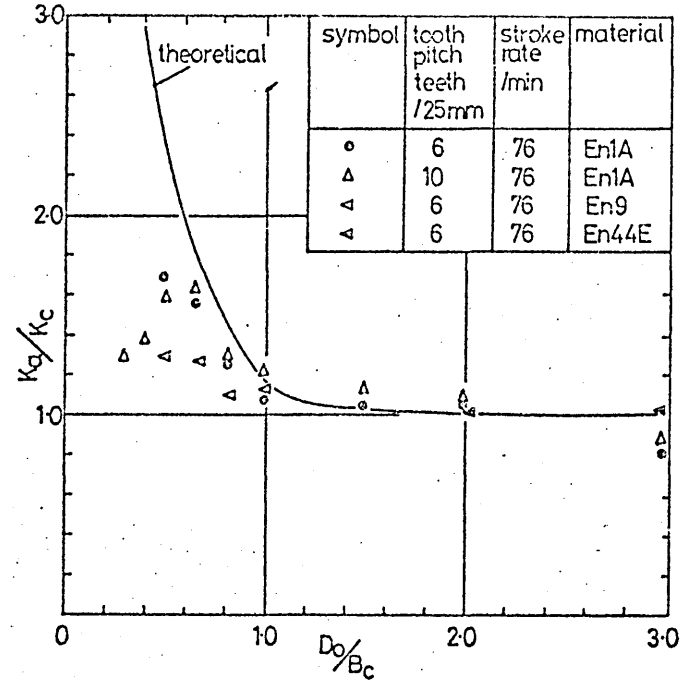


FIGURE 76.
Variation in the average cutting constant against the diameter of the section in dimensionless form.

[68]

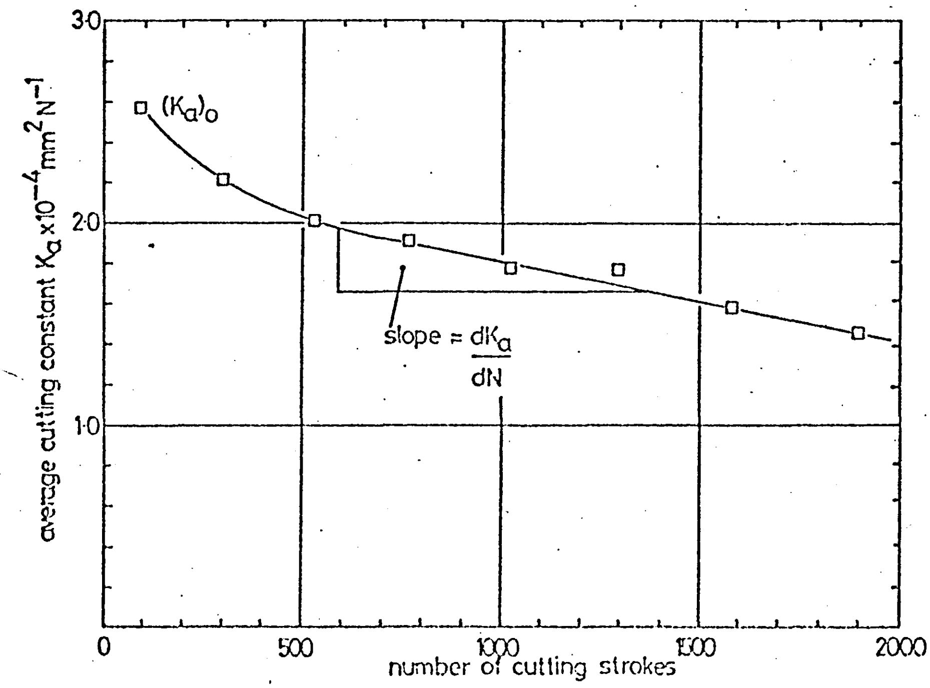


FIGURE 77.
Variation in the average cutting constant due to wear against the number of cutting strokes performed by the blade.

[68]

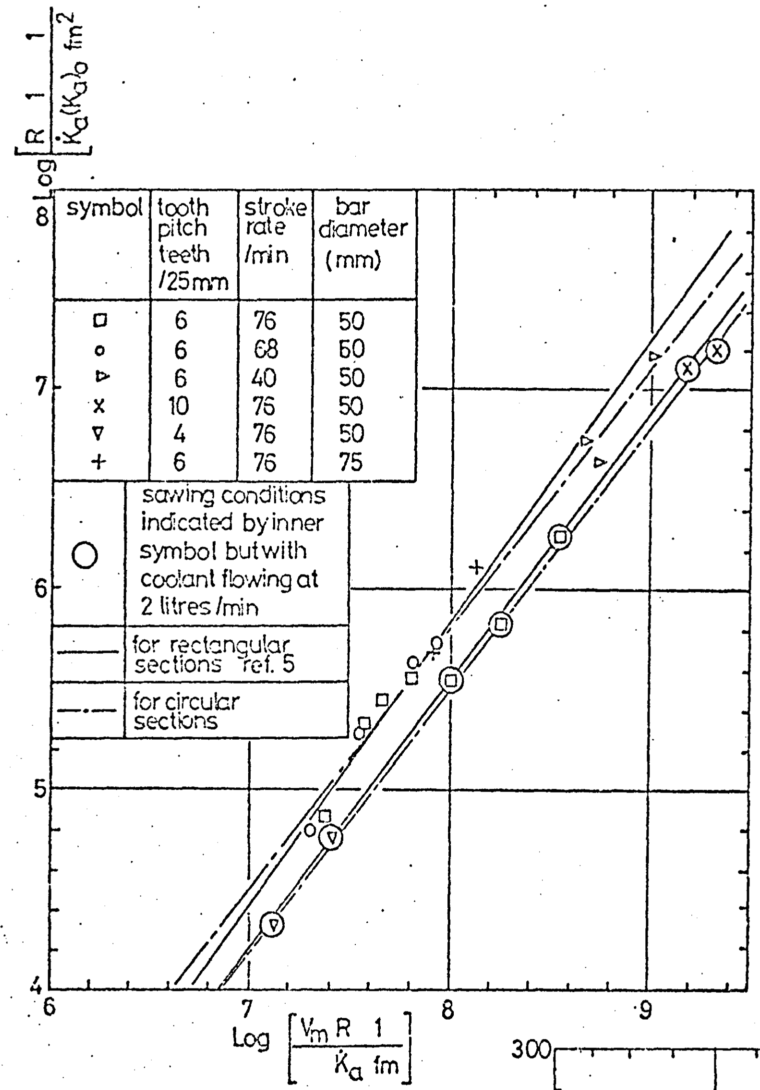


FIGURE 78.
A Log-Log plot of the variables in the blade life equation.

[68]

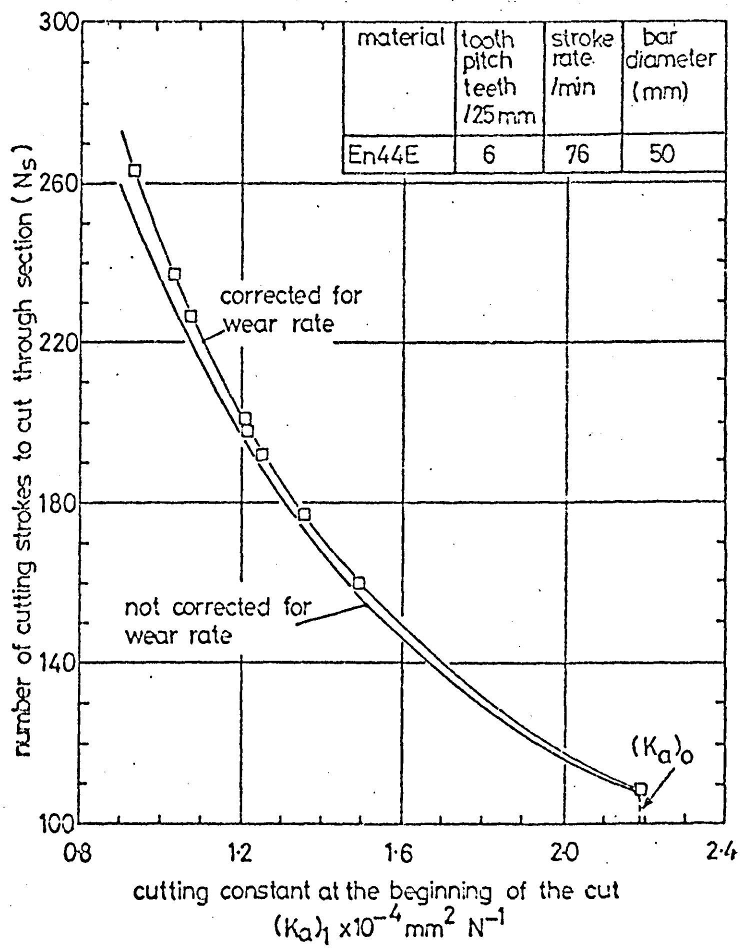


FIGURE 79.
The number of cutting strokes needed to cut through an En44E section 50 mm dia. against the cutting constant with predictions based on (164) and (165).

[68]

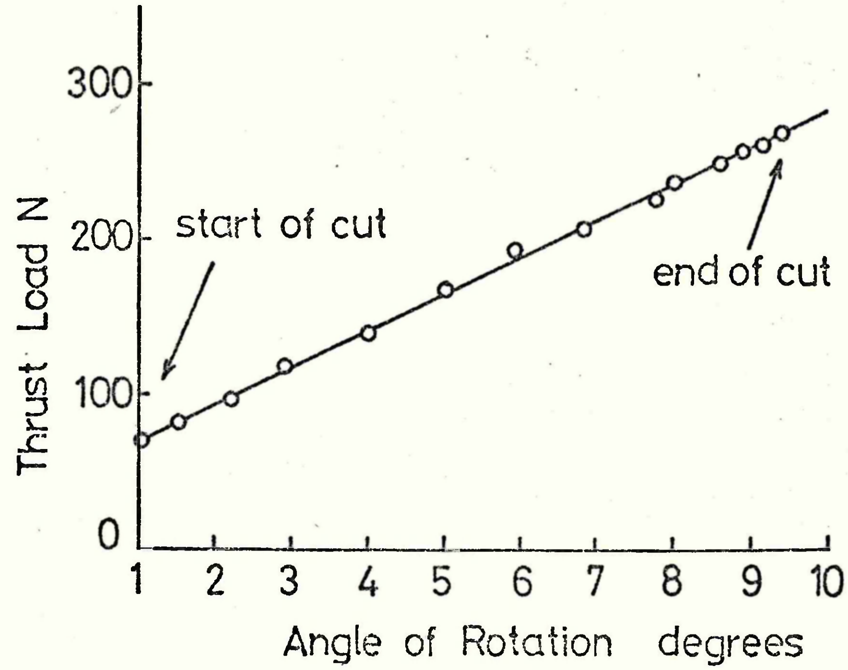


FIGURE 80.
Thrust load variation as the band passes through the workpiece before the spring system was fitted.

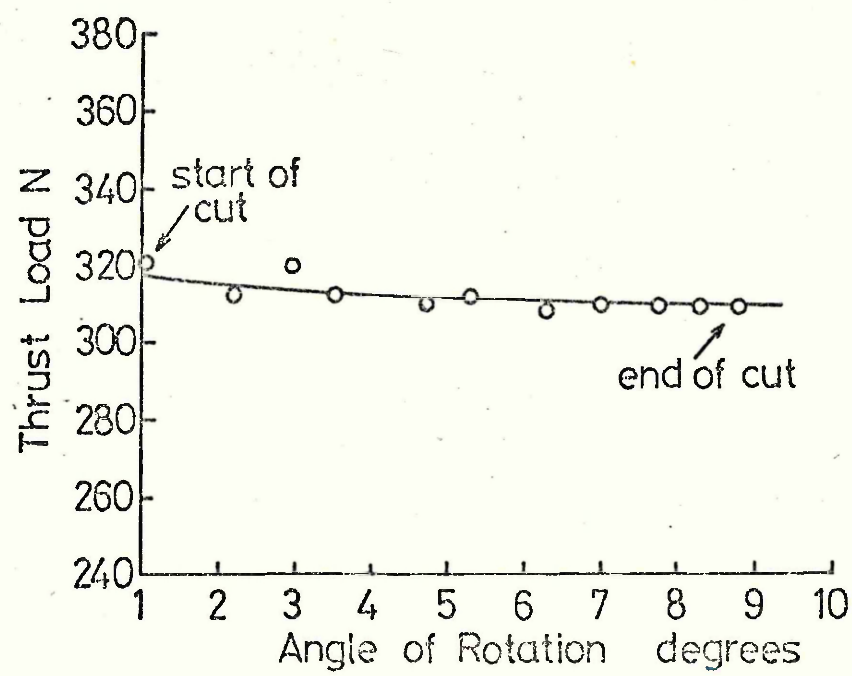
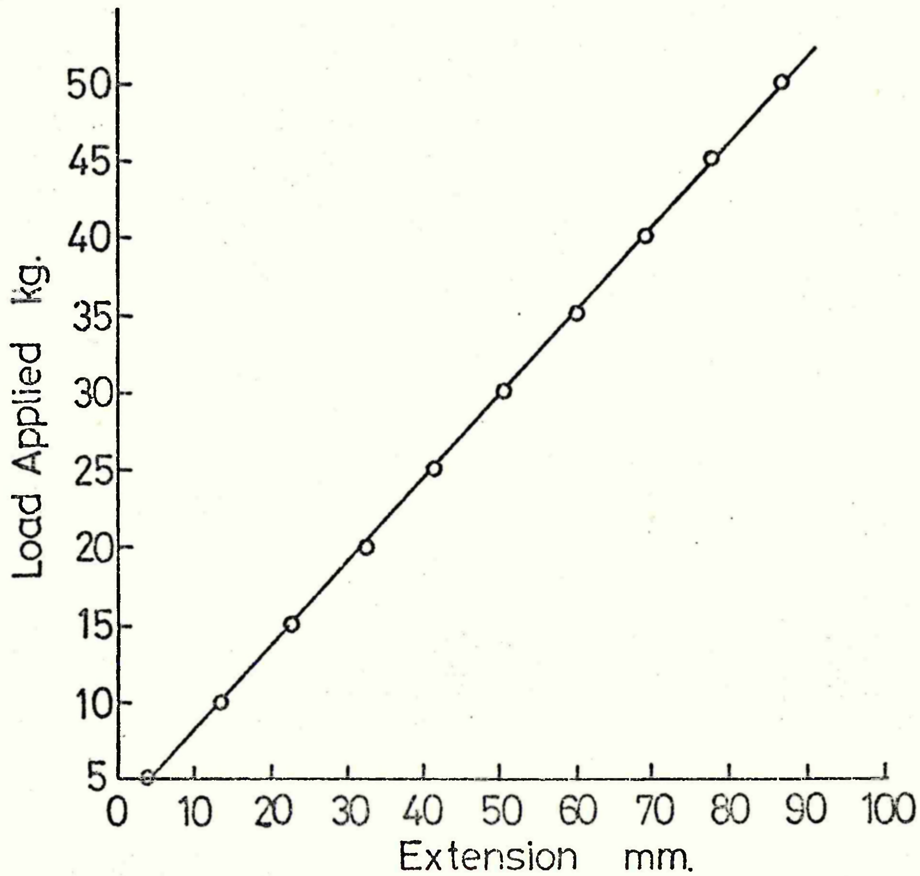


FIGURE 81.
Thrust load variation as the band passes through the workpiece with the spring system fitted.



$$\text{Spring Stiffness} = \frac{\text{Load}}{\text{Extension}}$$

$$= \frac{40 \quad 9{\cdot}81}{73{\cdot}5}$$

$$= 5{\cdot}339 \ \text{N/mm}$$

FIGURE 82.
Spring stiffness calibration.

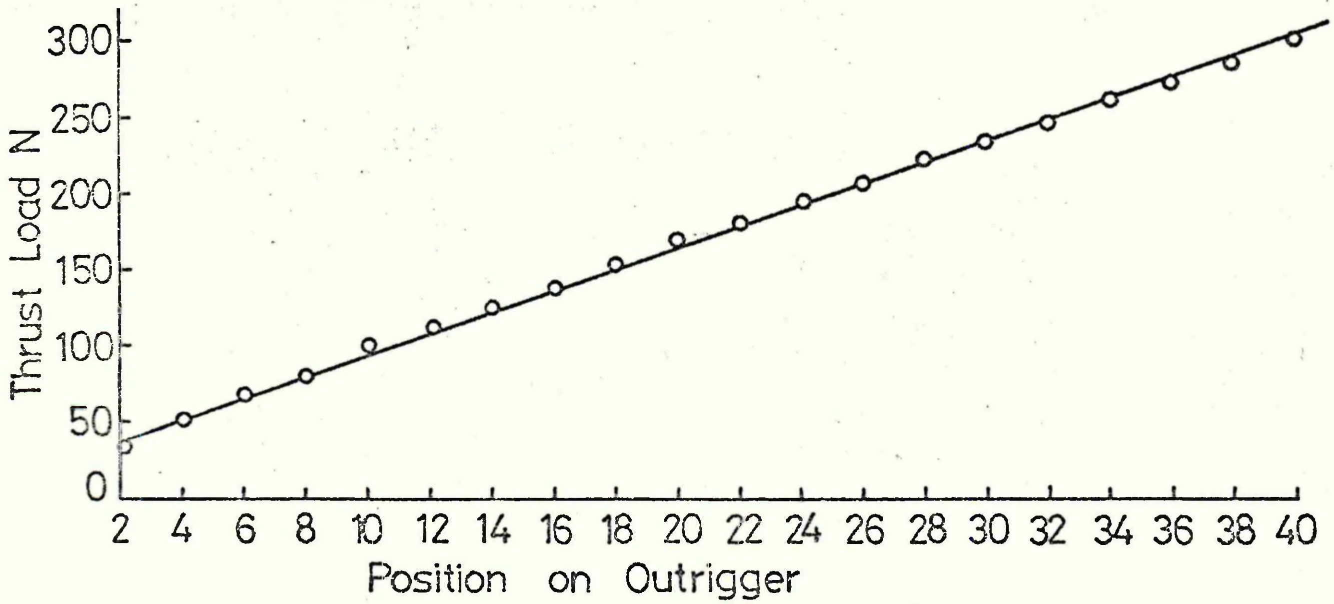


FIGURE 83.
Calibration chart for
the single jockey
weight system.

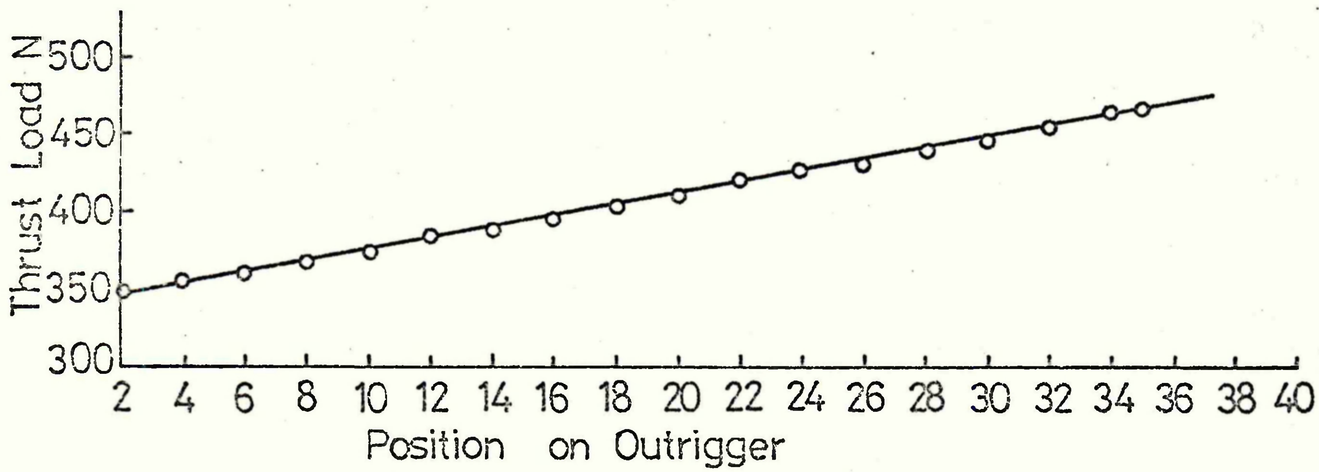


FIGURE 84.
Calibration chart for
the double jockey
weight system.

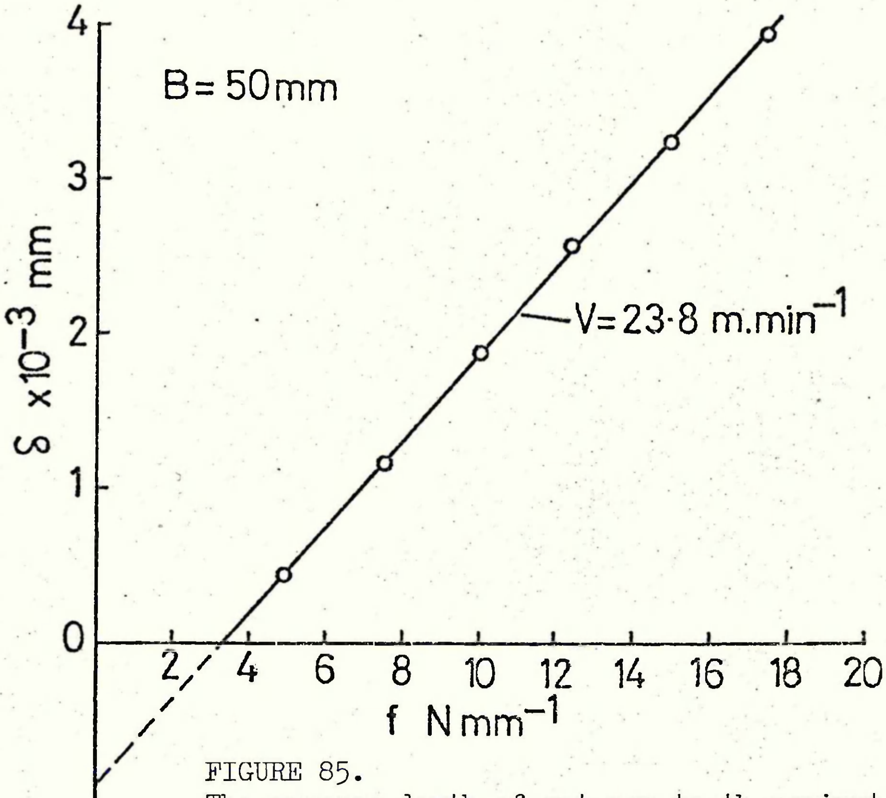


FIGURE 85.
The average depth of cut per tooth against the thrust load per tooth per unit blade thickness.

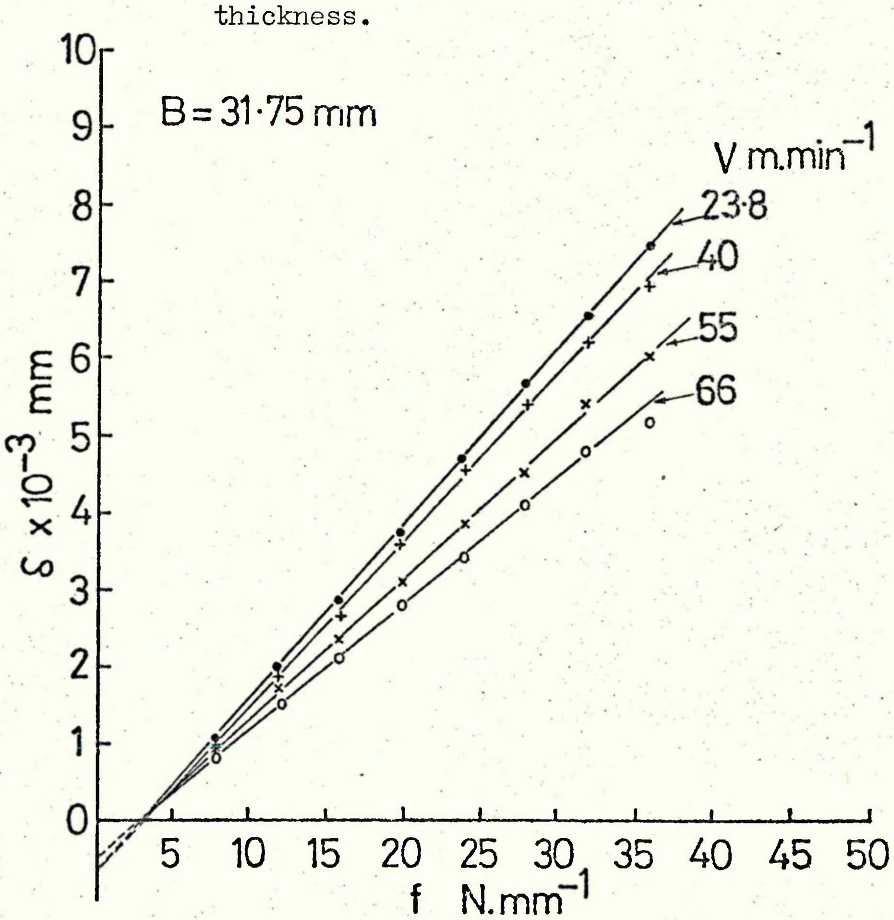


FIGURE 86.
The average depth of cut per tooth against the thrust load per tooth per unit blade thickness for various band speeds.

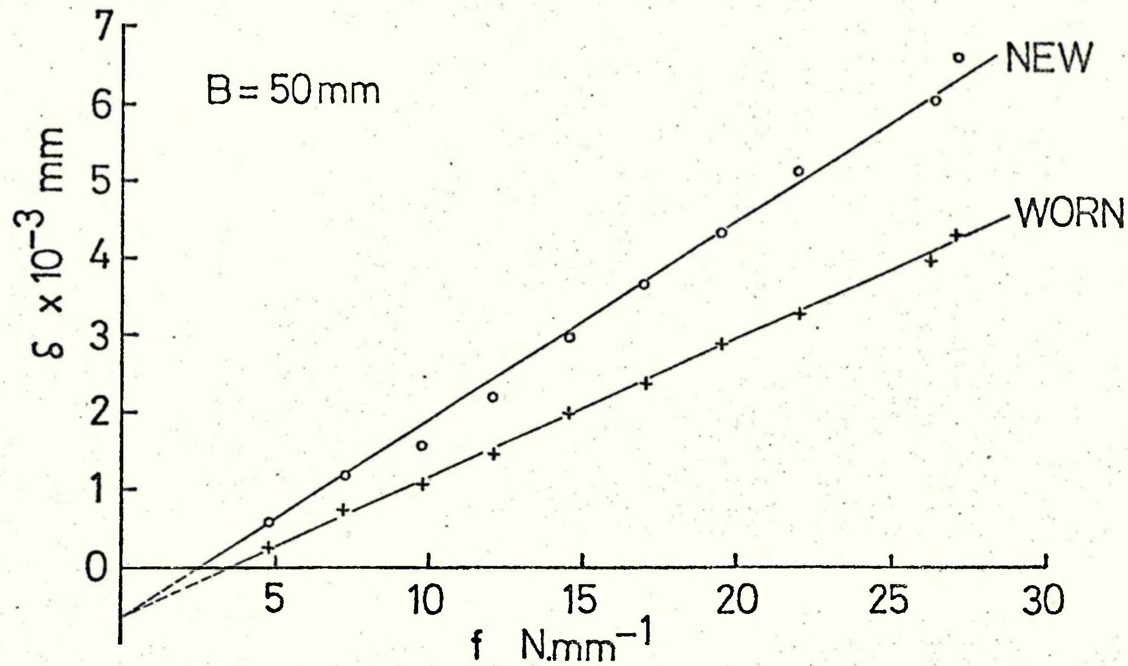


FIGURE 87.
The average depth of cut per tooth against the thrust load per tooth per unit blade thickness for new and worn conditions.

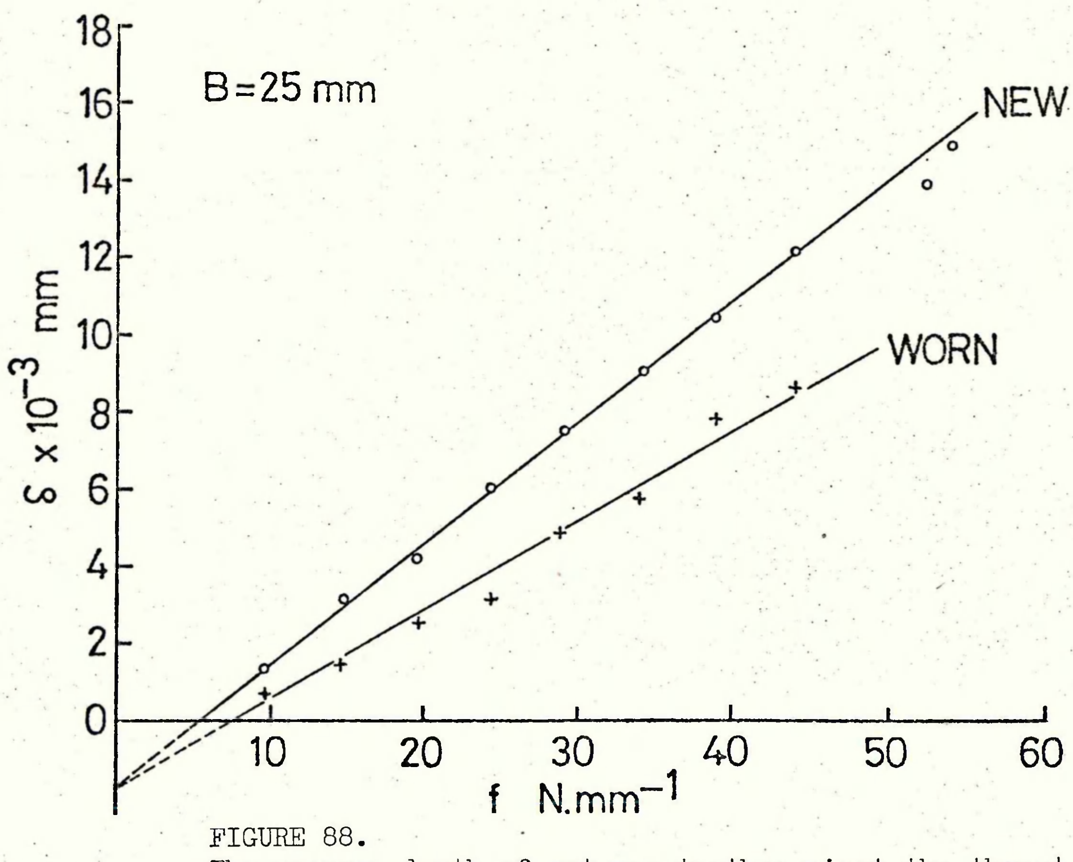


FIGURE 88.
The average depth of cut per tooth against the thrust load per tooth per unit blade thickness for new and worn conditions.

R.TAYLOR. MECHANICS OF BANDSAWING M.Phil. RESEARCH

TEST DESCRIPTION :- ______________________

Date of Test / /19 ______________________

BAND DETAILS :-
Material: ______________________

T.P.I. ____ Thickness (t) ____ mm. Slot Width (w) ____ mm.

Lengh of Band (L) ____ mm. Band No. ____________

Remarks : ______________________

WORKPIECE DETAILS :-
Material: ____________ Hardness ________ V.P.N. {@ 30 Kilo, 2/3 objective

Test Bar No. ________ Breadth (B) ____ mm Depth (D) ____ mm

Remarks : ______________________

TEST DETAILS :-
Band Speed (V) ____ m/min. = ____ mm/s

Coolant: ON/OFF Flow Rate ______ litre/min.

Coolant Type: Shell Dromus 'B' water/oil = 30/1

No. of Cuts	Jock. 1/2 position	Time min	F N	v $\frac{mm}{s}$	$K\times10^{-3}$ $\frac{mm^2}{N}$	ΣT min	Band Revs.
1		.		.	.		
2		.		.	.		
3		.		.	.		
4		.		.	.		
5		.		.	.		
6		.		.	.		
7		.		.	.		
8		.		.	.		
9		.		.	.		
10		.		.	.		
11		.		.	.		
12		.		.	.		
13		.		.	.		
14		.		.	.		
15		.		.	.		
16		.		.	.		
17		.		.	.		
18		.		.	.		
19		.		.	.		
20		.		.	.		
21		.		.	.		
22		.		.	.		
23		.		.	.		
24		.		.	.		
25		.		.	.		
26		.		.	.		
27		.		.	.		
28		.		.	.		
29		.		.	.		
30		.		.	.		
31		.		.	.		
32		.		.	.		
33		.		.	.		
34		.		.	.		
35		.		.	.		
36		.		.	.		

'Y'

$\propto$ ______

R ______

ΔK ______

K_o ______

$(f - f'_a)^2$ ______

$Y = \propto . R . \frac{1}{\Delta K} . \frac{1}{K_o (f - f'_a)^2} =$ ......

Log Y =

'X'

V ______

R ______

ΔK ______

$(f - f'_a)$ ______

$X = \frac{V . R}{\Delta K} . \frac{1}{(f - f'_a)} =$ ......

Log X =

FIGURE 89.
Mechanics of bandsawing test data sheet.

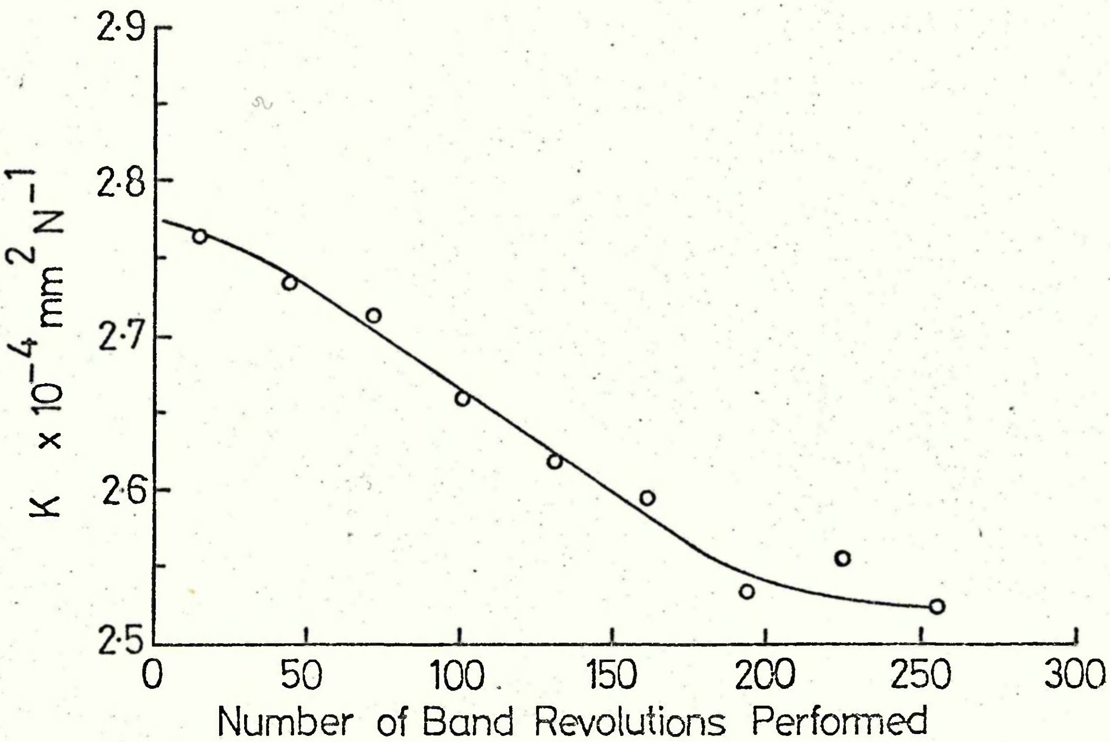


FIGURE 90.
Variation in the cutting constant against the number of band revolutions performed.

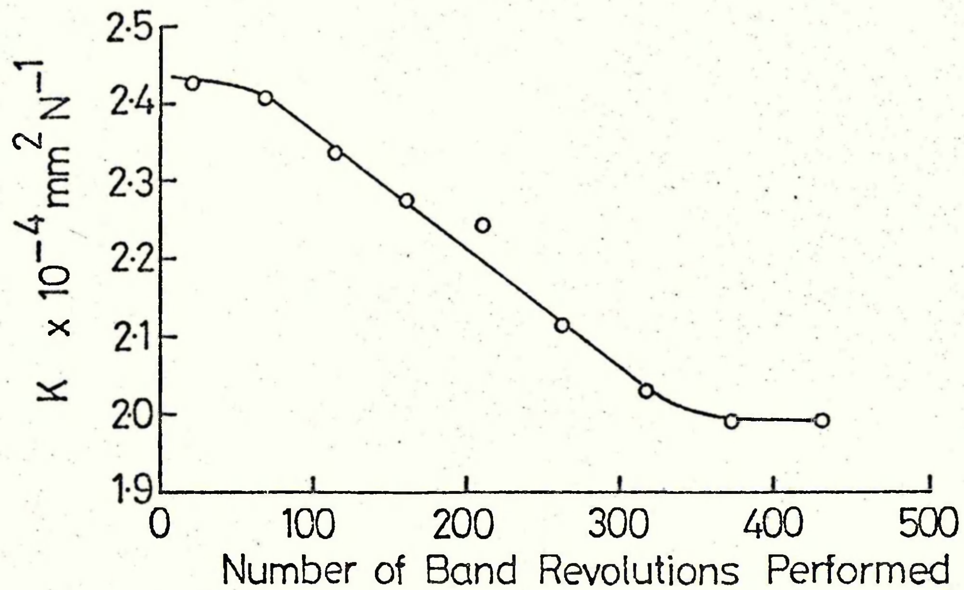


FIGURE 91.
Variation in the cutting constant against the number of band revolutions performed.

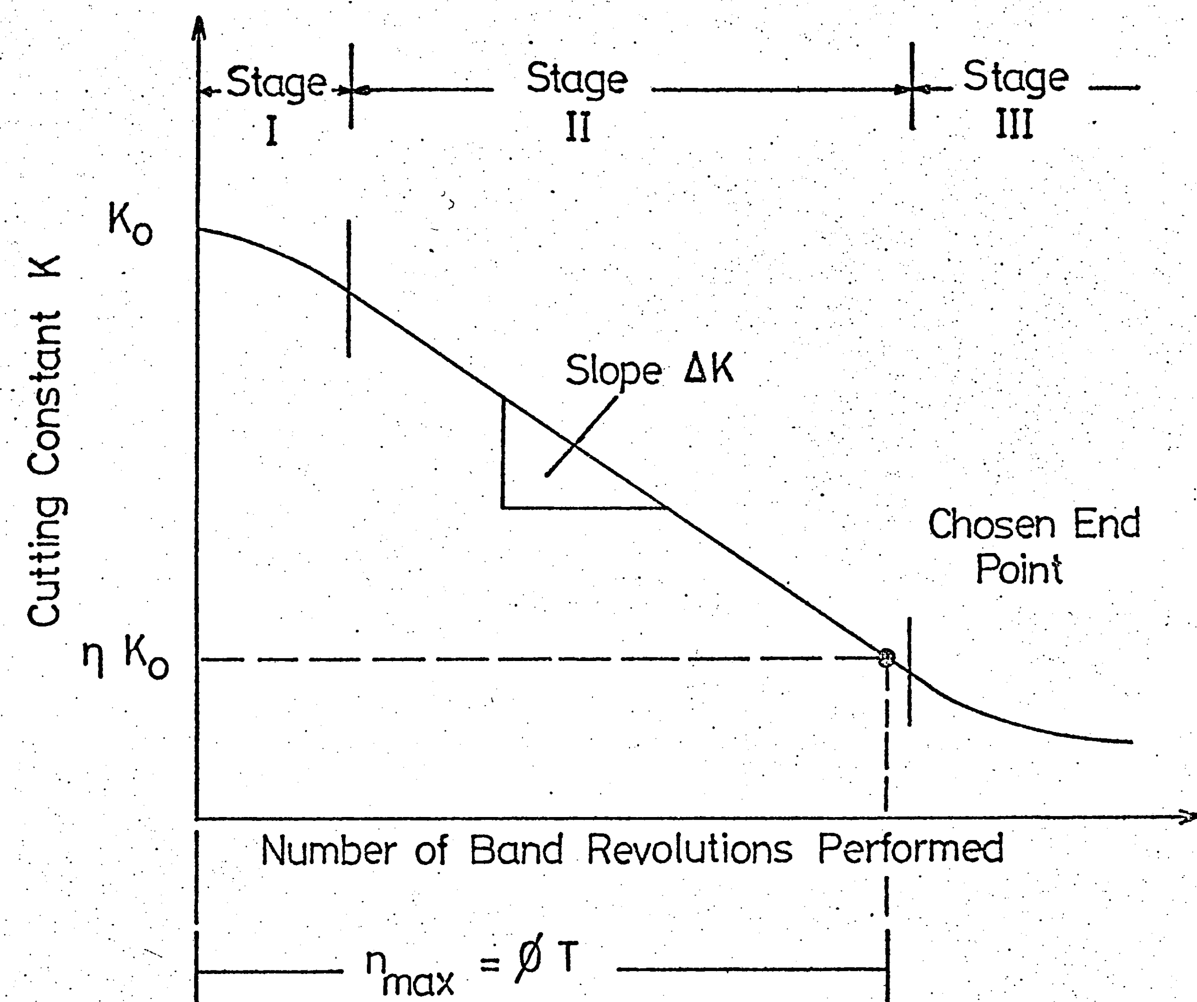


FIGURE 92.
Variation in the cutting constant against the number of band revolutions performed, showing some of the terms used.

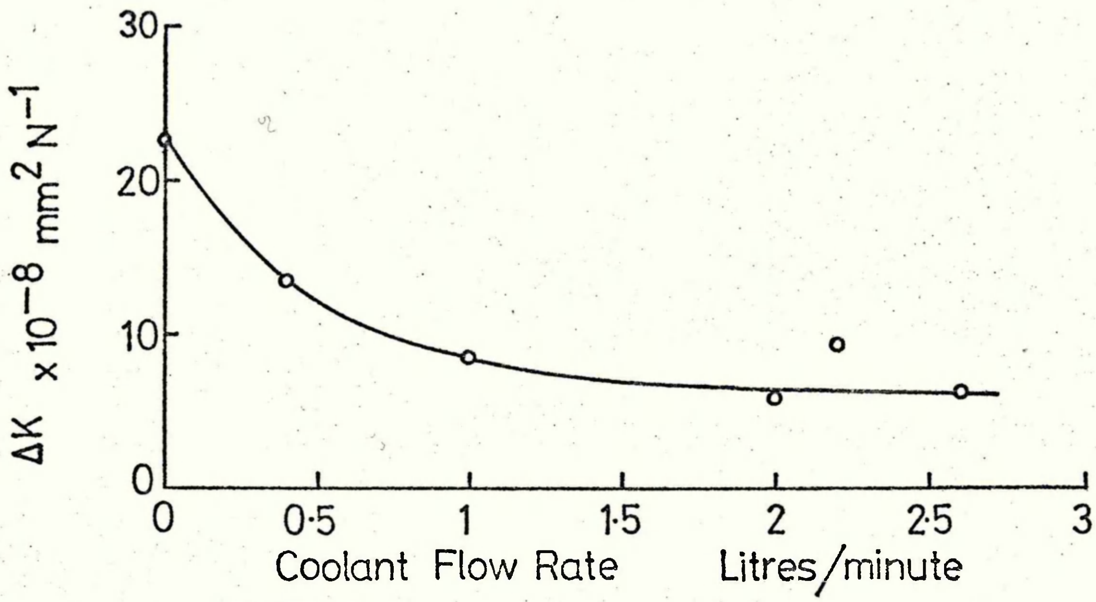


FIGURE 93.
The effect of the coolant flow rate on the change in the cutting constant per band revolution.

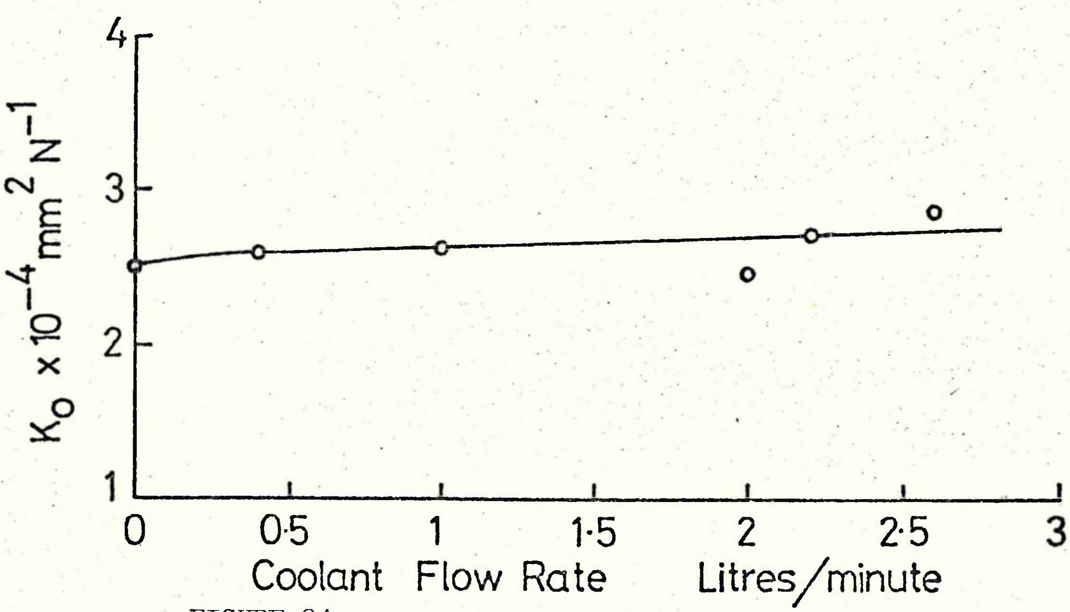


FIGURE 94.
The effect of the coolant flow rate on the initial cutting constant.

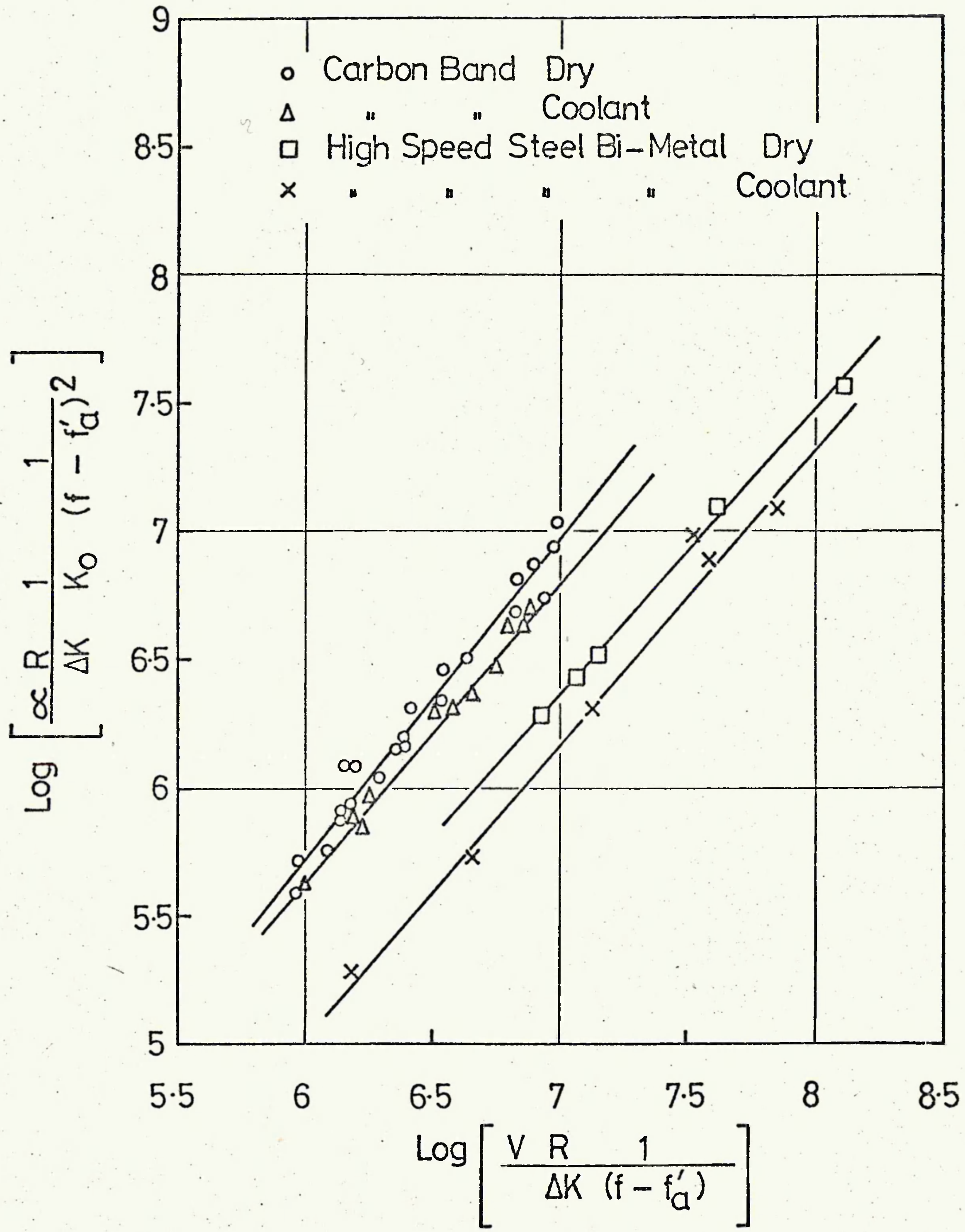


FIGURE 95.
Log-Log dimensionless plot for En44E for carbon and high speed steel bi-metal bands with and without coolant, showing the wear parameters.

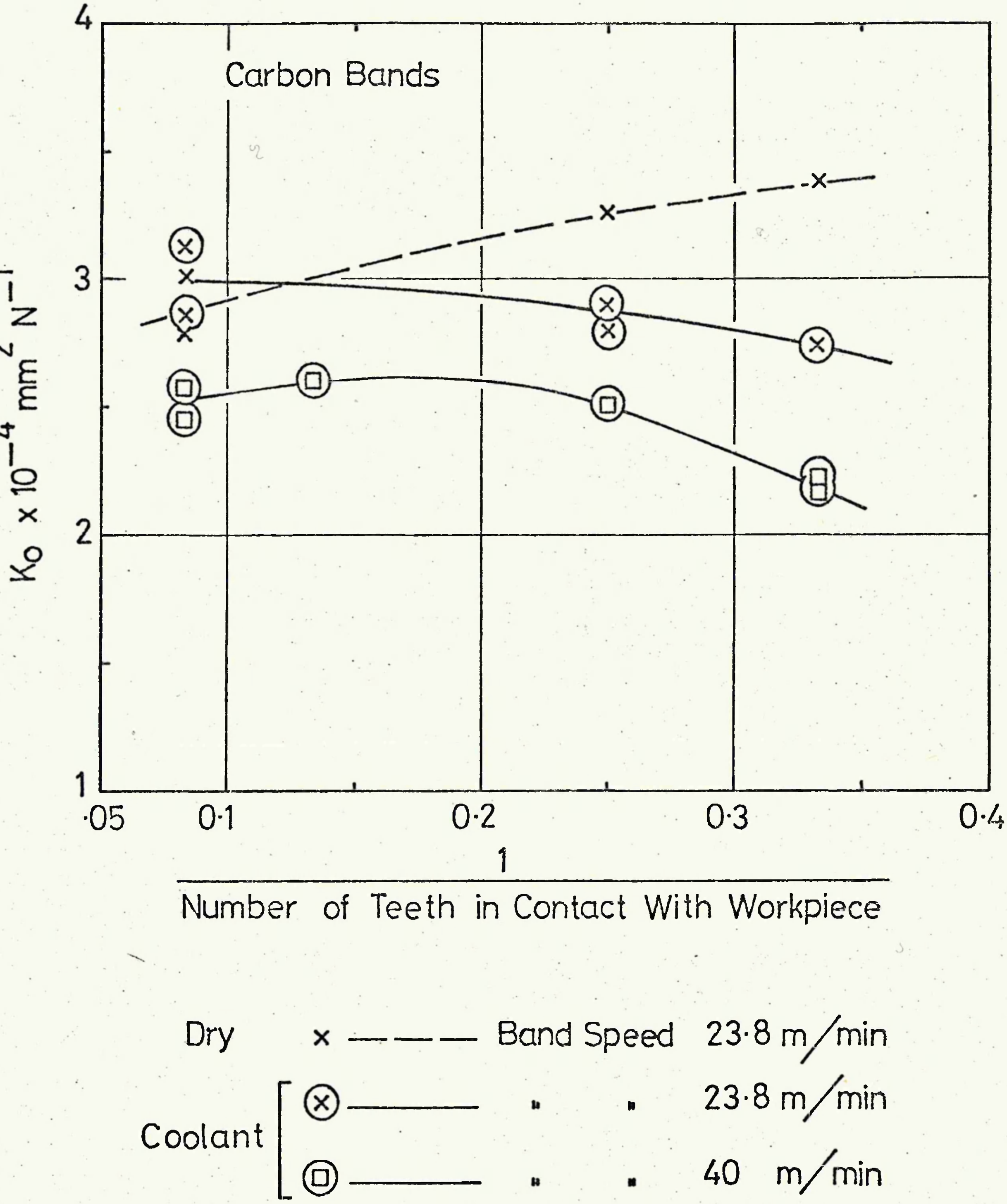


FIGURE 96.
Variation in the initial cutting constant against the reciprocal of the number of teeth in contact with the workpiece with and without coolant and for different band speeds.

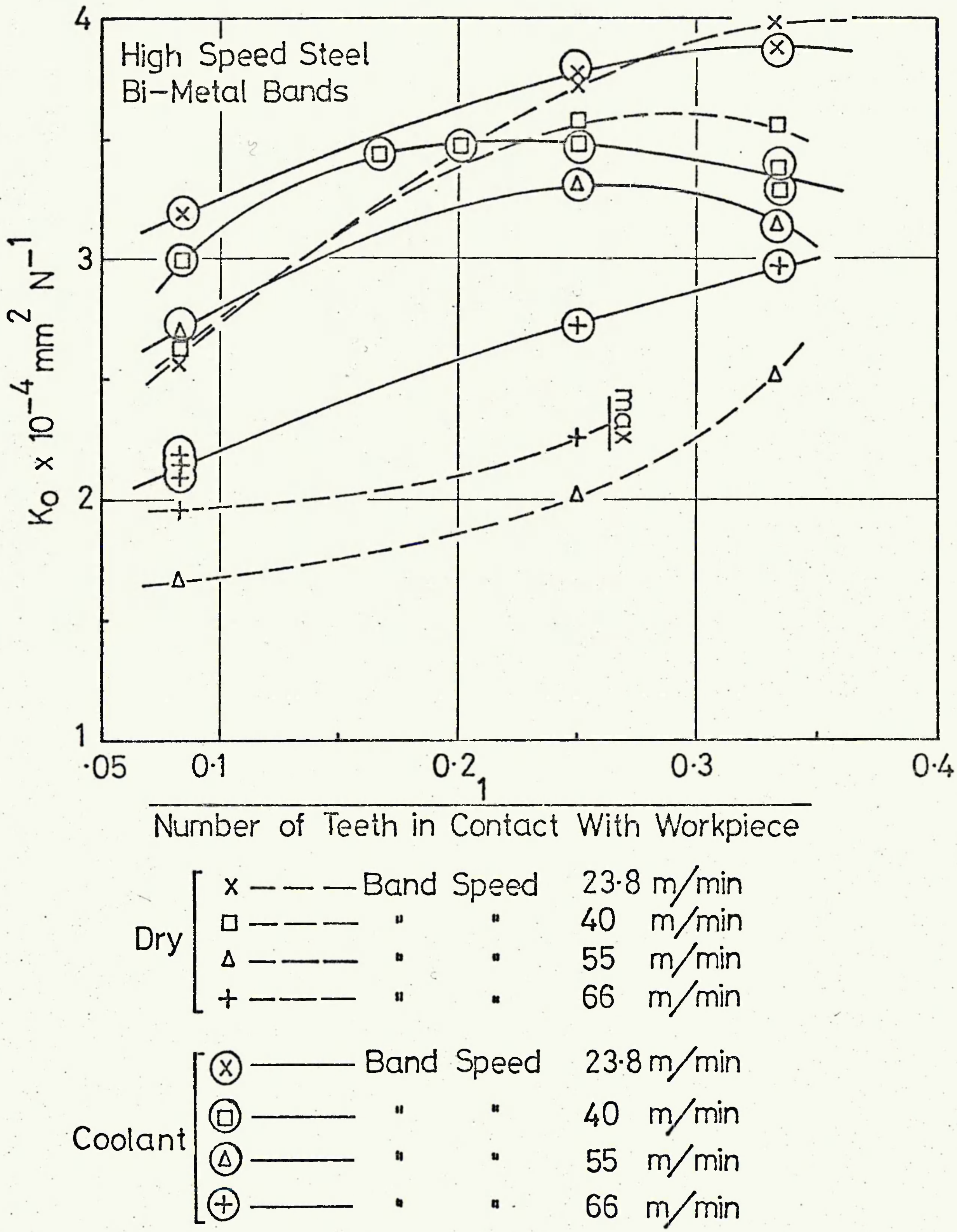


FIGURE 97.
Variation in the initial cutting constant against the reciprocal of the number of teeth in contact with the workpiece with and without coolant and for different band speeds.

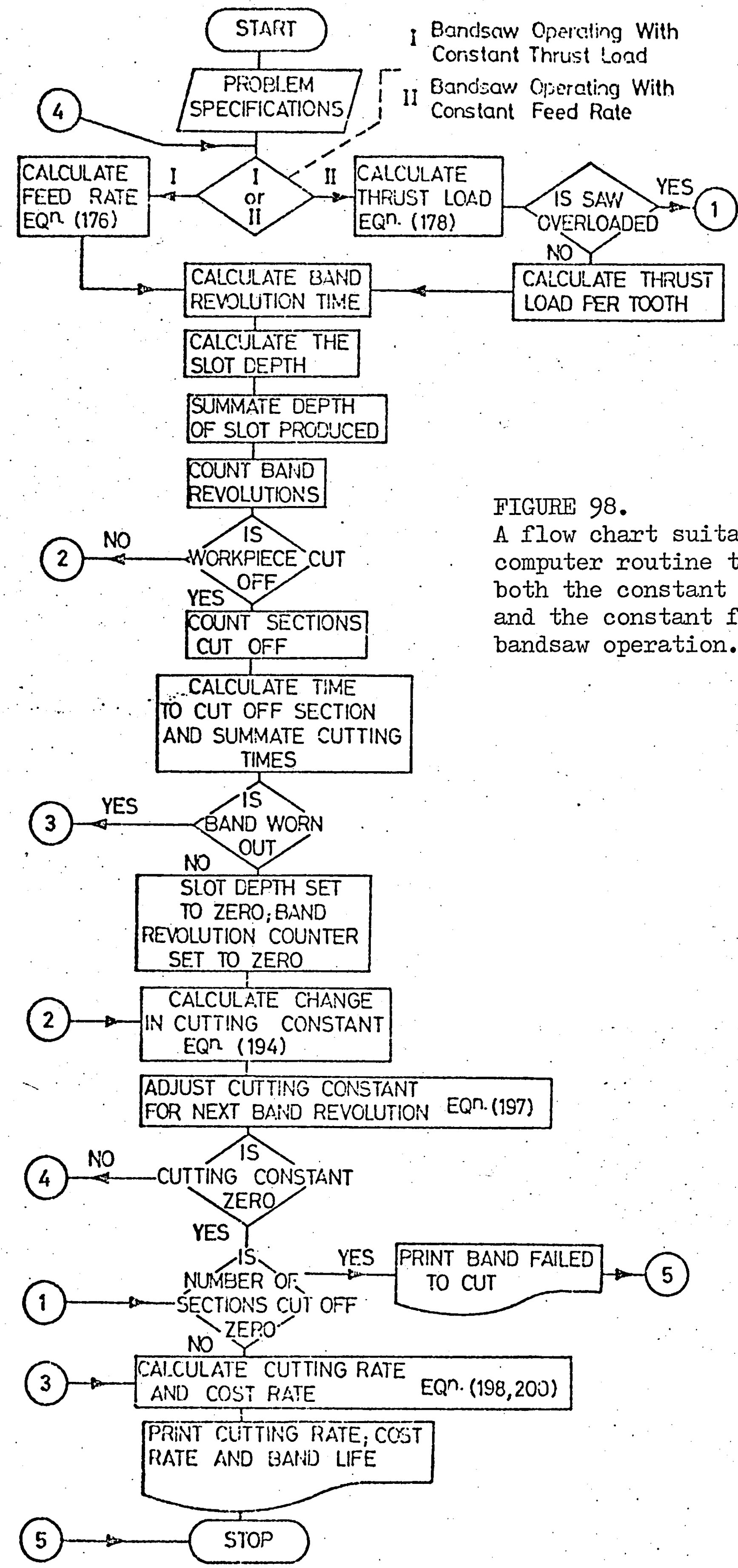


FIGURE 98.
A flow chart suitable for a computer routine to simulate both the constant thrust load and the constant feed rate bandsaw operation.

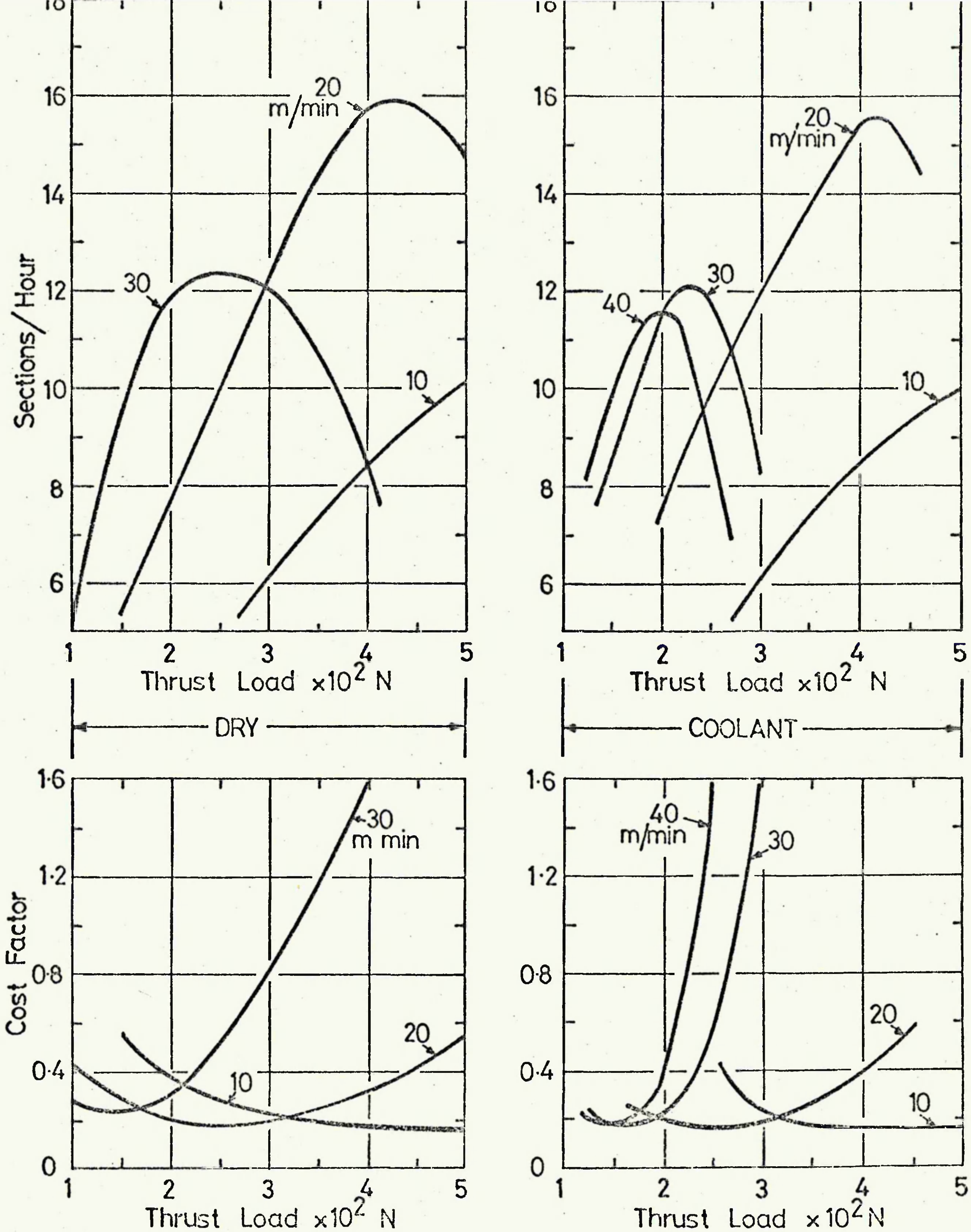


FIGURE 99.
The effects of band speed and thrust load on the average cutting rate and cost factor, for a bandsaw operating with constant thrust load and carbon blades, with and without coolant.

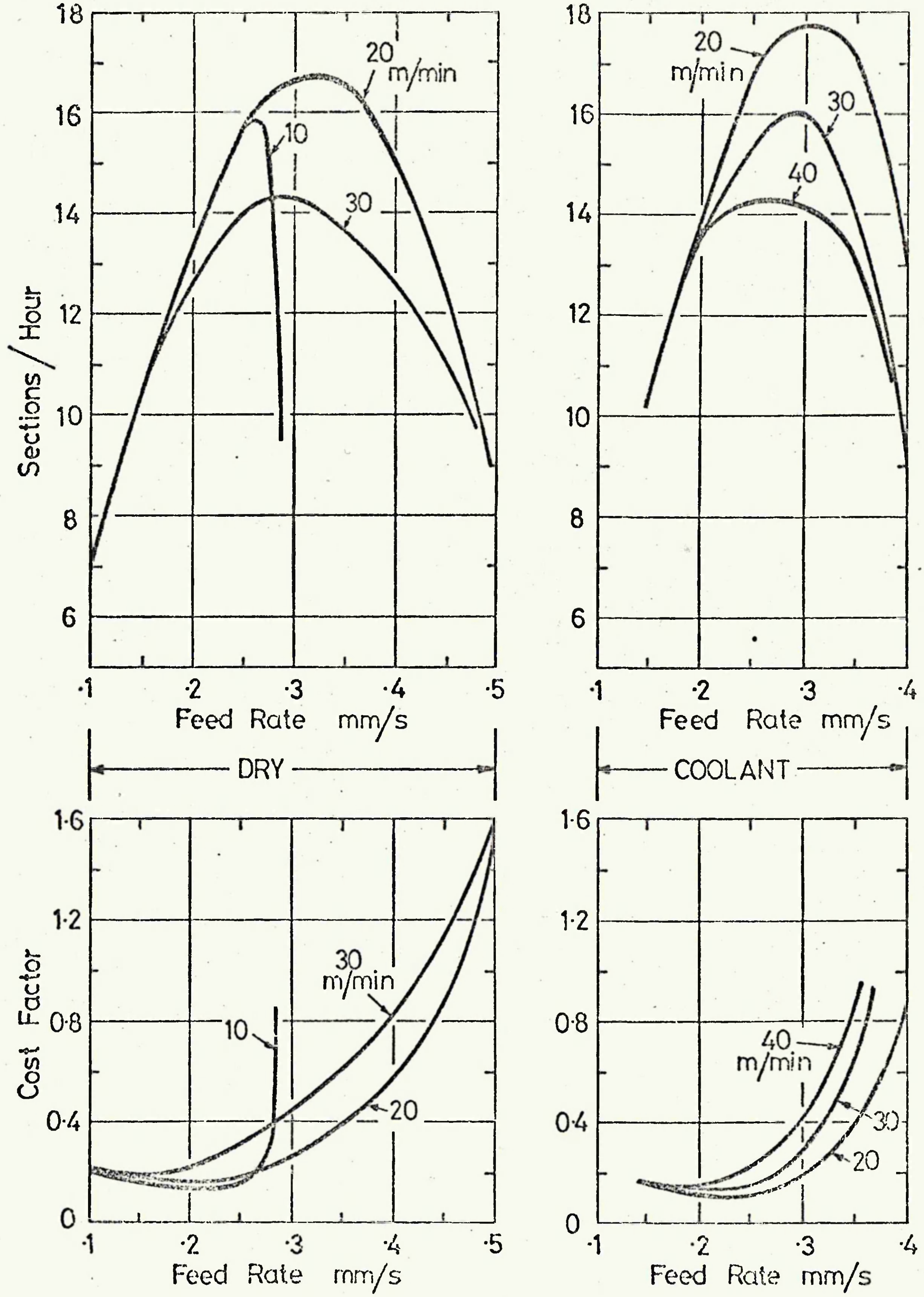


FIGURE 100.
The effects of band speed and feed rate on the average cutting rate and cost factor, for a bandsaw operating with constant feed rate and carbon blades, with and without coolant.

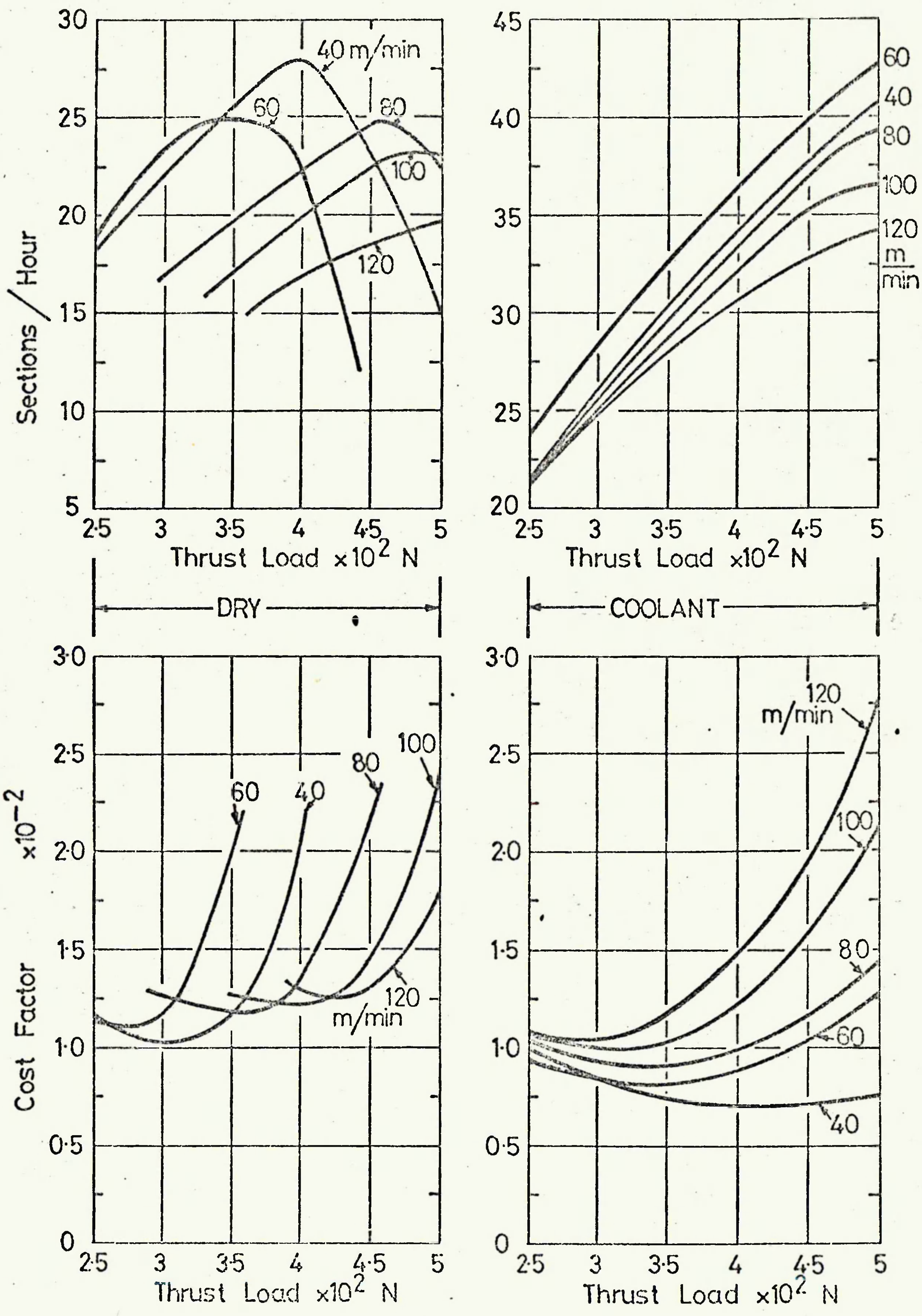


FIGURE 101.
The effects of band speed and thrust load on the average cutting rate and cost factor, for a bandsaw operating with constant thrust load and high speed steel bi-metal blades, with and without coolant.

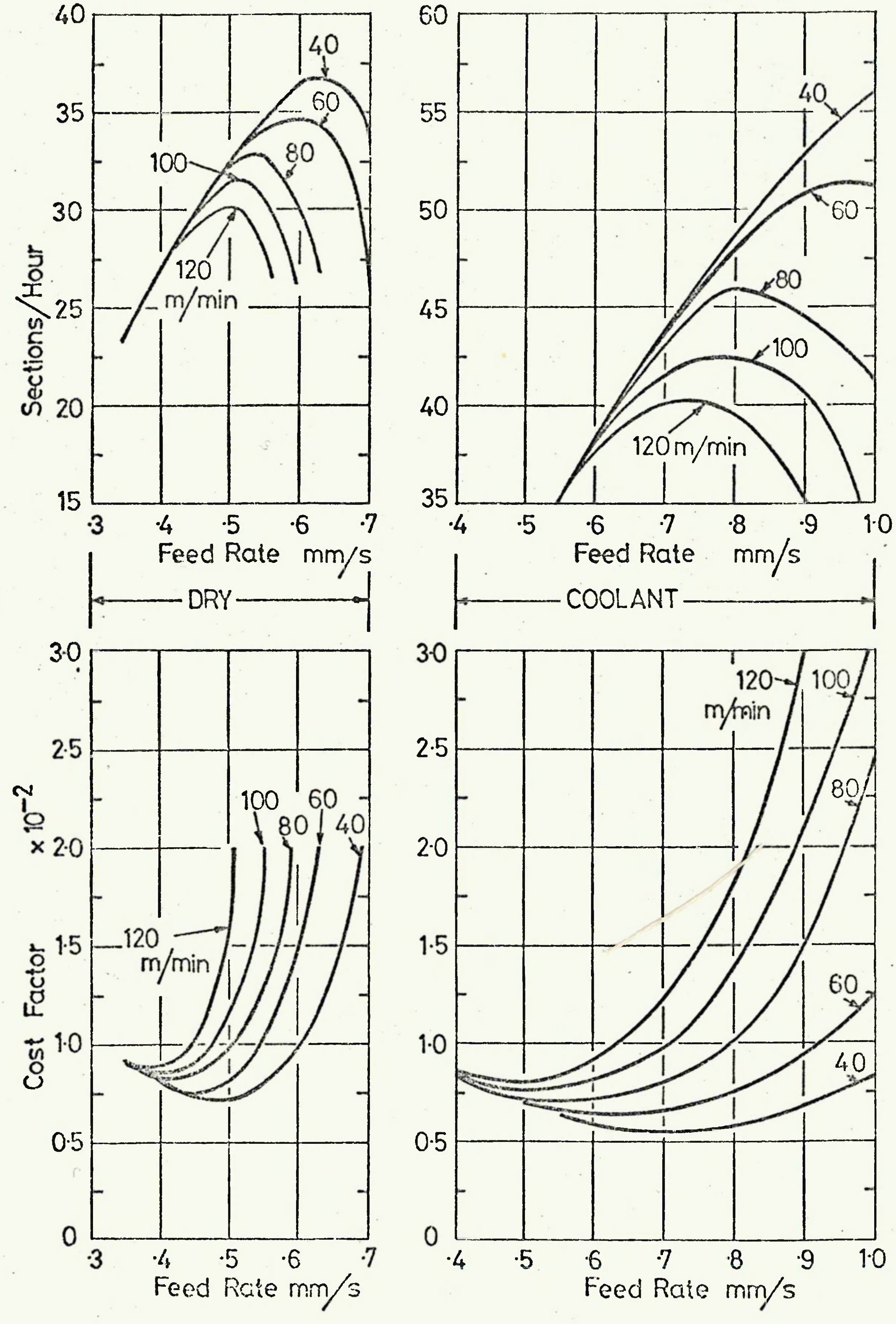


FIGURE 102.
The effects of band speed and feed rate on the average cutting rate and cost factor, for a bandsaw operating with constant feed rate and high speed steel bi-metal blades, with and without coolant.

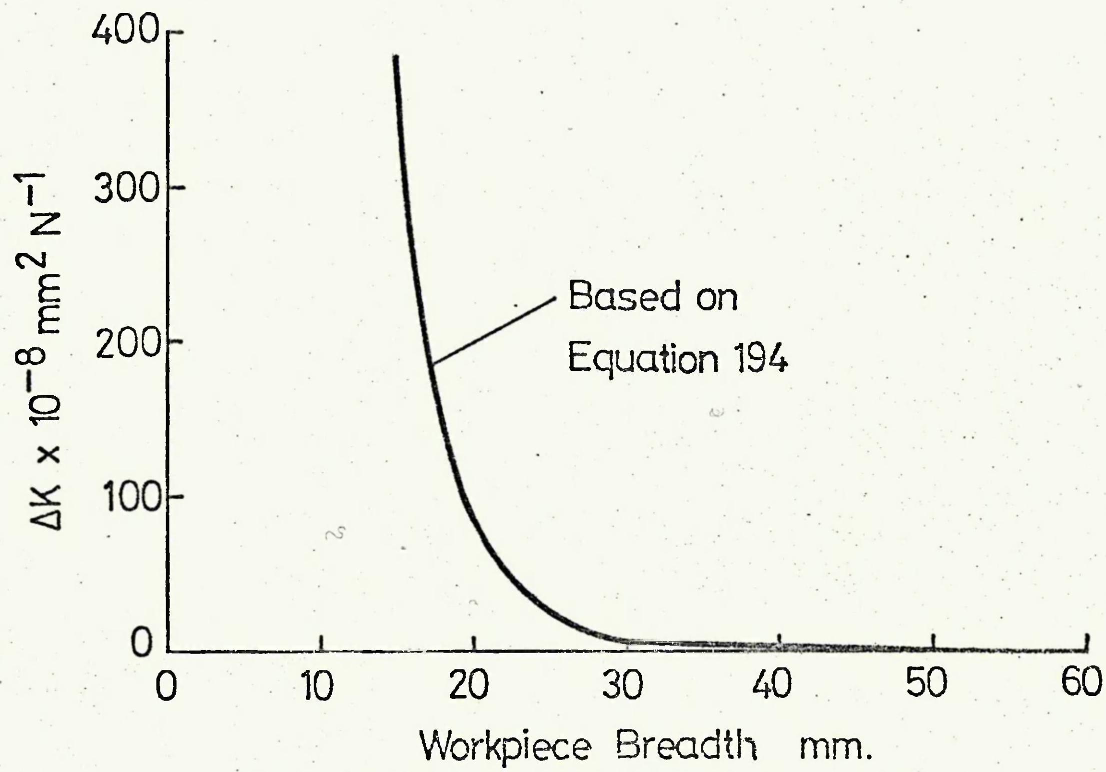


FIGURE 103.
The variation in the cutting constant per band revolution against the breadth of the workpiece, for En44E with coolant and high speed steel bi-metal band.

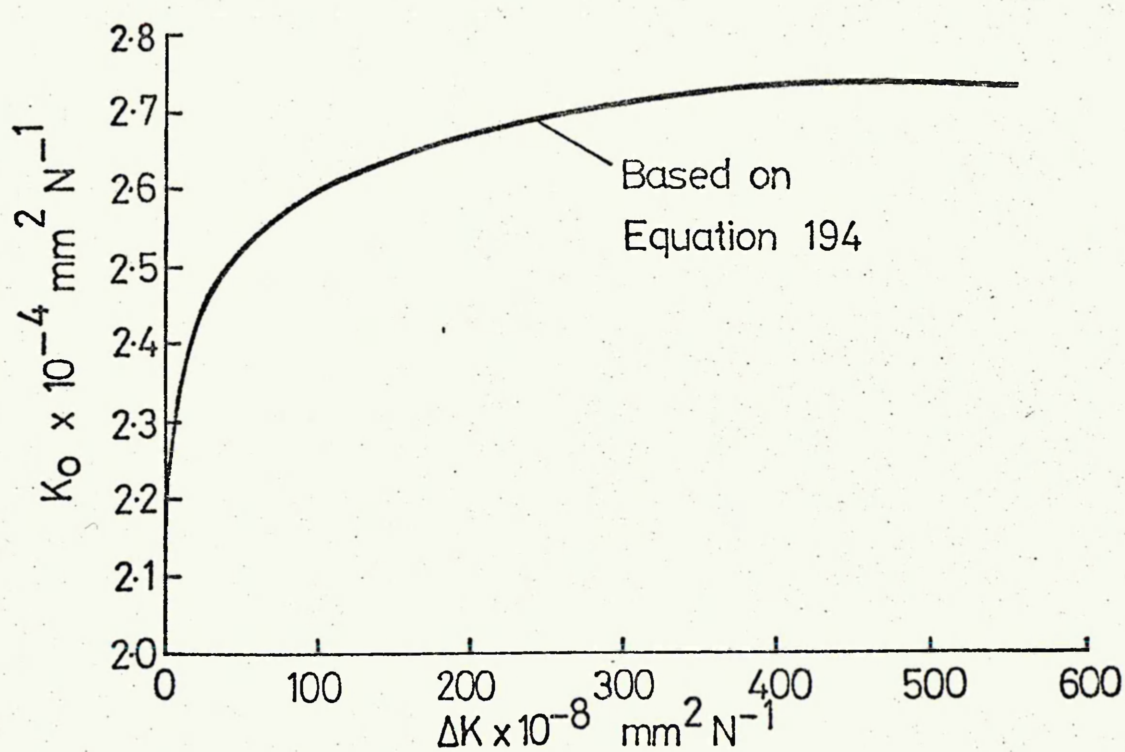


FIGURE 104.
The effect of the initial cutting constant on the wear rate, i.e. the decline in the cutting constant per band revolution.

REFERENCES

1 Thompson P. J. and Sarwar M., Power Hacksawing. Proceedings 15th I.M.T.D.R. Conf. 1974 pp. 217

2 BS 1919: 1967, London, British Standards Institution

3 BS 3877: Part 1: 1965, London, British Standards Institution

4 Sarwar M. and Thompson P. J., Simulation Of The Cutting Action Of A Single Hacksaw Blade Tooth. The Production Engineer, June 1974 pp. 195

5 Thompson P. J. and Taylor R. W., An Investigation Into Factors Influencing The Wear Rate Of Power Hacksaw Blades Using Dimensional Analysis - Blade Wear Testing. Presented to the Metal Cutting Seminar, 16th I.M.T.D.R. Conf. September 1975

6 Thompson P. J. and Taylor R. W., An Analysis Of The Lateral Displacement Of A Power Hacksaw Blade And Its Influence On The Quality Of Cut. Presented to the Metal Cutting Seminar, 16th I.M.T.D.R. Conf. September 1975

7 Thompson P. J. and Taylor R. W., A Computer Simulation Of The Power Hacksaw Operation And Its Use In Estimating Blade Life, Cutting Rate And Cost. The Production Engineer, January 1976 pp. 25 Volume 55 Number 1

8 Kislik V. A., The Wear Of Railway Engine Components. Transzheldorizdat, 1948

9 Zaitsev A. K., Principles Of The Study Of Friction, Wear And Lubrication In Machines. Mashgiz, 1947

10 Burwell J. T. and Strang C. D., Metallic Wear. Proc. R. Soc. 212 1952 pp. 470

11 Kostetskii B. I., Friction And Wear Phenomena In Machine Parts. Conf. Friction And Wear In Machines 4. Izd. Akad Nauk SSSR 1951 pp. 201

12 Kragelskii I. V., Friction And Wear. London: Butterworths 1965

13 Wright P. K. and Trent E. M., Metallurgical Appraisal Of Wear Mechanisms And Processes On High Speed Steel Cutting Tools. Metals Technology January 1974

14 Shaw M. C. and Dirke S. O., On The Wear Of Cutting Tools. Microtecnic, 10 1956 pp. 187

15 Brown R. H. and Armarego E. J. A., Tool Wear At Fine Depths Of Cut. Microtecnic, 17 1963 pp. 15

16 Taylor J., The Tool Wear Time Relationship In Metal Cutting. Int. J. of Mach. Tool Des. and Res., 2 1962 pp. 119

17 Trent E. M., Some Factors Affecting Wear On Cemented Carbide Tools. Proc. Int. Mech. Engs. 166 1952 pp. 64

18 Bhattacharyya A. and Gosh A., Diffusion Wear Of Cutting Tools. Advances in Machine Tool Design and Research, Oxford: Pergamon Press Ltd., 1965 pp. 225

19 Cook N. H. and Nayak P. N., The Thermal Mechanics Of Tool Wear. Trans. Amer. Soc. Mech. Engrs., Series B, J. of Eng. for Ind., 88 1966 pp. 93

20 Opitz H., Tool Wear And Tool Life. International Research in Production Engineering, New York: Amer. Soc. Mech. Engrs., 1963 pp. 107

21 Dorinson A., A Theory Of Cutting Tool Wear And Cutting Oil Action. Trans. Amer. Soc. Lub. Engrs., 1 1958 pp. 131

22 Taylor F. W., On The Art Of Cutting Metals. Trans. Amer. Soc. Mech. Engrs., 28 1907 pp. 31

23 Opitz H., Tool Tip Temperatures And Chemical Reactions In The Contact Zone. Annals C.I.R.P. 2 1953 pp.39

24 Colding B. N., Testing Of Machinability By Radioactive Methods. Acta Polytechnica Scandinavia Me 1, Stockholm, 1958

25 Colding B. N., A Wear Relationship For Turning, Milling And Grinding. Machining Economics, Stockholm, 1959

26 Kronenberg M., Machining Science And Application. Oxford: Pergamon Press Ltd., 1966

27 Gottwein K., Messung Der Schneidentemperatur Beim Abdrehen Von Metallen. Masch.-Bau Betrieb., 1925 pp. 1129

28 Kronenberg M., Machining With Single Point Tools. Transactions Amer. Soc. Metals. September 1940

29 Shaw M. C. and Loewen E. G., On The Analysis Of Cutting Tool Temperatures. Trans. A.S.M.E., Volume 76 1954 pp. 217

30 Herbert E. G., The Measurement Of Cutting Temperatures. Proc. Inst. Mech. Engrs., London 19 and 25 February 1926

31 Chao B. T. and Trigger K. J., Cutting Temperatures. Trans. A.S.M.E. Paper 50-A-43

32 Woxén R., Tool Life And Balance Of Heat In Lathe Work. Ingeniörs Vetenskaps Akademien, Handlingar No. 142 Stockholm, Sweden, 1937

33 Kronenberg M., Math Cuts Cost Of Machining Studies. American Machinist, Volume 93, September 1949 pp. 104

34 Trigger K. J. and Chao B. T., An Analytical Evaluation Of Metal Cutting Temperatures. Trans. A.S.M.E., Volume 73, 1951 pp. 57

35 Colding B. N., A Three Dimensional Tool-Life Equation - Machining Economics. Trans. A.S.M.E. 81, 1959 pp. 239

36 Kronenberg M., Trans. A.S.M.E. January 1951 pp. 51 Conclusion Number 6

37 Wallichs R., Schaumann H. and Schallbroch H., Testing Cutting Temperatures. Annual meeting 1938 of, Deutsche Gesellschaft Für Metall-Kunde V.D.I. Berlin

38 Barrow G., Tool Life Equations And Machining Economics. Proceedings 12th I.M.T.D.R. Conf. 1971 pp. 481

39 U.S.A.F. Report Number AD220540, US Dept. Of Commerce

40 Colding B. N., Machinability Of Metals And Machining Costs. Proceedings 2nd I.M.T.D.R. Conf. 1961

41 König W. and Depiereux W. R., Industrie Anzeiger 91 1969

42 Kronenberg M., Replacing The Taylor Formula By A New Tool Life Equation. Int. J. of Mach. Tool Des. and Res., 10 1971

43 Yellowley I. and Barrow G., Fertigung Number 1 1971

44 Tourret R., Performance Of Metal Cutting Tools. Butterworth Scientific Press 1958

45 Woxén R., Teknisk Tidskrift Mekanik H.4. Stockholm Sweden, 1931 pp. 43

46 Woxén R., A Theory And An Equation For The Life Of Lathe Tools. Ingeniors Vetenskaps Akademien, Handlingar No. 119, Stockholm, Sweden 1932

47 Ling F. E. and Saibel E., Tool Life And Temperature Relationship In Metal Cutting. Trans. A.S.M.E. Volume 78 1956

48 Brewer R. C., A Simplified Approach To The Optimum Selection Of Machining Parameters. Engineers Digest, 24, Number 9 1963

49 Colding B. N., EMK - Measurements With The Tool - Work Method. Report-Swedish State Council Of Technical Research, Stockholm, Sweden 1953

50 Takeyama H. and Murata R., Basic Investigation Of Tool Wear. Trans. Amer. Soc. Mech. Engrs., Series B, J. of Eng. for Ind., 85 1963, pp. 33

51 Judkin M. S. and Uecker W. C., Cemented Carbide Cutting Tools. Amer. Mach. N. Y., 77 1933 pp. 325

52 Crawford J. H. and Merchant M. E., The Influence Of Higher Rake Angles On Performance In Milling. Machinery, London., 81, 1952 pp. 54

53 Boston O. W., Metal Processing. Wiley, N. Y., and Chapman and Hall, London, 1941

54 Wilson F. W., (ed)., Machining With Carbides And Oxides. New York. McGraw - Hill Book Company, 1962

55 Gilbert W. W., Economics Of Machining, Machining Theory And Practice. American Society For Metals, Cleveland, 1950

56 Field M., Relation Of Microstructure To The Machinability Of Wrought Steels And Cast Iron. International Research In Production Engineering, New York: Amer. Soc. Mech. Engrs., 1963, pp. 188

57 Armarego E. J. A. and Brown R. H., The Machining Of Metals. Prentice - Hall, Inc. 1969

58 Anderson R. A., Band Machining And Friction Sawing. I. Mech. E. Proc. Conf. Technology Of Engineering Manufacture, 1958

59 Pahlitzsch G. and Willemeit A., Cutting-Off Steels With Carbide-Tipped Saws.Werskstattstechnik. 1968 58 Number 4, pp. 150

60 Barz E. and Oberwinter K., Phenomena In Fusion Sawing. Werskstattstechnik. 1966 56 Number 1, pp. 13

61 Fabrication Estimation, Part 3. Cold Sawing, Welding And Metal Fabrication, 1966 43, pp. 161

62 Nelson R. E., Bandsawing Or Hacksawing? American Machinist. 1965 109, Number 24, pp. 90

63 Remmerswaal J. L., On The Economics Of The Cutting-Off Of Metals. Int. Institution For Prod. Eng. Res. Microtechnic XV, Number 4

64 Gautschi G. H., Cutting Forces In Machining And Their Routine Measurement With Multi-Component Piezo-Electric Force Transducers. Proceedings 12th I.M.T.D.R. Conf. 1971 pp. 113

65 Thompson P. J., A Theoretical Study Of The Cutting Action Of Power Hacksaw Blades. Int. J. Mach. Tool Des. Res. Vol. 14, 1974, pp. 199

66 Lee E. H., and Shaffer B. W., J. Appl. Mech. 18, 1951, pp. 405

67 Thompson P. J., Factors Influencing The Sawing Rate Of Hard Ductile Metals During Power Hacksaw And Bandsaw Operations. Metals Technology October 1974, pp. 437

68 Thompson P. J. and Heaver G. R., The Characteristics Of Saw Operations When Cutting Circular Sections. To Be Published In Metals Technology

69 Yellowly I. and Barrow G., The Influence Of Thermal Cycling On Tool Life In Peripheral Milling. Presented To The Metal Cutting Seminar, 16th I.M.T.D.R. Conf. 1975

70 Fisher J. and Hargreaves J., The Collection And Dissemination Of Machining Data. Proceedings 14th I.M.T.D.R. Conf. 1973

71 König W. Eversheim W. and Pfau D., Systematic Determination Of Cutting Data Supported By An Information Centre. Proceedings 14th I.M.T.D.R. Conf. 1973

72 Kahles J. F. and Field M., Application Of Machinability Data Banks In Industry. Proceedings 14th I.M.T.D.R. Conf. 1973

73 Moore A. I. W., Satisfying Industry's Needs For Improved Machining Data. Proceedings 14th I.M.T.D.R. Conf. 1973

74 Sata T. Fujita N. Hiramatsu Y. Kokubo K. and Takeyama H., The Present Stage And Future Of The Machinability Data Service In Japan. Proceedings 14th I.M.T.D.R. Conf. 1973

75 Gall D. A., Adaptive Control Of The Abrasive Cut-Off Operation. Annals Of The C.I.R.P. Vol. XVII 1969, pp. 395