"Chip Breaking Performance of Cutting Tools With Unusual Forms."

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ABSTRACT

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This work shows one solution of the problem of predicting the chip breaking performance of a groove-type chip breaking device. The relationships between the dimensions of a simple grooved tool and the range of undeformed chip thickness which gives acceptable chip breaking are re-examined by conducting cutting tests on laboratory prepared tools. These experiments enable the repeatability of data to be assessed. The range of workpiece materials is also extended.

A nomogram is devised, using the results of these tests, to predict the range of undeformed chip thickness over which chips are broken satisfactorily from a knowledge of the tool dimensions. The nomogram meets one need specified in a survey of tool users in the Sheffield area which is for a simple, scientific method of fitting a chip breaker to cutting conditions. It is recognised that computers have a part to play in developing the nomogram principle and that the scope of the nomogram could be greatly increased using this medium.

In response to another requirement of tool users in industry the project is widened to consider the behaviour of some recently produced commercial tools. The aim of this investigation is to comment on the effect each profile has on the chip breaking performance of the tool. It is necessary to separate and classify features on the tools since the profiles are in some cases very complex and not easy to analyse. Assessment is made of how readily the nomogram can be applied to each of the tool-types considered.

LIST OF TABLES

NOMENCLATURE

A	=	$\dfrac{R_1 - R}{R_1}$
CC	=	Chip tool contact length.
LL	=	Land Length.
R	=	Radius of broken chip.
R_1	=	Radius of expanded chip at fracture.
W	=	Groove width.
W_{eff}	=	Effective groove width.
h	=	Undeformed chip thickness.
h_1	=	Undeformed chip thickness at onset of acceptable chip breaking.
hg	=	Undeformed chip thickness when chip begins to use the groove.
$h/_R$	=	Size ratio.
$(h/_R)$crit	=	size ratio at commencement of acceptable breaking.
n	=	material constant.
β	=	Built-up edge angle.
β_{max}	=	Maximum built-up edge angle.
γ	=	Land angle.
ε	=	Chip fracture strain.

There has recently been a proliferation of new designs of chip breaking devices and a need has arisen to provide an independent basis for the assessment of the performance of these tools. The manufacturer's information, whilst accurate and sometimes extensive, does not help the tool user to compare one tool with another, nor does it lead him to a better design if the tool in question does not quite suit his job. The problem dealt with here is one of providing a unified approach to assessing the chip breaking performance of a diverse range of devices.

Firstly, it is necessary to have a new look at the relationships between the simple-grooved tool and its chip breaking performance with the intention of re-stating the expressions in such a way as to provide a less theoretical guide to tool specification for the use of tool users in industry. The simple grooved tool referred to is one with a single, deep and curved groove which runs parallel to the cutting edge leaving a short land (figure 1). The theory to predict the chip breaking performance of this tool with reference to groove width, land length and land angle and the workpiece material has been presented previously by Worthington et al (1,2). This work is extended here to include a wider range of cutting conditions and workpieces. By building up a new set of data it was also possible to give an appraisal of the practical value of any information offered to tool users.

A survey was undertaken to discover what information the industrial users most required concerning chip-breaking problems. The findings were somewhat discouraging since, although many problems were readily acknowledged, very little thought had been given to their solution. Three main problem areas were identified:

a) Tool users and some small manufacturers are not aware of the basic principles of chip breaking and therefore they rely on trial and error methods when selecting or designing chip breaking devices.

b) Problems are more acute when machining some special steels.

c) The facilities which are available in modern tool designs are not being exploited to the best advantage.

The list of firms visited is given in Appendix A.

A number of times during this survey discussions took place with the craftsman who knew by experience exactly where to grind the chip breaking groove for each particular job and the production manager admitted that there was nothing to replace this key worker. It is perhaps because the Sheffield area has been fortunate in having excellent craftsmen in its manufacturing industry that there is now such a lack of documented information within these firms.

As automatic production lines have taken over and tungsten carbide and ceramic tools are being more widely used the problems of controlling swarf have become more serious since cutting speeds are much faster and down time is more expensive. The main work of the firms visited is automatic or semi-automatic and most firms had volumes of manufacturers' data on the wide range of sophisticated tools now available, but this information was largely of a commercial nature and was non-scientific. Advancements in sintering and coating technologies have enabled highly complex forms to be produced, for example curved cutting edges, protrusions on the tool face and multiple chip breaking grooves. Whilst these new designs may be improvements they have unfortunately added to the general confusion among cutting tool users. The approach by industry to finding the optimum tool for a particular operation is to conduct trials on a range of tools and to select the one which gives the best performance. This is an expensive approach, partly because considerable time is involved and partly because little is learned to help with a similar problem later, also it does not necessarily lead to the optimum tool configuration. There is a need for guidelines concerning the influence of tool geometry on chip breaking performance which should be presented in such a way that the cutting tool user will know the dimensions to aim for, and what he is compromising if the ideal tool is not available.

The second part of the project is concerned with providing some guidance when using these more complex chip breaking devices. The behaviour of a number of commercial tools is investigated. The contours which feature on these tools can be classified to a certain extent, for example, curved cutting edge, shallow groove and multiple groove are all features which can be identified on the range of tools examined. The assessment of the commercial tools and the subsequent guidelines are based on these features in the hope that this will facilitate the analysis of all tool configurations.

The report gives details of tests performed on the simple grooved tool and on a selection of commercial tools. A nomogram to determine the chip breaking performance of simple grooved tools has been devised using these and previous results and is presented in the report. The chip breaking performance of various commercial tools is discussed and guidelines are given for how a number of unconventional forms affect the chip breaking performance.

CHAPTER 2

A CRITICAL APPRAISAL OF PREVIOUS WORK ON GROOVE TYPE CHIP BREAKERS

2.1 Chip Formation and Modes of Chip Breaking

2.1.1 Chip Classification

In the discussion of chip control it is useful to have a method of classifying the size and shape of swarf which is produced by the machining operation. The chip classification system devised by Henriksen (3) is probably the most comprehensive and widely known system. Henriksen describes as "good" those chips with full or almost full turns and the system included a range of "ideal" and "acceptable" chips. Henriksen, Takeyama(4) and others found that acceptable chips are produced when the ratio of the radius of the expanded chip at breaking to the original chip radius is between 1.2 and 2.0 (assuming most of the expansion is elastic and the chip fractures at a point above the cutting edge, half way round, it collapses to produce a full turn chip when ratio = 2.0). Henriksen's classification is shown in figure 2.

Another important indicator of chip type and acceptability is the "size ratio" which is the ratio of the undeformed chip thickness to the radius of the broken chip. It is useful to note that the size ratio when chip breaking is acceptable is in the range of 2 to 6 times the fracture strain of the chip (2). Typically, therefore cutting a metal with chip fracture strain of say, 3% will give acceptably broken chip for size ratio (undeformed chip thickness/chip radius) of between 0.06 and 0.18.

There is remarkably little difference in the fracture strain of chips from different materials, even when the mechanical properties of the parent metal is very different (4). This simplifies the problem of transferring chip breaking information about a particular tool configuration from one workpiece material to another.

2.1.2 Chip Breaking Mechanism

The chip breaking mechanism has been described by a number of researchers, most notably Henriksen (1), Takeyama (4) and Nakeyama (5). (The chip breaker considered was usually an obstruction type but the same principle can be applied to groove-type chip breakers since once the chip has formed the breaking modes are identical). Four modes of chip breaking were described by Nakeyama (5), the most useful being that where the chip flows into the groove, is deflected by the groove heel to be curled (figure 3a) usually in a helix. The free end of the chip may then impinge on the tool flank (figure 3b) where it anchors and subsequent chip formation causes the chip radius to expand and eventually to break, usually at the point "A" where bending moment is greatest (figure 3c). This mode of chip breaking gives chips which are cool and controllable and is therefore highly suitable for industrial machining processes.

Another common mode of breaking is where the free end of the chip strikes the workpiece shoulder and subsequent chip formation causes the chip radius to expand and break often giving shorter chips than the previous mode and chips which may not be fully separated from each other, or alternatively the chip may be pushed downwards to form a coil, figure 4. Both these modes, described independently by Nakeyama (5) and Spaans (6) give rise to high, intermittant cutting forces and are therefore undesirable. If there is some sideways curl the chip is more likely to miss the workpiece shoulder and strike the underside of the tool. Once the chip has made contact with the tool flank it has two alternatives, either to anchor and break in the mode described previously (figure 3) or it may slip and a helixical chip will form which may break under its own weight after a short time, or it could form infinitely long helices which must be broken manually.

2.1.3 Controlled Contact Length Cutting

In order to understand the action of chip breaking devices on some, more complex tools it is necessary to consider more fully the conditions at the chip-tool interface. When metal is cut with a plain rake face tool there is a layer of stagnant workpiece material at the tool rake face known as the "built-up layer", sometimes this layer becomes work hardened and a number of layers build up to form a substantial structure known as the "built-up edge". This built-up edge, which may break away and re-form intermittantly, has been claimed by some researchers to be responsible for the natural chip curling process (5). The groove-type chip breaker, however, resembles more the cut-away or "controlled contact length" tool as described by Usui (7).

When metal is cut and continuous chips are formed with no built-up edge, the friction conditions are such that the chip apparently adheres to the tool for some distance from the cutting edge, figure 5. Close examination of the zone of chip-tool contact reveals two regions: the region close to the cutting edge where the real and apparent areas of contact are almost identical and the region further from the cutting edge where contact is between asperities only. These are respectively known as the regions of sticking friction and sliding friction. The contact length can be artificially controlled by relieving the tool in the area of chip-tool contact, and an improved tool life may be realised by the reduction of friction and temperature at the tool tip. When cutting with restricted contact length tools Usui (7) showed that a special plastic field exists on the land and is very much like a built-up edge in appearance. The special built-up edge appears to remain stationary on the land with the chip flowing over it, thereby causing the effective rake angle of the tool to be more positive. The chip will flow over the special built-up edge and then must change direction, figure 6, which causes the chip to be formed curved. The degree of this "natural" curl is determined by the effect of the reaction force on the built-up edge as the chip changes direction.

The groove type chip former has a short land and can behave as a controlled contact length tool, with the special built-up edge forming on the land. Worthington(1) investigated this further and found that when the undeformed chip thickness is such as to allow the length of the sticking friction zone to equal the land length of the tool, the chip will be formed straight, streaming at an angle equal to the special built-up edge angle.

2.1.4 Operation of Groove type Chip Formers

Worthington was then able to propose a method of operation for groove type chip formers. The chip streams into the groove and the free end is deflected upwards as it impinges on the groove contour. The free end of the chip then leaves the groove and the chip is formed across the groove making no contact with the groove profile. The radius of the chip is determined by the built-up edge angle and the width of the groove, figure (7).

The chip is plastically deformed at this radius and can be broken in the ways suggested by Nakeyama (5). The formed radius, R of the chip can be determined from the geometry (figure 3) as the groove width, W is divided by twice the angle of the special built-up edge, β or:-

$$R = \frac{W}{2 \sin \beta'} \qquad - \qquad (1)$$

There will be some elastic recovery of the chip as it leaves the groove, but since the chip deformation is mostly plastic the change in radius is negligible. Also, when the end of the chip encounters the tool flank the subsequent expansion in chip radius is mostly elastic. In experimental work it is assumed that measurement of the broken chips gives an accurate value for the formed radius of the chip. According to Zorev's (8) theory concerning the built-up edge angle, the special built-up edge will never exceed forty five degrees and therefore, unless stated otherwise, the groove inlet angle is made equal or greater than forty five degrees to ensure the groove profile never interferes with the chip (in many cases the maximum built-up edge angle is thirty degrees).

2.2 Relationships between the configuration of the simple groove type Chip Former, the workpiece material and the Chip breaking performance of the tool.

Work by Worthington et al (1,2) has led to a number of expressions which comprehensively describe the relationship between chip curl radius, undeformed chip thickness and tool geometry. The relationship between undeformed chip thickness and size ratio has been shown to be linear (1) with a gradient dependant on the workpiece material and the groove width:-

$$\frac{1}{R} = \frac{n}{W}\left(1 - \frac{hg}{h}\right) \qquad \text{———} \quad 2$$

where: n = constant for the particular workpiece.

h = undeformed chip thickness.

hg = undeformed chip thickness when the chip begins to use the groove.

At values of undeformed chip thickness less than hg the chip is assumed to be unaffected by the groove and is either streaming or curling naturally.

Once the undeformed chip thickness is sufficient to allow the chip to enter the groove the chip radius decreases with an increasing built-up edge angle and the relationship (2) is true providing the groove profile does not interfere with the chip flow. From equation (1) we can find the minimum chip radius :-

$$R\ min = \frac{W}{2\ \mathrm{Sin}\ \beta\ max}$$

Where β_{max} is the maximum built-up edge angle (which is never greater than 45° and is more usually about 30°).

Other experimental results (1) show that the chip will begin to "use" the groove at a value of underformed chip thickness, hg which gives the length of the sticking friction zone equal to the land length of the tool. This value of the undeformed chip thickness, hg is influenced by the configuration of the land and by the workpiece material. It can be shown (1) that the size ratio, h/R is related to chip fracture strain:-

$$\mathcal{E} = \frac{h}{R}\ A \qquad \text{———} \quad 3$$

where $\mathcal{E}$ = fracture strain of chip

R = formed radius of the chip

$$A = \frac{R_1 - R}{R_1}$$

and R_1 = expanded radius of the chip at fracture.

Applying the values of R/R_1 for acceptable breaking i.e., between 1.2 and 2.0 then A is between 0.166 and 0.5 when breaking is acceptable. Suitable rearrangement of equation (3) and substitution for A give the range of breaking in terms of fracture strain.

$$\left(\frac{h}{R} \right) = 2\,\varepsilon \text{ at the commencement of acceptable breaking.}$$

$$\left(\frac{h}{R} \right) = 6\,\varepsilon \text{ when "overbreaking" commences.}$$

It is useful to re-arrange in terms of undeformed chip thickness by substituting in equation (2):-

$$h_1 = \left(\frac{h}{R} \right)_{crit} \left(\frac{W}{n} \right) + hg$$

where h_1 = undeformed chip thickness at commencement of acceptable breaking.

$(h/R)_{crit}$ = size ratio when acceptable breaking commences.

and $$h_2 = 3 \left(\frac{h}{R} \right)_{crit} \left(\frac{W}{n} \right) + hg$$

where h_2 = undeformed chip thickness at the commencement of overbreaking.

2.3 The Influence of Fundamental Parameters

2.3.1 Groove width

The relationship between groove width and the chip breaking performance is given by a rearranged form of equation above :-

$$h = \frac{h.W}{R.n} + h_g \qquad \text{———} \qquad (4)$$

which is shown graphically in figure 8 for a number of the groove widths.

A number of effects can be noted as the groove width is increased:-

(a) The range of feeds for acceptable chip breaking increases. The slope of the h/R v.h. graph is equal to n/W but since n is constant for a particular workpiece it is the groove width which determines the slope of the graph and hence the chip breaking range.

(b) The lowest feed for acceptable chip breaking is higher.

(c) From, $R = W/2 \sin \beta$ the chip radius at a particular feed is larger as groove width is increased.

The effective width of a groove will be changed by changes in the direction of the chip flow. If the chip flow direction is $\emptyset^{o}$ to the cutting edge then the groove width will be effectively increased by a factor of $1/\cos \emptyset^{o}$. The chip flow direction is influenced by the nose radius and chip width and by the inclination angle of the tool (9).

The direction of the chip is particularly important when there is a groove in each face of the tool - as is described later.

2.3.2 Land Length and Land Angle

The configuration of the land is an important factor in that it determines when the chip begins to "use" the groove. On a plot of size ratio against undeformed chip thickness (figure 8) the undeformed chip thickness, hg, which causes chip streaming and, therefore, causes the chip to begin to use the groove is found where size ratio equals zero.

The radius of the formed chip increases with increase in land length for a particular undeformed chip thickness. The greater the land length, the greater the value of undeformed chip thickness for chip streaming and the undeformed chip thickness at which acceptable breaking commences.

The relationship between land length and hg value is shown in figure 9. The gradient of the graph is dependant on the land angle, typically when the land angle is 90° then

$LL = 0.4\ hg$

The presence of the special built-up edge allows negative land angles to be used effectively and the value of hg is lower than it would be with a tool with the same land length but positive rake angle.

2.3.3 Workpiece Material

The influence of the workpiece material on the chip breaking performance of a tool is represented by the factor "n" in the relationship:-

$$h = \frac{h}{R} \cdot \frac{w}{n} + hg \qquad (4)$$

The value of "n" is found to be very similar for a selection of plain carbon steels, as seen in table 1, and only varies significantly with major changes in the properties of the workpiece. The variation in the mechanical properties of the swarf from different materials was found by Takeyama (10) to be very much less than the variation between the properties of the parent metals. Takeyama (10) gives some results for a shallow groove-type chip former and concludes that the higher the carbon content of the parent metal the more difficult the chip breaking is, but the evidence he provides is scant. In Worthington's relationship (equation 4) the experimental results show the gradient of a size ratio (h/R) against undeformed chip thickness (h) to be dependant on the material constant, but in practical terms only when a steel with a "n"-value of 1.5 is compared with a steel with "n"-value of say, 2.0 is any significant difference in the chip breaking range observed. An example of the effect is shown in figure 8 which is drawn for an "n"-value of 1.5. The accepted values of the limits of acceptable chip breaking are set on the size ratio (h/R) against undeformed chip thickness graph at $\frac{h}{R} = 0.06$ and $\frac{h}{R} = 0.18$, which assumes a fracture strain for plain carbon steel chips of 3%.

The maximum and minimum chip thickness values for acceptable chip breaking can be read from the x-axis where the groove width line crosses these limits. From figure 8, the range of undeformed chip thickness would be from 0.22mm to 0.47mm, for a 3mm groove and "n" = 1.5.

The same exercise for a high speed steel with an "n - value" of 2.0 would give acceptable chip breaking from 0.19mm to 0.37mm, undeformed chip thickness. It can be seen that the undeformed chip thickness for the onset of acceptable breaking has not changed significantly but overbreaking commences at a lower undeformed chip thickness for the high speed steel which may well be noticeable.

CHAPTER 3

A DESCRIPTION OF EXPERIMENTAL EQUIPMENT AND PROCEDURE

The tools were prepared from plain, P30 cemented carbide inserts. The circular groove profiles were produced by spark erosion, using "elkonite" (a sintered bronze) bars as the electrodes, figure 10. The land angle was ground using a purpose made jig and an 8 inch, off-hand grinding wheel. All dimensions were measured using a Nikon tool-makers microscope.

The material used for most tests was EN8, but tests using M2, EN9, EN19b were performed to quantify the differences in values of the material constant. A section of the EN8 bar was examined to check the homogenity; no significant defects or variations were found. Cutting fluid was not used in any test since this would add inconsistencies in that control of the flow of fluid could not be guaranteed for each test.

An infinitely variable speed lathe was used for the tests, which enabled the cutting speed to be kept constant (at 120/min for most tests). The cutting speed was checked using a surface tachometer. The range of feed rate was between 0.1mm/rev and 1.0mm/rev - the u.c.t. can be regarded as nominally the same as the feed since the tool cutting edge angle was 15° in most cases i.e., a difference of about 3%.

Tests were performed using a variety of tools with groove widths ranging from 1.8mm to 4.2mm, and land lengths in the range 0.1mm to 0.6mm.

In each test the chips produced were collected and the outside radius of the chips was measured using radius gauges, micrometers or rule, as appropriate for the size of the chip. Several chips from each test were measured and the average radius was found.

Variations to the basic groove shape were required for some tests. A tapered groove was produced using an elkonite rod which had been taper turned and was carefully aligned to ensure that the land was formed parallel to the cutting edge. In testing the effect of a "dimple" the "dimple" was produced by spherically forming the end of an elkonite rod and using it to spark erode the P30 insert close to the corner. For the tests comparing the effect of rough and smooth tool flanks, the roughness was provided using a knurled piece of brass as the electrode to spark erode the inverse shape of the knurl onto the tool, two patterns were used, a diamond knurl which gave a dotted flank and a knurl giving a series of grooves parallel to the cutting edge. In order to examine the deformation at the chip-tool interface, quickly stopped samples were obtained using the device shown in figure 11.

The device consists of a humane killer gun with a captive bolt, mounted above a tool holder, pivoted slightly below centre height and supported by a pin. The screws preload the tool holder to prevent it from moving. Cartridges were used to fire the device. The gun is fired whilst the tool is in cut, the bolt strikes the toolholder, the supporting pin shears and the toolholder accelerates from the workpiece. Plasticine under the tool cushions the fall, preventing rebound and damage to the toolholder. The shear pins are made of silver steel and are notched to facilitate quick fracture. The device is mounted in place of the tool post on the cross slide of the lathe.

The difficulties of removing the sample from the bar were overcome by machining a mild steel tube and parting off the section holding the sample. It was then a simple matter to saw around the sample to obtain a specimen suitably sized to be mounted.

The samples were cleaned of dust and mounted in clear perspex. The mounts were ground to reach the section to be examined and then polished and etched.

Always at least three, and usually more, quick stop samples were taken for each analysis required, to ensure the section examined was representative.

Description of the specific tests carried out on individual tools are included in the account of the performance of those tools, in the following chapters.

CHAPTER 4

EXPERIMENTAL WORK ON THE SIMPLE GROOVED TOOL

4.1 The relationship between Chip Radius, Groove Width, Land length and Workpiece material.

A number of tools were prepared in the Laboratory with various dimensions - details of four of these tools are given in table 2. Each of these tools was used in tests cutting EN8 steel and noting the chip type and radius over a range of feeds. The object of the tests was to verify the relationships described previously (equation 4) for the particular workpiece and to examine the repeatability of the chip breaking performance. The feed was accepted as the value of undeformed chip thickness and the average radius of a number of chips formed at each feed setting was found. The results of the four tools are given in table 3 and are plotted in figure 12. The best straight line was found by linear regression, giving a value for the gradient and the interception with the feed axis. The workpiece constant can be determined from the gradient and the tool groove width, and since the same workpiece was used throughout the changes in gradient on figure 12 should be due to groove width only. The dimensions in brackets in table 2 are those calculated from the graph of figure 12 for each tool.

The interception gives the undeformed chip thickness (feed) at which the chip began to use the groove and since there is a fixed relationship between land length and this undeformed chip thickness value (land angle and workpiece assumed the same) then the interception value should change in direct proportion to land length.

The inverse of the gradient for each tool was taken and plotted against the tool groove width to give a new plot figure 13 with a gradient equal to the material constant, n for the workpiece. The results for five workpieces are given in table 4.

4.2 The Chip Fracture Strain and Size Ratio Relationship.

The fracture strain, ε for the chip has been shown to be related to the size ratio when chip breaking just becomes acceptable (equation (3)). Tests were carried out to estimate the fracture strain for a 0.45% carbon steel by recording the undeformed chip thickness and chip radius at which single full turn chips were produced with a number of tools. These results are given in table 5 and the average fracture strain is calculated to be 2.2%, which can be compared to the values for similar steel, found by Spaans(6), Nakeyama (5) and Takeyama (10) which were 0.7% to 1.5%, 0.4% to 1.49% and 4.5% to 5.5%, respectively. A similar exercise for the size ratio and undeformed chip thickness when overbreaking commences (indicated by chips of half turn or less) yields a fracture strain of 3.5%.

4.3 The Land length and Land Angle Relationship.

The ratio of the undeformed chip thickness at which the chip uses the groove to land length: $\frac{hg}{LL}$ is shown to be dependant on the land angle (Worthington and Rahman (2)). The constants in the relationship for an EN8 steel workpiece were obtained from the results shown in table 6.

Figure 14 gave a value of $\frac{hg}{LL} = 0.378$ at land angle = 0°. The measured land length was compared with the land length calculated from $\frac{hg}{LL}$ = constant where the constant was 0.39 from figure 14 for a -5° land angle and hg was the undeformed chip thickness at size ratio = 0 in the plots of figure 12. The comparison of actual and calculated land lengths is given in table 2, the calculated values being the figures in brackets.

4.4 Discussion of results of tests on the Simple Grooved Tool.

The graphs of size ratio against undeformed chip thickness demonstrate the high correlation between the theoretical relationship and the chip breaking performance found. In each test linear regression gave over 90% correlation between the best straight line and the experimental point. In some cases there was an obvious change in gradient which is explained by the groove inlet angle being less than the maximum built-up edge angle which will cause the chips to be formed at a fixed radius once the built-up edge angle equals the inlet angle of the groove. If this is allowed to occur then equation (2) no longer applies.

Ideally, only one test need to be carried out to find the workpiece constant, "n" but, because the machining process is so inconsistant, a number of tests with grooves of different widths were carried out. The inverse of each gradient of the h/R graphs from these tests was plotted against the groove width of the corresponding tool and the slope of the best straight line through these points and the origin gives the "n"-value. There was always some scatter about this experimental line, for example, the tests to give "n" for EN8 (table 4) had a standard deviation of 0.19 and mean of 1.43. The variation in n-value for any one material can be as high as 14% and this is to be compared with the variation in the average "n"-values for the different materials tested which is of the same order. Since the "n"-value is so inprecise it is not appropriate to differentiate between any of the materials examined for chip breaking purposes. From the range of workpieces tested it is reasonable to group all plain carbon steels together with an "n"-value of say 1.5. Further grouping can be envisaged allocating an "n" value, which is equally suitable for all steels within the group. Many chip breaking problems have been encountered by users machining "special" steels e.g., stainless and aircraft metals and it would be useful for such users to be able to relate the "n"-value to a property or properties of the parent metal. A list was drawn up of a number of commonly available parameters for the properties of the steels tested (e.g., carbom content, hardness) and compared with the n-value of that steel. No correlation was found from this direct comparison, but the possibility that a deeper investigation with a wider range of steels may reveal some relationships cannot be ruled out. It may, however, be the case that if relationships are found the practical difficulties will still exist because the properties of any one steel will vary due to the company and method of manufacture and the heat treatment it has received. In this investigation a steel with greatly different properties from the plain carbons was examined to find the material constant. EN19 was chosen because Spaans, Nakeyama and Takeyama all reported the fracture strain of the chips of Cr.Mo. steel to be two to three times greater than the chips from plain carbon steels. The particular steel used did not reflect this change in fracture strain in its chip breaking performance and the average "n"-value was 1.53. A significantly different "n"-value was found for a very low residual 3% Ni.Cr. Steel. The type and radius of chip produced at each undeformed chip thickness were highly erratic for this steel and it was impossible to estimate the chip fracture strain from a knowledge of the onset of acceptable chip breaking. The average "n"-value was 2.46 from tests with four tools with individual "n"-values varying from 2.1 to 3.2.

In some tests, for example those to give the land angle relationships for EN8 and EN19, the same tool was used several times and the hg value was found to vary by as much as 25%, although the points gave a good straight line. The tools were measured both before and after the test but any change due to wear was negligible. The explanation for this type of error can only be in the inconsistancies inherant in the Metal Cutting process.

4.5 Inconsistancy of Results.

Metal Cutting is not a consistant process, there are a vast number of variables involved, many of which cannot be quantified. Inconsistancies can arise from the dynamic behaviour of the machine tool, which may change from one machine to another.

The homogeneity of the workpiece is also important, the chemical and physical properties may change along the bar and even slight changes could affect the chip breaking performance. Likewise, the material of the tool, and how it behaves in contact with the workpiece is an important factor, particularly since at the chip root the tool and workpiece are in intimate contact. Kluft (11) discussed the intricate balance of forces in the shear zone, and how easily they are influenced by very minor changes in the materials. More significant changes in chip breaking are brought about by the inconsistancy of the behaviour of the first chip - when the chip slips from its anchoring position at the tool flank a change in the force at the chip root is experienced and the chip form can be significantly altered. According to Kluft (11) the range of strains, strain rates and temperature which are found in machining operations are much greater than for any other metal forming process, this explains the high number or equally valid but different results which are found from the tests and how a wide margin can be expected in any predictions made.

CHAPTER 5

THE CHIP BREAKING NOMOGRAM

5.1 Introduction

This chapter shows how the nomogram is designed and examines its effectiveness.

The industrial survey indicated that it is important to have a means of comparing the chip breaking performance of one tool with another and to be able to build up a model of the Optimum tool. The nomogram helps in this process since each significant dimension of the tool is isolated and, after a little practice, the effect of changing any parameter is readily seen.

5.2 The Nomogram to predict Chip Breaking Performance of a tool.

A nomogram was devised which incorporates the dimensions of the geometry of a simple grooved tool which have the most significant effect on the chip breaking performance. These parameters are the groove width, the land length and the land angle. The nomogram is shown in figure 15. It comprises three graphs, each primarily concerned with one parameter of the groove, but all are interdependant. The land angle and land length graphs have a common axis, namely the hg/LL axis. The undeformed chip thickness, (h) axis of the groove width graph is graduated in mm but no absolute values are marked, this is because the intercept at h/R = 0 is dependant on the hg value determined from the land length and land angle graphs.

The chart provides a guide to the performance of a chip breaker under specified cutting conditions, or alternatively it can be used to select the optimum groove configurations required for a particular job. Whilst the nomogram is only numerically appropriate for a simple grooved tool the overall effects of changing the cutting conditions, when using tools with complex profiles, can be found by extrapolation. An explanation and example of how to use the chart are given in Appendix B.

The reliability of the chart was examined by comparing the range of feeds for acceptable chip breaking in tests with the values predicted from the chart, a reasonable correlation was found, some typical results are given in table 7.

Cutting speed has relatively little effect on chip breaking performance and also the variation of material constant (see table 1) for plain carbon steels is slight which indicates that the one chart can be used as a guide for a wide variety of cutting conditions and steel workpieces. The nomogram can, of course, be drawn to fit the user's own tests and the "n"-value which he finds most appropriate.

5.3 Application of Computers.

When the user wishes to draw his own nomogram or to use the method for a wide range of cutting conditions then much of the tedium of accurate re-drawing can be handled by a suitably programmed mini or micro-computer. Not only has computer hardware improved considerably in recent times but also the software is now so greatly advanced that the computer layman can write quite powerful programmes. These two facts lead to the inevitable transfer of the nomogram to a computer.

Many versions of the nomogram can be programmed to suit particular problem areas, or in fact a very versatile package could be written to cater for many models of use. To demonstrate the principle a simple program has been written for a BBC micro computer. This program will accept any reasonable tool dimension and workpiece material [illegible] for acceptable breaking and gives results both numerically and graphically. Appendix C shows the listing and a sample problem.

CHAPTER 6

THE INVESTIGATION INTO THE PERFORMANCE OF TOOLS WITH UNCONVENTIONAL PROFILES AND THEIR SIGNIFICANCE

6.1 An Introduction to Recently Produced Tool Profiles.

In recent times cutting tool manufacturers have designed around the "conventional" chip breaking groove (which has a parallel land and a parallel groove) in order to improve the chip breaking performance and often to meet specific cutting conditions. It is unfortunate that communication between manufacturer and user is so poor that little is generally known of how the special features of these tools operate or even how the fundamental variables such as land length and groove width affect the chip breaking feed range. This lack of information leads to tools being tried and used in an ad-hoc manner which is both very time consuming for the user and does not necessarily result in the optimum tool shape for the particular application.

This work explains the effect of some "special" features, for example, tapered grooves, multiple grooves and "dimple" grooves. Explanation is given of how conventional theory can be extended to the unconventional features and, by demonstrating the similarity with the conventional groove, leads to a unified method of predicting chip breaking performance from examination of the tool profile.

The description of a particular feature was not always simple since commercial inserts usually combine features, for example, the shallow grooves and multiple groove feature is combined on the "Sandvik" insert, Often, as in this example, one feature is necessary for another to operate and it becomes a problem to attribute each chip breaking property to the appropriate feature. This problem was solved, whenever possible, by producing tools in the laboratory with the only particular feature which is to be examined.

It is, of course, impossible to reproduce the complex, sintered-in, contours of some commercial inserts but the object was to identify "profile-types" which could be recognised on a number of tools, and not to remake commercial tools. Each parameter was physically investigated with all the available laboratory techniques e.g., the use of a quick stop device.

6.2 The Effect of Tapered Grooves on Chip Breaking Performance.

If the probability of the chip avoiding the workpiece shoulder can be increased, that is by the helix angle of the chip being large, then the chip breaking performance is likely to be more favourable. It has been suggested that a tapered groove allows the chip coil to take up a helix with greater pitch, however, as will be shown this did not occur. In this investigation both a commercial insert and tools prepared in the laboratory were examined. The commercial tool was produced by "Valenite" and its form is shown in figure 16(a), it should be noted the tool has other non-conventional features - a tapered groove and a shallow groove and a curved cutting edge. The tool underwent a series of tests in which the feed was steadily increased and the chip radius was noted at each feed setting. Since the chips were helical the radius of each edge of the chip was measured and the average recorded.

Figure 16(b) shows the size ratio versus undeformed chip thickness relationship. It is clear that the relationships for a simple grooved tool do not apply to the Valenite tool and, unlike the case of a more conventional shallow groove tool, no approximations can be made. The nomogram is of no help for this particular tool.

A number of tools were prepared in the laboratory each with steadily widening grooves but the land remaining parallel (figure 17(a)). Very little effect could be determined from the small tapers, the chips being as expected from a parallel groove, the results recorded in table 8 are for the widest taper angle produced - a taper of 27°. The comparison of the helix angle from straight and tapered grooves indicates that the taper has influence only at very small depths of cut. The helix angle is equal to the chip flow direction as reported by Boothroyd (12) and this remains true whether the groove is tapered or not. Observing the chip bending process at very slow cutting speeds gives some insight into why the chip fails to be influenced by the angle of the back of the groove. The chip is seen to make contact at one point on the back edge of the groove only and does not therefore recognise the shape of the groove. (Henriksen (3) reported that very little force is required to deflect the chip and observed the chip curling as it met the nearest part of the groove heel which supports the supposition that the chip does not necessarily follow the shape of the back of the groove.)

Fine (13) described fan-shaped chips and these were occasionally found in these tests (figure 17(b)). There was, however, no evidence that the taper formed the fan and it is expected that the edge of the chip furthest from the tool nose was carried by its own momentum into a larger radius than the radius of the formed edge of the chip, thus producing a fan-shape.

Commercially tapered grooves have been used in boring tools for quite a different purpose, that is directing the chip away from the cutting area. This appears to be the only advantage; the results did not show that the taper changed the helix angle, and the fan shaped chips which were sometimes produced are disadvantageous because they are less likely to break cleanly, and may form half broken chips. The chip helix angle, being dependant on the chip flow direction would be increased by increasing the ratio between the tool nose radius and depth of cut. In predicting the chip breaking performance of tapered groove tools, the width of the narrowest part of the groove should be used when using the nomogram.

6.3 The Influence of Shallow Groove Inlet Angles on Chip Breaking Performance.

It has been stated previously that the built-up edge angle of the chip will not exceed 45° and, therefore, a groove inlet angle of 45° will ensure that the chip is always free to take up its preferred radius with minimum contact with the groove profile. This arrangement may cause the cutting edge to be too fragile and reduce the life of the tool, particularly when using double sided inserts, therefore manufacturers tend to prefer shallow inlet angles. "Cintride" is an example of such a manufacturer and an investigation of the action of one of their tools (shown in figure 18) is used to illustrate the behaviour of tools with shallow inlet angles.

The dimensions of the "Cintride" tool are shown in figure 18 and the tool holder presents the tool at a -7° rake angle to the work. The "Cintride" tool was used over a range of feeds and the chips produced were collected and the outside radius was recorded. Figure 19 shows a graph of both chip radius and size ratio against undeformed chip thickness. The type of chip at each feed was recorded, and particular attention was paid to the undeformed chip thickness at which the chip began to use the groove and when chip breaking was acceptable. A number of "quick-stop" samples were acquired and prepared for examination under the microscope in order to investigate conditions at the chip-tool interface and to establish which parts of the groove were in contact with the chip.

The chip was observed as the tool was used at steadily increasing feeds. At low feeds it did not use the groove but curled naturally with a large radius. The chip began to use the groove at an undeformed chip thickness of 0.13mm, chip breaking was acceptable from undeformed chip thickness values of 0.22mm and at an undeformed chip thickness value of 0.48mm, it was clear that the groove profile was interfering with the formation of the chip.

From figure 19, three phases of chip formation can be identified. In the first phase, phase I the tool is operating as a controlled contact length type; the groove does not interfere with the chip and it is assumed that the relationships referred to previously are valid (although in this particular case the feed range is too small to verify this). The chip radius over this range is given by:

$$R = \frac{W}{2 \sin \beta}$$

where β = the built-up edge angle of the chip.

Over the next phase, phase II the chip radius is almost constant (changing only 0.6mm over 0.2mm change in undeformed chip thickness) which indicates that the built-up edge angle is equal to groove inlet angle. Any further increase in built-up edge angle is prevented since there is a reaction force acting on the built-up edge from the bending of the chip against the groove heel. In the case of most tools which have a groove inlet angle less than the maximum built-up edge angle the chip radius will remain constant for all subsequent increases in undeformed chip thickness. In this case, however, the chip radius began to decrease again giving phase III of chip formation. In this phase the area of chip-tool contact is not restricted by the land but extends over the land and into the groove. This is only possible since the inlet angle of 10° is very shallow and the 0.1mm land length is short. Photomicrographic evidence from quick-stop specimens (figure 20) showed the chip-tool contact area extending into the groove. Under these conditions the radius of the chip is:

$$R = \frac{W_{eff}}{2\sin 10^{o}}$$

where W_{eff} is the effective "groove" width which is the nominal groove width plus the land length minus the chip tool contact length (W_{eff} = W+LL-CL). The contact length for a particular rake angle and workpiece is proportional to undeformed chip thickness. Typically, contact length is 1.5 times, or 2 times the undeformed chip thickness, the chip radius would then become:

$$R = \frac{W+LL-2h}{2\sin 10^{o}}$$

The radii expected from this equation and by using a contact length to undeformed chip thickness ratio of 1.5 are compared with the measured radius in table 9.

The nomogram has limited use in predicting the chip breaking performance of shallow groove tools, since the relationships are only valid for the first phase of chip forming described.

6.4 The Moat Effect.

Many commercial tools have grooves in all four faces which run into each other at the corners, creating complex geometries. The depth of cut used with these tools is particularly significant since, at small depths of cut, the chip flow direction is strongly influenced by the nose radius and the chip direction is difficult to predict and may strike the groove obliquely (figure 21a). Slightly increased depths of cut will change the chip flow direction and may cause the chip to hit the groove of the secondary cutting edge (figure 21b), or run along the length of the groove (figure 21c). If the tool is operating in one of these areas, chip breaking will be unpredictable. There will be a depth of cut where the chip width will be sufficient to ensure that the chip is always curled by some part of the groove (figure 21d). The proportion of the chip which makes contact with the groove does not need to be large since the force required to bend the chip is small.

6.5 The Influence of Multiple Groove on Chip Breaking Performance

The Sandvik SNMM double groove tool (figure 22) was used to demonstrate the action of multiple grooves. This tool has double grooves in all four faces, therefore the depth of cut was selected to be always large enough to prevent the "moat effect" described earlier coming into operation. The grooves of this tool are also shallow and the investigation into the "Cintride" shallow groove tool supported this investigation.

The operation of this tool relies on the groove being shallow, to allow the area of chip-tool contact must move into the groove (as occured in the case of the "Cintride" tool), alternatively the 1st groove could fill with stagnant workpiece material for the second groove to operate. The effective inlet angle of this tool is shallower than that of the Cintride tools-so much so that the operation of the tool, even at very low values of uct cannot be identified as typical of a conventional grooved type tool. The chip-tool contact moves into the groove at very low values of uct, quickly causing crowded and overbroken chips.

A series of tests was undertaken in which the chip radii were noted for gradually increasing undeformed chip thicknesses.

The results obtained are shown in figure 23 and it is clear that the theory of equations (1) to (5) does not apply. The results show two slopes, over two ranges of feed which correspond to first one groove operating then the second.

It is stated by the manufacturers that the groove nearest the cutting edge will operate at small values of uct, and the second groove will come into operation at high values of uct. This was found to be the case, but the transition from one groove to the other is not smooth, and there is a wide range of uct where breaking is unpredictable and often unacceptable. The range of undeformed chip thickness over which acceptable chips were found, when the first groove is operating, is very small.

According to Lundgren (15), the second groove begins to operate when the sticking friction zone has extended across the width of the first groove. The chip then "sees" the first groove as a land and uses the second groove. If the grooves were deeper, it was thought unlikely that the area of chip-tool contact would ever exceed the land of the first groove. In order to test this hypothesis a tool with deeper grooves was made in the workshops and tested by machining at an undeformed chip thickness high enough to give a contact length exceeding the first land and groove, but the chip did not then, or at any higher feed, use the second groove of this tool.

Evidence of the action described by Lundgren was obtained from quickly stopped specimens of the "Sandvik" tool. The photomicrograph (figure 24) shows the dead metal zone extending over the first groove and therefore is not used for curling the chip. The photomicrograph does not positively show that the second groove is in operation - this is assumed.

In the tool of this test, the second groove appears to operate consistently above an undeformed chip thickness value of 0.7mm, which gives an estimated "land length" of 1.4mm using the expression: contact length = 2 x undeformed chip thickness. This is a reasonable estimate; the measured "land length" was 1.3mm. The graph of h/R against h, figure 23, shows the range of the two grooves; straight chips were produced at u.c.t. below 0.15mm, the first groove operated between an uct of 0.15mm and 0.4mm, althought not always producing good chip types. Chip breaking became inconsistent until an uct of 0.7mm when the second groove appeared to operate.

The nomogram will apply for the very small range of undeformed chip thicknesses below that which gives a built-up edge angle equal to the inlet angle of the first groove. It may be possible to use the nomogram to predict the land length required on the tool - it is unlikely to be able to predict the "land length" of the second groove, (that is, the width of the first groove plus the land length) because the "land" is not flat and may cause the land angle - land length relationship to change, although Henriksen's contact length formula seemed to apply. The nomogram cannot be used to predict the range of feeds for acceptable chip breaking because the chip-tool contact length is not restricted to the land but moves into the first groove at low feeds.

6.6 The Influence of Change in Chip Cross Section on Chip Breaking Performance.

Both notched tools and waved cutting edges cause the chip to break more easily by changing the cross section of the chip. The waved cutting edge form can be considered as a series of wide notches. There is a range of cutting edge forms available commercially - the "Valenite" tool has one gentle 1/2 cycle wave, the "Sandvik" type 61 tool uses a full cycle of wave and the "Sumitomo" "Wavy A" has two cycles in the length of the cutting edge

In order to investigate the effect of changing the cross section of the chip a small, hemispherical notch was spark eroded in the land of a tool which had a conventional groove (figure 25). The notch was positioned close to, but not interfering with the tool nose radius. Samples of chips over a range of feeds were collected, mounted and polished to show the cross section of the chip, and photographed. The outlines of these chips are shown in figure 26.

The chips at low values of undeformed chip thickness followed the contours of the land quite closely, giving the chip a ridged spine. The kinked cross section gives the chip a stiffer structure, thereby making the chip easier to break, as there is less chance of it being deflected sideways at the tool flank and additionally the chip has an increased moment of inertia. As the feed is increased the notch is filled with dead metal and the chip becomes almost rectangular. The degree of "kink" in the chip appears to be dependant on the undeformed chip thickness and the land length of the tool. The land lengths of the prepared tools were 0.18 and 0.46mm. The chips from the tool with a 0.46mm land length became almost rectangular at an undeformed chip thickness of 0.6mm, whereas the chips produced by the tool with the shorter land reached a similar cross section at 0.4mm undeformed chip thickness.

There was a tendancy for chips to split along their spine, which is not at all acceptable since these chips are hazardous. In these tests it was noticed that the chips sometimes formed without using the back of the groove but this peculiarity was found only occasionally and there was insufficient evidence to identify the cutting conditions which caused this to happen. It was, therefore, noted but not investigated further.

The action of the notch used in these experiments is harsh and a shallower notch could possibly be used to enhance the advantages, but avoid the shortcomings of this type of tool.

The change in cross section of the chip is usually much more severe with the notched tool than with the waved cutting edge, and there is evidence of severe deformation of the chip at high cutting feeds when using the notched tool. This is not found with the waved cutting edge tool and indicates undesirable friction conditions, when the chip is subjected to harsh changes in section.

Cutting with the notched tool produces a chip section which becomes more rectangular as the feed is increased, suggesting that the chip breaking range will be extended at the low feed end of the range. Overbreaking at a lower feed than that at which overbreaking would occur with an un-notched tool can be avoided if the tool is designed to produce rectangular chips at a feed lower than the upper limit of favourable chip breaking.

Using the waved cutting edge tool the chip section follows the contour of the cutting edge and does not change as the feed is increased, which indicates that both the upper and lower limits determined by the size ratio relationship will be decreased.

In using the nomogram to predict the performance of notched tools or tools with wavy cutting edges, the limits of acceptable chip breaking should be changed to agree with the estimated fracture strain values of the shaped chip.

6.7 The Influence of "Dimples" or Protrusions on the Chip Breaking Performance.

At very small chip widths the chip flow angle is almost perpendicular to the secondary cutting edge and the conventional groove is not effective. A small hemi-spherical hollow or dimple was found to give adequate breaking at these depths of cut. Many tool manufacturers use this idea, but an alternative is a protrusion near the nose of the tool which is favoured since a hollow is quickly filled with dead metal when larger chip widths are employed. The tools produced by "Sumitomo" are a typical commercial solution as seen in figure 27.

A number of tools were produced in the laboratory with small hemispherical "Dimples" on the rake face, near the corner of the tool (figure 28). Each of these tools was tested at various depths of cut and over a range of undeformed chip thickness values. The outcome of these tests are summarised in table 10. The depth of cut was important on two accounts; firstly because depth of cut is a main influence on chip flow direction and for the dimple to operate the chip must flow across it and, secondly, unless the cut was very light the dimple tended to fill with stagnant metal and did not operate. This second effect was the cause of two of the smaller dimples not operating at all, and dimple "e" with diameter 1.4mm was prone to filling with swarf for depths of cut in excess of 0.4mm. The other reason for failure was that the dimple was too far from the cutting edge and the undeformed chip thickness was not high enough for the chip to use the dimple.

The radii of the chips produced by the two tools which were effective were recorded and a size ratio versus undeformed chip thickness plot was drawn (figure 29). Estimates of "groove" width which is comparable to dimple diameter can be made and also of "land length". The plot shows a linear relationship and the estimates given in table 11 are reasonable and, therefore, it is suggested that the hollow, or dimple, obeys the same form of relationships as those found for the conventional groove. If the tool is sectioned through the dimple in the direction of the chip flow at low depths of cut, the profile is found to be very similar to the profile of the conventional grooved tool (figure 28). This reinforces the supposition that it is appropriate to use the same form of relationships as used for the groove type breaker, since the chip is responding to the equivalent geometry.

The dimple is preferred to a groove of equivalent width because such a groove would result in a very fragile cutting edge.

The "Sumitomo" "Bumpy - G" and "Spiky - S" tools were tested over a range of feeds and depths of cut. The results are shown in tables 12 and 13. The size ratio versus undeformed chip thickness relationship is linear (figure 30), and gives an estimate for groove width of 1.75mm which corresponds well with the distance from the land to the protrusion, the estimate of land length of 0.25mm is, however, high. The chips were found to wrap around the protrusions slightly and produce chips with curved cross sections, a typical section is shown in figure 31. The marks on the "Bumpy-G" tool, figure 31. give some indication of how the chip was formed. The limits of chip breaking at size ratio of 0.06 and 0.18 on the size ratio plot correspond well with the type of chips found for both "Bumpy-G" and "Spiky-S" tools with chip breaking commencing at 0.19mm and over-breaking commencing at 0.32mm undeformed chip thickness. This indicates that the change in section does not significantly change the chip fracture strain. Further testing would be necessary before the nomogram could be confidently used for these highly unconventional tools.

6.8 The Influence of Anchoring Conditions on Chip Breaking Performance.

When turning, the behaviour of the first chip which is produced often influences the behaviour of those which follow. Spaans (6) used the term "history" to describe this phenomena and showed, by high speed photography, how chips tend to follow the path and therefore the mode of breaking as the ones which precede them. One important aspect of this is the anchoring conditions at the tool flank. If the chip curls round and the free end anchors at the tool flank, then the possibility of breaking in an acceptable manner is increased. The free end of the chip may slide down the flank, however, and fall under the toolholder which can cause the chip to begin snarling, rendering it almost impossible to break. Alternatively, the free end of the chip may slip upwards and cause the chip to form a helix, which will either break under its own weight after a few turns, or may form very long helices which have to be broken manually. Chips can often be seen to be broken during the first few seconds of machining, but then the chip slips from the tool flank and helices are formed, rarely does the chip type revert to broken chips. It is, therefore, important to encourage the chip to anchor and avoid undesireable chip form action. One way in which this can be achieved is by giving the tool flank a rougher surface, which will cause increased friction between the tool and the free end of the chip, when the chip strikes the flank. Figure 33 shows the horizontal groove on the tool flank being used.

A tool was prepared with horizontal grooves on the flank in order to provide anchoring positions for the chip. The types of chip produced with this tool and a tool of identical geometry, but with a smooth flank were compared. A range of feeds, close to the feed at which the chips just begin to be acceptable was chosen for the comparison. From figure 32, which shows the proportion of chips of each type produced in the test, it can be seen that there is an improvement in each case, i.e., a lower proportion of underbroken chips for the rough flank tool. In this simple way consistent breaking is encouraged at the lower end of the acceptable chip breaking range. The comparison between the types of chips produced with the smooth and textured tool flank consistently shows an advantage with the rough tool, however, the advantage is only marginal, and this could explain why no manufacturers have adopted the principle.

The influence of the rough flank is cummulative, once the chip has anchored successfully other chips will follow. The main effect is an improvement in the consistency of chip breaking throughout the chip breaking range and this could make it worthwhile to manufacture.

The nomogram is readily applicable to these types of tools with a possible amendment to the limit for the commencement of acceptable chip breaking.

This work has shown that it is possible to provide an easy guide relating chip breaking performance to tool dimension for a simple tool geometry. The method can be easily adapted to fit many chip breaking situations by preparing a few, quick tests to establish the material constant and the chip fracture strain. The inconsistancies of metal cutting render it inappropriate to expect precise ranges of chipbreaking from the nomogram but this is rarely necessary since even the definition of good chipbreaking from various users will span a range of undeformed chip thickness. Trends in how the chipbreaking performance change with geometry can always be established from the nomogram even when absolute values cannot be given.

The effect of unconventional profiles has been considered and the results of the investigation can be summarised as follows:-

1. Tapered Grooves: The chips tend to be fan shaped. The radius can be predicted from the nomogram using the width at the narrowest part of the groove. The size ratio limits for acceptable chip breaking will probably need setting by performing a few tests since these chips will be harder to break.
2. Shallow Grooves: It is usually inappropriate to use the nomogram because the radius of the chip is confined by the profile of the groove and this contravenes the criteria necessary for the expressions to be used.

3. Moat Effect: Care must be taken that the depth of cut used allows the chip to "use" the groove.

4. Multiple Grooves: A chip breaking range for each groove can be determined but, because the grooves are usually shallow, the nomogram cannot be used.

5. Non-parallel cutting edge: shaped cutting edges change the cross-section of the chip rendering it easier to break and, for this reason, the appropriate size-ratio limits for acceptable chip breaking should be established for the particular tool under test, if the nomogram is to be used.

6. Protrusions on the rake face: If the cross sectional geometry of the tool can be considered equivalent to the simple chip breaking groove then it is appropriate to use the nomogram.

7. Rough Flank: Anything which encourages the free end of the chip to anchor at the tool flank will encourage favourable chip breaking. The limits of acceptable chip breaking may need adjustment for the nomogram to be used.

The greatly increased availability of small computer systems with much enhanced software provides a very good medium for using the nomogram. A computer programmed with the nomogram appropriate to a particular user will give very quick access to the behaviour of the tool in question, without hand drawing and scaling the problem on the nomogram. A large number of additional facts could be included in a computer system, for example, details of the behaviour of unconventional profiles or a large number of materials constants. The scope for computer aided design in this field is considerable and available to any firm who can make the initial, quite substantial effort to set up a flexible nomogram program.

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TABLE 1

Workpiece Constant "n" for a selection of steels

Material	Average "n" Value
EN24	1.24
EN3B	1.3
EN8	1.43
EN9	1.48
M2	1.78

TABLE 2

The Dimensions of Four Simple Grooved Tools which were Prepared in the Laboratory

Tool	Groove Width (mm)	Land Length (mm)
1	1.87 (1.84)	0.30 (0.32)
2	2.36 (2.13)	0.47 (0.48)
3	3.00 (1.82)	0.30 (0.46)
4	3.76 (3.44	0.32 (0.41)
Corner radius:0.8mm,Land Angle: 0°		

Note: The figures in brackets refer to the values of groove width and land length calculated from experimental work.

Grooved Tools.

Tool 1

Symbol △

h (mm/rev)	R (mm)	h/R
0.176	5.7	0.031
0.198	4.0	0.050
0.227	3.3	0.069
0.276	2.55	0.108
0.334	2.25	0.148
0.396	2.1	0.189
0.488	2.0	0.244
0.552	1.85	0.298

Tool 2

Symbol ⊙

h (mm/rev)	R (mm)	h/R
0.317	3.25	0.098
0.352	4.0	0.088
0.396	3.61	0.11
0.454	2.78	0.16
0.488	2.88	0.17
0.552	2.45	0.23
0.635	2.25	0.28
0.704	2.25	0.30

Tool 3

Symbol +

h (mm/rev)	R (mm)	h/R
0.227	4.8	0.046
0.244	4.3	0.057
0.276	3.8	0.073
0.317	3.8	0.083
0.352	3.5	0.101
0.396	3.1	0.128
0.454	2.5	0.182
0.529	1.95	0.271

Tool 4

Symbol X

h (mm/rev)	R (mm)	h/R
0.264	7.0	0.037
0.289	6.5	0.044
0.334	4.75	0.070
0.352	4.75	0.074
0.396	4.25	0.090
0.454	4.75	0.096
0.529	3.75	0.141
0.578	3.65	0.158
0.667	3.6	0.185
0.704	3.5	0.201

Material constant, n for five workpieces

WORKPIECE 1	
W	$^1/m$
1.87	1.45
2.2	1.39
2.3	1.69
3.0	1.43
3.76	2.7
3.82	2.17
3.86	3.18
n = 1.27	

WORKPIECE 2	
W	$^1/m$
1.95	1.098
2.5	1.37
2.83	1.61
n = 1.78	

WORKPIECE 3	
W	$^1/m$
1.805	1.47
2.82	1.85
4.12	2.66
n = 1.64	

WORKPIECE 4	
W	$^1/m$
2.75	1.48
2.78	1.92
3.01	2.33
3.4	2.38
3.44	1.74
3.5	2.63
3.55	2.63
n = 1.53	

WORKPIECE 5	
W	$^1/m$
3.45	0.675
3.65	0.875
3.85	0.55
4.22	0.525
n = 2.46	

TABLE 5

Estimate of Chip Fracture Strain from Tests showing the onset of Acceptable Chipbreaking

TOOL	Size Ratio at commencement of acceptable breaking (h/R) crit	0.5 (= h/R)crit
1	0.035	0.0175
2	0.05	0.025
3	0.045	0.0225
4	0.05	0.025
5	0.04	0.020
Average		2.2%

TABLE 6

Results of Tests showing change in hg value for various Land Angles

Tool	Land Angle	Land Length	hg	hg/LL
1	-40°	0.47	0.16	0.34
2	-16°	0.53	0.17	0.32
3	-10°	0.36	0.125	0.33
4	-21°	0.52	0.115	0.22
5	-32°	0.53	0.14	0.26
6	-62°	0.78	0.15	0.21

TABLE 7

Comparison of Acceptable Chip Breaking ranges of Undeformed Chip Thickness found by Experiment and Predicted from the Nomogram

Tool Dimensions		Acceptable Chipbreaking	
Groove Width	Land Length	Observed Range (mm)	Predicted Range
3.76	0.32	0.28-0.70	0.33-0.69
2.37	0.30	0.27-0.5	0.28-0.48
1.87	0.32	0.21-0.42	0.23-0.40

TABLE 8

Comparison of Chip Helix Angle and Chip Flow Direction for a straight Groove tool and a Tapered Groove tool of similar dimensions

Depth of Cut	Chip Flow Direction		Chip Helix Angle	
	Straight	Tapered	Straight	Tapered
1mm	50°	50°	0°	20°
2mm	15°	10°	13°	13°
3mm	15°	10°	12.5°	14°

Taper was 27°, cutting speed = 120m.min, Feed 0.244mm/rev
Cutting edge Angle = 15°
Chip Flow direction measured with respect to secondary cutting edge.

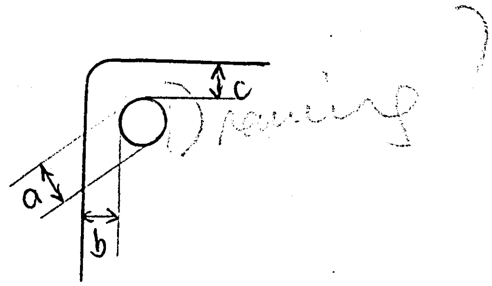
TABLE 9

Calculations of Chip Radius compared with Measured Chip Radius for a range of Undeformed Chip Thickness using the "Cintride" Tool

Undeformed Chip Thickness h (mm)	Measured Chip Radius, R (mm)	Calculated Radius $R=\frac{W+LL-2h}{2\sin 10^\circ}$	Calculated Radius $R=\frac{W+LL-1.5h}{2\sin 10^\circ}$	Notes
0.086	9.0			Not using Groove
0.102	6.7			Not using Groove
0.140	6.0			
0.173	5.6	5.3	5.6	Helices
0.224	5.4	5.0	5.4	C/B Acceptable
0.321	5.0	4.5	4.9	: :
0.410	4.8	4.0	4.6	: :
0.470	4.4	3.6	4.3	Groove interfering
0.560	3.8	3.1	3.9	: :
0.641	3.0	2.6	3.6	: :
0.69	2.8	2.4	3.4	: :

TABLE 10

Summary of Operation of "Dimple" Tools



Dimple	Dimensions (mm)			Operation of Tool
	a	b	c	
a	1.03	0.33	0.23	Filled with dead metal did not operate.
b	1.86	0.8	0.6	Land too long did not use groove.
c	2.07	0.66	0.47	Land too long did not use groove.
d	1.05	0.27	0.2	Dimple filled with dead metal.
e	1.42	0.46	0.24	Chip breaking satisfactory for .38mm undeformed chip thickness 0.3mm depth of cut.
f	1.8	0.26	0.18	Use groove from about 0.23mm undeformed chip thickness.

TABLE 11

Comparison of measured and calculated

Tool dimensions for two "Dimple" Type Grooves

Tool	Measured W	Calculated W	Measured LL	Calculated LL
e	1.62	1.42	0.46	0.5
f	1.85	1.06	0.26	0.37

Summary of Operation of Sumitomo "Spiky-S" Tool

(i) Depth of Cut = 1mm

Feed (mm/rev)	Radius (mm)	Length or Number of Turns
0.056	4.42	
0.112	3.8	
0.14	3.3	100mm
0.18	2.7	Three Quarter Turns
0.25	2.4	Half Turns
0.28	2.2	One third turns
0.31	1.9	Fragments
0.40	1.76	Fragments
0.50	1.65	Fragments
0.63	1.6	Fragments

(ii) Depth of Cut = 2mm

Feed	Radius (mm)	Length or number of turns
0.1	6mm	
0.125	3.3	(one and three Quarter turns)
0.20	2.5	Half turns
0.31	1.5	Fragments
0.4	1.4	Fragments

(iii) Depth of Cut = 3mm

Feed	Radius (mm)	Length or number of turns
0.05	12mm	
0.10	7.0	
0.125	4.0	40mm and 100mm coils
0.16	3.0	60mm coils
0.2	2.8	30mm coils
0.25	2.4	One turn
0.28	1.9	One turn
0.31	1.8	One turn

(all tests speed = 160m.min, cutting edge angle = 15°)

TABLE 13

Summary of Operation of Sumitomo "Bumpy-G" Tools

(i) Depth of Cut = 1mm

Feed	U.C.T.(mm)	Radius(mm)	Length or No. of Turns
0.16	0.113	4.25	150mm coils
0.25	0.117	3.0	Half turn
0.31	0.22	2.2	One turn or 40mm coils
0.63	0.44	1.85	12mm coils

(ii) Depth of Cut = 2mm

Feed	U.C.T.(mm)	Radius(mm)	Length or No. of Coils
0.16	0.113	2.7	
0.25	0.177	2.46	
0.31	0.22	2.43	15mm coils
0.63	0.44	1.73	Full turns

(iii) Depth of Cut = 3mm

Feed	U.C.T.(mm)	Radius(mm)	Length or No. of Turns
0.16	0.113	5.8mm	
0.225	0.159	5.0mm	100mm to 50mm
0.31	0.22	(2.25)	One to One and a half turns

(All tests cutting speed = $158 m.min^{-1}$, cutting edge angle = 45°)

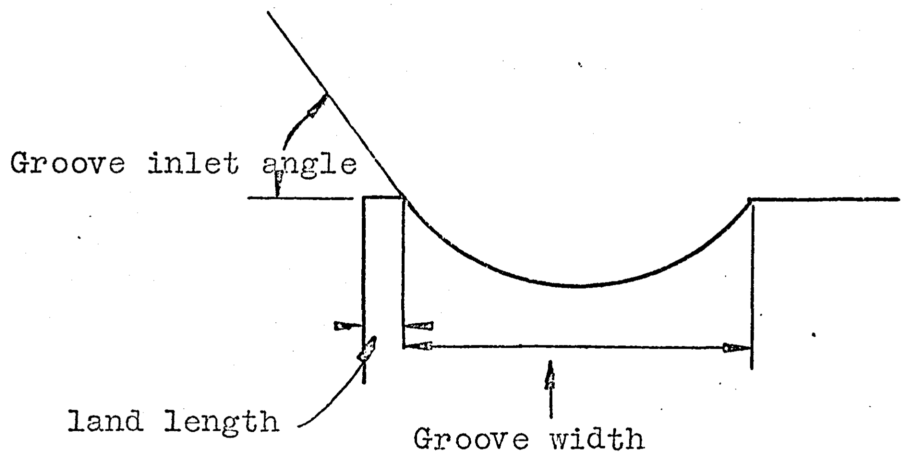


Figure 1 - Simple Grooved Tool

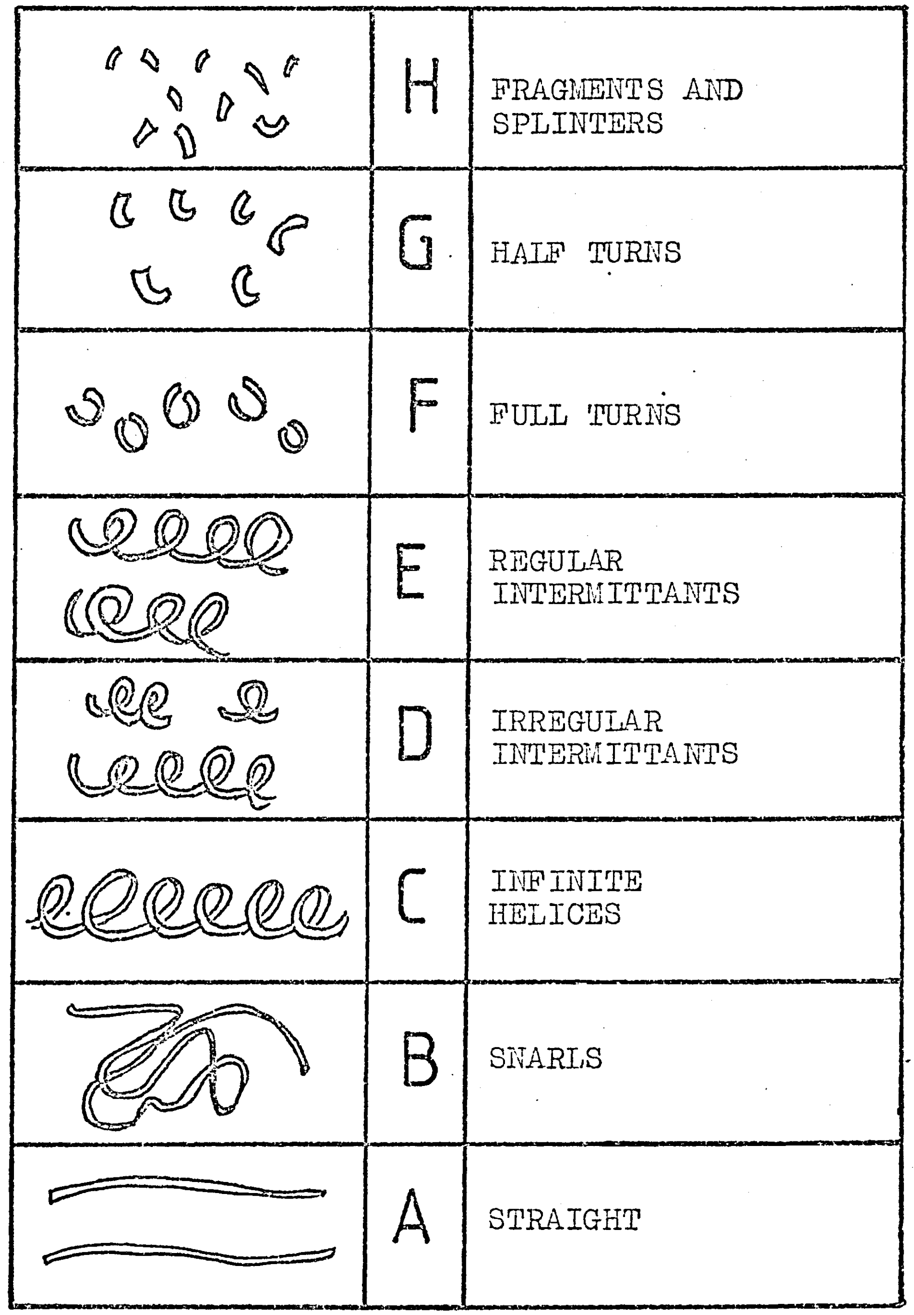


Figure 2

System of Chip Classification (After Henriksen (1))

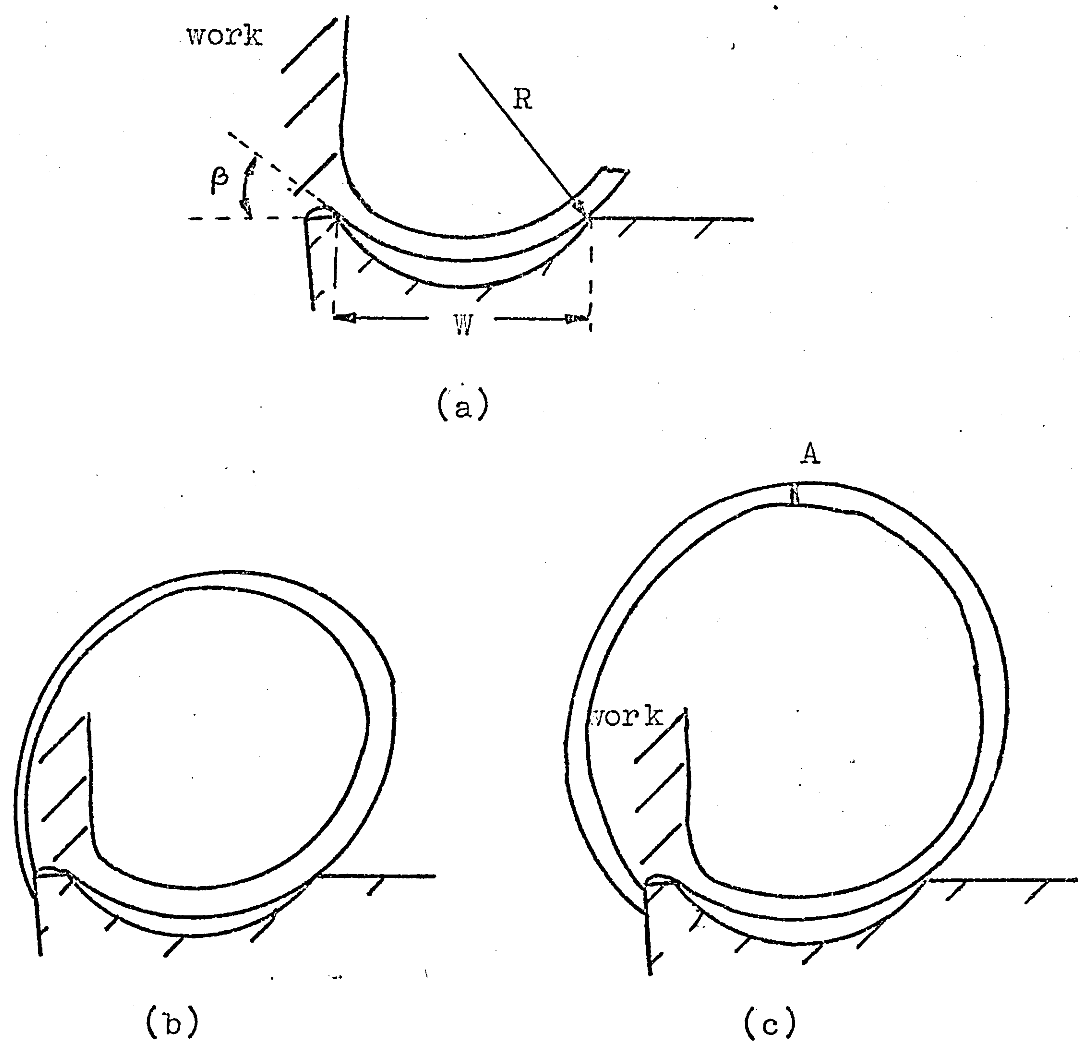
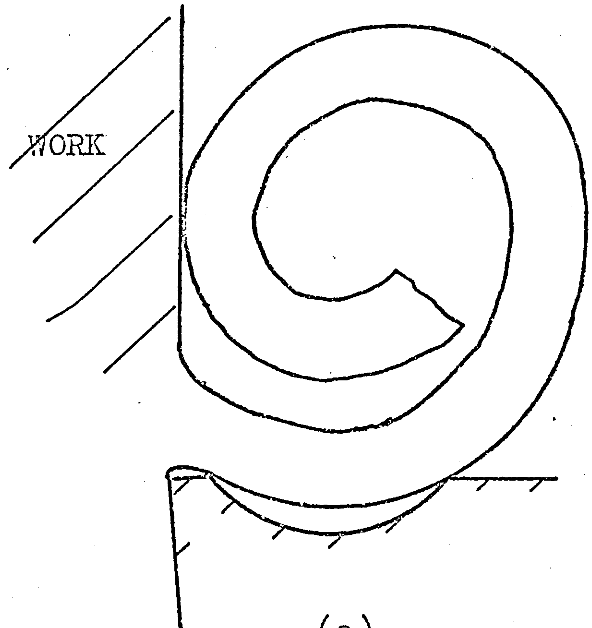
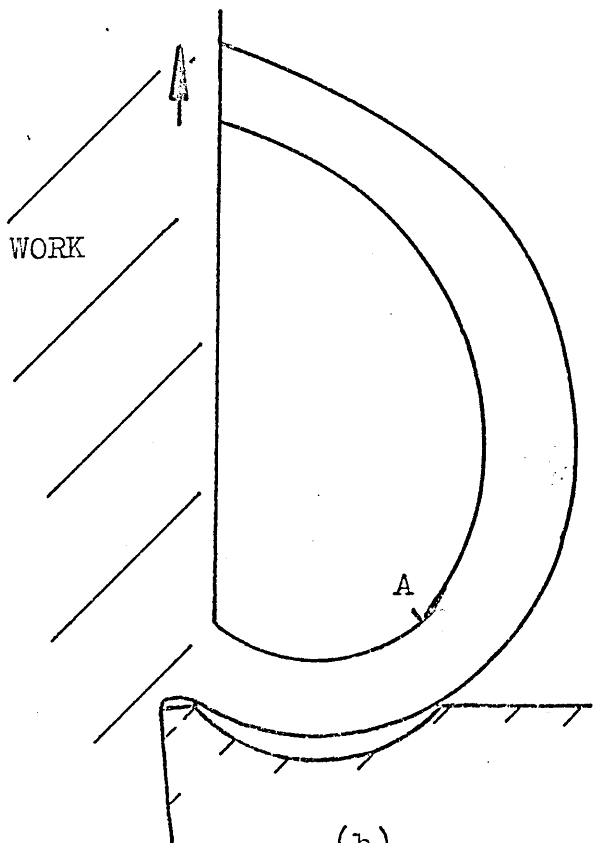


Figure 3

Formation, Expansion and Fracture of Chip

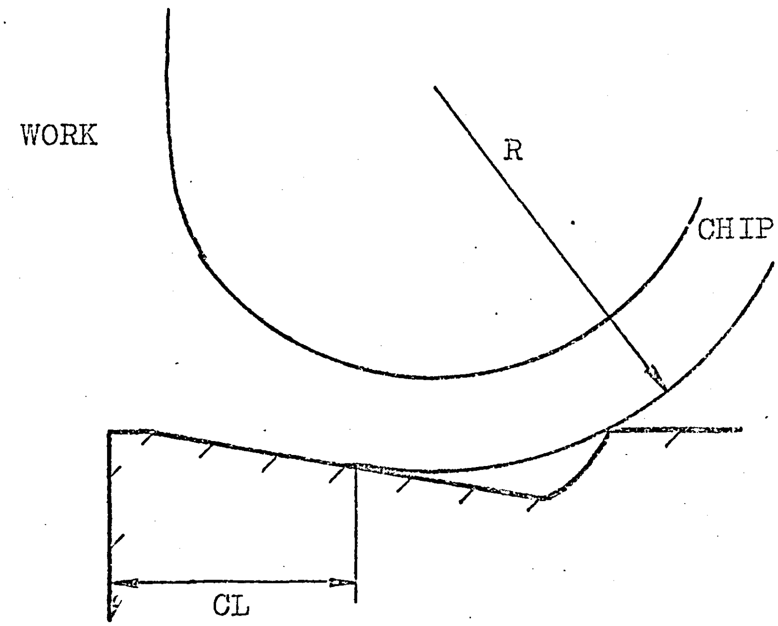


(a)



(b)

Figure 4
Two Modes of Chip Breaking
against the workpiece shoulder



R = Chip Radius

CL = Chip-Tool contact length

Figure 5

Chip-Tool contact

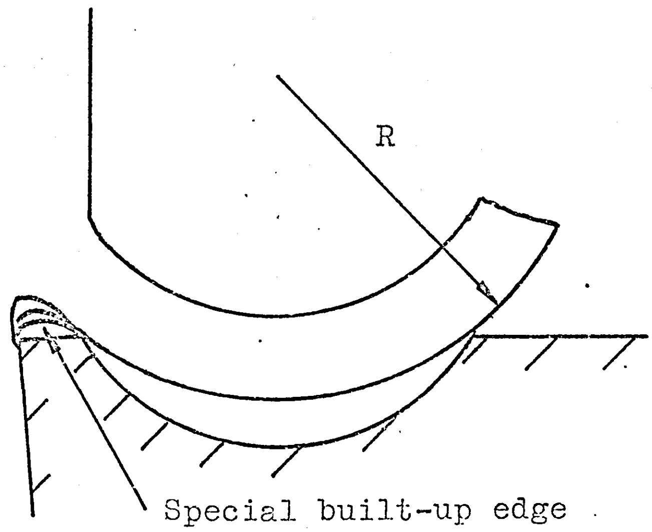
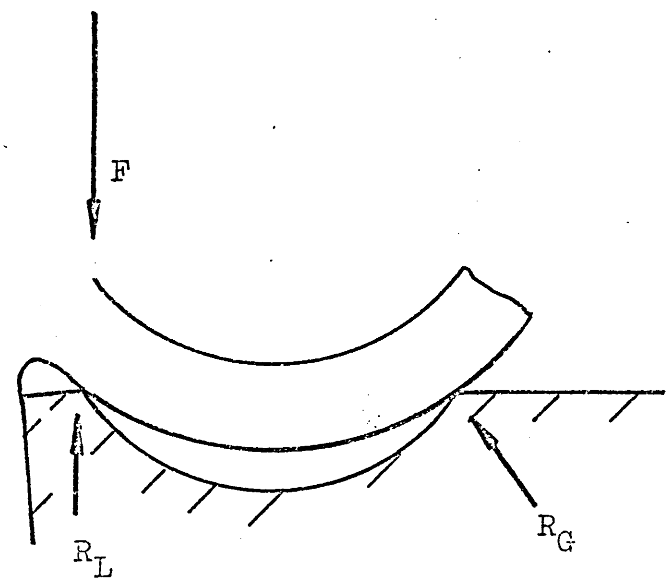
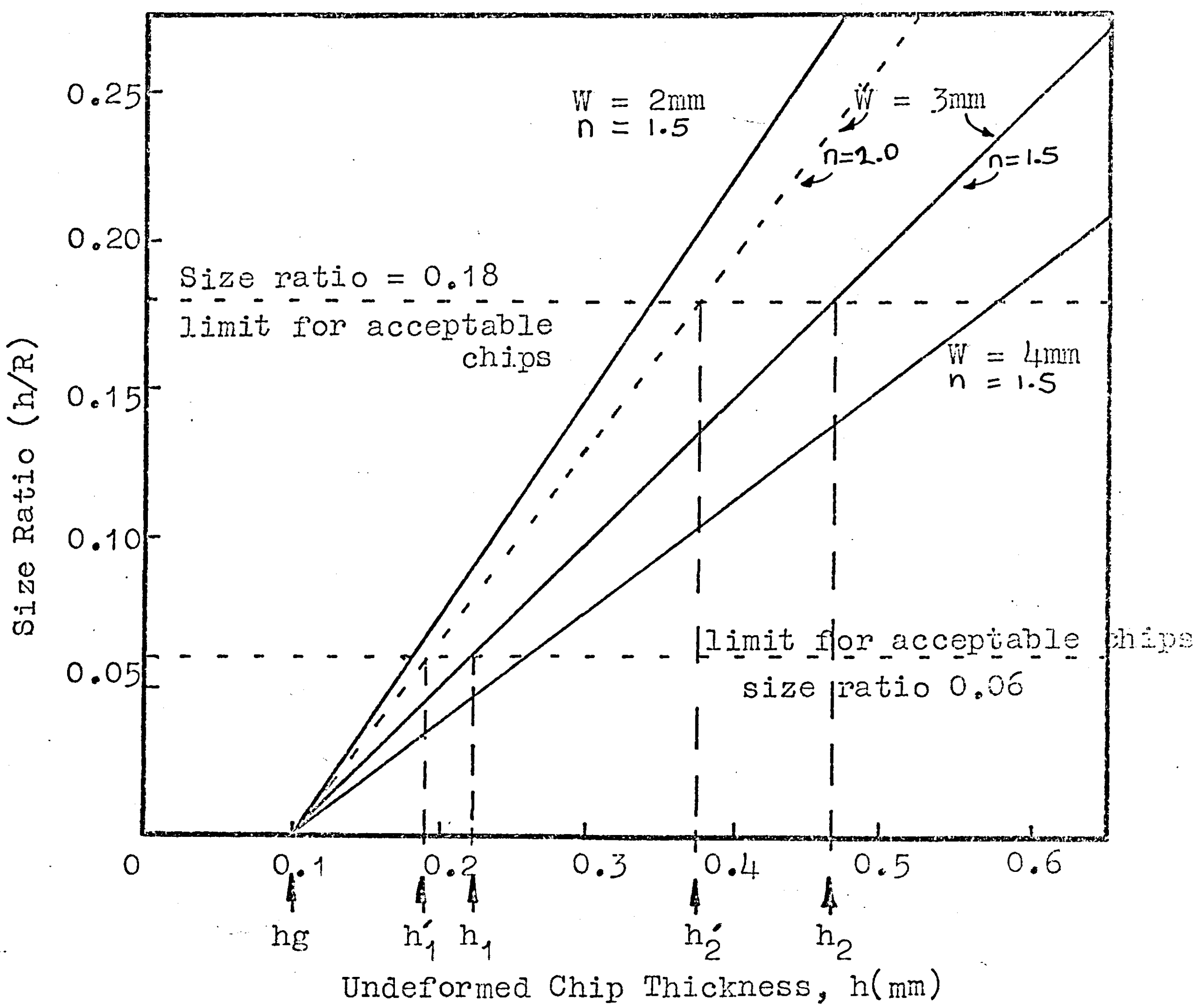


Figure 6
Chip Formation over Built-up edge



F = Cutting Force
R_L = Reaction at Land
R_G = Reaction at Groove heel

Figure 7
Forces in Chip Formation



W = Groove width

hg = U.C.T. for chip to use the Groove

h_1 = U.C.T. at onset of acceptable breaking for n = 1.5

h_1' = U.C.T. : : : n = 2.0

h_2 = U.C.T. at onset of overbreaking for n = 1.5

h_2' = U.C.T. : : : n = 2.0

Figure 8

Effect of Groove Width on
Chip Breaking Performance of a Tool

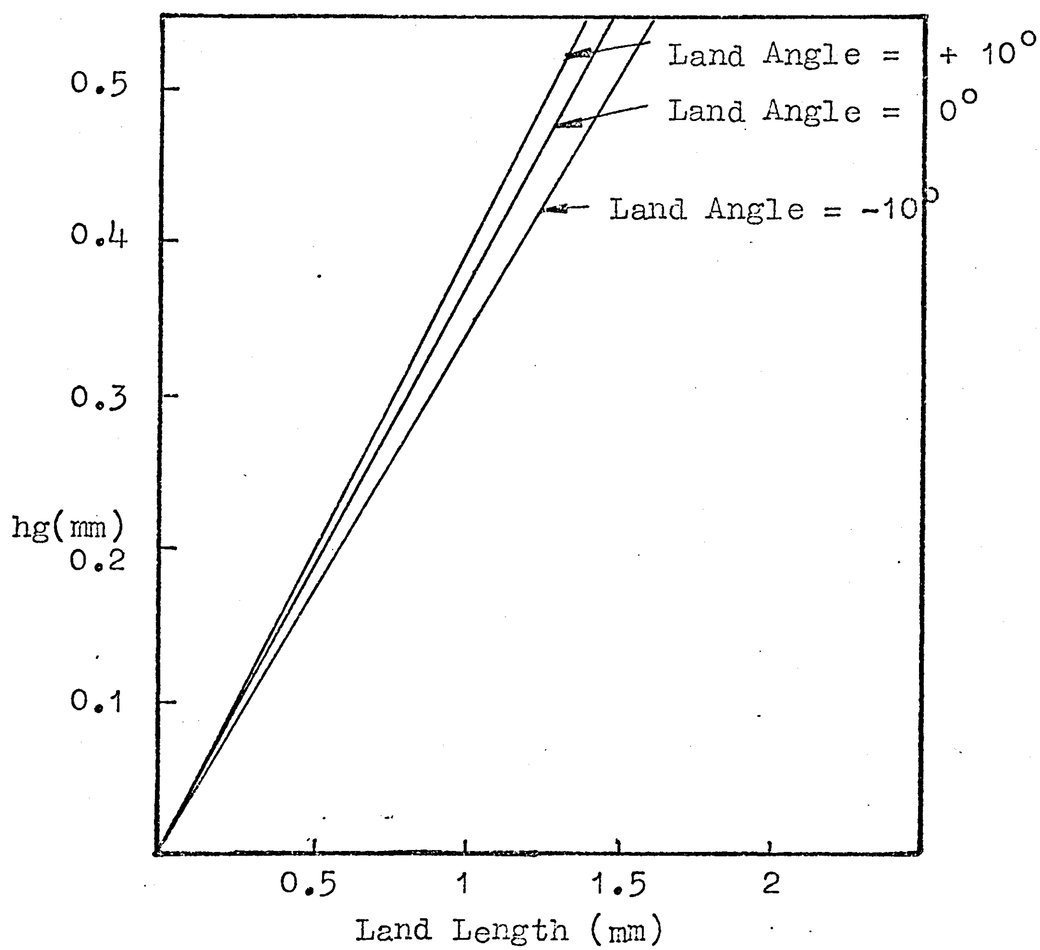


Figure 9

Land Length - hg relationship

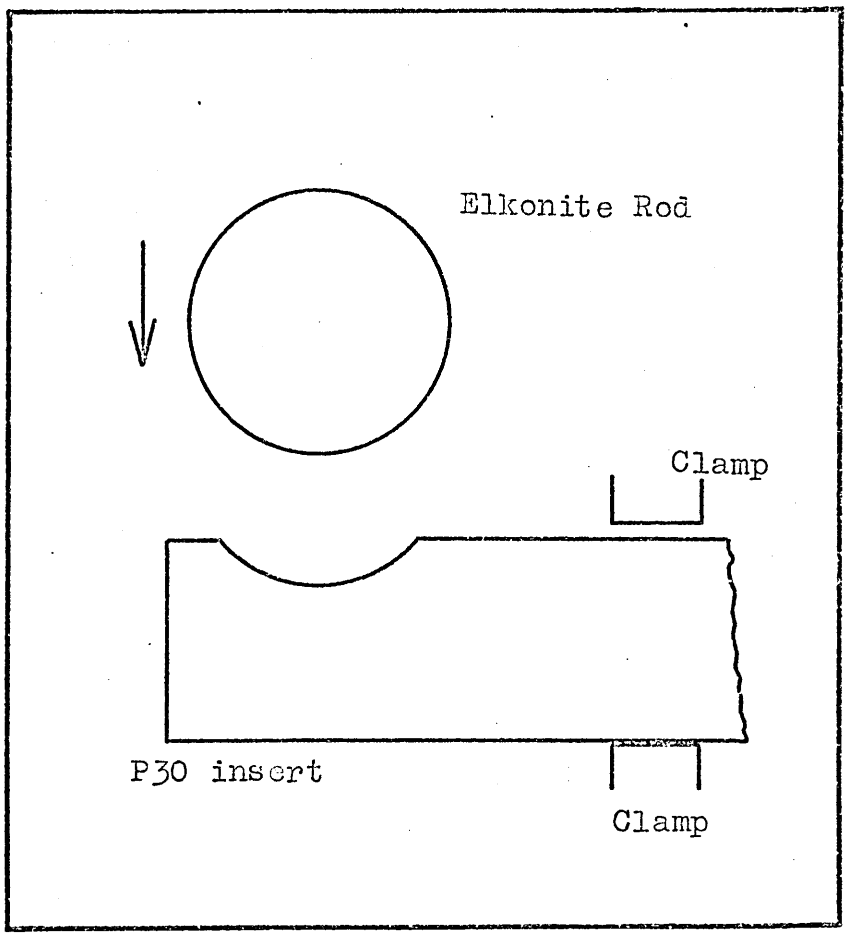
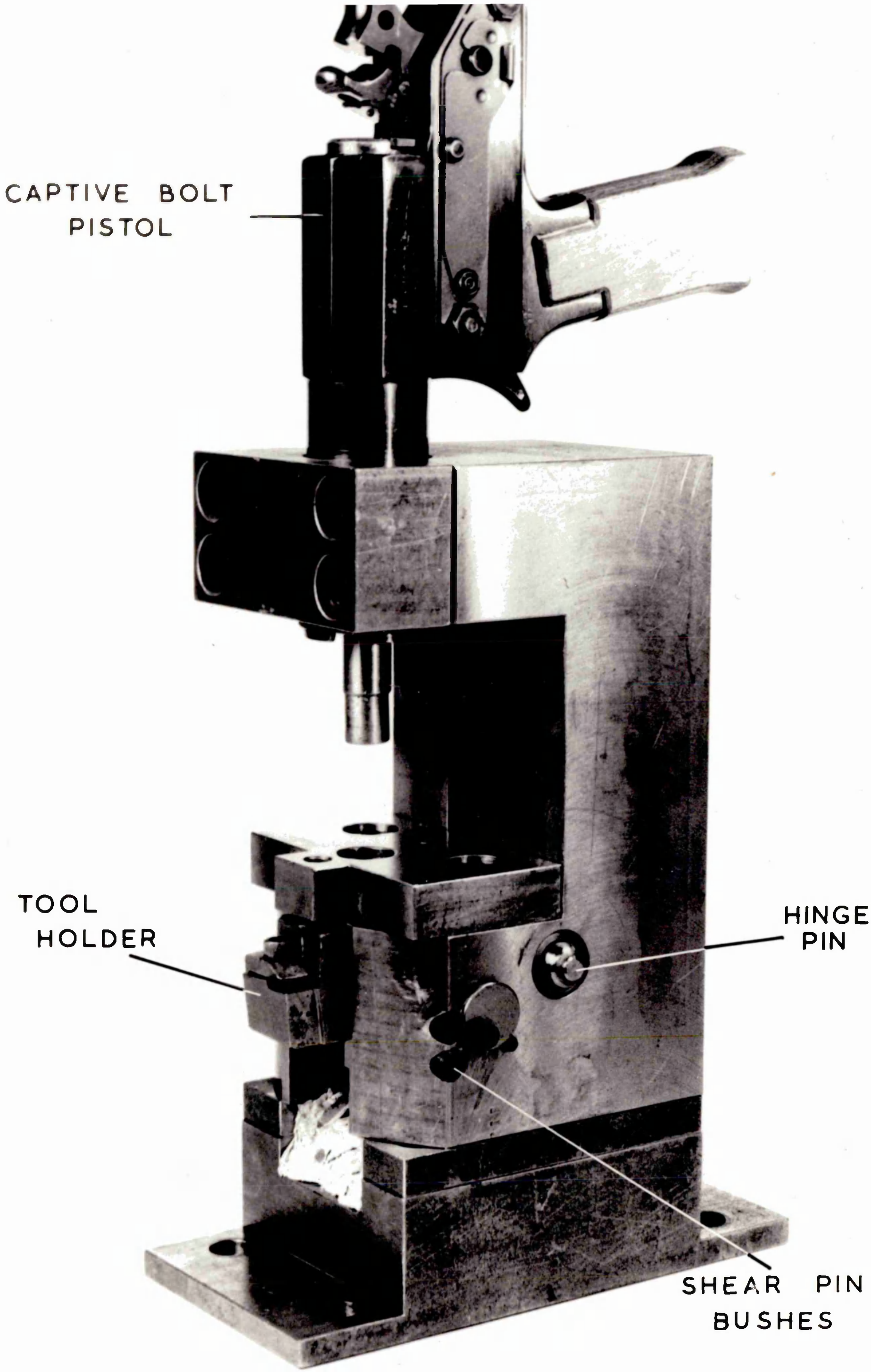


Figure 10

Method of Spark Eroding Groove



QUICK STOP DEVICE FIGURE 11

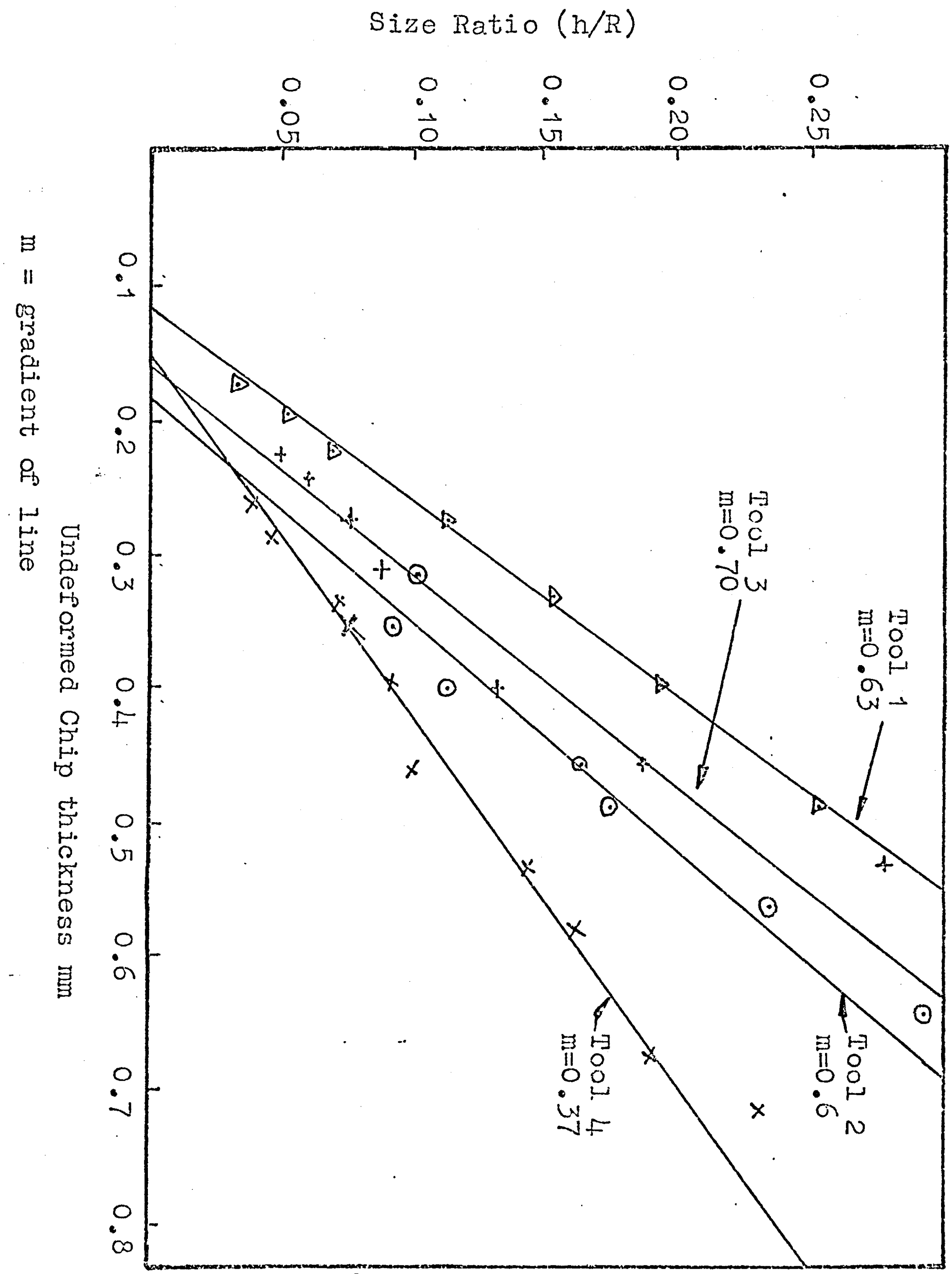


Figure 12

Size Ratio versus underformed chip thickness for four tools of various dimensions

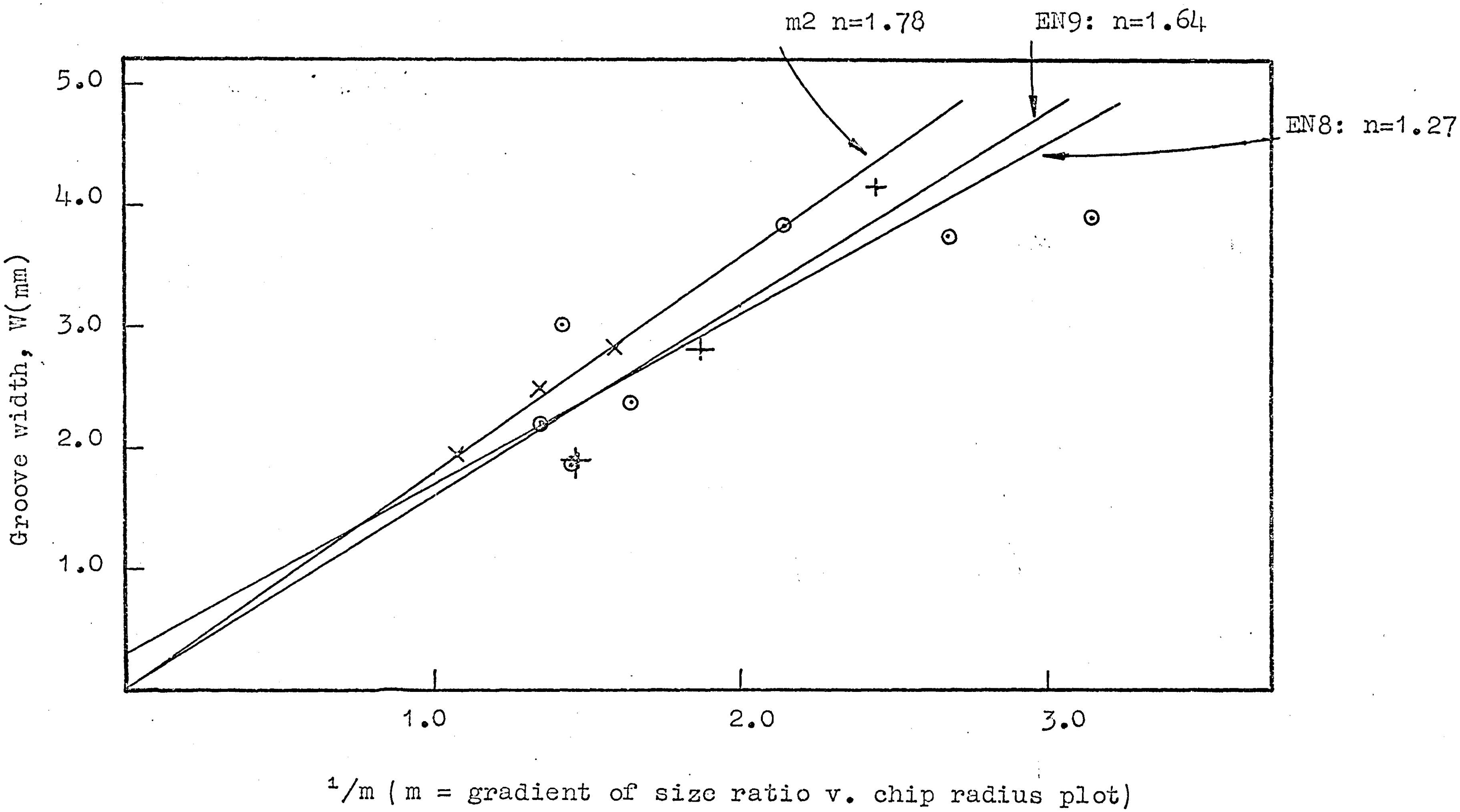


Figure 13

Material constant for EN8, M2 and EN9

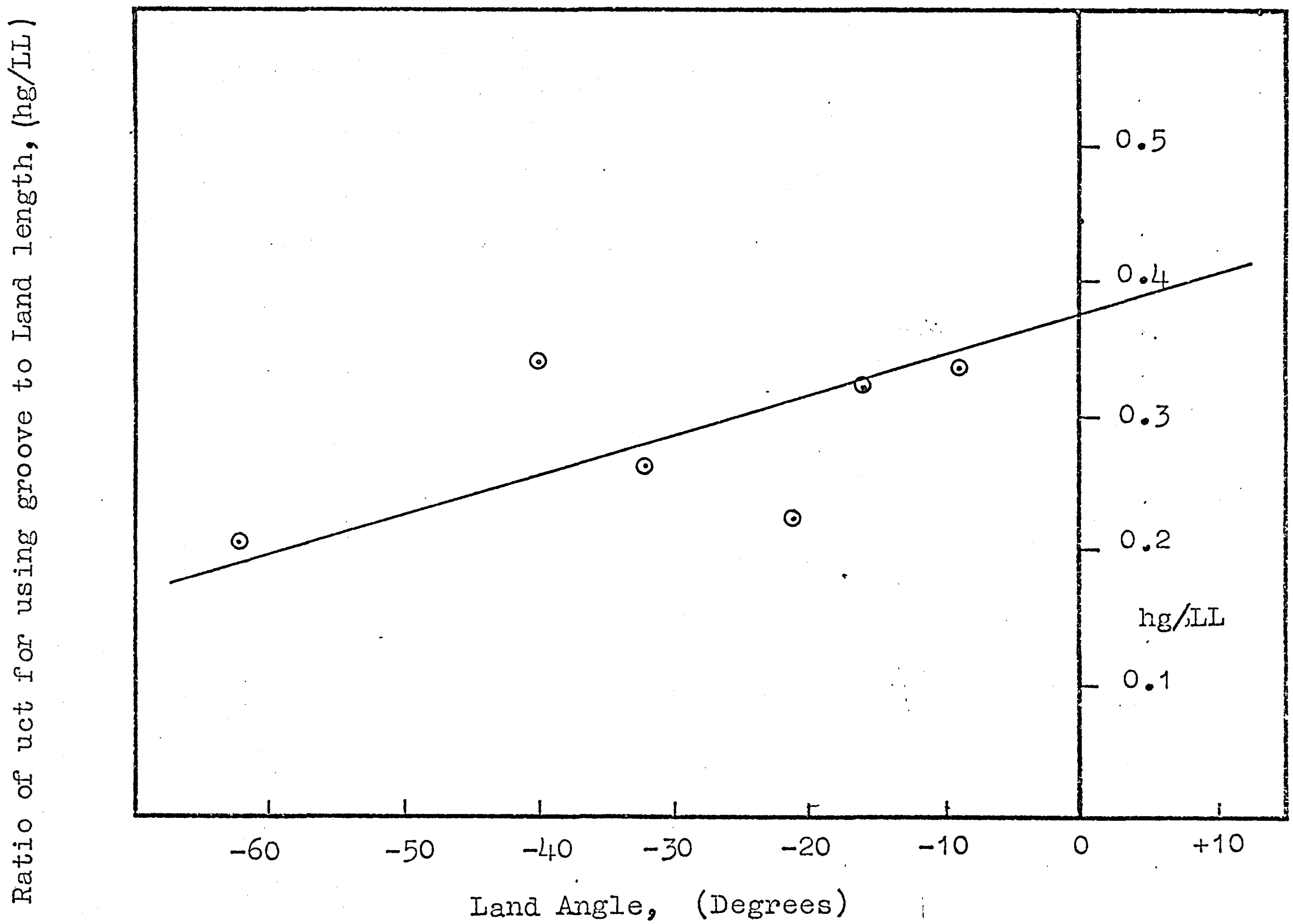


Figure 14

Land Angle Relationship for EN8

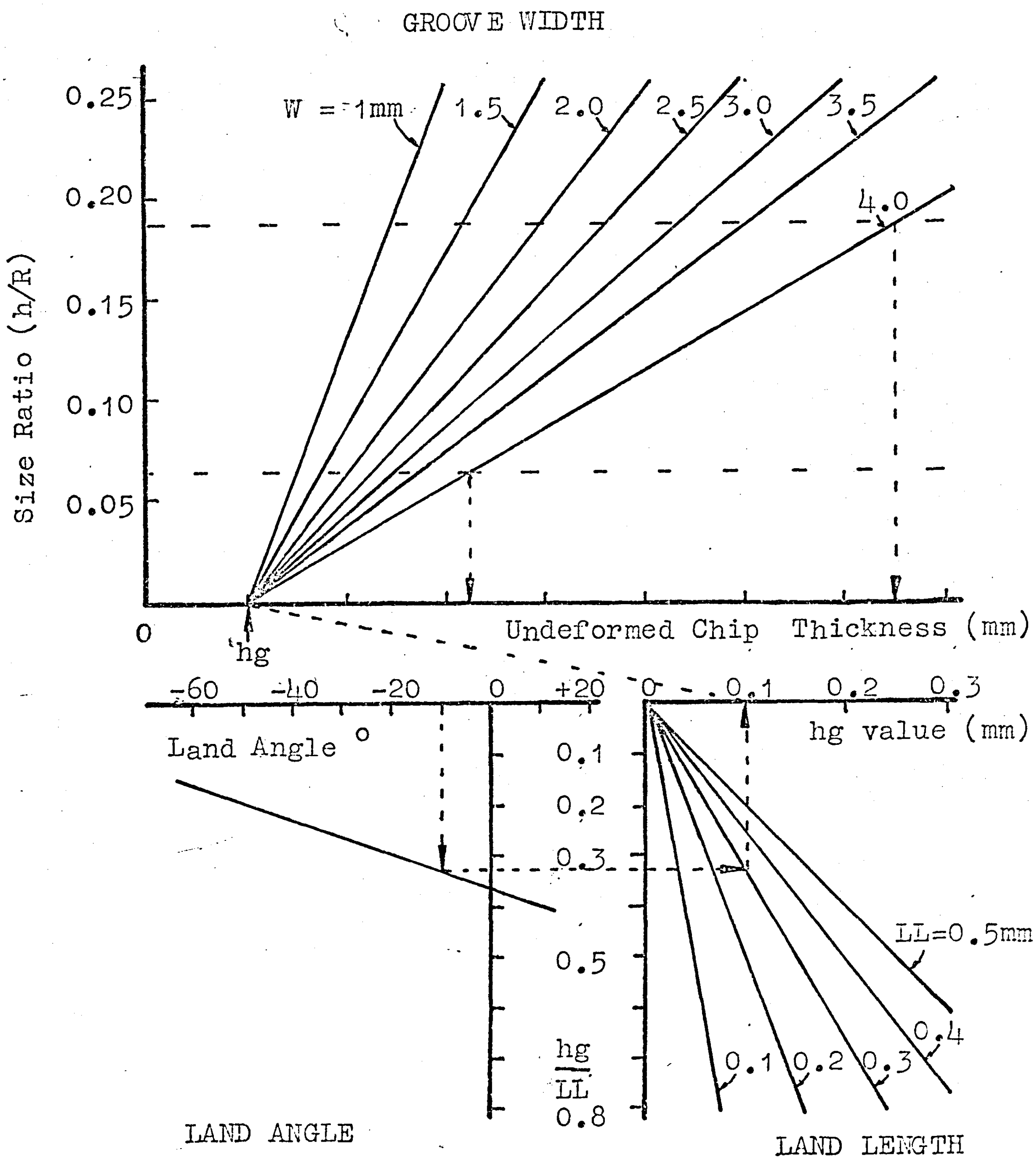
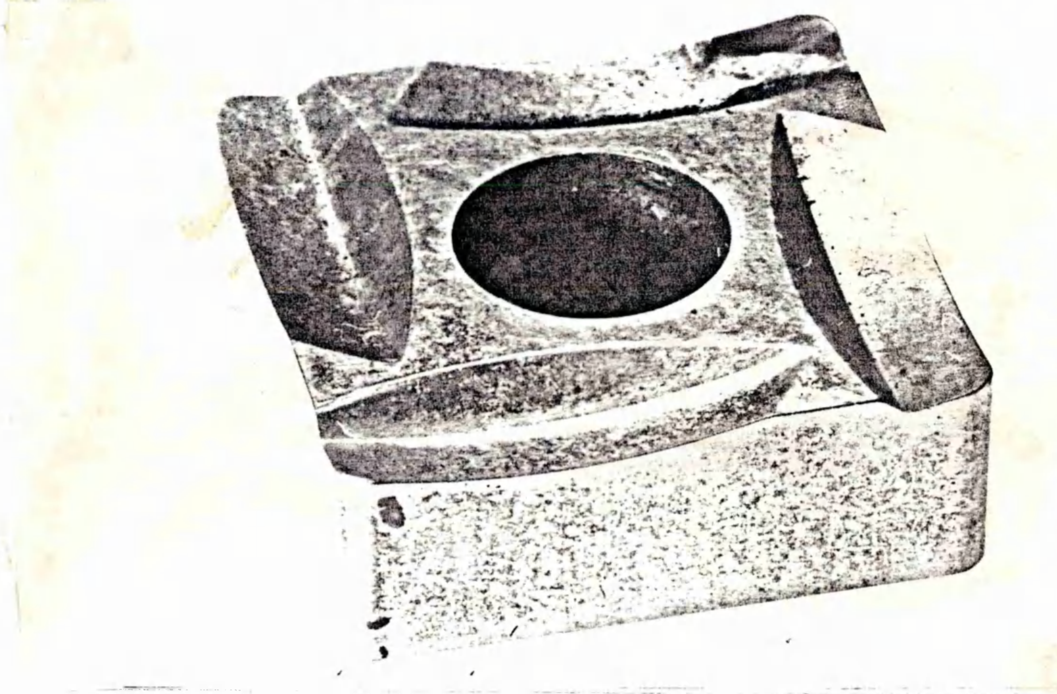
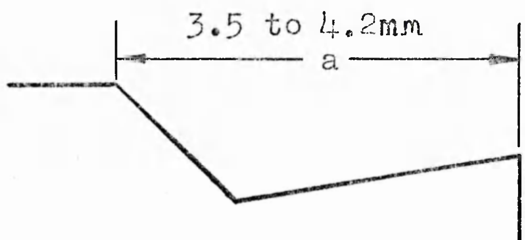


Figure 15

The Nomogram





Profile away from Nose of Tool

Profile at Nose of Tool

Figure 16(a)
"Valenite" Tool

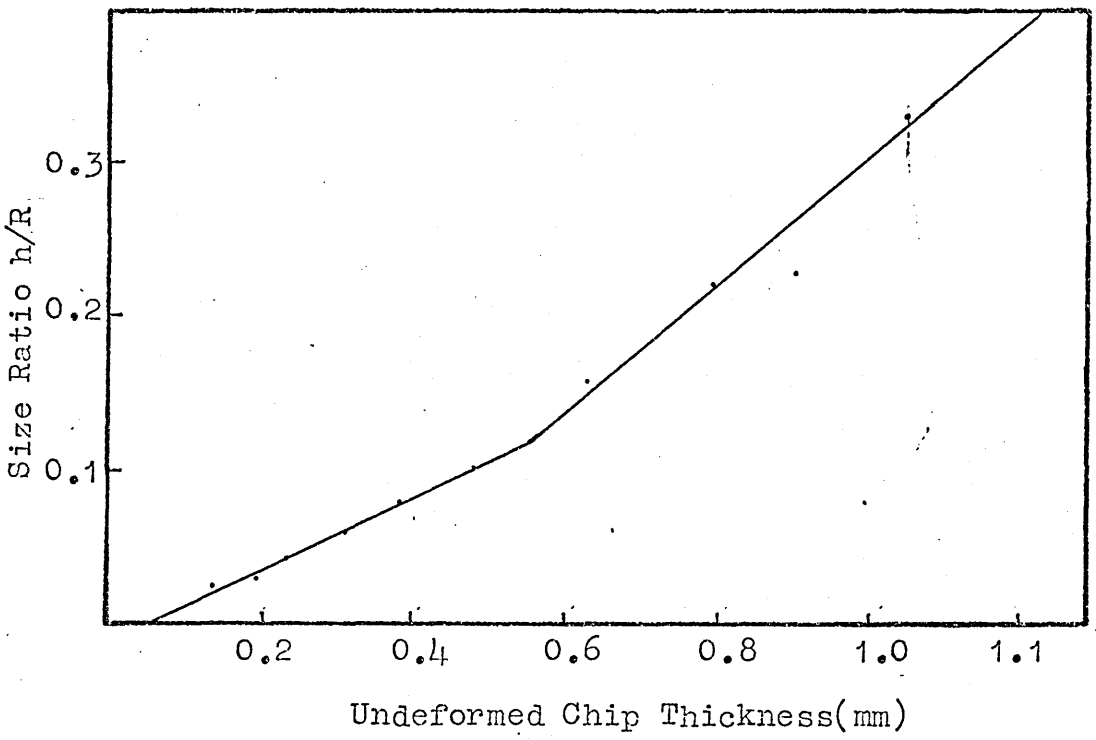
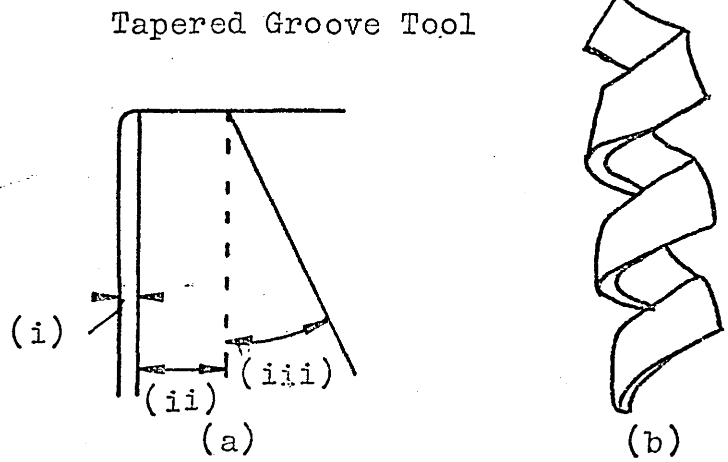


Figure 16 (b)

Size Ratio versus Undeformed Chip Thickness for the "Valenite" Tool

Figure 17 (a)

Taper Groove Tool produced in Laboratory and a (b) fan shaped chip typical of those sometimes produced by Tapered Groove Tool

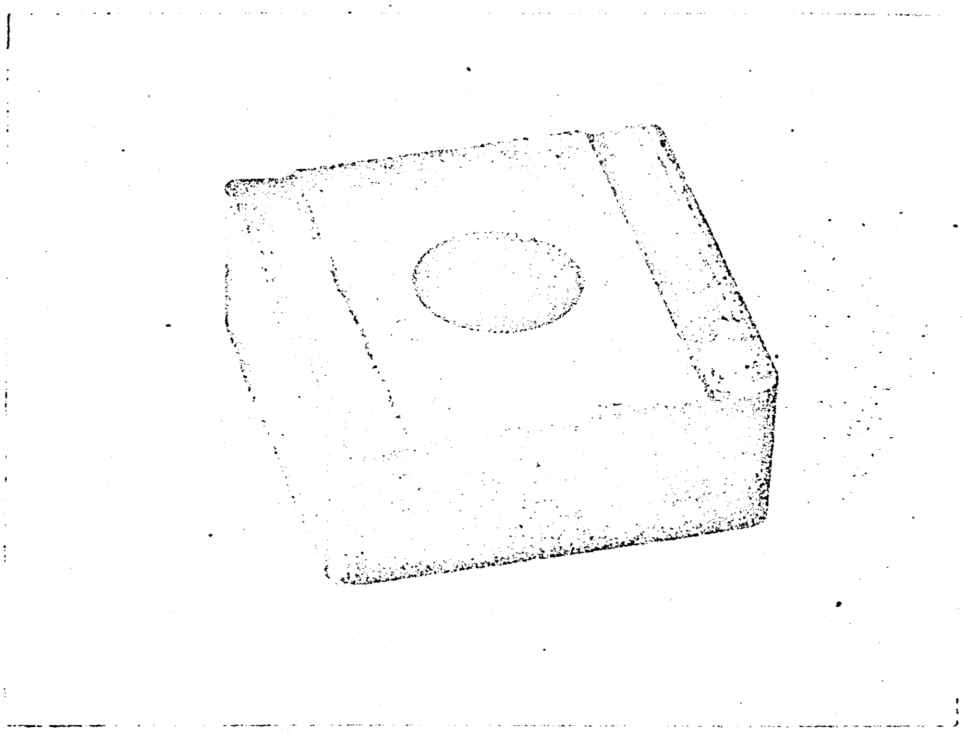


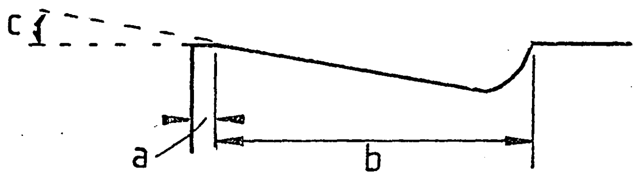
Dimensions

(i) Land Length = 0.4mm

(ii) "Nominal" groove width = 2.5mm

(iii) Taper Angle = 27°





Dimensions

a. Land Length 0.1mm

b. Groove Width 2.0mm

c. Groove Inlet Angle 10°

Figure 18
"Cintride" Tool

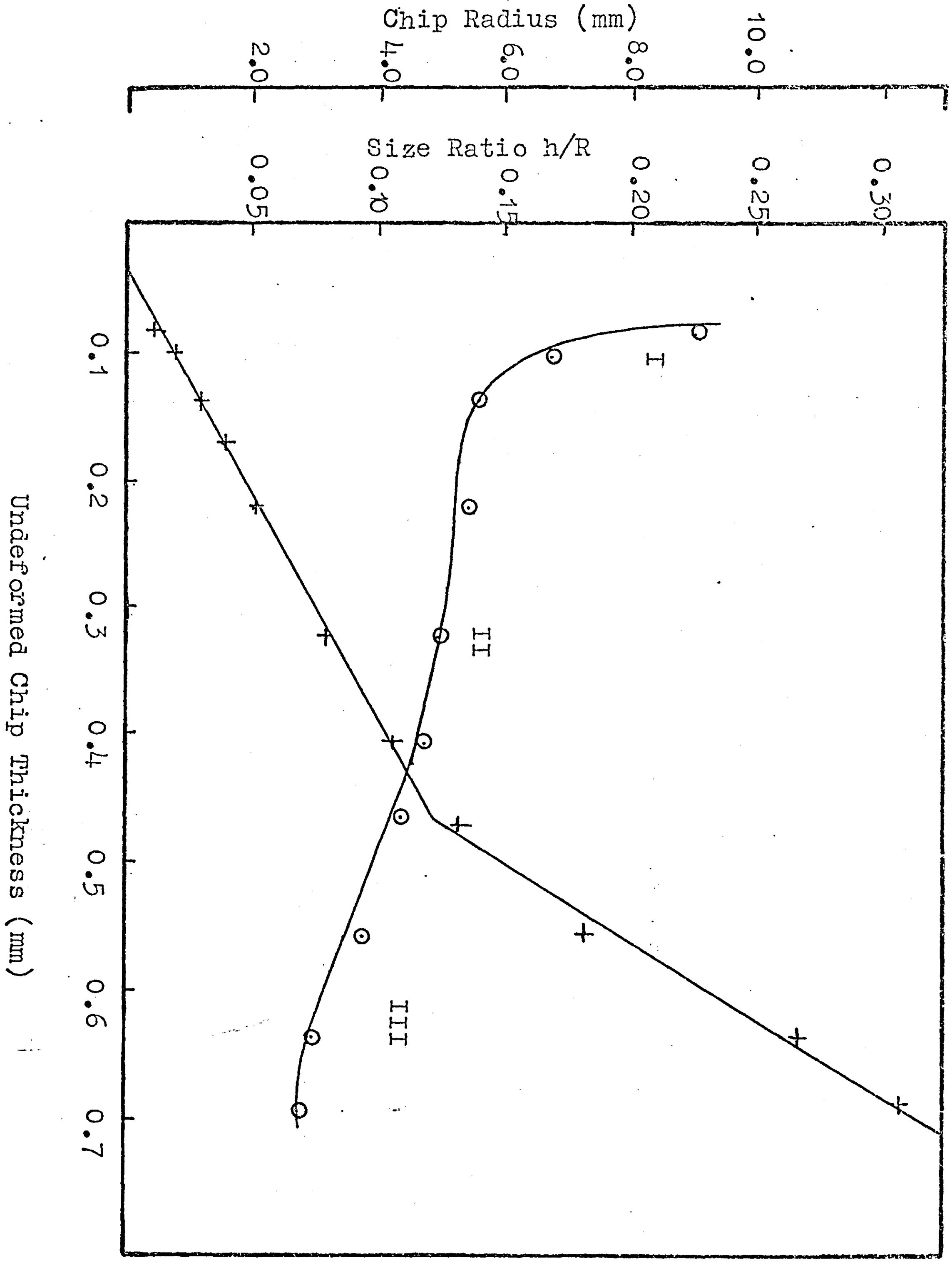
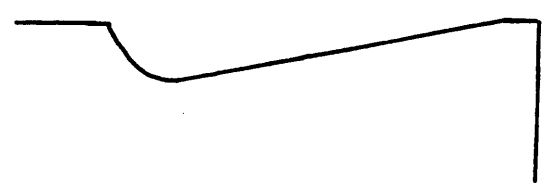
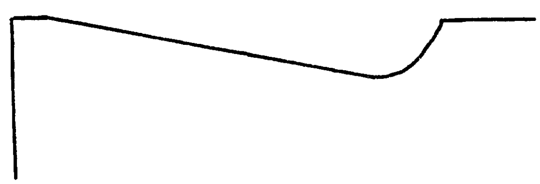


Figure 19

Size Ratio and chip radius versus
undeformed Chip Thickness
for "Cintride" Tool





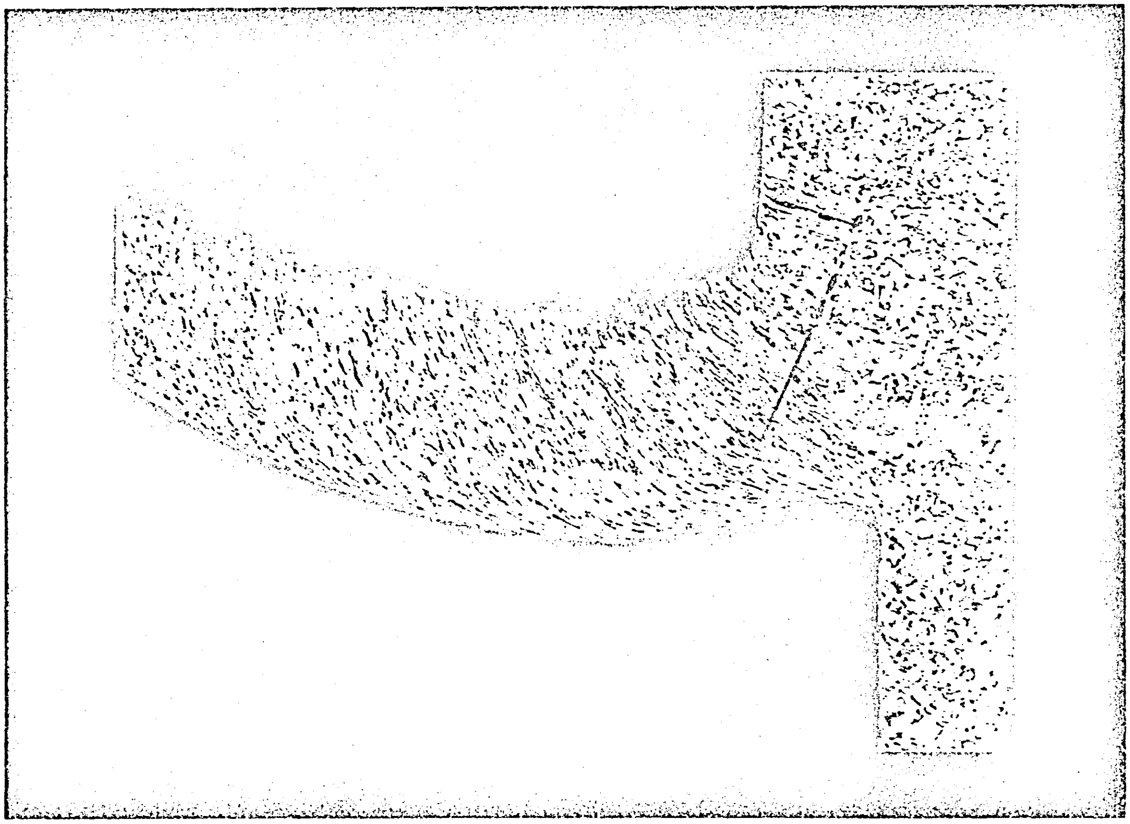


Figure 20

Quickly Stopped Sample of "Cintride" Tool at undeformed chip thickness=0.64mm.rev^{-1}. (X27) with overlay showing tool profile to same scale.

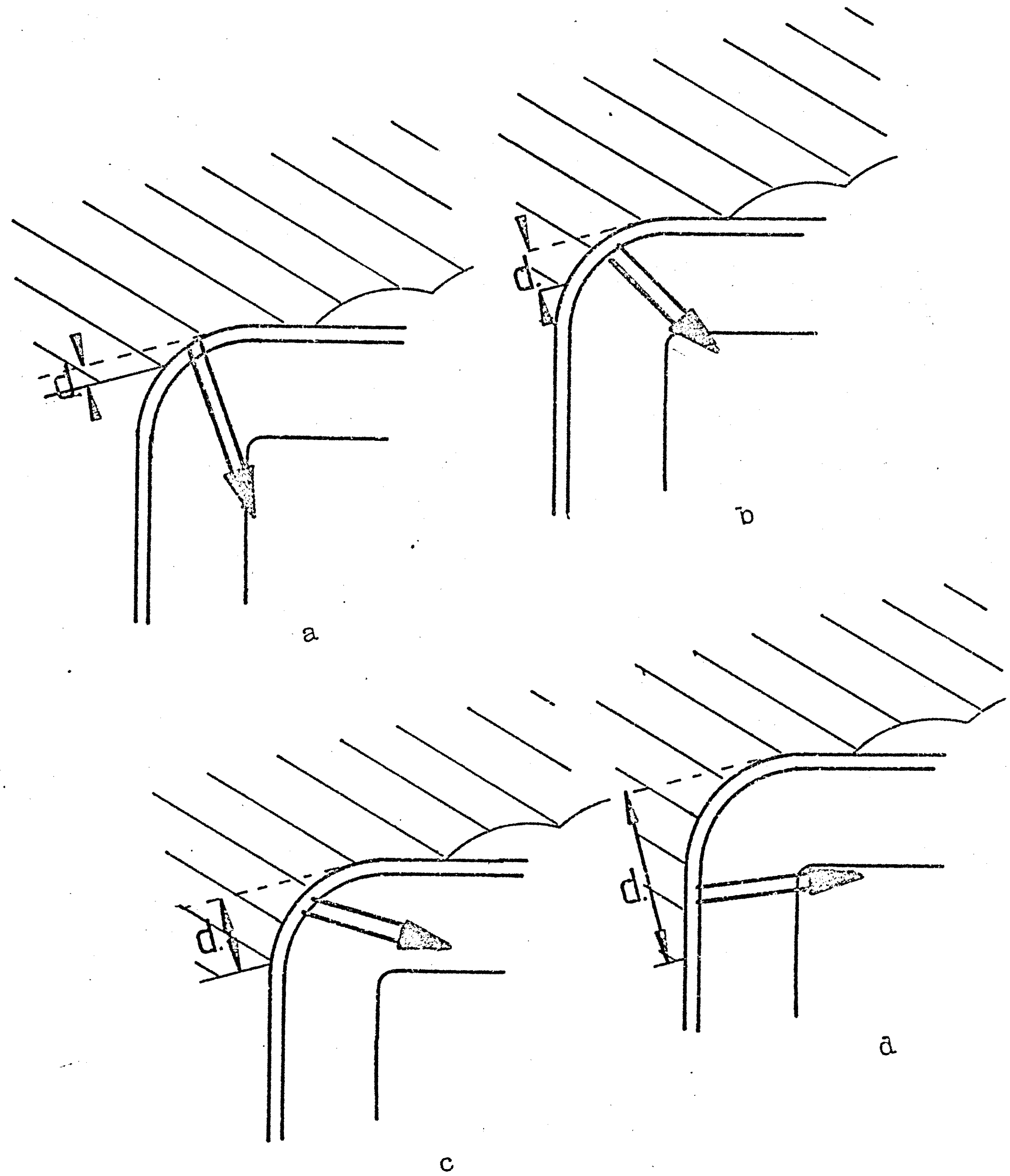
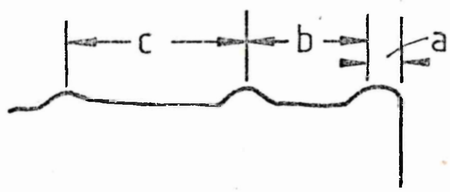


Figure 21

The importance of Chip Flow direction
For tools with "Moat type" Grooves
d = depth of cut



Dimensions

a "Land" Length 0.2mm

b Width of First Groove 1.0mm

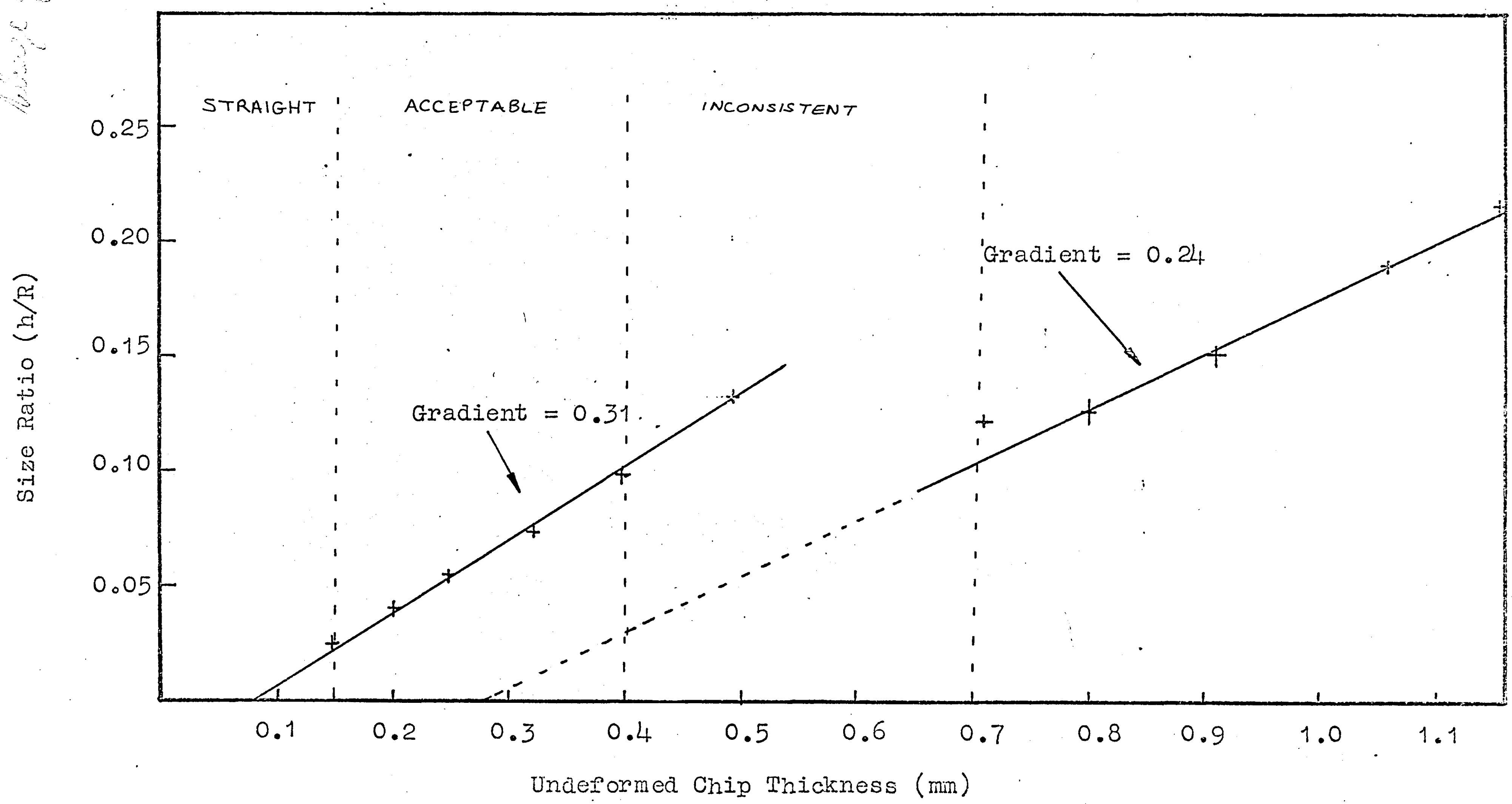
c Width of Second Groove 1.5mm

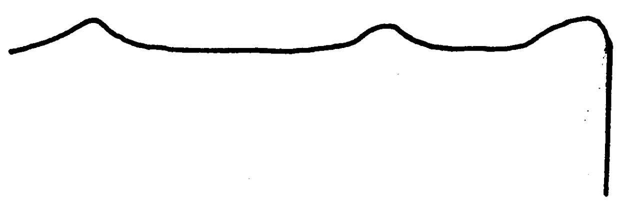
Figure 22

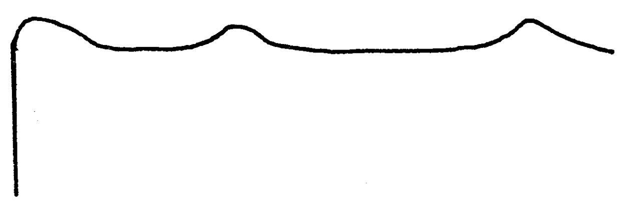
"Sandvik" Double Groove Tool

Figure 23

Size Ratio versus Undeformed Chip Thickness for "Sandvik" Double Groove Tool







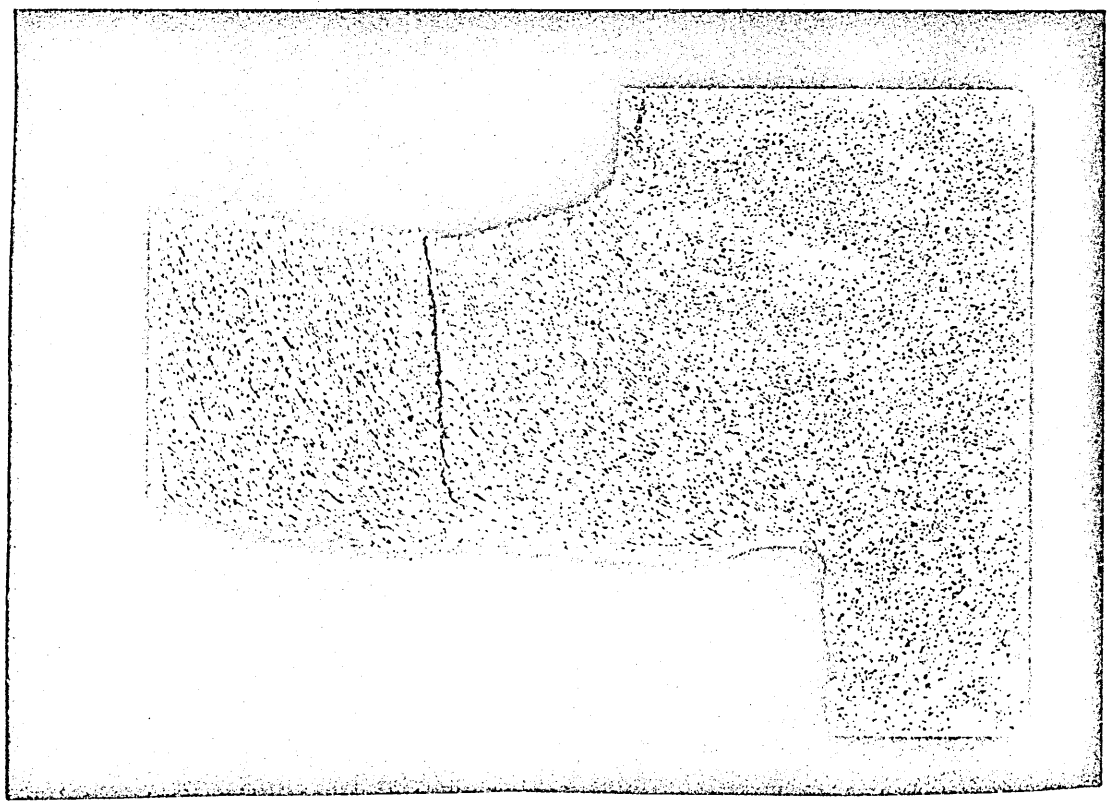
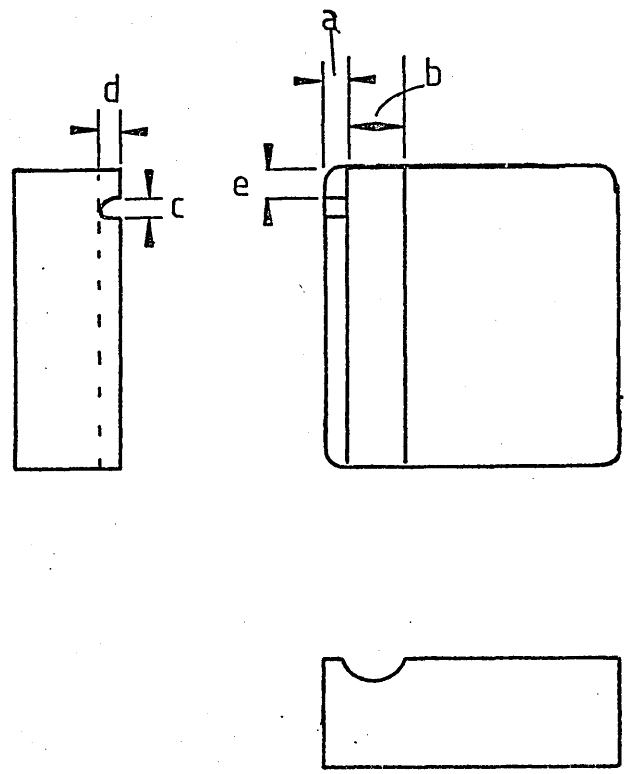


Figure 24

Quickly Stopped Sample using Sandvik Double Groove Tool at undeformed chip thickness = 0.7mm.rev^{-1} (X27) with overlay showing tool profile to same scale.



	Notch 1 (mm)	Notch 2 (mm)
a. Land Length	0.18	0.46
b. Groove Width	4.22	4.07
c. Notch Width	1.22	1.47
d. Notch depth	0.57	0.53
e. Notch distance from nose	0.97	0.92

Figure 25

Tool with "Notched" Land

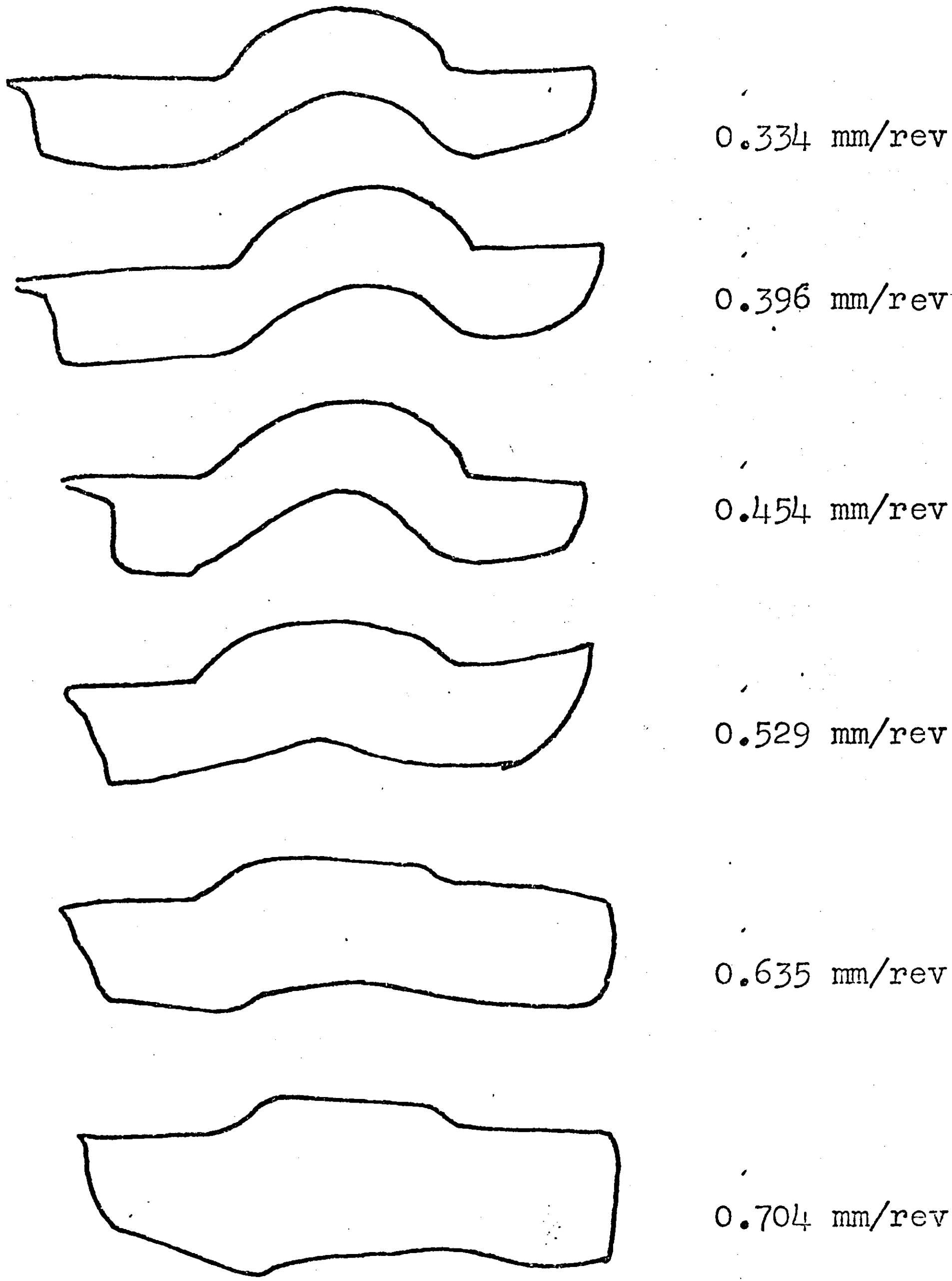
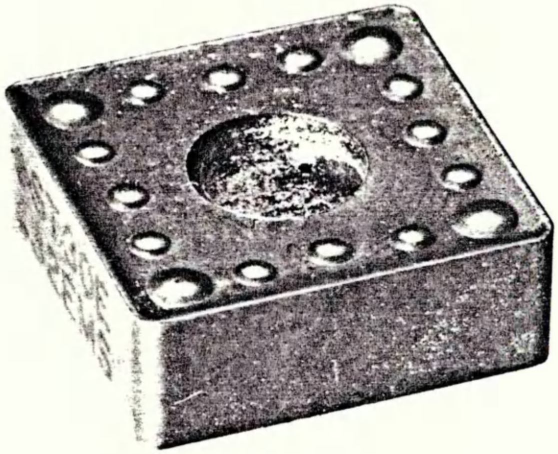
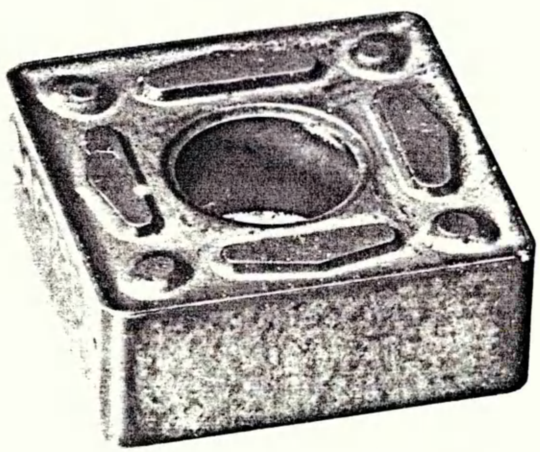


Figure 26

Cross sections of chips produced by notched tool (notch 2) at various feed rates.



(a)



(b)

Figure 27

Sumitomo (a) "Spiky-S and (b) "Bumpy-G" Tools

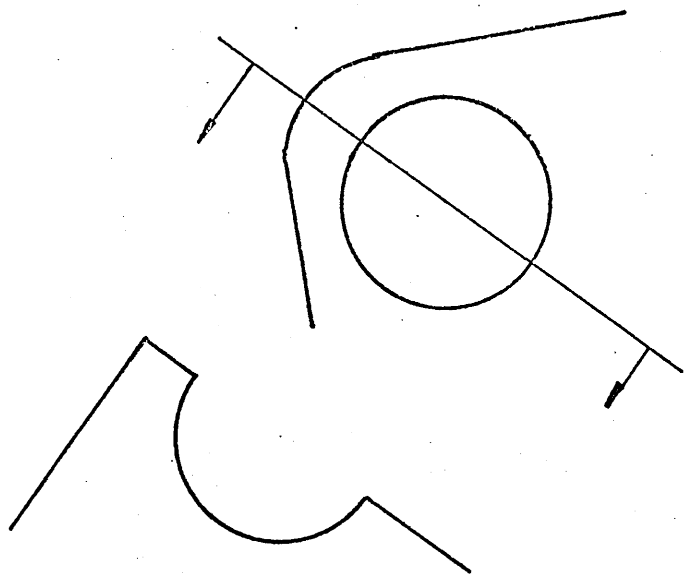
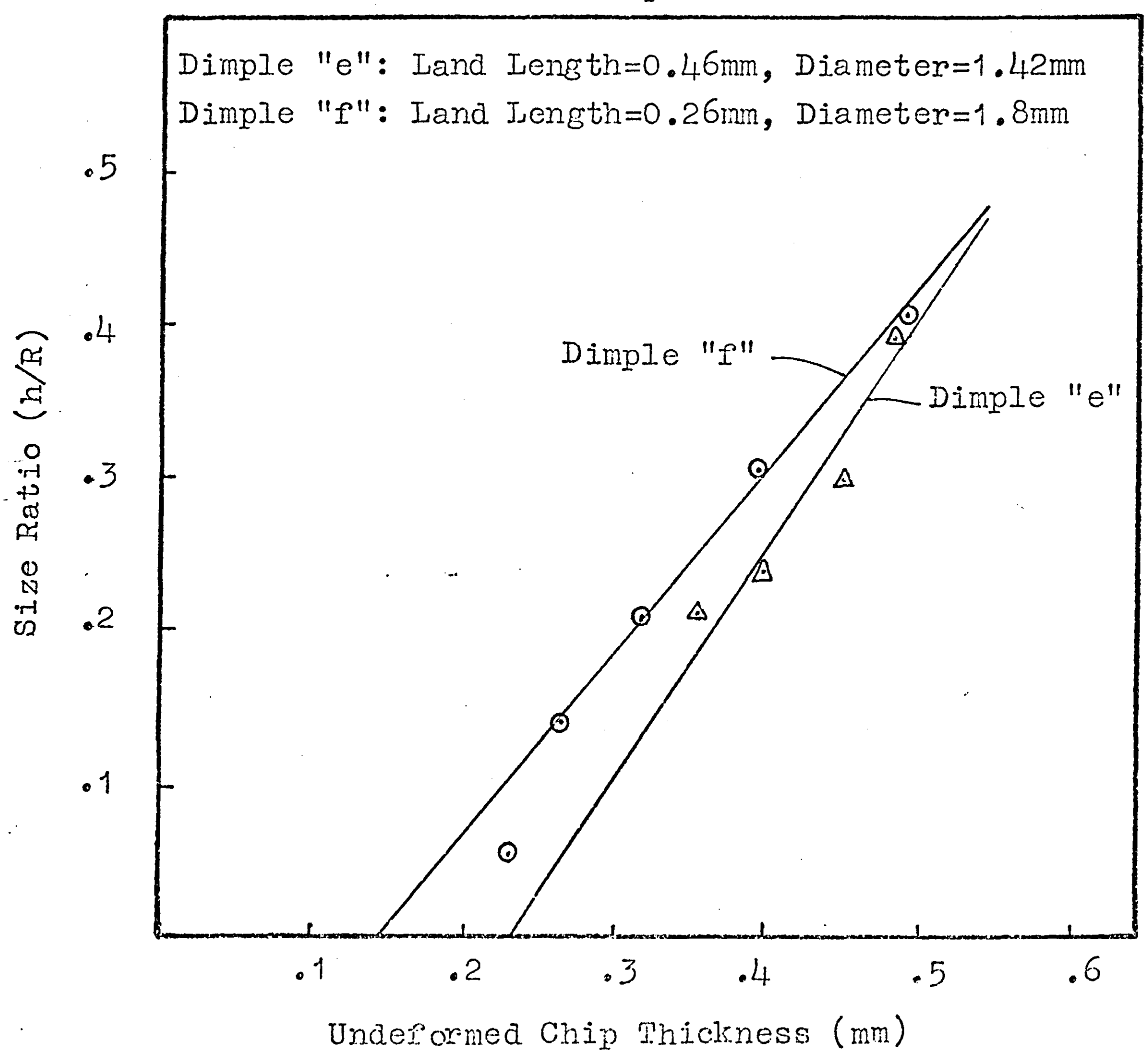


Figure 28
"Dimple" Tool produced in Laboratory

Figure 29
Size Ratio against Undeformed Chip
Thickness for two "Dimple" Tools



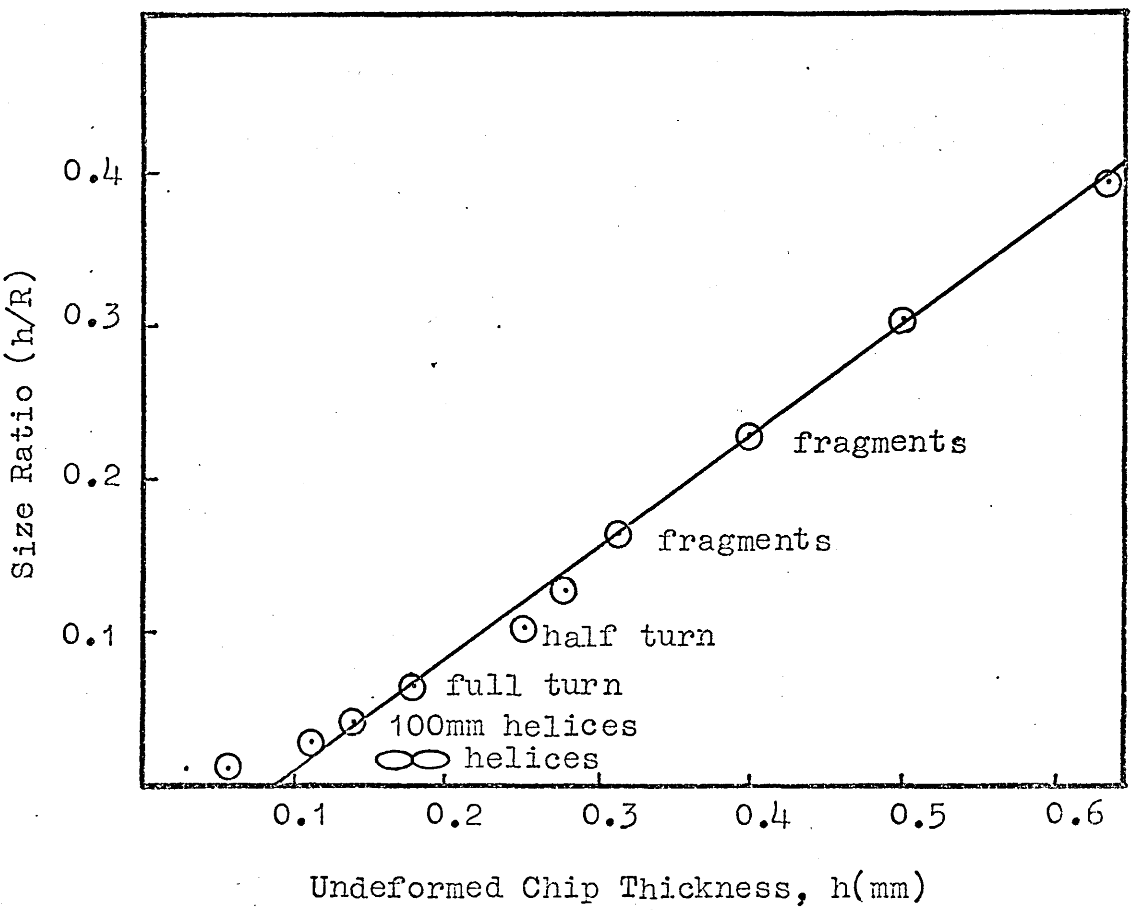


Figure 30

Size Ratio against Undeformed Chip Thickness
for Sumitomo "Spiky-S" Tool showing chip type

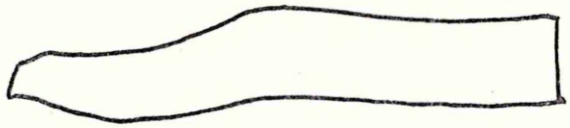


Figure 31(a)
Cross Section of Chip produced by "Bumpy-G" Tool
at 0.37mm Undeformed Chip Thickness (X20)

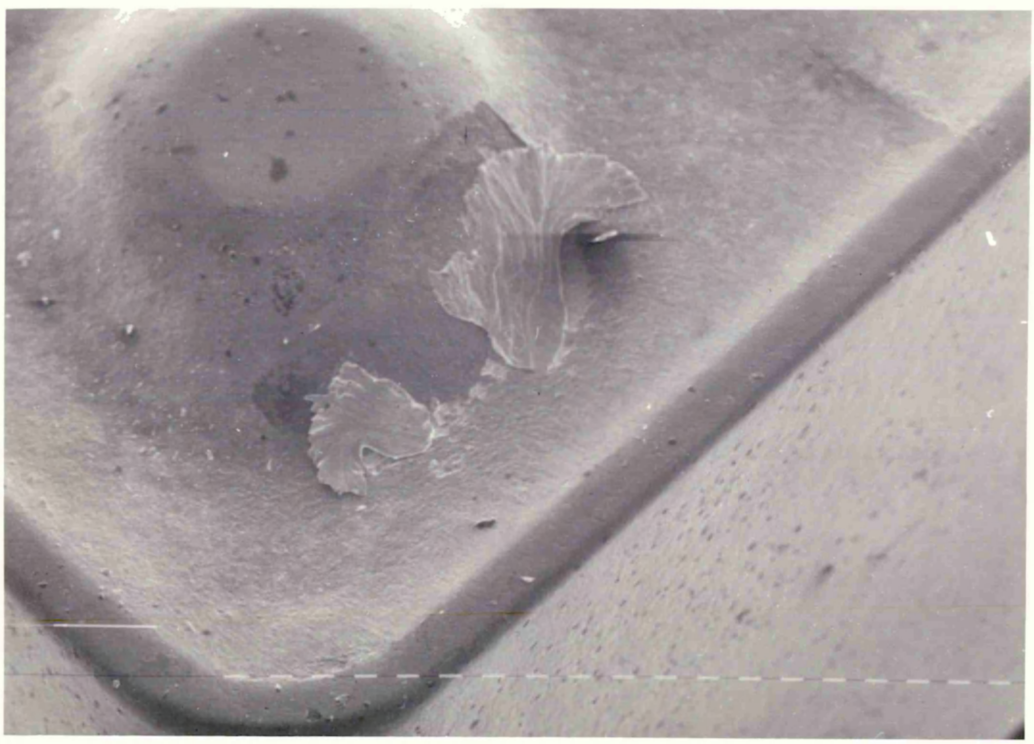


Figure 31(b)
Corner of "Bumpy-G" Tool after cutting (X5) showing
showing contact of Chip with the Tool

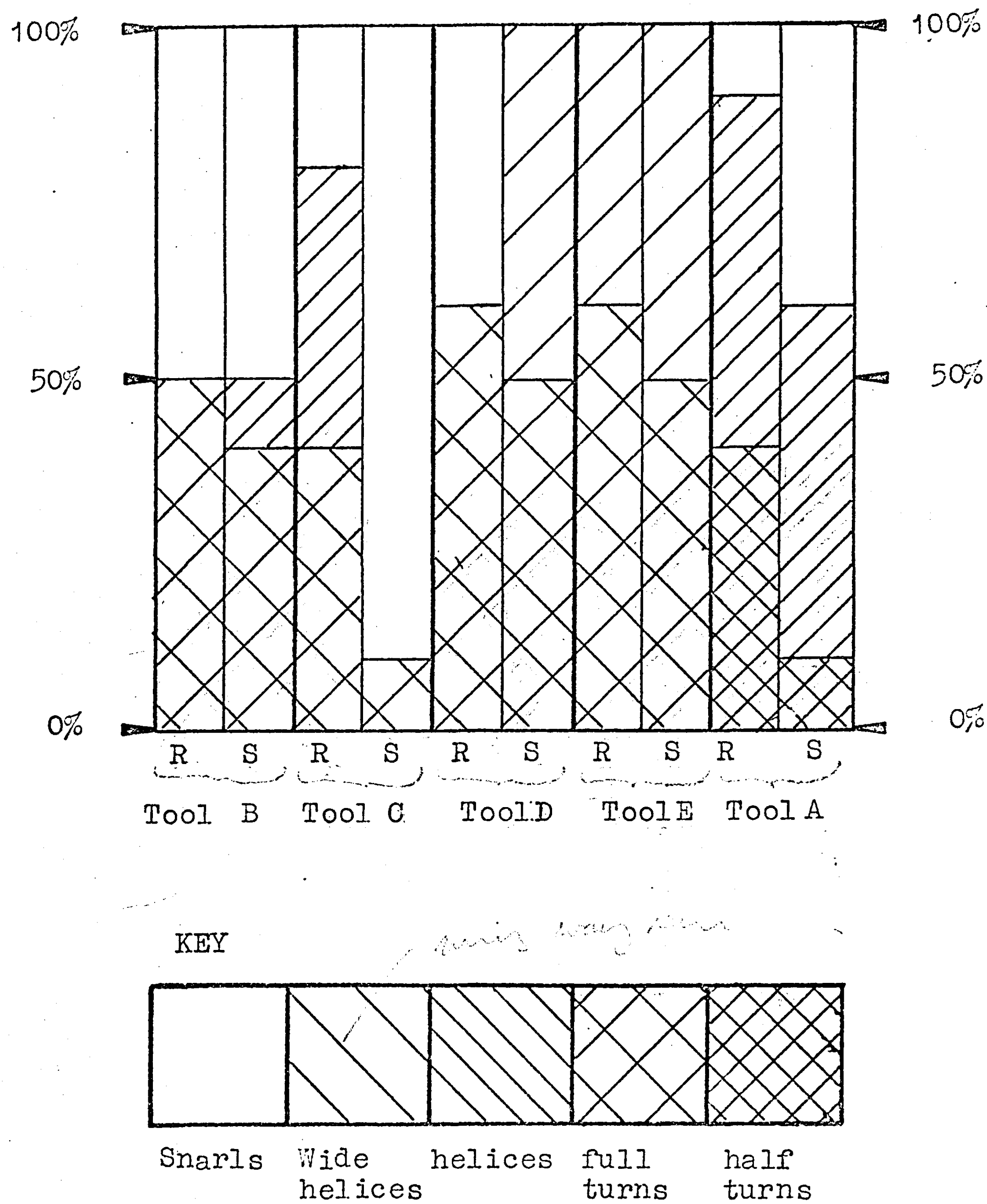


Figure 32

A comparison of the proportion of Chip Types produced with Rough (R) and Smooth (S) Flanked Tools at a feed of 0.334 mm

Figure 33
High Speed Photograph showing Chip
Anchoring on Specially Textured Tool Flank

APPENDIX A

LIST OF COMPANIES VISITED

Firth Brown Limited

Record Ridgeway Limited

Higher Speed Metals Limited

Sheffield Twist Drill and Steel Company Limited

Spear & Jackson Limited

British Steel Corporation

Davy Roll Company Limited

Easterbrook Allcard and Company Limited

APPENDIX B

An example of the use of the Nomogram

The tool for which the chip breaking range is to be established has the following dimensions:-

groove width, W = 4mm

land length, LL = 0.30mm

land angle, γ = -10°

The material to be cut is EN3b which has chips with a fracture strain of 0.03 (determined either from mechanical testing or from chip breaking tests and the relationship: $2\varepsilon = (h/R)_{crit}$). Cutting speed is not specified since tests have shown that it does not significantly influence the chip breaking performance of the tool.

The following procedure using the nomogram will give the range of feeds for acceptably broken chips.

1. Start at the graph showing land angle against hg/LL. Note the value of hg/LL for a land angle of -10° (which is found to be hg/LL = 0.41).
2. Trace a line at hg/LL = 0.41 on the land length graph until the intercept with the appropriate land length line is found. Read the value from the other axis which represents the undeformed chip thickness at which the chip begins to use the groove, hg. (In this example the land length is 0.3mm, giving hg as 0.14mm). The hg value is the undeformed chip thickness at which n/r is zero on the groove width graph.

3. Graduate the undeformed chip thickness axis on the groove width graph by setting hg=0.14mm and marking each division in steps of 0.1mm as shown in figure A1.

4. Set the limits of acceptable chip breaking at $h/R = 0.06$ (2ε) and $h/R = 0.18$ (6ε).

5. Find the feed range for acceptable chip breaking by noting the value of undeformed chip thickness where the appropriate groove width line crosses the size ratio limits. In this example the groove width is 4mm and the lower limit is $h_1 = 0.35$mm and the upper limit is $h_2 = 0.77$mm.

Therefore, a tool of the above dimensions will break chips of fracture strain 3% in an acceptable manner between the undeformed chip thickness values of 0.35mm and 0.77mm. If the rake angle was more negative, or the land length shorter the acceptable chip breaking would commence and terminate at a lower value of undeformed chip thickness. A narrower groove width would reduce the undeformed chip thickness at which acceptable chip breaking begins and the range would also be narrower.

If the problem is stated from the point of view of specifying a tool to suit particular cutting conditions, then the Nomogram can be used to indicate the optimum tool configuration. Assuming the material with chip fracture strain = 0.03 and the range for machining is from undeformed chip thickness values of 0.2mm to 0.5mm the method is as follows:-

1. On the groove width graph it can be seen that a range of 0.3mm undeformed chip thickness between the size ratio limits for acceptable chip breaking is satisfied by a groove width of 3.5mm.

2. Set the lower limit of undeformed chip thickness at $h/R = 0.06$ and graduate the undeformed chip thickness axis from $h_1 = 0.2$mm in both directions.

3. Transfer the value of hg (which can now be read from the groove width graph) to the land length graph and using the land length graph in conjunction with the land angle graph select the most appropriate land configuration. In this example hg was 0.04mm and the possible land configurations include:-
land length = 0.09mm with angle $\approx 0^{\circ}$
land length = 0.10mm with angle = -10°

4. If hg is found to be less than, or very near to zero, then no physically possible land configuration will be found. It will then be necessary to amend the original range for chipbreaking. Adjustments can be made, bearing in mind the original machining problem to give a tool configuration which will give slightly overbroken chips at 0.5mm undeformed chip thickness and slightly underbroken chips at undeformed chip thickness of 0.2mm.

APPENDIX C

A programme listing showing one example of how the computer can be used with the Nomogram to present Chip breaking information.

```
 10:
 20:
 30REM        PART 1 : DATA INPUT
 40:
 50 MODE 7
 60PRINT TAB(5,5);CHR$(141); "SPECIFY TOOL PLEASE"
 70PRINT TAB(5,6);CHR$(141); "SPECIFY TOOL PLEASE"
 80INPUT"1. GROOVE WIDTH (m.m.)=",W
 90 IF W<0.5 OR W>4.0 THENPRINT"OUT OF RANGE":GOTO 80
100INPUT"2. LAND LENGTH (m.m.)=",L
110 IF L<0.1 ORL>1.0 THEN PRINT"OUT OF RANGE":GOTO 100
120INPUT"3. LAND ANGLE (Degrees)=",A
130 IF A<-50 OR A>10 THEN PRINT "OUT OF RANGE":GOTO 120
140INPUT"IS N-VALUE=1.5 SUITABLE (Y/N)",AN$
150IF AN$="N" THEN INPUT"ENTER N-VALUE",N ELSE N=1.5
160INPUT"IS CHIP FRACTURE STRAIN=0.03(Y/N)",AN$
170IF AN$="N" THEN INPUT"ENTER CHIP FRACTURE STRAIN",E ELSE E=0.03
180 KEY=GET
190:
200:
210REM       PART 2 : CALCULATIONS
220:
230REM    HG - UNDEFORMED CHIP THICKNESS AT WHICH CHIP BEGINS TO
240REM                USE THE GROOVE
250REM    H1 - UNDEFORMED CHIP THICKNESS AT ONSET OF GOOD CHIP BREAKIN
260REM    H2 - UNDEFORMED CHIP THICKNESS AT ONSET OF OVERBREAKING
270:
280:
290HG=(0.00286*A+0.378)*L
300H1=2*E*W/N+HG
310H2=6*E*W/N+HG
320 PRINT TAB(5,20);"PRESS SPACE BAR TO CONTINUE"
330 KEY=GET
340:
350:
360REM       PART 3 : DRAWING THE NOMOGRAM
370:
380REM   PROCEDURES: GLX -DRAW & GRADUATE X-AXIS
390REM               GLY -DRAW & GRADUATE Y-AXIS
400REM               LABX-CALIBRATION FOR X-AXIS
410REM               LABY-CALIBRATION FOR Y-AXIS
420:
430:
440 MODE 1
450COLOUR128:CLS
460:
470 REM  TO DRAW GROOVE WIDTH AXIS
480:
490MOVE 150,925
500PROCGLY(150,900,500,-80)
510 PROCGLX(500,250,950,100)
520 DRAW 1000,500
530:
```

```
540 REM TO DRAW LAND LENGTH AXIS
550:
560 MOVE 1000,425
570PROCGLX(425,950,650,-100)
580PROCGLY(650,425,25,-50)
590:
600 REM  TO DRAW LAND ANGLE AXIS
610:
620MOVE 450,25
630PROCGLY(450,75,425,50)
640 PROCGLX(425,550,150,-50)
650 VDU 5
660 MOVE 530,452 :PRINT"+20"
670 MOVE 315,452 :PRINT"-20"
680 MOVE 125,452 :PRINT"-60"
690 MOVE 940,452 :PRINT"0.3"
700 MOVE 1030,475:PRINT"mm."
710 PROCLABY(0.25,-0.0500000,10,900,-80,5)
720 PROCLABX(.2,.2,300,485,200,3)
730 PROCLABY(0,.2,500,430,-100,4)
740:
750 REM TO DRAW GOOD CHIP BREAKING LIMITS
760:
770MOVE 150,596
780 PLOT 17,800,0
790 MOVE 950,788
800 PLOT 17,-800,0
810:
820 REM TO DRAW GROOVE WIDTH LINE
830:
840XH=(HG*1000)+150:XY=N/W*(0.8-HG)*1600+500
850 MOVE XH,500
860 DRAW 950,XY
870:
880 REM TO DRAW LAND LENGTH LINE
890:
900 IF L*0.8<0.3 THEN XC=L*800:YC=-400 ELSE XC=300:YC=-150/L
910 MOVE 650,425
920 PLOT 1,XC,YC
930  @%=&0020202
940 MOVE 800,880:PRINT"Groove Width"
950 MOVE 120,50 :PRINT"Land Angle"
960 MOVE 700,50 :PRINT"Land Length"
970 MOVE 900,700:PRINT"HG=";HG
980 MOVE 900,660:PRINT"H1=";H1
990 MOVE 900,620:PRINT"H2=";H2
1000 MOVE 180,1000:PRINT"*** CHIPBREAKING NOMOGRAM ***"
1010:
>
```

```
L.1020,1380
1020 REM TO PLOT LAND ANGLE LINE
1030:
1040 MOVE 200,307
1050 DRAW 500,222
1060 END
1070:
1080:
1090REM   PROCEDURE TO DRAW & GRADUATE Y-AXIS
1100:
1110REM    X= START X CO-ORDINATE
1120REM    W= START Y CO-ORDINATE
1130REM    Z= END Y CO-ORDINATE
1140REM    S= GRADUATION DISTANCE
1150:
1160DEFPROCGLY(X,W,Z,S)
1170 FOR Y=W TO Z STEP S
1180 DRAW X,Y
1190DRAW X-10,Y
1200 MOVE X,Y
1210 NEXT Y
1220ENDPROC
1230:
1240REM   PROCEDURE TO DRAW & GRADUATE X-AXIS
1250:
1260REM    Y= START Y CO-ORDINATE
1270REM    W= START X CO-ORDINATE
1280REM    Z= END X CO-ORDINATE
1290REM    S= GRADUATION DISTANCE
1300:
1310DEFPROCGLX(Y,W,Z,S)
1320 FOR X=W TO Z STEP S
1330DRAW X,Y
1340DRAW X,Y-10
1350 MOVE X,Y
1360 NEXT X
1370 ENDPROC
1380:
>
```

```
1390REM   PROCEDURES TO CALIBRATE Y(X)-AXIS
1400:
1410REM      A= VALUE AT FIRST CALIBRATION MARK
1420REM      I= INCREMENT TO NEXT CALIBRATION MARK
1430REM      X= X CO-ORDINATE FOR START OF TEXT
1440REM      Y= Y CO-ORDINATE FOR START OF TEXT
1450REM      S= DISTANCE TO NEXT GRADUATION MARK
1460REM      B= NUMBER OF INTERVALS REQUIRED  .
1470:
1480 DEFPROCLABY(A,I,X,Y,S,B)
1490 @%=&0020203
1500 FOR P=0 TO B STEP 1
1510 MOVE X,Y+(S*P)
1520 PRINT;A+(P*I)
1530 NEXT P
1540  @%=&10
1550 ENDPROC
1560:
1570 DEFPROCLABX(A,I,X,Y,S,B)
1580 @%=&0020203
1590 FOR P=0 TO B STEP 1
1600 MOVE X+(S*P),Y
1610 PRINT;A+(P*I)
1620 NEXT P
1630 ENDPROC
>
```

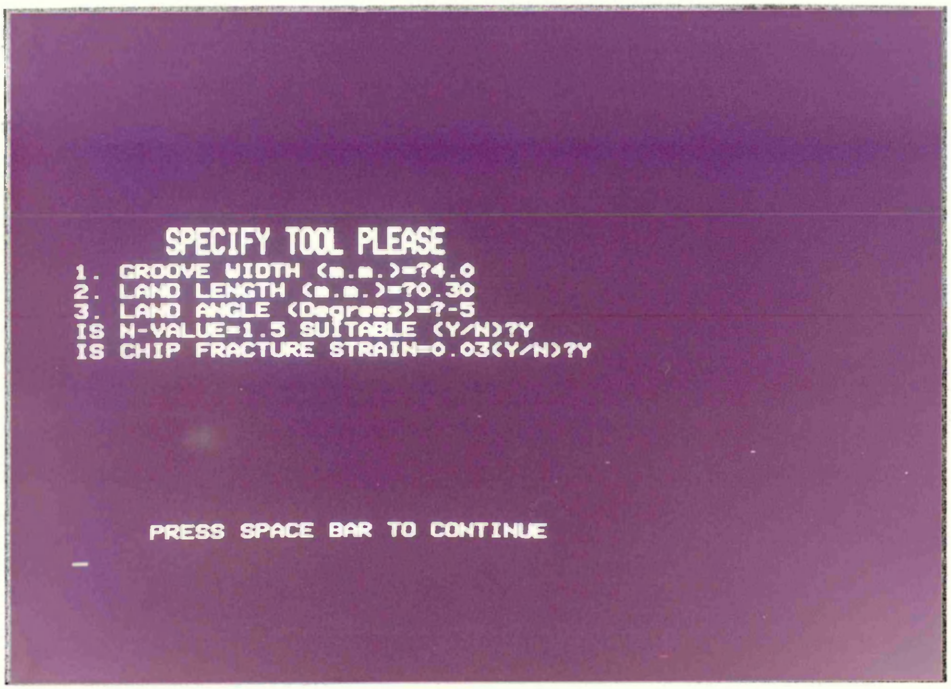


Figure C1

Computer Display showing data input for simple groove tool having groove width=4mm, land length=0.3mm, land angle= -5° and cutting a plain carbon steel.

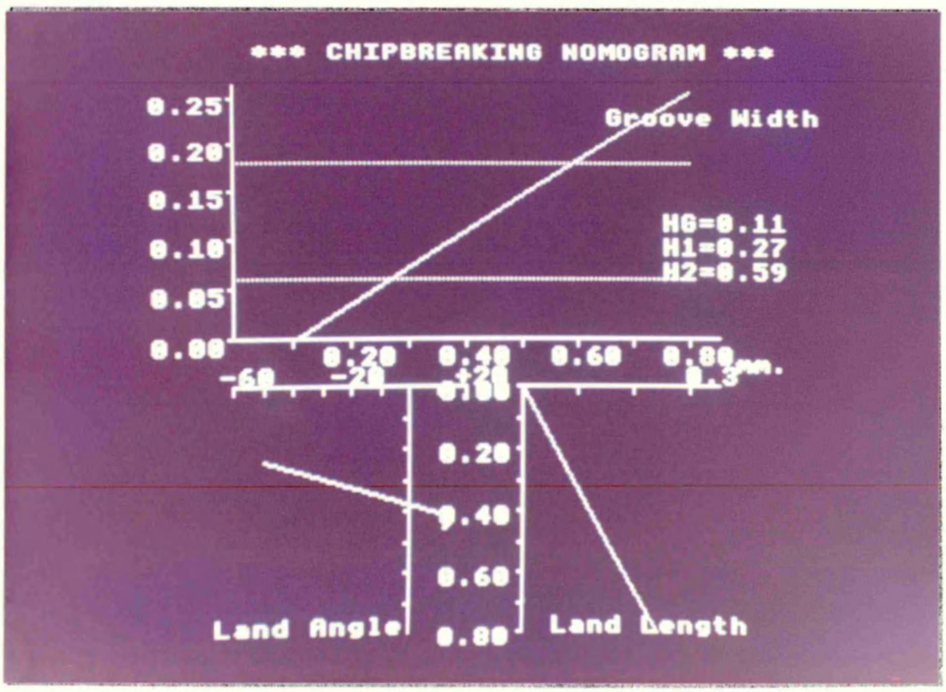


Figure C2

Computer Display showing Nomogram for the tool specified above, giving acceptable Chip breaking between h_1 = .27mm and h_2 = 0.59mm.