A study of transfer films formed on the surface of automotive friction couples.

MCCLURE, Steven.

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Steven McClure

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Abstract.

During recent years both ride comfort expectations and vehicle refinement have increased such that any brake vibration problems are quickly highlighted. Much emphasis has been placed on the elimination of uneven disc wear and the reduction of un-sprung mass. Problems generally associated with the use of cast iron as the brake rotor, including uneven wear, corrosion and distortion, have been overcome using a thermally conducting coating. The thermally sprayed coating (HIPAC) is a composite of dispersed silicon carbide abrasives in a copper matrix. The coating has excellent thermal conductivity and wear resistance with high energy absorption and heat dissipation. With careful selection of friction material adequate levels of friction can be generated over a wide range of operating temperatures. When applied to aluminium discs dramatic reductions in rotor mass can be achieved without the interface melting problems generally associated with aluminium metal matrix discs. However, problems may still be encountered with excessive bulk temperatures. As a result the coating may find initial success when applied to cast iron discs.

It is widely accepted that the performance of automotive friction couples is influenced by the transfer film or third body layer formed between the friction surfaces. Optical, scanning electron optical and energy dispersive X-ray techniques have been used to examine the frictional surfaces of the two elements of the couple. Films on both cast iron and HIPAC coating have been examined extensively. Evidence is presented which relates the friction characteristics to the distribution and chemistry of the transfer film.

Contents.

2.0 Literature Review.

1.0 Introduction.

As increasingly severe requirements are placed on the automotive brake system, intensive efforts have continued to improve all contributing components. Presently the majority of braking systems are the friction couple type utilising either a metallic disc or drum and a mating friction material.

With driving patterns changing, automobile development improving, and 'feel' factors becoming an important part of a successful braking system, previously unimportant problems have become much more obvious. Uneven disc wear and the associated 'cold judder' phenomena has been the direct cause of a high number of brake system replacements under warranty resulting in a massive unexpected expense to the manufacturer. As would be expected in the light of this, the problem has seen considerable attention.

During braking materials are transferred and back transferred between the two mating components. The transferred material present on the contacting surfaces is known as the third body layer or more commonly, the transfer film. This film forms the running surface between the friction couple such that there is no contact between the original surfaces. Film analysis has been the subject of much recent work which has indicated a clear connection between the nature and composition of the film and the wear and frictional performance of the friction couple.

The purpose of this present section of work is to study in detail how variations in the friction material composition effect the tribological performance of the couple and the nature of the transfer film. The film on both sides of the couple will be analysed with variables such as thickness, distribution and elemental content considered. It is hoped that the analysis of the films will further the understanding of the mechanisms occurring at the friction interface and aid in the reduction of judder problems.

The initial analysis concerns cast iron discs, presently the most common disc material, and friction materials consisting of standard lining components. Recently a very low wearing copper coating has been introduced by Plasma Coatings Ltd. Applied to cast iron discs this may provide a possible solution to brake judder as well as common disc corrosion problems. Additionally when applied to aluminium discs a drastic reduction in the un-sprung mass of the vehicle can be achieved resulting in superior ride comfort. Although in terms of manufacture and performance the coating is largely developed, there is still little known about the surface mechanisms occurring during braking. It is intended to conduct a test and analysis schedule similar to that performed with cast iron discs in order to aid in the development of a suitable friction lining for this coating.

1.1 Programme of Research.

In an automotive brake system frictional forces are generated between two surfaces, the friction material and the disc or drum. Previous work has shown that the friction coefficient, fade and wear characteristics of the friction couple are extremely dependant on the transfer film chemistry. The nature of the film, which is essentially a complex oxide, is dependant on the composition of both disc and friction material as well as the severity of the braking application. The project aims to investigate how the friction characteristics of a particular couple are controlled by the transfer film and how improvements can be made to braking performance by changing the constituents of the friction material.

The initial section of work will involve subjecting a cast iron disc to different formulations of friction material in similar braking situations in order to gain an insight into how various lining components effect performance and film composition. Drum brakes will be neglected from this study as the front discs tend to perform the majority of the braking action and it is within the disc brake unit that judder problems generally arise. The friction materials used will be experimental compositions mixed and donated by B.B.A. Friction Ltd. All testing is to be conducted on a laboratory based F.A.S.T. Machine, also donated by B.B.A. Friction Ltd.

The second section of work concerns the development of a lining material suitable for coupling with copper coated friction discs. Working closely with Plasma Coatings Ltd., an intensive testing and development regime has been implemented utilising both university and industry based facilities. Friction test results and surface analysis form part of a continuing loop of lining alteration with the aim of producing the optimum material for the required braking parameters.

Friction testing has been conducted by both leading automobile and friction material manufacturers using a range of equipment including dynamometers and actual on-vehicle testing. Investigation of the same lining materials on the university based F.A.S.T. machine ran in conjunction with the industry testing. Following completed tests the couple surfaces were analysed by both optical and electron microscopical techniques in an attempt to explain how the nature and composition of the transferred film effects friction performance.

The majority of the friction testing used only a small selection of lining materials chosen for their suitability for coupling with the coating. These were donated by both B.B.A. Friction Ltd. and Ferodo Ltd.

2.1 Automotive Brakes.

Brake systems in current production automobiles are the result of a long evolutionary process beginning with the first practical hydraulic patent in 1917. Most early brake systems were mechanically operated by either cables or rods and although their performance was adequate there were some inherent problems that led to the development of the hydraulic system. These problems included friction in the linkage components, difficult adjustment, and little compensation for friction material wear. Also the early brake systems were only employed on the rear wheels due to the difficulty of routing cables or rods around complex steering and suspension systems. This in particular posed serious problems during heavy braking.

Automotive brakes are devices that reduce the velocity of a vehicle or hold it in a static position. During retardation they work by converting the kinetic energy of the vehicle into some other form of energy, generally heat. A vehicle has two braking systems operating independently from each other, these are the service brake and the parking brake.

The service brake is operated by the driver when he applies pressure to a foot pedal. This pressure is transmitted to the brakes on all four wheels using a hydraulic system.

The sole purpose of the parking brake is to hold the vehicle stationary, under normal circumstances it should not be used for retardation. The holding force is generally operated mechanically as opposed to hydraulically to ensure brake failure cannot occur due to fluid leakage whilst the vehicle is left unattended. The parking brake generally acts only on the rear two wheels of a car, this being more than sufficient to hold the vehicle stationary on even the most severe of gradients.

By far the most common braking devices are disc or drum brakes. For both systems retardation or holding of a vehicle is achieved by friction between two mating surfaces. When the brakes are applied brake pads or shoes are forced against a revolving disc or drum. Other types of brakes include fluid brakes and electric brakes. Fluid brakes have a revolving impeller inside a chamber which when filled with liquid will induce a retardation force. The kinetic energy of the vehicle is converted into heat through the turbulence within the fluid. Electric brakes induce a braking force by converting kinetic energy into electric energy which may be dissipated as heat or stored and re-used. This type of brake system has been introduced into some public transport vehicles which are repeatedly stopping and starting and therefore wasting a large amount of energy with friction brakes alone. Both of these alternative systems tend to be rather heavy and bulky, but more importantly they provide little braking effect at low speed and none when stationary. Therefore they must always be combined with some type of friction brake system.

2.1.1 Brake Operation.

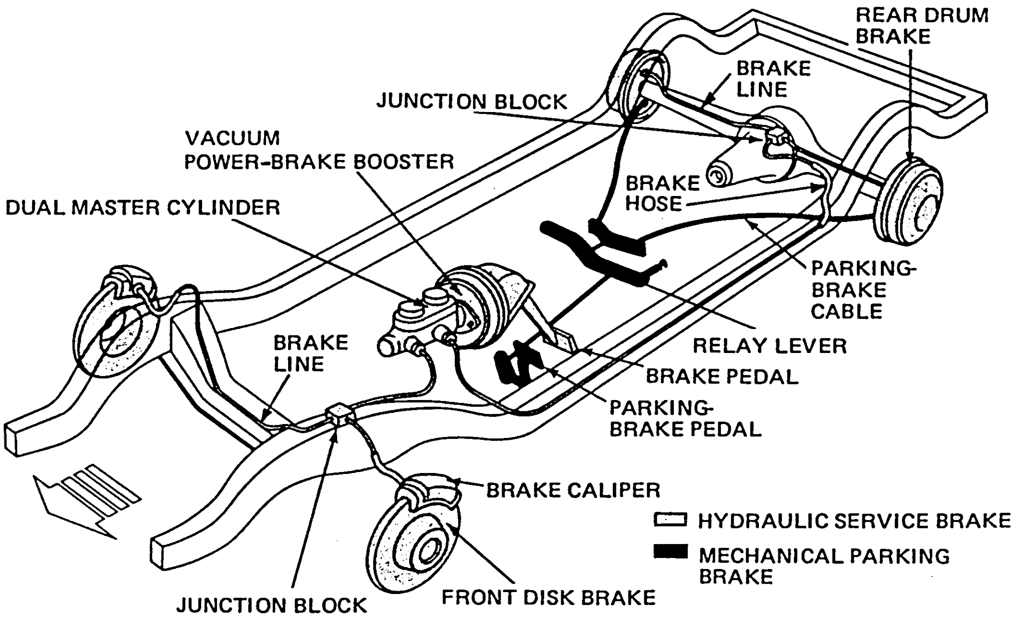


Figure 2.1.1. Typical brake system layout.

A typical brake system layout is shown above in figure 2.1.1. Braking of a vehicle begins with pressure applied to the pedal by the driver. This pressure, via a mechanical linkage, forces a pushrod into the master cylinder. The master cylinder is the distribution centre for the hydraulic fluid and generally has two chambers with a piston in each thus dividing the brake system into two separate halves. This is a dual braking system, generally a diagonal split is used where each cylinder supplies a front wheel and a diagonally opposite rear wheel. Dual braking systems are essential to prevent complete brake failure should a fault occur in one half of the unit. Presently the majority of cars have a vacuum assisted brake system which greatly helps the driver in applying pressure to the brakes. This ensures that only relatively light and far more comfortable pedal pressures are required by the driver even when rapid deceleration is required. For a more detailed explanation of braking systems the reader is directed towards the many available reference books, particularly the excellent text by Crouse and Anglin [89].

2.1.2 Drum Brakes.

Drum brakes are friction braking devices consisting primarily of a rotating drum, fixed brake shoes and an actuating mechanism. The wheel is bolted directly onto the drum such that they revolve together. Drums are made from aluminium, steel, or most commonly cast iron. Inside the drum are the brake shoes and brake actuating device. Each brake shoe is attached at only one point such that it can pivot and move towards the inside of the drum. Springs hold the shoes away from the drum when the brakes are not applied. Upon application of the brakes the brake shoes are pressed against the inside of the drum thus slowing or holding the vehicle. Bonded to the brake shoe is the friction material or brake lining which is responsible for the frictional work done during slowing the vehicle or the frictional force required whilst holding it stationary. The wear of the friction material is accounted for with a self adjusting mechanism in most vehicles.

2.1.3 Disc Brakes.

Disc brakes have a metallic disc (or rotor) instead of a drum to which the wheel is bolted. Hence the wheel and disc revolve together. Two or more brake shoes (more commonly known as brake pads) are positioned on each side of the disc and held in place by a calliper unit. The calliper unit is fixed to the steering knuckle and so prevents any rotation of the brake pads. When the brakes are applied the two pads are clamped onto the disc thus providing the braking force. As well as holding the pads in position the calliper unit is also responsible for distributing and applying the braking force equally to each pad. Callipers can be divided into two major designs, the floating calliper and the fixed calliper. Schematics of a floating caliper are shown overleaf in figures 2.1.3 and 2.1.4.

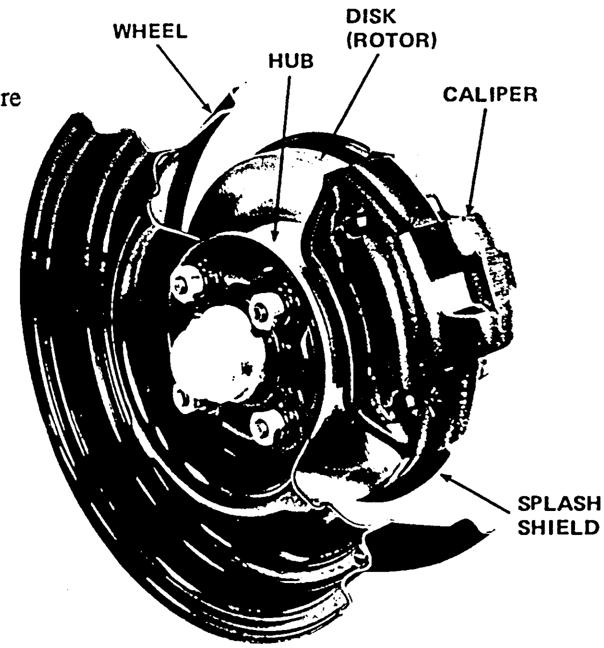


Figure 2.1.2. Cut-away of a disc brake.

Floating calliper - The floating calliper, as its name would suggest, is not rigidly fixed to any part of the vehicle but is held in position by an adapter plate, this being bolted firmly to the steering knuckle. The calliper unit stretches across the disc as shown in figure 2.1.3. Guide pins passing through the adapter and fixed to the calliper allow the calliper to slide in an axial direction but prevent any rotation. This movement allows equal pad pressure can be applied to each side of the disc with the use of only one piston.

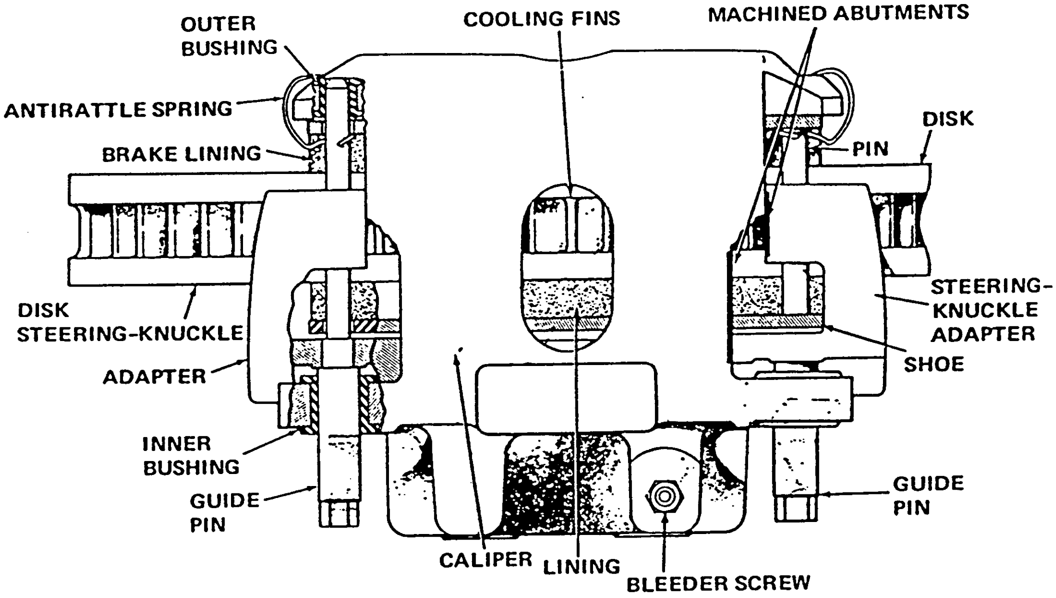


Figure 2.1.3. Plan view of a floating calliper unit.

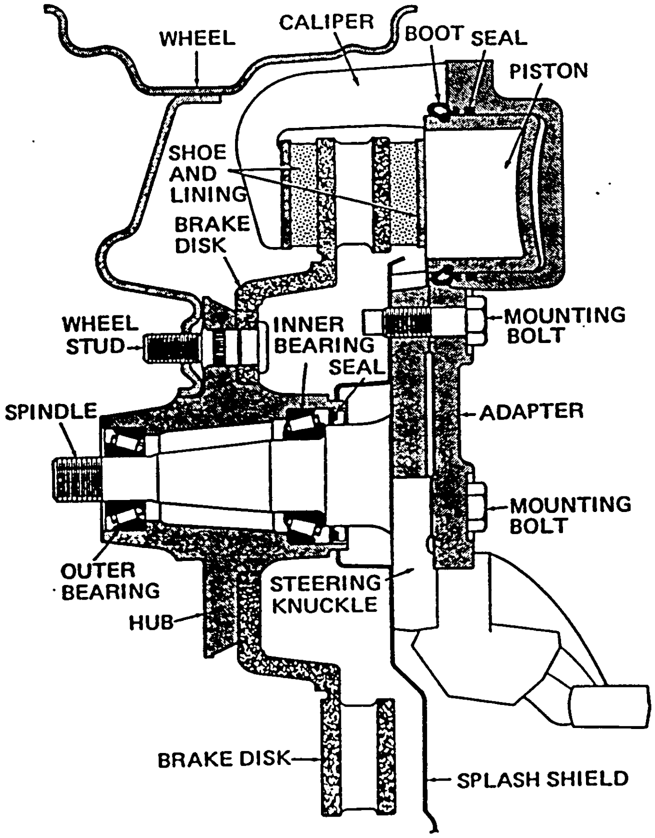


Figure 2.1.4. Cross section of a floating calliper unit.

By far the majority of light vehicles are fitted with floating callipers primarily because they are cheaper and easier to manufacture. Their smaller size also allows more simple positioning within small wheels. Fixed calliper units have the advantage of more uniform pressure distribution, this being of prime importance in high performance vehicles when maximum braking force is required. Additionally, the increased number of pistons within a fixed calliper unit increases the 'piston seal rollback'. This feature of the seal is particularly important as it is the only mechanism by which the piston is retracted once braking pressure is released. The rubber seal which prevents fluid leak from around the piston is distorted as the piston is pushed out, when the pressure is released the seal returns to its original shape pulling the piston with it as shown in figure 2.1.5. Fixed calliper units offer at least twice the roll back of single piston floating units, this factor being extremely important in off brake wear, a phenomena occurring entirely due to insufficient retraction of the pads.

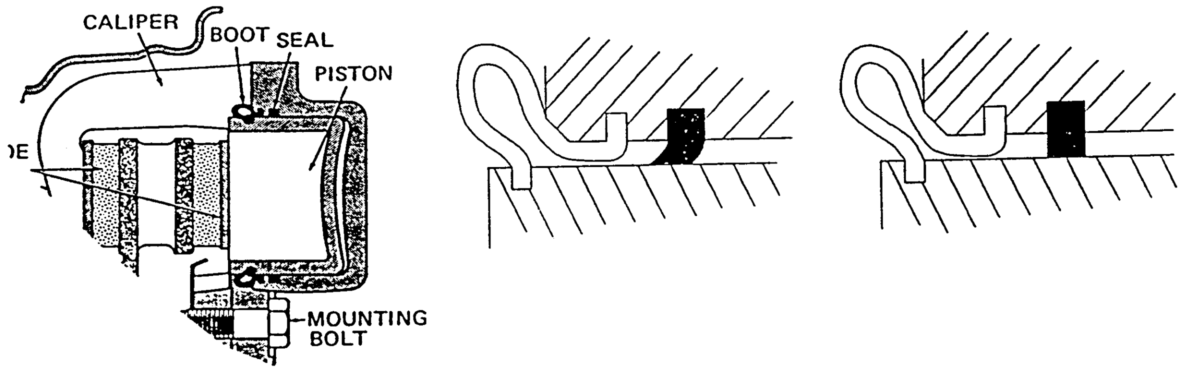


Figure 2.1.5. Piston seal roll back.

As well as preventing leakage and aiding pad retraction, the seal also compensates for friction material wear. When the piston is pushed out the seal deforms and moves with it, however, due to pad wear a point is reached when the piston travels further than the seal is able. The piston will then move through the seal and adopt a new position.

2.1.4 Brake Proportioning and Energy Dissipation.

During braking vehicles suffer a forward pitching motion about the centre of mass. Hence, the front of the vehicle tends to be forced downwards and the rear tends to lift. This results in different braking forces being required on the front and rear wheels, if they were equal then the rear wheels could easily lock up resulting in a skid. A proportioning valve is used to divide up the applied pressure between front and rear brake units. During heavy braking the front brakes may account for 80% of the braking force and as a result this is where most of the energy must be dissipated.

Light vehicles were initially fitted with drum brakes on all wheels but as the performance requirements of brakes increased the front drums became unable to cope with heat dissipation demands. Due to the enclosed nature of drum design, by far the majority of the heat energy created during braking is removed by conduction resulting in overheating of the unit during heavy or prolonged braking. In contrast the open nature of disc brakes allow air flow around all components resulting in a large proportion of the heat being dissipated into the air. Much thought has gone into channelling air flow over the components and with careful design around 30% of the total heat energy can be dissipated to the air when travelling at high speed. At present, nearly all small vehicles are fitted with disc brakes to the front wheels and drums to the rear, although recently both front and rear wheels have been fitted with discs on high performance cars. Because of the difference in braking requirements on the front and rear wheels it is very uncommon for rear drums to overheat.

Despite the large proportion of energy lost to the air around disc brakes, overheating of the system is still a very real problem. Besides convection the heat can only be either conducted or radiated, although even at high temperatures radiation will only account for a small proportion of heat loss. Design and material choice of both the disc and friction material are extremely important in controlling the conduction into the surrounding brake unit. It is critical that the friction material is a good thermal insulator to avoid conduction into the piston and hydraulic fluid as this may boil resulting in 'spongy' brakes. Unfortunately, although the friction material must be an insulator, high temperatures on its mating surface can cause rapid deterioration of braking performance. Hence, in order to remove the heat quickly from the interface, the disc must have a very high thermal conductivity. Coupled with this the disc must be made from a high specific heat capacity material to avoid rapid heat build up and excessive conduction into the hub and bearing unit. Disc design is covered in the following chapter.

2.2 Disc Materials.

Disc brakes, originally developed for aircraft use, were introduced into automotive vehicles by the Conze brothers at the 1951 Indianapolis 500 race in the U.S.A. Then, in 1953 Jaguar won the Le Mans 24 hour race with solid discs fitted to its C-type sports car [70]. Since the introduction of the disc little has changed to the basic design and material. Disc design itself offers limited scope for alteration since its shape is dictated by the need for a dimensionally constant friction path passing between the two stators. Developments in design have tended to focus on geometrical considerations with a view to reducing high temperature problems. To date, grey cast iron has remained the most popular disc material and it appears it will remain so for the foreseeable future. Different materials or combinations of materials have been proposed but only recently are these being introduced into widespread use. Even then materials other than cast iron only tend to be used in vehicles where expense is not a major consideration. Cast iron remains the material of choice because it fulfils many of the requirements essential to a rotor material as well as being considerably cheaper than the alternatives.

When considering a brake disc material the following points must be considered-

- Economy
- Castability
- Machinability
- Mechanical strength and hardness
- Corrosion resistance
- Heat conductivity
- Thermal expansion
- Melting or phase change temperatures
- Mass
- Environmental considerations
- Resistance to wear

When considering all the essential points cast iron is clearly an excellent rotor material, however recent trends in aesthetics, ride comfort and performance have pushed the search for alternative disc materials to new levels of importance.

2.2.1 Cast Irons for Disc Brake Rotors.

Cast irons describe a group of iron-carbon alloys with a wide range of properties. Cast irons differ from steels mainly in their carbon content, typically 2.5 - 4.5 %, which can exist either as free carbon or combined as iron carbide. Cast iron generally has a pearlitic structure interspersed with graphite flakes. Grey cast iron accounts for up to 85% of U.K. castings due to its machineability, good wear resistance, medium tensile strength and fatigue life and low cost. Its only major downfall is its very low resistance to impact loading. For more details on cast irons, alloying additions and microstructure the reader is directed to the many available reference books [81, 82].

When considering brake performance the responsibility is generally left with the friction material supplier, the usual process of optimising performance and wear being to continually modify the lining material until the desired properties are met. However, there is a continual drive to improve performance by advancing rotor technology. Recently, as disc brakes are being introduced into heavy vehicles, new impetus has been given to cast iron development from the need to solve the problem of rotor cracking. The development of disc material is generally an extremely complex process since each alteration inducing an increase in one aspect of performance is likely to diminish another, hence designers are striving for an optimum material for the requirements demanded.

Initially any variations in the performance of a friction couple were attributed to the lining or friction film since no change in the microstructure of the iron was observed. However, it was found that even for the same standard B.S. grade 17 cast iron generally used for rotors, the change from high to low grade could account for a drop in friction coefficient of 50%, and decreases in lining wear of three times and disc wear of up to ten times [4].

Investigations into the microstructure and alloying additions first began in the 1970's with many reports of the steering pulling to one side during braking. Differences between discs were first blamed on microstructure after extensive testing revealed surface grinding had no effect on their performance. Prior to this point the problem never came to light as a vehicle manufacturer would generally obtain all their discs from a single supplier, often from a single batch. Additionally steering sensitivity was increasing and more emphasis was being placed on ride comfort.

2.2.1.1 Alloying Additions to Cast Iron Discs.

During the production of grey cast iron many alloying elements are added to alter its friction and wear characteristics. Phosphorous can improve wear characteristics when added in amounts of between 0.06 and 0.75% [3]. The phosphorous forms a eutectic, a hard interdendritic phase, which can exist in two forms known as pseudobinary and ternary. High thermal conductivity is desirable as this leads to lower interface temperatures. Conductivity may be improved with a high carbon content or by reducing silicon content. This confirms the work of Johnson *et al* [5] although they concluded that increasing carbon actually increased lining wear. However this appears to be contrary to the findings of other research programmes. The work of Johnson covered the effects on performance of elements in isolation as opposed to optimising the cast iron with carefully controlled alloying mixtures.

Alterations to mechanical properties can be made with small additions of alloying elements. Silicon and aluminium are added to increase the graphitising potential but this may also coarsen the pearlite and hence weaken the iron. Other elements for example manganese, chromium, molybdenum or vanadium can increase the strength and hardness of the iron although their addition must be carefully controlled as they decrease the graphitising potential and hence promote carbide formation. Table 2.2.1 below lists many commonly used alloying elements and their main function. Also shown is the effect of these elements on the friction and wear performance of disc brakes from a detailed study by Chapman and Hatch [4].

	Graphitiser	Carbide stabiliser	Deoxidiser	Hard particle	Ferrite promoter	Friction coefficient and wear rate
Ti	*		*	*	*	Both reduced
V		*		*		Both reduced
Nb		*		*		Both reduced
Cr		*				None
Zr	*		*		*	None
W		*				None
Mo		*				None
Al	*		*		*	None
N						None
S		*				None

Table 2.2.1. Typical alloying additions.

Of all the alloying additions titanium has seen the most attention [4, 5, 6, 7]. Titanium is added to promote undercooling and reduce fissure defects in casting by combining with excess nitrogen to form titanium carbo-nitride. Additionally, it increases the amount of free ferrite observed in the matrix. However, above a certain concentration the very small and very hard blocky titanium carbo-nitride particles drastically reduce friction performance and increase the pad wear. Typically, concentrations of titanium need to be kept below around 0.02% to prevent such large drops in performance as shown in figure 2.2.1.b below. The titanium proportion can also effect friction performance in different ways for different friction materials complicating matters further as shown in figure 2.2.1a. More recently materials have been developed that are resistant to the 'titanium effect' [7].

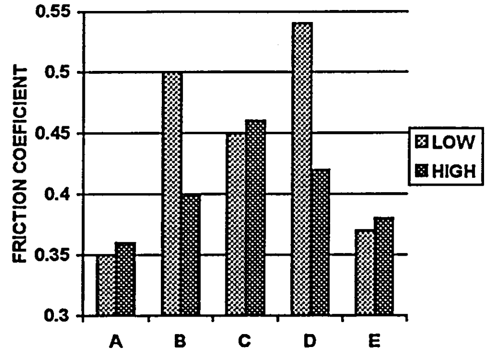


Figure 2.2.1.a. Performance variation for a range of materials.

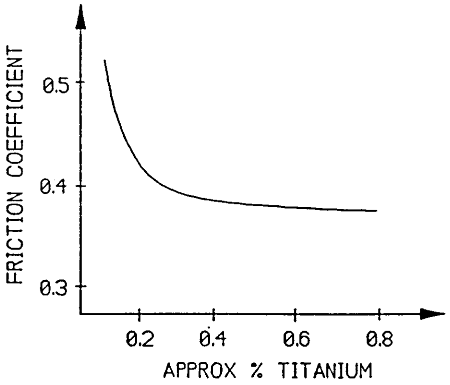


Figure 2.2.1.b Friction coefficient variations with titanium content.

2.2.1.2. Microstructure.

Microstructural analysis has shown that a disc with fine undercooled graphite flakes will give lower friction and wear than those with a well developed structure. Also, traces of ferrite within the pearlitic matrix are known to reduce the disc performance although the matrix structure in general has little effect on performance.

The thermal expansion of the matrix is also of importance since if differing rates are found in the same structure there will be localised thermal stresses. Pearlite and ferrite are known to have the same expansion although that of bainite is considerably larger and hence should be avoided in the matrix structure [8].

The high conductivity of grey cast iron is largely a result of the close proximity of the graphite flakes, graphite having excellent conduction. Hence the more graphite the better, although as increasing the carbon has a detrimental effect on mechanical strength, an optimum must be found.

2.2.1.3 Microstructural Changes During Running.

Since brake linings are essentially thermal insulators the bulk of the energy created during braking, typically 90%, enters the disc [9]. Surface temperatures are dependant on the rate of heat input and the thermal conductivity, with final bulk temperatures dependant on both conductivity and heat capacity. Emergency braking can lead to extremely steep temperature gradients at the surface (up to 370°C across 1.75mm [10]) as shown in figure 2.2.2 below [8]. Despite cast iron being a good thermal conductor temperatures exceeding 700° C may be achieved on the disc surface. Above this temperature there may be microstructural changes in the rotor material whereby the cast iron is changed from pearlitic to spheroidic.

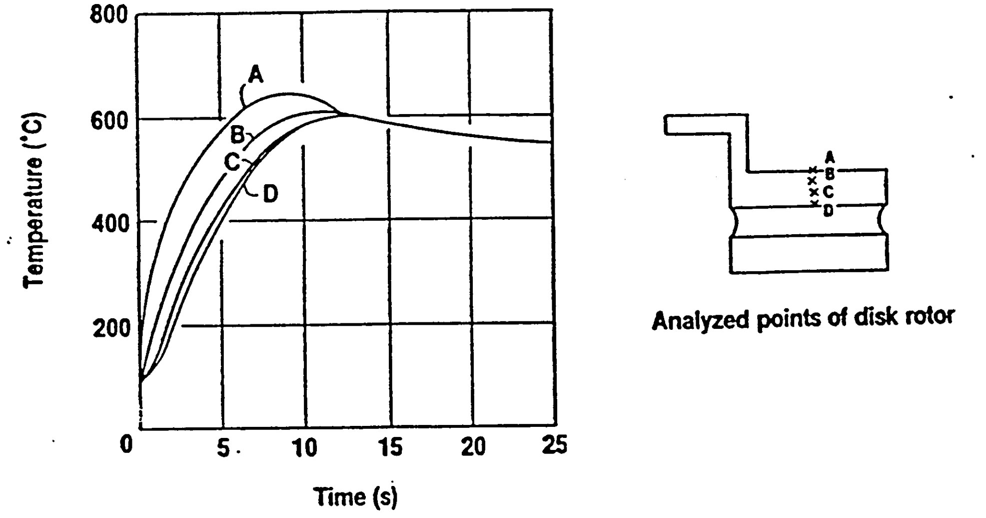


Figure 2.2.2. Temperature change during the course of braking.

Hydrogen production occurs with very high interface temperatures due to the breakdown of friction material binder resins. This can be absorbed into the iron increasing the hydrogen concentration three to six times up to a depth of 3mm. The diffusion of hydrogen results in hydration of the cementite and the formation of spongy ferrite which has extremely poor mechanical properties [45].

Dynamometer testing by Coyle and Tsang [74] showed how the resultant microstructure of a heavily tested disc was partially spheroidized with most of the transformation occurring at the surface. In order to study the affects of this transformation the performance of standard discs were compared with discs fully speroidized by furnace heating up to 788°C. The results showed no change in friction levels although the wear of both disc and lining material was increased by over 15%. This work suggested that after extreme brake use and microstructural change there is no loss in braking performance, an important factor when considering safety.

2.2.1.4 Hot Spots.

The hot spots that form on the disc surface can conveniently be divided up into four types, these being compared in table 2.2.2 below [75]. It should be pointed out that for a particular hot spot on the disc surface there is a corresponding one on the pad surface.

Hot spot	Width (mm)	Temp (°C)	Life time
Asperity	<1	up to 1200	<1ms
Focal	5 - 20	750 - 1200	0.5 - 20s
Distortional	20 - 100	100 - 700	>10s
Regional	50 - 200	10 - 100	>10s

Table 2.2.2. Hot spot classifications.

Asperity hot spots are the result of microscopic contact points with 'flash' temperatures being relatively high but short lived. Temperatures are dependant mainly on rubbing speed and not so much on applied pressure. Despite their small size the cumulative effect of the asperity hot spots will quickly raise the temperature of the entire rubbed surface, however there is no permanent damage done to the disc. This type of heating is thought to aid the production of the oxide film coating the running surfaces.

Distortional hot spotting is generally associated with thermal distortion or warping of the rotor surface. Primary thermal buckling of the disc inducing three peaks and troughs around the rubbing surface is the most common which induces three corresponding hot spots. Distortional hot spots may well be the precursor to focal hot spots.

Regional hot spots are the result of non-uniform heating of specific sections of the disc due mainly to thickness variations and disc run-out. Differences between bulk and hot spot temperature may well be below 100 °C although uneven thermal expansion may add to the distortion and dramatically affect brake torque variations as described in section 2.4.

Focal hot spots are small contact sites generated by thermoelastic instabilities. Often the spots will form on a narrow band and tend to occur repetitively at the same site. For hot spots of this kind to occur high speeds are required with little cooling between consecutive lining contacts. For vehicles with relatively short friction material arcs there may be no cases of focal hot spots, conversely when employing a material with a long contact length a hot spot may be formed during a single revolution.

The type of focal hot spot formed can be defined as either critical or non critical depending on whether martensite has formed. Above temperatures of about 780°C ferrite changes to austenite in which carbon is freely soluble. In emergency braking situations the surface temperature gradients are extremely steep resulting in relatively low bulk disc temperature compared to the surface. As a result there may be a sudden back quenching of the hot surface upon brake release as the heat passes to cooler adjacent portions. If the surface cools rapidly enough (to less than 540 °C in under 1 sec) pearlitic transformation occurs forming martensite [75]. The transformation results in a 4 % volume increase as the crystal structure of the iron changes from body centred cubic to face centred cubic. This may produce severe local strains often leading to localised cracking as well as elevating the spot slightly above the running surface. Due to the high hardness of martensite, raised areas are not worn away ensuring preferential heating during further brake applications aiding in crack formation and hot spot enlargement. Repeated high temperature braking with a self-intensifying hot spot of this type can lead to total mechanical failure of drum brakes with bursting of the unit. For disc brakes total failure is unlikely although replacement may be necessitated by running surface distortion or even crack formation leading to the disc outer edge.

2.2.1.5 Disc Cracking.

Tests have shown that at temperatures below 650°C there may be severe oxidation of surface impinging graphite flakes and the surrounding matrix. Although small, these voids act as stress raisers and become the weakest points in the structure with the potential to develop into surface cracks. Work aided by the author [7] indicates insufficient attention has been paid to the affect of transfer film chemistry on crack formation.

Complex oxides were observed penetrating the entire depth of the oxidised void and it is suggested that these oxides, combined with thermal cycling, may assist the crack initiation and penetration. Studies are ongoing into the affects of individual lining elements on the oxide aid of crack formation.

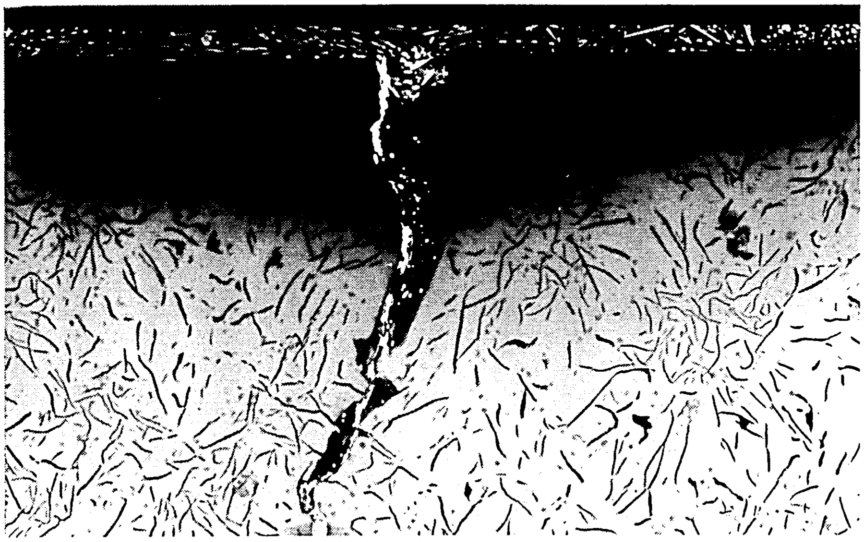


Figure 2.2.3. Oxide penetrating a surface impinging crack.

Disc cracking may also occur as a result of thermally induced distortions. In situations of severe surface temperature the compressive stresses due to expansion may lead to permanent plastic deformation of the metal. Upon cooling the deformed surface will be placed in tension against the unaffected bulk of the disc now in compression, this may be sufficient to cause surface rupture. Tests by Angus *et al* [10] showed residual stresses in a cracked disc to be up to five times higher than in an unused disc, before cracking occurred the stresses may have been double this!

It is apparent that to reduce disc cracking a high level of conductivity is required. High speed bench tests have shown that maximum crack length in the rotor surface decreased as the thermal conductivity increased. Jimbo *et al* [8] set about developing a high conductivity cast iron by altering the content of carbon and alloying additions. The optimum balance was found to be-

Carbon	3.7 - 4.0 %
Silicon	1.4 - 2.0 %
Molybdenum	0.5 - 0.6 %

Table 2.2.3. Optimum composition of high thermal conductivity cast iron as proposed by Jimbo *et al.*

Jimbo also showed how increasing the carbon content towards 4% increased the ferrite area ratio and this in turn made uniform disc machining difficult. Careful control of the metal whilst in a molten state proved effective in lowering the area ratio to an acceptable limit.

Other methods to reduce the temperature of discs have been to alter the proportions of energy transfer from the disc. Noyes *et al* [11] reported that of the total energy entering a disc over ten stops, 60% will be dissipated by convective cooling, 34% is retained as thermal energy and 6% is lost through radiation and conduction into the lining material. Increasing the mass either by eliminating vanes or altering the geometry is one way of increasing the heat capacity although this is generally an undesirable solution reducing ride comfort. Air flow can be ducted towards the discs but this requires additional components on the vehicle which may be bulky and add both weight and cost. However, many of the solutions are only effective at reducing the bulk disc temperature when the majority of the thermal problems are concentrated at the surface. Considering the surface temperature may rise by up to 100°C in just one pass through the caliper section [11] a solution to surface temperature problems will most likely be found in higher conductivity materials.

2.2.2 Alternative Disc Materials.

Interest in alternative disc materials has recently increased as overall vehicle standards are continually advanced, reduction of the unsprung mass being a major benefactor to ride comfort. Additionally, new materials with higher conductivity and low wear rates may help reduce or even eliminate may of the wear, judder, noise and fade problems generally associated with cast iron rotors. Presently most vehicle manufacturers are researching the suitability of alternative materials with much of the work concentrated on aluminium metal matrix composites. To date, only a limited number of production vehicles are fitted with alternative material discs, the Lotus Elise being the first vehicle to be fitted with aluminium discs all round.

Although many materials may have advantages over cast iron they often have relatively low maximum operating temperatures. This may lead to excessive scoring of the rotor surface or even complete failure of the friction couple at temperatures as low as 450 °C.

Finite element work by Grieve *et al* [12] on a number of materials indicated that aluminium was the most suited for cast iron replacement when comparing estimated maximum temperatures reached during alpine descents (figure 2.2.4). Magnesium was clearly unsuitable due to its low melting point and copper nickel alloy due to poor tribological properties despite the low temperatures achieved.

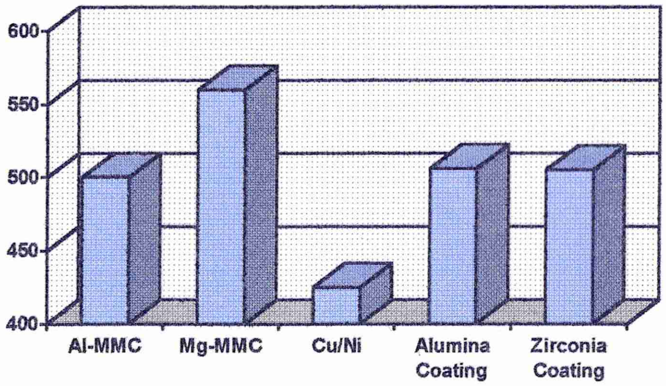


Figure 2.2.4. Alpine decent temperatures for high conductivity materials.

Aluminium discs coated with alumina and zirconia were eliminated from further studies as they appeared to offer limited insulation to the aluminium substrate. Although some kind of insulating properties were sought from the coating, this is likely to be a negative attribute leading to extremely high surface temperatures thus reduced frictional performance. The coating of aluminium discs with high conductivity materials forms the major part of the authors current programme of research.

Research into new materials is not just a recent phenomena, work by Rhee and Byers [13] in 1972 investigated the potential of substituting cast iron discs with copper alloy discs. They concluded that the alloy was superior to cast iron in many aspects and foresaw an imminent move to the new material. However, twenty six years later this has still not happened! Their results showed the alloy (99% Cu - 1% Cr) had a thermal conductivity six times higher than cast iron thus reducing fade and pad wear and cutting disc wear by up to three times. Friction performance did not appear to be compromised in any way and as such there is no reason why the alloy did not receive much further attention, except for the material costs.

	£/tonne	Density (g/cm^3)
Cast iron	140	7.2
Aluminium	1300	2.7
Copper	2250	8.96

Table 2.2.4. Approximate price and density comparison (mid 1989).

2.2.2.1 Aluminium Metal Matrix Composites.

Recently there has been a great deal of work by the manufacturers of Aluminium Metal Matrix Composites (Aluminium MMC's) demonstrating the suitability of these materials for brake rotors. These materials are so called as they contain a proportion of reinforcing particles, the most commonly used ceramic particles being silicon carbide or alumina. Recent developments in rapid solidification techniques have enabled production of high performance matrix powders which greatly enhance the properties of the composite [14]. The wear resistance of aluminium composites is known to be high. Garcia-Cordovilla *et al* [17] noted wear rates to be similar to conventional cast iron despite being up to 60% lighter. Denholm [69] however, reported a 20 % loading of silicon carbide resulted in an order of magnitude increase in wear resistance over iron. Additionally, the thermal conductivity increases with temperature, this being the opposite to iron. Hence they can transmit progressively more energy away from the rubbing surface with increasing temperature. As ever there are drawbacks, the reduced density means a much smaller heat sink despite the increased thermal capacity of aluminium over cast iron. Thus for large inputs of heat the overall disc temperature will be higher than otherwise observed with iron discs. Additionally the melting point of aluminium is substantially lower than that of iron, indeed lower than temperatures regularly observed on the interface surface. This factor is the primary reason for their limited use in the automotive industry at present.

It is likely that the performance of the couple may be enhanced by careful matching of both components. The transfer film is an essential part of successful braking with a characteristic black film being formed on the aluminium surface [15]. Once the film has been established the aluminium is protected and further contact between disc and pad is eliminated resulting in negligible wear regardless of the friction level. It has been suggested that the hard reinforcement particles contained within the aluminium contribute to the transfer film and its friction performance. Brittle fracture of exposed particles results in an abundance of abrasives being incorporated within the film forming an abrasive layer dictating the friction coefficient. Should there be a limited amount of reinforcement material available prior to film formation it will be devoid of abrasives and most likely have reduced friction performance.

Much work has been covered regarding the structure and properties of Aluminium MMC discs. The amount and type of reinforcement has been the subject of various research programmes. Garcia-Cordovilla *et al* [17] showed that aluminium composites reinforced with silicon carbide were more resistant to abrasive wear than with alumina, although this could have been a consequence of different abrasive morphology. Literature concerning other reinforcement materials was limited. Work by Feest [16] showed how increasing the concentration of silicon carbide increased both the melting point and resistance to deformation with temperature. However this work was limited to pure material testing as opposed to brake specific research.

The main thrust of research into particle reinforcement has tended to be into the effect of volume loading. With increasing particle concentration the material can withstand higher temperatures before the friction surface breaks down. Research into reinforcement has been hindered by the need to keep other metallurgical factors constant. Some properties such as elastic modulus and thermal expansion vary predictably with particle content but other properties such as strength and ductility do not. The particle size, distribution and morphology also affect the overall properties of the metal matrix. The table below, duplicated from reference 16, gives an indication of property variations with increasing volume fraction.

SiC (vol %)	10	20	30	40	55	70	GCI
Elastic Modulus	88	99	125	147	200	230	70
Thermal conductivity		180	156		180	226	47
Thermal expansion coefficient	20	16	14	11	6	6	12
Specific heat		1.04	0.82			0.75	0.5
Elongation	0.7	0.5	0.5	0.4	0.3	0.2	
Density	2.7	2.8	2.8	2.9	2.95	3.0	7.2

Table 2.2.5. Property variations with volume fraction (GCI = grey cast iron).

Grieve *et al* [12] studied the effects of conductivity and thermal capacity on the disc temperatures attained during braking. This was achieved by studying a wide range of prospective materials along with complex finite element techniques. As expected it was shown that the disc temperatures were increased with decreasing conductivity, and that during high thermal input tests the heat capacity was a dominant factor in peak temperatures. For a simulated emergency stop situation few of the proposed materials remained within their operating limits and exceeded their maximum operating temperatures sometimes by alarming proportions as shown in figure 2.2.5 below.

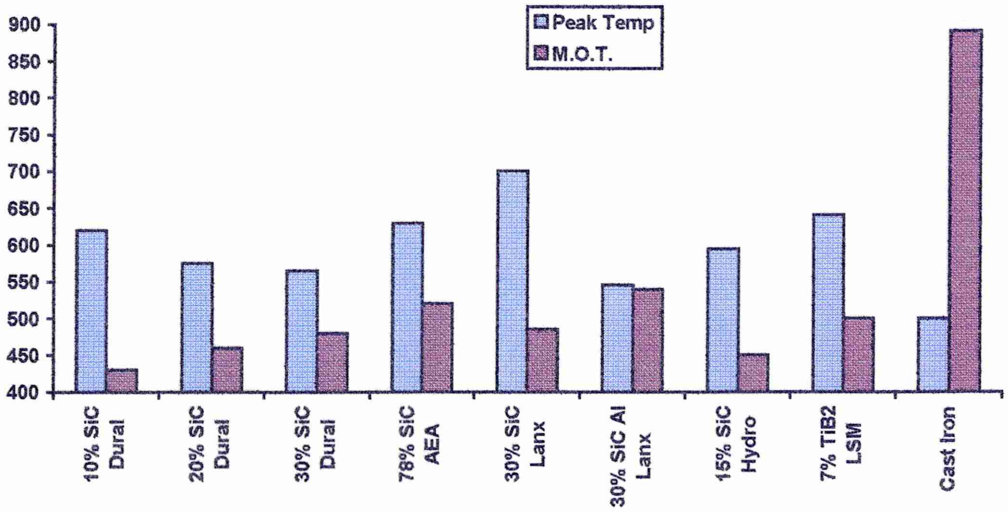


Figure 2.2.5. Predicted peak temperatures after single high thermal input stop test. (Duplicated from ref. 12).

Material	Manufacturer	Density Kg/m³	Sp. Heat cap. J/Kg/K	Conductivity W/m/K	Estimated M.O.T.
Cast Iron		7200	449	47	1000
10% SiC-6061 Alloy	Duralcan	2711	879	151	428
20% SiC-6061 Alloy	Duralcan	2770	838	181	460
30% SiC-6061 Alloy	Duralcan	2850	996	197	485
30% SiC-3050 Alloy	Lanaxide	2780	820	156	485
30%Al_2O_3-4040 Alloy	Lanaxide	3030	828	98	540
15% SiC-6061 Alloy	Hydro Al	2730	837	175	455
68% SiC-2014 Alloy	AEA	3040	810	220	520
7% TiB_2-2101 Alloy	LSM	2818	882	218	500

Table 2.2.6. Material Properties of Al-MMC's.

In order to prevent certain catastrophic failure the results indicated disc temperatures need to be reduced. This was shown to be possible by increasing the mass of disc material by widening the cheek thickness compared to the vane thickness. By changing from 7.3mm (The thickness used for the test shown above) to 10mm many of the materials did not reach their maximum operating temperatures.

Hayes [66] have recently proposed an increased airflow rotor design where the standard straight cooling vents in the disc (typically around 40) have been replaced by up to 72 curved fins. This dramatically enhances the surface area available for cooling and also increases the airflow through the rotor by up to 35%. Separate work at the University of Illinois resulted in a 70% increase in flow velocity at the rotor vane outlet with only small alterations to the disc design [69].

However, in all cases it is clear that unless the surface temperatures achieved during heavy duty braking can be significantly reduced, either by material considerations, geometry factors or ducted air-flow, there will be cases of brake failure.

Dynamometer testing of Al MMC's revealed that above bulk temperatures of 450°C the friction level rapidly fell to below 0.2, this being attributed to surface melting of the aluminium. This resulted in severe disruption of the rotor surface such that, having cooled and the brakes re-applied, the friction material wear rate is significantly increased to critical levels, i.e. lasting only one or two stops before total wear-out.

Despite such problems it is likely that with appropriate design the positive benefits of these materials can be realised and be incorporated into vehicle braking systems.

2.2.2.2 Disc Coating.

As discussed earlier, copper based discs may have many advantages over cast iron but are likely to be prohibitively expensive as well as there being no saving in weight. Under current investigation is the coating of aluminium discs with high conductivity materials such as copper. Copper metal with dispersed silicon carbide particles has similar low wear rates and friction performance to aluminium metal matrix composites. Thus the benefits of copper discs and the low mass of aluminium can be combined. The high conductivity of copper allows for very rapid conduction of heat from the interface into the disc and, due to the high melting point, there is little chance of interface melting. Various properties of copper, aluminium and iron are compared in table 2.2.7. Despite the advantages of the coating, the aluminium disc itself still suffers from a low maximum operating temperature and relatively low heat capacity compared to cast iron. For successful introduction into automotive use increased levels of disc cooling will probably be required.

Although coating of aluminium discs offers huge potential for reduction in unsprung mass, where high disc temperatures cannot be avoided the coating of standard cast iron or other materials will be of benefit. Disc wear will be reduced and judder problems due to off-brake wear (section 2.4) may be eliminated. Additionally lining wear will decrease as a result of the rapid conduction of heat from the interface. Fade effects and corrosion problems may also be much reduced. Although disc coating may prove to solve many of the problems currently under attack, whether the process comes into widespread use will to some extent be dependant on the overall disc cost compared to that of cast iron. However, where expense is not the primary consideration these discs may have a promising future.

	Aluminium	Copper	GSI
Melt point °C	660	1084	1175
Density g/cm³	2.7	8.96	7.2
Spec. heat cap. J/gK	0.897	0.385	0.449
Thermal conductivity W/cmK	2.2	3.9	0.47
Coef. linear expansion (at 25°C) (10 E-16)/K	23.1	16.5	10.5

Table 2.2.7. Metal properties [88].

2.3 Friction Materials.

Braking of road vehicles in a safe manner relies upon adequate friction between both the tyre and road, and disc or drum and friction material. As motor vehicles have developed the demands placed upon the friction material have also increased. Although in effect both the mating components in the friction couple are friction materials, convention has dictated that the more consumable element is known as the friction material. The design of a material that can operate effectively across a range of conditions which may include interface pressures of up to 10 Mpa, rubbing speeds of 22 m/s and temperature variations of -40 to 800°C represents a considerable technical challenge. The ideal friction material should have a defined and relatively stable friction coefficient, heat stability, exhibit low noise and be low wearing both of itself and the disc rotor. Additionally low material and production costs are of prime importance except in situations where expenditure is placed secondary to weight and performance.

When developing a friction material particular concern must be placed upon the following points-

- Adequate coefficient of friction.
- Stable coefficient of friction (with varying temperature, wear).
- Low wear.
- Low wear of the disc which it will run against.
- Reasonable mechanical strength which remains stable.
- Unaffected by external environment e.g. water, mud, salts.
- Low heat conductivity
- Environmental considerations.

Prior to the 1900's wood, leather or felt was used to provide friction and it was not until 1897 that the first impregnated materials were developed. Cotton fabric was impregnated with resins and was probably one of the first materials developed specifically as a friction material. Unfortunately, although friction performance was reasonably good, cotton begins to burn at around 120 °C and so an alternative material was sought as the requirements of the friction material gradually increased. Asbestos fibres proved to be ideal for friction materials for many reasons, they have low thermal conductivity, good friction performance and chemical resistance, high strength and are relatively low wearing. Also the fibres are inexpensive and easy to process. Unfortunately in the 1970's concerns were raised over the health aspects and within five years asbestos was being replaced by alternative fibres for many of friction material applications. By 1993 asbestos was almost entirely eliminated from all passenger cars in the developed countries of the world [19]. Presently friction materials are complex mixtures of fibres, binders, fillers and friction modifiers and although their performance is generally excellent there is still much research into their further development.

2.3.1 Friction Material Requirements.

Coefficient of friction - The friction material must have an adequate friction coefficient when coupled with the disc material. Theoretically the coefficient can be any value as long as it surpasses a certain level, for increasing friction levels a corresponding reduction in pedal pressure would be required. However, the 'feel' of the brakes is important to the driver and high friction levels may lead to rather harsh or abrupt braking. Friction material manufacturers tend to produce formulations with specific coefficient values, typically these being between 0.35 and 0.43 for general automotive use. This represents medium duty materials with 0.43 - 0.55 being heavy duty and 0.2 - 0.35 being light. Of particular importance is the stability of the friction performance. If during braking the friction level varies then the required pedal pressure must also change a corresponding amount thus making steady braking difficult to control. The friction coefficient can vary under various operating conditions although tends to be most affected by temperature. As temperatures increase physical and chemical changes may occur leading to the performance decreasing or 'fading'. In extreme cases this can result in catastrophic brake failure. The figure below (2.3.1) shows the fade characteristics of two materials, one reasonable and one poor. Most materials will fade to a certain extent but it is critical this happens steadily and that, upon cooling, a full recovery is made.

Pressure and speed tend to have relatively little affect on lining properties although if these variables are increased the power absorption of the material also increases thus raising temperature [20]. This means that separating each affect is difficult as they are all inter-linked.

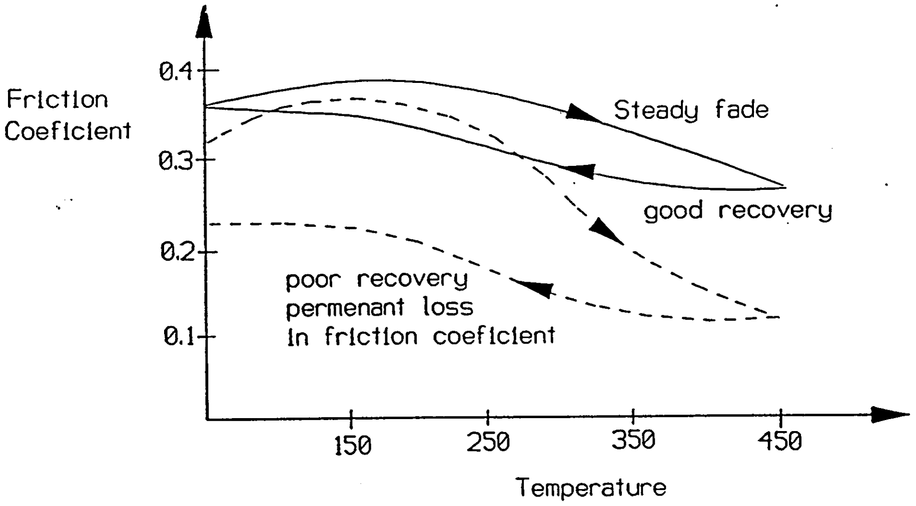


Figure 2.3.1. Fade and recovery characteristics.

wear rate - The wear rate of both the disc and friction material must be considered. Although the pads are generally regarded as interchangeable items manufacturers must ensure low wear rates particularly with the extended warranties being offered by may automotive companies. The friction materials must certainly outlast this period, however a friction material manufacturer does not want their product to last forever as their income is dependant on sales!

Friction materials must be avoided that induce excessive disc wear. Non-aggressive pads will obviously lead to long rotor lives but there may be little 'clean-up' of the disc. Disc cleaning may be required in some cases to control the transfer film or to remove any corrosion. Additionally, where the disc is visible through thin spoke alloy wheels, aesthetics may be important. A rusty brown disc is not quite as pleasing to the eye as a nice shiny one, especially if the rest of the car looks perfect! Non-aggressive pads may also have low friction levels and suffer from fade problems. More aggressive pads are generally more desirable due to stability and increased clean up. Also, any roughness formed on the disc surface needs to be smoothed away otherwise pad wear may be dramatically increased. The major problem with aggressive pads, other than high disc wear, is the production of disc thickness variations which lead to the phenomena of brake judder. This problem is covered in section 2.4. At present there is no real optimum abrasive level, but more a matter of matching the material to the expected customer requirements.

As a result of the wear process there will be some debris which presents an important environmental issue. Clearly the dust must not be harmful to any life forms which is the principle reason for the elimination of asbestos. Other materials are now also considered harmful, for example copper may be banned from friction material formulations in the near future.

Strength - Friction materials must have enough strength, particularly in shear, to withstand the high stresses placed upon them during braking. There must be no loss in strength with varying external factors, particularly high temperature. In addition the material must have an adequate resistance to compressive forces, again not drastically affected by varying brake conditions.

External conditions - The full range of operating conditions and environments that a friction material may encounter must be considered, even for the most demanding situations there should be no dramatic loss in any of the materials characteristics. Resistance to corrosion is important especially if sticking occurs when the couple are left in stationary contact. Similarly, after prolonged braking, a hot pad left in contact with the disc may stick and some force may be required in the release. Once released there is also a possibility of the 'stuck' area having a different thickness or friction coefficient to the rest of the disc due to transfer of material either from disc to pad or visa versa. Many materials will suffer a loss in friction coefficient when in a wet environment. Water must be expelled from the surface rapidly and the lining should not behave erratically when drying. For some materials the dust produced as a result of pad wear attracts water, for pads containing iron based components a layer of iron oxide will be formed on the mating surface if the vehicle is left standing. This rust layer will lead to erratic performance for the first few brake applications.

Heat conduction - Overall the conductivity of the friction material must be low to avoid excessive heat transfer into the caliper unit and brake fluid. If the temperature of the brake fluid rises sufficiently then the phenomena of vapour lock may occur where the fluid boils and gases become permanently trapped. Upon further brake applications a larger pedal stroke than normal will be required for a given pressure as the gases in the fluid are compressed. It is however desirable for the material to have some level of conduction to avoid very hot asperity contacts which may result in complete breakdown of that area and increase wear.

Manufacture and Machineability - Although these factors may have no affect on the actual performance, if the lining is very difficult to work with it may prove too costly to produce. The material components must mix thoroughly and hold together adequately when passing through all the production procedures. The material must not break up or crack during milling and the surface should not pluck when ground or clog up the grinding wheels.

2.3.2 Friction Material Classifications.

Friction materials can broadly be divided into the categories listed in table 2.3.1 below (duplicated from reference 3).

Braking severity	Friction material	Fade-free operating regime	Max. limit
1	asbestos-based organic	< 300°C	600°C
2	Non-asbestos organic (N.O.A.)	< 350°C	650°C
3	Semi-metallic organic	< 400°C	750°C
4	Sintered metallic	< 500°C	850°C
5	Cermets (ceramic-metallic)	< 700°C	900°C
6	Carbon-fibre reinforced carbon	< 700°C	1000°C
7	Ceramics	< 800°C	N/K

Table 2.3.1. Friction material categories.

Organic lining materials are most suitable for general automotive use with Cermets, Carbon-fibre and ceramics being reserved for aggressive high performance situations. Carbon-fibre reinforced carbon (a.k.a. carbon-carbon), first developed for use on Concorde, has been used almost exclusively on formulae 1 racing cars since the mid 1980's [3].

Sintered friction materials generally provide superior thermal wear and friction properties to organic materials although their use so far has been generally limited to the aircraft industry. Production of these materials involves the sintering of iron or copper based systems with abrasives, lubricants and low-solubility refractory metal particulates. Higher thermal fluxes encountered with these linings generally mean that standard cast irons are unsuitable for the disc material and low alloy or stainless steels are often used in preference [3]. If the proportion of ceramic abrasives in the sintered lining is above 50% the material is placed in the cermet classification.

Organic friction materials are complex composites containing many components each contributing to the overall performance of the lining. Semi-metallic friction materials are very similar to those termed organic, the essential difference being the inclusion of metallic fibres for the matrix reinforcement. With all of the authors work concentrating on standard automotive brake linings the scope of this present section of work has been limited to the organic type as covered in the following section.

2.3.3 Friction Material Components.

To a certain extent the composition of lining materials is usually formulated through extensive trial and error testing programs combined with experience of existing material performance. Table 2.3.2 below lists some of the components that may be found in a typical organic (or semi-metallic organic) friction material and briefly outlines their role. However, friction behaviour is extremely complex and dependant to some extent on all the components and how they act when in combination [21].

Constituent	Varieties of constituent	Nominal Function
Resin	Phenolic, Epoxy, Silicone, Rubber	Binder
Fibre	Glass, Aramid, Potassium Titanate, Steel	Reinforcement
Lubricant	Graphite, MoS_2, Sb_2S_3, Sn_2S_3	Friction Coefficient
Metal Powder	Cu, Zn, Fe, Al	Prevents Micro-stick to rotor
Abrasive	Al_2O_3, SiO_2, MgO, Fe_3O_4, Cr_2O_3, SiC, $ZrSiO_4$	Rotor Cleaning
Organic Filler	Cashew nut, rubber crumb	Reduce low temp wear
Inorganic Filler	Vermiculite, $BaSO_4$, $CaCO_3$, MgO	Reduce high temp wear

Table 2.3.2. Major constituents of organic friction materials (duplicated from reference 3).

Fibres - Since the elimination of asbestos other fibres have had to be developed to take its place. Unlike asbestos, no single fibre has yet been able to provide all the characteristics required by the friction industry. Presently there are many fibres used in friction materials, although none could be described as being perfect. Combinations tend to be used to take advantage of the positive attributes of various types. Table 2.3.3 below indicates the characteristics of various fibres used in friction materials.

Characteristics	Asbestos	Steel	Copper	Aramid	Glass	Rockwool	Carbon	Ceramic	Potas. Titanate
Friction	0K	0K	0K	0K	0K	0K	□	0K	0K
Therm. stability	0K	0K	0K	□	□	0K	✓	0K	0K
Wear rate	□	✓	0K	0K	0K	□	0K	0K	0K
Strength	0K	✓	0K	0K	0K	×	0K	□	□
Noise	□	□	0K	0K	□	□	0K	□	□
Rotor wear	0K	□	0K	0K	□	□	0K	×	□
Resistivity	0K	×	×	0K	0K	0K	×	✓	0K
Processing	0K	0K	0K	□	□	□	□	□	0K
Cost	✓	0K	□	□	0K	✓	×	□	□

Table 2.3.3. Fibre characteristics. ✓ = excellent. 0K = good. □ = fair. × = poor.

The fibres themselves are mainly used to hold the matrix together although they do generally have many other affects on the lining performance. Various fibres have shown to increase the thermal wear resistance of the lining when included in the matrix. Early work on potassium titanate fibres showed a decrease in lining wear by up to 40% when they partially replaced asbestos [23]. In addition, the friction performance was improved by up to 30%. This performance increases could not be explained further than possible altered interactions between the fibres and other lining components.

Fibre dimensions and concentrations can affect performance and much research has been conducted into the optimisation of these properties. Work on ceramic fibres [24] indicated that the higher the aspect ratio the better the reinforcement with approximately 100 to 1 being a limit above which no increase was observed. Also, for ceramic fibres in particular, the length had little affect on wear or performance but, without affecting the friction characteristics, an increase in diameter can increase the strength of the lining. Other fibres have different properties, for example up to certain limits the lining wear is decreased with increasing amounts of Aramid fibres. A complex mixture of cellulose, Aramid and glass fibre has excellent wear resistance but if the proportion of glass is too high these benefits are rapidly negated. Mixing of glass fibres with resin is a difficult process leading to non-homogenities in the lining. This problem alone promotes the pulling of the glass fibres from the composite leaving holes and thus aiding the disintegration of the lining [21]. The hardness of the lining is also partly dictated by the fibre content.

Resins - The resin is used to bind all the friction material components together. Although friction coefficient, clean up, reinforcement and other characteristics are largely determined by other ingredients it is important that the resin has, in particular, a low thermal conductivity as it will be distributed throughout the material. Low compressibility once cured and overall stability at high temperatures are both desirable. The resin may also have some influence on disc wear rates and production of judder and, in particular, noise problems. A high fluidity during pressing is desirable as mixing of all components needs to be as thorough as possible. Heterogeneous distributions of structural components have been shown to degrade both the thermal and mechanical properties [21].

Phenolic resin is the most commonly used material although there are various types, each with slightly different characteristics. Most linings use a thermosetting resin for the matrix binder which tend to have a high degree of cross-linking leading to undesirable levels of brittleness. In order to alter the toughness a softener is generally added. Such modifiers may include polyvinibutyral, nitrile rubber and cashew nut dust. Cashew nut dust is also known to improve thermal stability.

The wear of friction materials generally remains insensitive to temperature up to around 260°C below which rates are dominated by abrasion and adhesion. Above this temperature the wear rate increases exponentially with temperature. This has been attributed to the thermal degradation of the organic ingredients, namely the phenolic resins [22]. Once broken down the resin offers reduced support and is easily brushed from the pad surface. Typically, degradation occurs between 260 and 330 °C suggesting that the controlling mechanism is pyrolysis (thermal degradation) as opposed to oxidation as resin oxidation would generally require a higher activation energy (30-50 kcal/mol) than could be provided at this temperature. Upon decomposition the resins form phenol, benzene, toluene, e.t.c. and with secondary oxidation of these products hydrogen may be formed. As temperatures increase further the resins are carbonised.

Lubricants - Lubricants are included in the lining to smooth retardation and reduce brake 'grab' occurring as the brakes are applied. Generally they aid in the formation of the transfer film and hence minimise the wear to both disc and lining material. Few lubricants remain affective over the full range of expected temperatures and so a combination is often incorporated into the composite. Various lubricants are used including graphite, molybdenum disulphide, mica and antimony trisulphide. Lubricants may also reduce the production pressures required during the formation of the brake pad.

Metal powders - Metal powders are added to the material to increase the friction coefficient, with just fibres, fillers and resins it would most likely be too low. So as not to increase disc wear the powders are chosen with a hardness lower than the cast iron disc. Copper and brass powders are the most commonly used. Zinc or aluminium powders are often used when the friction material is not expected to reach high temperatures, for example in rear drum brakes. Inclusion of metal powders also reduces the temperature gradient at the interface without dramatically affecting the overall conductivity, this being particularly relevant to friction materials containing non conducting fibres [25]. Steep temperature gradients tend to promote excessive pad wear particularly at high velocities and heavy loads. Research by Shibata *et al* [19] showed how pad wear can be affected by the diameter of metal powders. Materials with smaller diameter powders tend to wear faster simply because the powders fall out during sliding. It was shown that the optimum for wear was a range of powder diameters from 70 to 250 μm, although ratios of coarse to fine needed careful control. The reason for the lower wear is believed to be connected to an increased charging density which prevents the finer powders from dropping out. However, it is well known that due to the soft nature of the powders any loosened material is incorporated into the transfer film effectively recycling any lost material. Pure iron powder is often added to linings due to the ease of which it is included into the transfer film. The soft iron rapidly work hardens leading to micro cracking and eventual transfer into the friction film.

Metal powders are also known to affect brake noise. Due to the frictional heat, metal powders move to the surface, condense, and are spread thinly across the pad surface. Metal to metal contact is thus increased resulting in vibrations due to stick-slip mechanisms. At present, additions are being researched which prevent such condensation.

Ceramic powders - These powders are used as abrasives, their principal action being disc clean-up. It is also quite likely that they affect the coefficient of friction. The addition of abrasives must be controlled carefully as they are the major cause of disc wear and brake judder. Without abrasives, however, a friction couple is likely to suffer from poor braking performance. Commonly used abrasives are silicon carbide, alumina, zirconium silicate and magnesium oxide. The size, shape and hardness all effect the powder characteristics.

Crosa *et al* [26] studied the affects of abrasives in simple friction material composites with the majority of the work focusing on alumina and chromic oxide. Variations in size, shape and concentration were compared to pad and disc wear as well as friction performance characteristics such as fade and recovery. It was concluded that the abrasives add to the friction coefficient by 'ploughing' affects and that this increased with size and coarseness of shape. The friction coefficient observed with pads containing chromic oxide was lower than with alumina, this not being due to different chemical composition but more the shape of the abrasive (spherical compared to pyramidal). Disc wear also increased for large alumina particles although, for alumina abrasives smaller than about 10 μm, disc wear appeared to be reduced. In all cases pad wear was seen to be reduced with the addition of abrasives. An explanation for this was found in the reinforcement action of the powders which increase the load-carrying capacity and hence wear resistance of the composite. Furthermore, any asperities protruding from the disc surface are likely to induce high wear to a friction material incapable of abrading these away. Wear rates of pad and disc material both increase with increasing abrasive concentration [26, 19] as indicated in figure 2.3.2. However it was shown, again by Crosa *et al* [26], that for smaller abrasives the concentration has little effect on wear rates. Although the friction coefficient was increased with larger abrasives due to ploughing action it was noted that the larger the abrasive, the more that material tended to fade at high temperature. This was explained by the softening of the matrix allowing the abrasives to be pushed back into the pad. It was in fact shown that at very high temperatures of around 500 °C the abrasive affect is effectively eliminated and the friction coefficient tends towards that of the base friction material.

Some of these results however are contrary to the findings of the author (see section 4), the wear rates of both pad and disc and the friction performance often being affected by more than abrasive action.

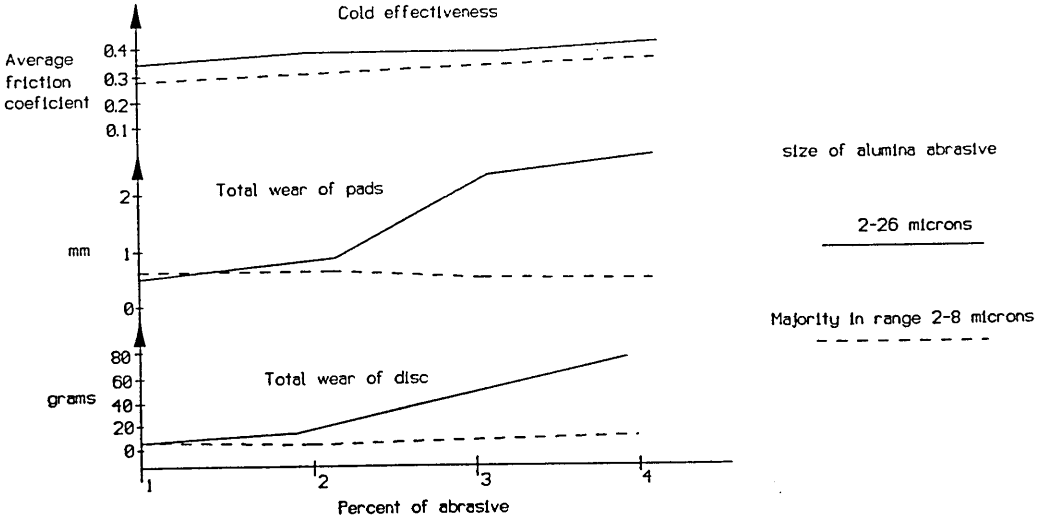


Figure 2.3.2. Abrasive concentration effects on wear. (duplicated from Crosa *et al*).

Fillers - As the name may suggest these constituents are used to fill out the friction material although they generally have affects on the overall lining performance. As such a filler material should ideally be low wearing, thermally and chemically inert and low in density. Barytes ($BaSO_4$) is a common example of an inorganic filler and ground cashew nut dust an example of an organic filler. Barytes is used as it has all the filler requirements (heat stability, low conductivity, etc.) but polishes rather than fracturing thus not falling from the surface and promoting lining wear.

Vermiculite is used in many lining formulations as an inorganic filler due its exceptional thermal, corrosion, acoustic and crack resistance as well as also contributing to lubrication due to its essentially plate-like structure. Broadly speaking, vermiculite is a monoclinic, hydrated ferro-magnesium alumino-silicate which is mined principally in the U.S.A. and South Africa [27].

Other materials may be added to the filler mixture to act as pH conditioners, such as calcium hydroxide, since the friction material must be alkaline to prevent it sticking to the disc rotor through corrosive adhesion.

2.3.4 Friction Material Manufacture.

Initially friction materials were of the woven type where yarns of asbestos fibre were treated with resins and wound together before being pressed and heated to cure. Presently, for disc brake use, all friction materials are of the moulded type. This process allows for a much greater number of additional ingredients to be introduced into the mix and so obtain the required characteristics. There are two types of moulding procedure-

Wet moulding - Basically this process involves making a resin dough and mixing up all the ingredients in a mixing unit. The resin is first dissolved using solvents to give enough fluidity for complete mixing. Once mixed the material is cold rolled and shaped before curing and final machining.

Dry moulding - Resin binder in a fine dry powdered form is thoroughly mixed with all other ingredients and then pressed and cured to a 'pre-form' state. This stage is required to allow the material to be handled, to obtain an approximate shape, and to increase the density to a maximum before final curing. After the preforming stage the material is bonded directly to the steel backing plate during the final curing process. This may involve applying high moulding pressures to the friction material (in excess of 160 kN/m^2) until the resins flow and bind all the ingredients together. Following this the complete pad is usually placed in an oven and heated typically up to 180°C. The length of heating is dependant on the material and may be up to an hour. Most materials to be used as disc brake pads are produced by dry moulding.

2.3.5 The Backing Plate.

Friction materials are generally bonded to a rigid backing plate to distribute the piston pressure evenly throughout the material and hold the pad within the caliper. For friction materials with relatively high conductivity, an intermediate layer of insulating material may be required between pad and backing plate to prevent excessive heat conduction into the brake fluid. Although the backing plate may appear as a rather simple component, a flat rectangular piece of steel with locating lugs, careful design is essential for braking performance. With most disc brake pads the pre-form is moulded directly to the backing plate which has a series of holes punched into it.

There has been extensive research into the affects of uneven pressure distributions between pad and disc [28, 29, 30]. High actuating pressures and thermal stresses set up a complex system of forces which are extremely hard to analyse. Experimental techniques have shown that the pressure distribution varies considerably over the pad with the highest pressures being under the piston or the caliper fingers as indicated in the pressure distribution diagram below [28, 31].

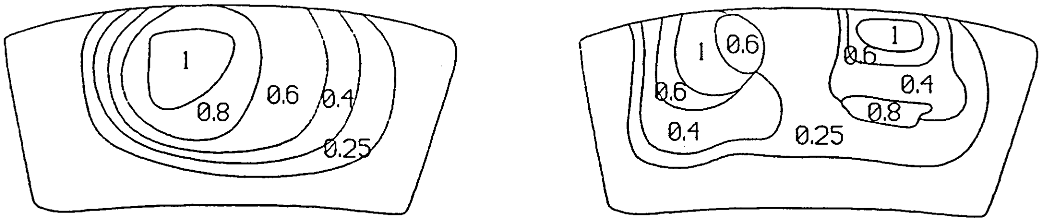


Figure 2.3.3 Pressure distribution for piston side pad on disc.

Pressure distribution on pad due to caliper fingers.

This variation in pressure combined with the induced thermal stresses and friction drag forces leads to specific areas of the pad providing most of the frictional work. The leading and trailing edges of the pad may even lift off the disc during braking due to the complex force system [28]. The flexing of the backing plate is a major contributor to the pressure distributions with loaded linings being distorted as shown below.

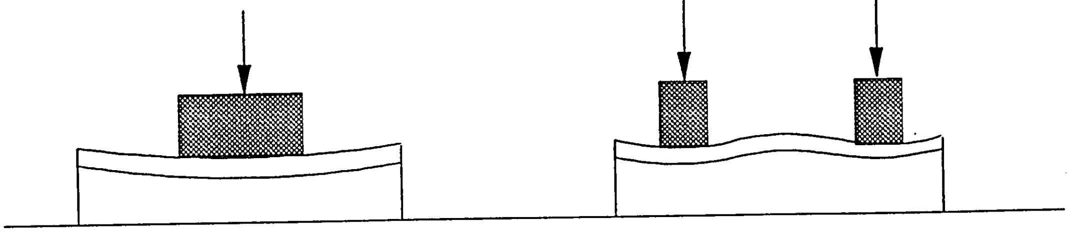


Figure 2.3.4. Compression effects on backing plate distortion.

With pad wear being heavily dependant on both temperature and pressure there will be a greater wear rate corresponding to the loading from the piston or caliper fingers. Any flexure of the backing plate will tend to accentuate the wear in the pad centre in the case of single piston pressure, thus resulting in concave shaped friction material. This wear pattern has the consequence of a long air chamber under the pad and hence further pedal travel is required to initiate full braking. Additionally, any piston seal roll-back affects are likely to be eliminated resulting in permanent contact between disc and pad leading to increased drag and judder formation (section 2.4). Once a wear pattern of this type has been established further heavy brake applications will again deform the back-plate leading to possible cracking of the friction material and in extreme cases eventual separation of the two components. Increasing the backing plate thickness is not a satisfactory solution as this increases both weight and caliper bridge gap, but more importantly, increases the thermal stresses at the friction material / backing-plate interface due to differential expansion [29]. Although undesirable, the automotive industry generally accepts a small amount of backing-plate flexure with emphasis being placed on material choice once the dimensions are optimised. Although steels are the most common materials the quality must be carefully monitored, variations in microstructure may lead to differences in performance as shown by the author in earlier work [32]. In situations requiring high performance braking back-plate flexure may be considerable leading to the possibility of yielding. In this case single piston pressure is unacceptable and two or four opposing piston callipers are generally employed.

2.3.6 Pad Design and Shape.

The actual shape of the lining is under continual development although it is generally constrained to fit the disc rubbing path. Typically the lining covers 7 - 25% of rubbing surface as opposed to drum shoes covering around 50 - 70% [32]. Slots may be introduced to decrease thermal stresses although their position and dimension must be carefully controlled as they may inadvertently act as stress concentrators. Additionally, pad slotting helps reduce the amount of undesirable particles (e.g. sand, grit) that are trapped between the friction couple.

Careful design of the lining shape in conjunction with the other brake components can also help reduce the phenomena of noise (section 2.4).

2.4 Brake Vibration Problems.

Brake vibrations problems have been around for almost as long as the automotive industry itself, there being references to the phenomena dating back to 1926. Initially these problems received relatively little attention in comparison to development of other aspects of automobile design. High speed, acceleration, road holding and aesthetics all having a more positive appeal to the consumer. Vibration problems being neither performance or safety critical had to wait until modern demands for refinement necessitated more detailed investigation. Today's vehicles are incredibly sensitive and the ride comfort so important that the driver is quickly drawn to any vibration problems resulting in high warranty costs. Hence, particularly in recent years the causes and effects of vibrations have seen some significant attention. Brake vibration problems can broadly divided into two areas, these being judder and noise.

2.4.1 Noise.

The phenomena of brake noise occurs as a result of self excited oscillation or dynamic instability of the brake unit. During braking, frictional vibrations may occur and these are fed into the braking system. If the energy input into the braking system becomes in phase with the natural frequency response of components within the system then a positive feedback effect occurs. High frequency vibrations detectable by the human ear are characterised as noise whilst lower frequencies associated with the judder phenomena are generally felt as much as they are heard. The sensitivity of the human ear dictates that frequencies of between 2 and 5 kHz are perceived as the loudest although noise at higher frequencies may be unpleasant to many people. Hence vibration problems covering the entire audible frequency range must be addressed, this range stretching from 100Hz to as high as 20 kHz [56]. In recent years a greater concern in noise pollution and increased levels of vehicle refinement have led to noise problems being highlighted. Recent market research indicated that over 25% of cars developed brake related problems within just one year, the majority of which were noise related [56].

Modern small vehicles generally have a high front disc to rear drum braking ratio which has resulted in any drum vibration problems being overshadowed by those occurring in the disc brake. Hence, particularly in recent years the main thrust of research has been directed at disc brake noise. The majority of drum noise problems tend to be associated with heavy vehicles and, as most people would agree, are particularly apparent in buses operating in urban environments. Although brake noise covers the range of frequencies audible to the human ear this can be further divided into specific categories such as Groan, Hum, Squeal and Squeak, each describing a specific frequency range [58].

Noise may be reduced to some extent by altering the dynamic geometry of the brake. This can be achieved by changing the mass and stiffness of components or altering component contact points. Newcombe and Fieldhouse [59] investigated the effects of varying the contact point between piston and pad. It was concluded that by moving the contact area more towards the pad leading edge, and thus decreasing the 'sprag angle', the system tended to become more unstable. Various methods of altering the sprag angle are now used in production including the use of shims between piston and pad and the removal of some friction material from the pad leading edge [60]. The introduction of disc slots is also an effective way of reducing squeal [78]. With conventional discs the pad/disc contact point is the source of excitation and will always be a fixed position antinode. With a slotted disc the antinode positions become independent of the excitation point and move with the disc rotation. Under this condition stable vibration cannot occur.

2.4.2 Brake Judder.

Brake judder is an excitation of the vehicle suspension and thus vehicle structure during braking. Judder is fundamentally different from noise in that it is a forced vibration caused by cyclic non-uniformities in the braking force. These vibrations are typically low frequency (5 - 500Hz) and so are felt as much as they are heard. Vibrations generally remain throughout the majority of the braking application, the frequency being directly proportional to the rotational speed of the wheel and thus reducing as the vehicle decelerates. As with the phenomena of noise, vibration amplitudes may vary considerably during braking due to coinciding resonant frequencies of brake components or systems transmitting the vibration. Vibrations are felt by the driver at the heel point, seat track, steering column and even through the whole vehicle. Judder may also be detected as brake pedal pulsation or steering wheel shimmy, this being a vibration of the wheel around its axis. By far the majority of the vibrations originate in the front section of the car as the front discs absorb the majority of the brake duty.

The judder phenomena has only recently come to light with problems first being encountered around 15 years ago [61]. Initially vehicles were fitted with semi-elliptic, multi-leaf spring front suspension units which, due to their inherent high torsional damping effects, disguised any juddering to well below acceptable limits. With the move to independant suspension units combined with increased sensitivity and changes in driving patterns, the judder phenomena has come to the forefront of brake vibration concerns [61,62]. Judder problems are most commonly encountered after prolonged driving without using the brakes, typically long distance motorway driving. According to recent road traffic statistics up to 80% of all new cars sold are to be company owned, many of which will be subjected to this type of long distance driving [63]. Judder problems are of particular concern as to alleviate, but ultimately not provide a cure may involve new discs, friction pads, callipers and even new hubs and bearing units.

2.4.2.1 Source of Excitation.

A mass imbalance in any of the rotating components will cause a vibration. These imbalance forces are obviously acting whenever the vehicle is moving but are generally absorbed by the suspension system. However, during braking the suspension compliance bushings increase in stiffness as well as other components in the suspension system changing geometry and vibrations are more easily transmitted to the driver. This is really 'vehicle shake' during braking as opposed to brake judder itself but accounts for much of the complaints lumped into the brake judder problem [64].

Brake judder itself is the direct result of brake torque variations. This is where the braking effect is increased and decreased once or a number of times during a single revolution of the wheel during braking. The reasons for the torque variation may be due to thermal, chemical or mechanical effects, all of which are often connected.

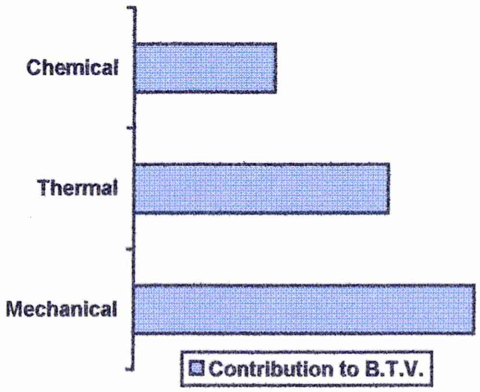


Figure 2.4.1. Contribution to brake torque variations.

2.4.2.2 Cold Judder.

Cold judder is due to mechanical effects and is connected to the kinematic behaviour of the disc rotor and the subsequent uneven wear of its side faces. This uneven wear results in variations of the disc thickness around its circumference. When the brakes are applied variations in the braking torque will occur as thicker and thinner sections of the disc pass between the brake pads.

Uneven wear of the rotor surfaces occurs when the brakes are not applied and is a direct result of disc face run-out, or error of form (or 'wobble'), and the inability of the friction material to retract sufficiently away from the disc subsequent to braking. The run-out causes the disc face to move towards and away from the friction material as it revolves and hence there is light contact with some sections of the disc and not others. This results in the phenomena of disc thickness variation or D.T.V. Thickness variations occurring by this mechanism can only be produced when the brakes are not applied, when the brakes are applied it can be assumed that the pad pressure around the disc circumference will be roughly uniform. Hence, this type of wear is termed 'off-brake wear'. The light, intermittent contact between disc and pad causes little wear in the short term but mat be built up over a period of time. The most simple error of form shape results in a single higher wear section on each surface of the disc (thus two disc thickenings per revolution) as shown in figure 2.4.2 below.

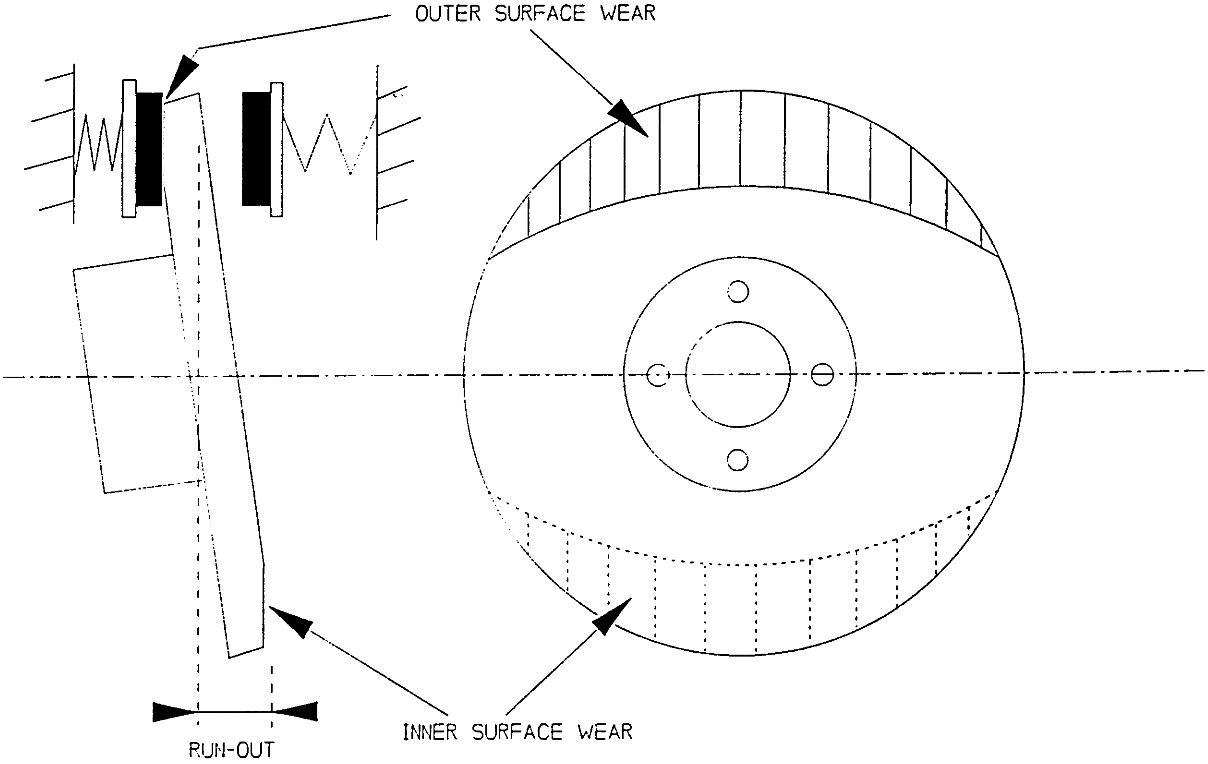


Figure 2.4.2. Disc run-out resulting in D.T.V. Disc wear due to off-brake wear.

The mechanism by which thickness variations are introduced is dependant on non braking over long distances. Heavy braking on a disc with thickness variations would then cause the thicker sections to wear faster reducing the judder problem. Repeating the production and removal of D.T.V. will also slowly reduce the runout resulting in a 'truing' of the disc [61] which is, of course, desirable. Unfortunately this is a rather simplified view as temperature effects, loosening and re-tightening of wheel nuts and many other factors can vastly complicate the situation. Throughout the lifetime of the disc, depending on the driving patterns, both the amount and positions of disc thickenings can vary resulting in noticeable juddering in higher orders of the wheel speed. Figure 2.4.3 shows how D.T.V. can be created or reduced with differing driving styles. From the manufacturers point of view some D.T.V. may not be a problem provided it is not be brought to the drivers attention. It should be appreciated that thickness variations as little as 15μm may be detected on a sensitive vehicle [64] and for a typical vehicle 25-30μm would be undesirable.

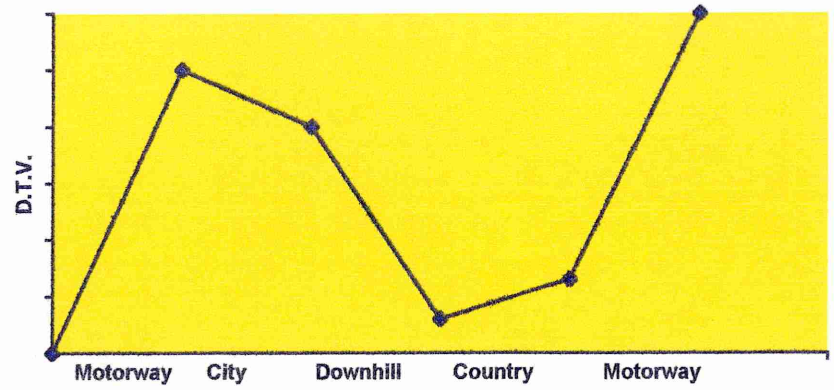


Figure 2.4.3. Typical pattern of D.T.V. production and removal on a brake disc.

Although there may be some D.T.V. on a new disc (anything more than 10 μm would be rejected by most manufacturers) the majority is likely to occur during driving. However, any initial thickness variations may be important particularly if the wear due to runout coincides with the as machined D.T.V. Even if a disc can be machined with low initial run-out the actual value may exaggerated by tolerance stacking effects from other components in the braking assembly, particularly the bearing and hub units since the disc is bolted directly to the hub. Manufacturers have even gone as far as to machine the disc once the brake system has been completely assembled although this leads to higher production costs.

2.4.2.3 Thermal Judder

During braking the kinetic energy of a vehicle is converted into heat at the brake unit. If the energy input into the system is sufficient then brake judder may occur as a result of thermal deformation or alteration of the brake disc [56, 69]. Thermal judder may occur as a result of-

- Waving around the circumference of the disc.
- Uneven thickness expansion of the disc leading to thickness variations.
- Micro-structural changes on the surface of the disc.

These non-uniformities in the disc running surface occur as a result of temperature variations across the surface. When the disc bulk temperature increases there is a corresponding expansion of material. If the expansion is great enough the running surface will suffer some distortion because of the constraints of the 'top hat' section and unequal conduction within the running surface. The deformed shape may lead to juddering effects and also aid in the formation of further thermal judder problems. Some typical distortions of the disc running surface may be coning or wave form as shown below [3].

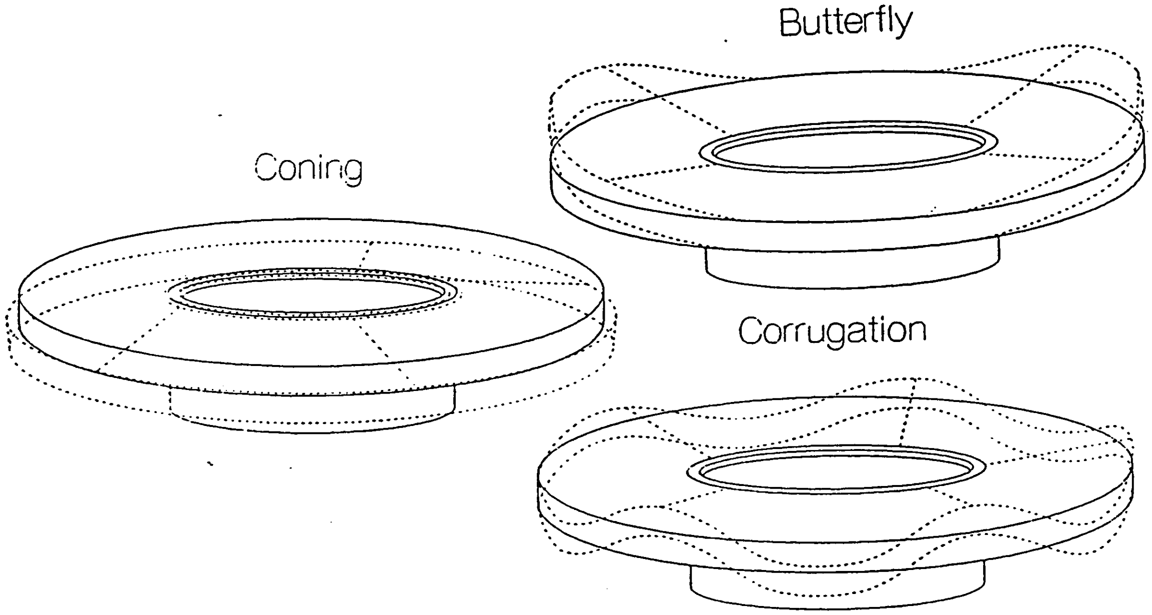


Figure 2.4.4. Various thermally induced disc deformations.

As described in section 2.2 focal hot spots may appear on the running surface of a cast iron rotor due to martensitic transformation. The associated volume increase induces severe local strains and also raises the spot slightly above disc running surface, effectively producing a thickness variation.

2.4.2.4 Solutions to the Judder Phenomena.

Because torque variations are initiated at the braking system the best solution to the judder phenomena will be found at this stage. Reduction of vehicle sensitivity may well remove any judder as perceived by the driver but the torque variations must be damped out at some stage along the transfer path. This will induce some level of repeated component stressing which may lead to problems in the long er term. Despite this a large proportion of the overall reduction in judder has so far been found in damping solutions due to the complex problems encountered at the excitation source.

As with the problem of noise the first step to reducing the sensitivity of the vehicle to judder is to consider the natural frequencies and harmonics of key components in the transfer path. Depending on the wheel order excitation and the vehicle speed the main vibration frequencies due to D.T.V. will be between around 15 to 40 Hz and so the resonant frequencies of transfer components should be moved away from this critical region, or failing that be damped to below acceptable limits. Work by Haigh *et al* [61] revealed that the front suspension of a typical small saloon car had a resonant frequency of 15Hz which is equivalent to a velocity of 90 km/hour!

Elimination of the excitation can be found in two main areas, by avoiding intermittent contact or, if intermittent contact must occur, minimisation of the disc wear via careful material choice. To avoid intermittent off-brake contact the pads must retract enough to ensure some clearance between themselves and the dynamic shape of the disc [61, 67]. However, increasing the pad retraction to cope with disc run-out may cause problems with excessive brake pedal travel. Opposing piston callipers are generally better than floating units due to increased roll-back effects.

When considered in isolation the piston retraction may be enough to provide clearance between pads and disc, unfortunately friction material compressibility and flexure of calliper components, particularly the calliper fist itself, can almost entirely eliminate any positive retraction. Flexure of the backing plate may result in uneven lining wear as described in section 2.3. With the braking pressure removed the backing plate will return to its original shape and the least worn areas of the lining will be left in contact with the disc. Haigh *et al* [61] showed that at low pressures the pad contact area for the inboard pad may be as low as 12%.

One possible solution to judder is in the futuristic 'brake by wire' techniques where the callipers and brake pedal are linked by some form of computer processor. Pedal pressure monitored by the processor would lead to a corresponding braking force applied by the calliper. The major advantage of this system is that the pads can be retracted any distance desired with no effect on pedal travel, however, removal of the mechanical link between driver and brake must be considered a dangerous move when considering safety, no matter how reliable computers may appear to be.

Friction materials for judder reduction.

Because the elimination of intermittent contact has proved so difficult the main thrust of recent research work has been towards the reduction of D.T.V. via careful choice of materials. In short, a pad and disc couple that exhibit minimal wear particularly during light and intermittent contact.

All friction materials have a finite compressibility which is dependant on applied load and temperature [68]. When optimising the compressibility the following points should be considered-

- Highly compressible pads tend to absorb much of the piston retraction.
- High compressibility materials are relatively forgiving to D.T.V.
- Due to the conforming nature of high compressibility pads, hot spots are less frequently formed.

Although high compressibility may appear to be advantageous the lack of retraction and associated parasitic drag and off-brake wear dictate an optimum is required. It is important to note that during the off-brake wear situation the pads are generally cold and so compressibility will be at a minimum. Materials with relatively large compressibility/temperature gradients should be avoided as retraction is reduced after braking due to the high temperature but, upon cooling, there will be high pad to disc forces. Care must also be taken to ensure that upon cooling the friction material does not form a hard skin, possibly trapping any abrasives and forming an aggressive surface.

Wear rates of friction materials are also affected by both temperature and pressure. For a material with a high temperature/wear gradient severe tapering of the pads may occur as a result of the higher velocity and hence increased temperature towards the disc outer edge. Tapered pads result in un-equal pressure distribution as well as combining with compressibility in reducing positive retraction.

Brake judder is wholly dependant on uneven disc wear and hence on the abrasive nature of the friction material. At present there are two main schools of thought concerning abrasive properties. One is a material inducing minimal disc wear and thus few D.T.V. problems. However, a material of this type is likely to have a low friction coefficient and suffer from inadequate fade stability. A relatively high wear material on the other hand will produce D.T.V. under off-brake conditions but during braking a planing affect will 'true' the disc. Materials of this type are likely to have good friction performance but may lead to premature disc replacement. With higher wearing materials a balance must be found considering the expected driving styles to ensure that D.T.V. production is not faster than the planing affects.

Transfer film engineering is currently the subject of much investigation and forms a major part of the authors research. With the correct choice of friction material ingredients a film can be formed that reduces the wear of both the disc and pad. For the reduction of off-brake wear a protective film is required over the lightly contacting areas. During braking, abrasive action may remove this to ensure even wear around the circumference. In some cases however, the formation of a low wearing film on only part of the surface may cause further problems, particularly if it has a different friction coefficient compared to that of the uncoated disc. Furthermore, if the film is allowed to build in thickness then a thickness variation is introduced!

The inclusion of abrasives in the friction material of different size and morphology may give desirable wear rates under different braking conditions. To reduce off-brake wear, hard smooth particles can be incorporated which stand proud of the pad surface and run against the disc when pressures are light. In this way wear will be low and the friction coefficient will be at a minimum thus reducing parasitic drag. With increased brake pressure the hard particles are pushed back into the friction material and contact between the disc and all of the pad material is made.

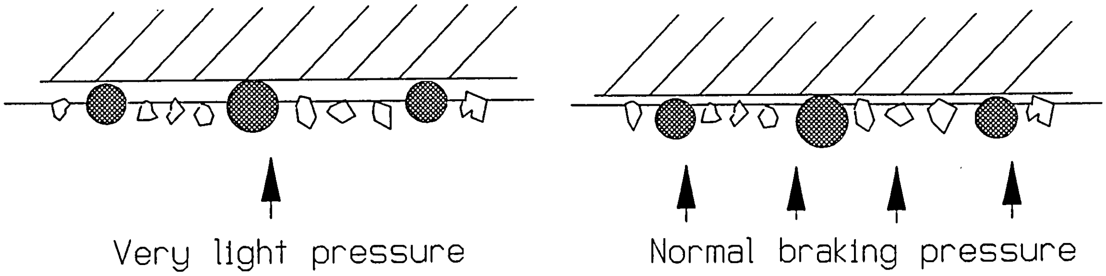


Figure 2.4.5. Use of different abrasives in a friction material to reduce D.T.V.

2.5 Transfer Films and Wear Mechanisms.

When friction occurs between two sliding bodies there is often a heat affected layer introduced into the surface of each component together with transfer of material from one or each of the surfaces to form a transfer film. In automotive braking the transfer film or 'third body layer' between pad and disc is generally accepted to have a large influence on the tribological characteristics of the couple. The third body layer is defined as the zone that has different composition to either of the rubbing surfaces. Transfer films are generally associated with the film formed on the running surface of the disc although in many cases there is often a film of similar composition formed on the surface of the friction material. For a complete understanding of transfer films both components of the couple need to be studied in combination.

Friction materials that quickly form a stable film or 'glaze' on the disc surface are generally noted to exhibit stable friction levels provided the film remains intact [2]. The ease of film formation is dependant on the friction material composition, the disc material and to some extent the surface finish of the rotor. The stability of the film is dependant on the cohesive bond strength within the film material as well as the adhesive bonds between film and sliding surface.

Many attempts have been made to characterise the transfer layer on cast iron discs and describe the wear mechanisms occurring during braking. Much of the published work has tended to focus on films formed by just one or a small number of lining materials in given situations and when viewed in isolation may give misleading information. Generally the film content is noted to contain thermal degradation products from both the friction material and to a lesser extent, the cast iron disc. Liu *et al* [34] showed how the film was made up essentially from asbestos or its degradation products and iron when using asbestos based lining materials. Jacko *et al* [2] showed how the friction film is a result of wear debris compaction generated from both the disc and pad.

2.5.1 Mechanisms Occurring at The Interface

The four main mechanisms of wear are adhesive, abrasive, surface fatigue and corrosive. Additionally there is thermal wear to consider, particularly for the lining material, since at elevated temperatures the cohesive strength of the material decreases. The mechanisms occurring between disc and lining material are extremely complex with there generally being more than one operating at a given time. Furthermore, the mechanisms may change considerably with differing braking conditions and may even alter during a single brake application as the interface temperatures rise.

Adhesive Wear.

The basic mechanism of adhesive wear is that cold welds are formed at some asperity junctions between the contacting surfaces which must be sheared for sliding to continue. The amount of wear depends upon where the junction is sheared. If shear occurs at the interface then wear will be zero but if it takes place away from the interface a fragment of material will be transferred. Transfer of material normally occurs from softer to harder material although occasionally the reverse is true. Figure 2.5.1 shows the adhesive transfer of both a thin flake particle and a wedge like wear particle [37]. Adhesive wear may lead to abrasive wear as transferred material is heavily worked, often oxidised and perhaps harder than the parent material. Hence the roughened surface may now act as an abrasive counterface.

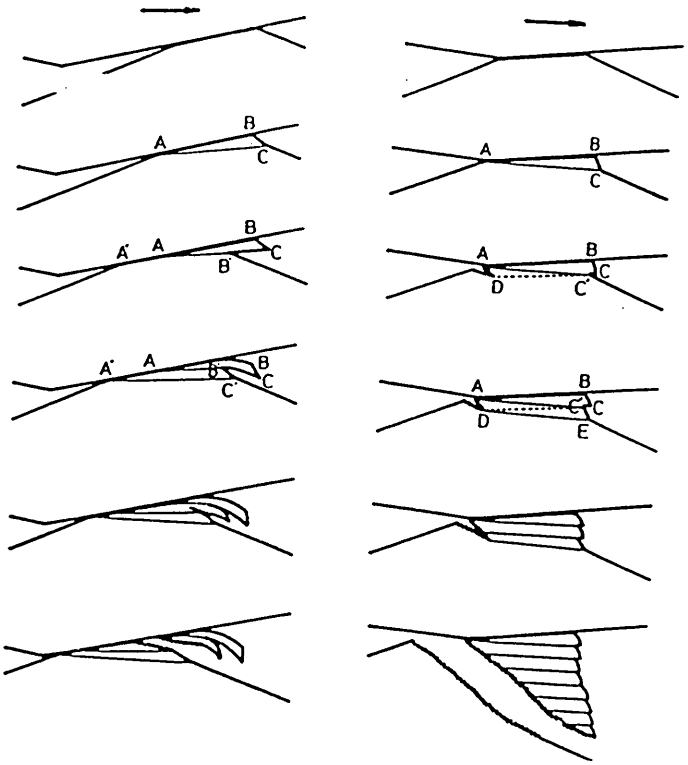


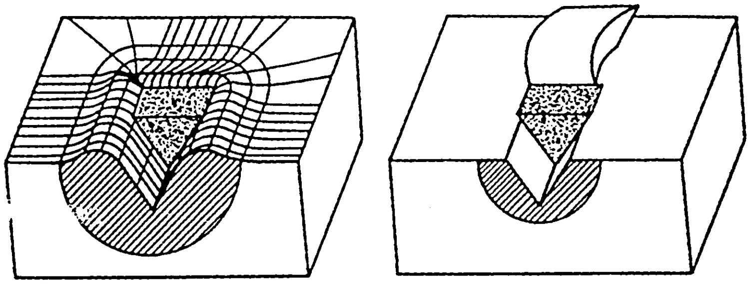
Figure 2.5.1. Adhesive transfer of wear particles [37].

Abrasive Wear.

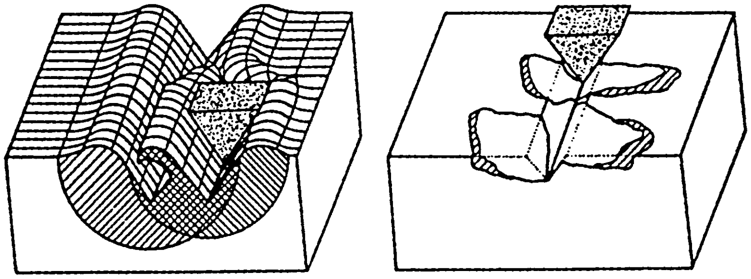
Abrasive wear can be divided into two categories these being two-body and three-body abrasion. Two-body abrasion describes a rough hard surface sliding against a softer surface whereas in three-body abrasion hard particles trapped between the sliding surfaces cause one or both of them to be abraded. The rate of three-body abrasion may be an order of magnitude lower than that by two-body as the hard particles may spend up to 90% of their time rolling [35]. Spherical abrasives generally induce less wear than angular particles although the effect of shape is reduced in three-body abrasion where particles are able to orientate themselves to the least resistant.

Abrasive wear is common to lining materials containing steel fibres and abrasive particles. Generally there will be both two and three-body abrasion with two-body abrasion due to protruding abrasives and hard fibres in the friction material. Escaped and often shattered abrasive particles originating in the lining together with work-hardened wear debris will result in three-body abrasion.

The actual hardness of the surface material being abraded has a large influence on the overall wear rates. There are four types of abrasive interaction as indicated in figure 2.5.2. [35].



Microploughing Microcutting



Microfatigue Microcracking

Figure 2.5.2. Interactions between abrasive and sliding surface.

Microploughing leads to no loss of material and hence is a desirable form of abrasive action when low wear is required. However, repeated passes of abrasives over the surface lead to micro fatigue and eventual material loss. Microcutting clearly leads to rapid material loss and is the mechanism used when machining most materials. This is the dominant mechanism for the abrasive wear of cast iron. Microcracking is generally connected with hard surfaces where large wear debris can become detached from the surface by crack formation and propagation. Materials exhibiting this type of wear are undesirable for friction couples.

In many cases it has been observed that harder materials have a greater wear rate than softer materials. Biswas [36] showed how the wear of copper against aluminium oxide abrasives was substantially lower than for titanium, a much harder metal. The difference in wear is a result of the strain rate response of the metals. For hard materials a very high strain rate is observed on the surface promoting easy shear and fracture resulting in loss of material. The strain rate within the softer copper is much weaker and instabilities are transmitted into the substrate. As a result plastic deformation tends to occur as opposed to fracture. Increasing the temperature of the titanium allows instabilities to be transmitted away from the uppermost surface and thus the wear rate approaches that of copper as shown in figure 5.2.3.

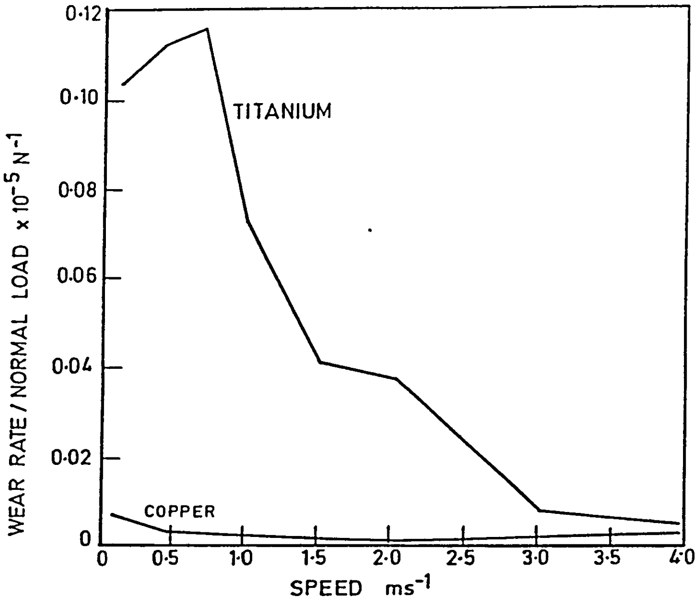


Figure 2.5.3. Abrasion of titanium and copper. [Duplicated from ref. 36]

In the case of protruding abrasives in friction linings it could be argued that once the abrasive has 'cut a path' in the disc it will have a much reduced effect. This is partly true, especially for large abrasives and may explain the initial short lived high friction observed when the lining is applied to a virgin disc.

Fatigue wear.

Fatigue wear is to a certain extent linked to both abrasive and adhesive mechanisms. During sliding contact asperities are deformed with the higher asperities being deformed the most. Repeated deformation will eventually lead to a wear particle being produced. For adhesive wear mechanisms it may be expected that once transferred, the material will remain bonded with no actual loss of material. However, the adhesive forces required to pluck away material may be very low. Fatigue of the softer surface by the harder surface may have much reduced the cohesive bond strength of the material near the interface. Adhered material may then be knocked free by relatively un-fatigued material resulting in escaped debris.

Adhesive wear is associated with a transfer layer which has adhered to both the disc and pad surfaces. The cohesive strength of the film material is lower than the adhesive strength of the film to the sliding surfaces. There may be constant transfer and back-transfer of film material between each surface as the relative strength of the bonds are altered by fatigue. In situations where previously adhered material is recombined with the film, material it is not lost but continually recycled resulting in minimum wear. In this situation the film is said to be viscous or flowing and often results in relatively low friction coefficients.

For some pads abrasive wear may operate almost exclusively although there is likely to be some element of adhesion of metallic fibre material to the disc or even disc material being plucked from the surface. However, material transferred is likely to be strongly adhered, there being no back transfer. Wear scars can often be seen on the transferred material indicating it has become a permanent part of the surface [38].

Often an abrasive transfer film is formed consisting of lining material complete with abrasives. If the abrasives are larger than the film thickness there will be abrasion of both couple surfaces. If the film is allowed to increase in thickness the abrasives will become less affective. In the case of thick films subjected to two body abrasion the ploughing action of the pad may be limited to the film alone. Hence the actual disc will be untouched provided the film can repair itself as fast as it is being attacked. For this situation it is the ploughing resistance of the film that will in part dictate the friction performance.

2.5.2 Surface Oxidation.

Most metals are thermodynamically unstable in air and react with oxygen to form an oxide layer. As the layer grows it shuts off the metal more and more such that the attack is no longer controlled by chemical reaction but by either passage of metal outwards through the film or oxygen inwards. Hence the physical process is greatly dependant on both temperature and lattice defects in the film [40].

When metals are heated a colour change is noted due to interference between the light reflected from the inner and outer surfaces of the oxide film. The colours will vary with the thickness of film [40].

As most braking applications occur in the atmosphere the surface reactions occurring generally include some element of oxidation. The formation of an oxide film may be beneficial in many cases as it prevents contact between the friction couple. Liu *et al* [41] showed how the wear rates of grey cast iron were considerably greater when oxygen was removed from the interface by friction testing in an argon environment. Film stability will be dependant on its adhesive bonds to the substrate, the hardness of the substrate and its relative mechanical properties. During braking the oxide film is continually formed and removed, this is known as oxidational wear.

The effect of oxidation can be well demonstrated by examining two carbon steel surfaces sliding against each other [42]. The wear rate variation with load is shown below in figure 2.5.4. At low loads wear rates are low, wear debris is oxidised, and any exposed steel surfaces have time to oxidise such that an oxide film is always separating the couple. At the transition load, due to increased contact area there is insufficient time for the contact spots to reoxidise between successive contacts and thus no film separating the surfaces. As a result adhesion enhanced wear occurs. As the load increases the temperatures also increase to a point where oxidation is rapid enough to prevent any metal contact. If 'flash' temperatures are sufficiently high the film will grow at a faster rate than it is removed up to a certain point when the oxidation process slows due to barrier effects. In the case of iron there is a limiting thickness where the oxide film will break and thus expose unoxidised material.

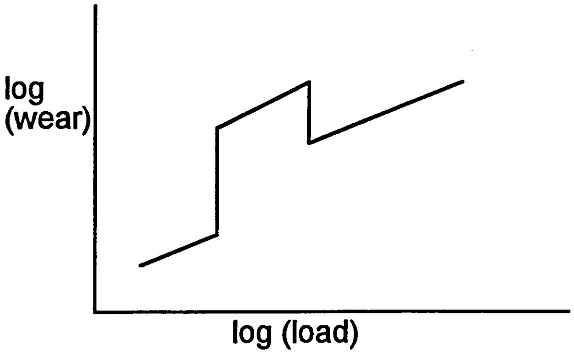


Figure 2.5.4. Mild to severe wear transformations of sliding unlubricated steel.

Under static conditions the oxidation of iron below 570 C is relatively slow forming Fe_3O_4 scale which provides good protection. Above this temperature FeO becomes thermodynamically stable and develops between the iron and the Fe_3O_4. Diffusion then controls the rate of film growth and as FeO is very defective the growth rate is rapid [43]. During sliding the rapid growth of iron oxide will lead quickly to the critical thickness and thus spallation of the film scales. The change in oxide product has further implications to frictional performance as for some lining materials FeO and Fe_3O_4 may have different coefficients of friction. If critical film thickness is not reached the removal of the top surface of Fe_3O_4 by abrasion will expose FeO which will now form the interface material. In addition as the proportion of FeO in the debris increases there will be more compacted into a film.

2.5.3 Transfer Film Formation.

Upon application of the brakes the couple surfaces undergo microstructural and chemical changes which may include the formation of a transfer film on both the pad and rotor surfaces. There is much evidence to suggest that the wear of metallic alloys can be reduced when the wear debris is retained on the contacting surfaces. Stott [43] proposed a method of film formation whereby debris is trapped in surface tracks and subjected to repeated fracture and plastic deformation. Eventually the material can be agglomerated due to developing adhesive forces as a result of increasing surface energy of the debris. The debris can become load bearing and due to the generally oxidised and work hardened nature the resultant surface will give protection against further damage. This sintering process is to some extent dependant on temperature as below a certain energy the debris will not be held together strongly enough.

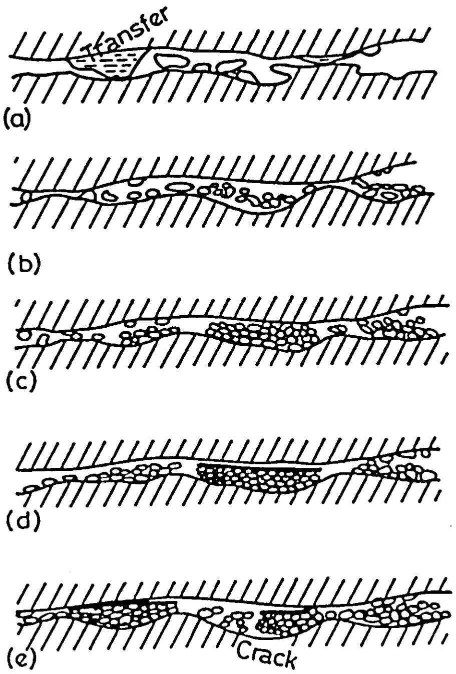


Figure 2.5.5.
Process of wear debris compaction into a film.

The theory by Stott may also help explain the period of poor or erratic braking performance in the early stages of testing. Rhee *et al* [1] showed how during extended burnishing tests the friction coefficient rose to a maximum before decreasing to a steady level. Surface analysis revealed the erratic performance occurred as the transfer film was being created. Repeated testing reduced the maximum peak friction level and eventually, upon brake application the friction coefficient was seen to steadily rise to a relatively constant value. Holinski [44] showed that upon initial brake application there is no transfer of material into a film, this begins to occur only above a certain friction level.

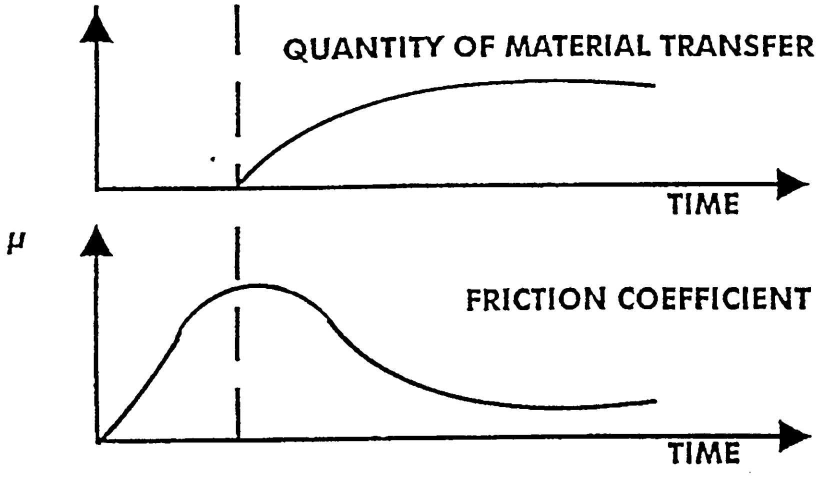


Figure 2.5.6. Transfer of friction material with time as shown by Holinski [44].

Dynamometer testing by Wirth *et al* [76] also showed an initial rise in friction coefficient for all tested samples. Rhee *et al* [1] showed the magnitude of the increase and subsequent friction level was related to initial brake temperature and the number of stops performed. With higher initial brake temperatures the coefficient rise was reduced perhaps as a result of more rapid film formation.

During high temperature braking Jacko *et al* [2, 1] proposed that the drop in friction coefficient was a result of thermal degradation of the compacted wear debris. As the temperature increases the mechanical integrity of the debris became weaker resulting in a situation similar to three body rolling contact in which friction will be reduced. If this is the case it would appear that there is a temperature range over which the film is stable outside which it cannot be formed, although more likely the two proposed mechanisms are true for the individual lining materials tested and perhaps not for them both.

An alternative mechanism to compaction is the direct adhesion of material from the lining to the disc. At some point, perhaps dictated by fatigue or temperature, the adhesive forces between the sliding surfaces is stronger than the cohesive forces within the composite. Once material begins to transfer a stabilisation period occurs where friction decreases and the film spreads and reaches an optimum thickness for the given braking situation. The mechanisms are to a large extent dictated by the lining material, for more abrasive materials there may be little adhered lining material but instead a large proportion of the film is formed from iron oxide debris originating in both disc and pad. Softer, less abrasive pads may be more prone to direct adhesion of lining material. Hermansson *et al* [38] proposed that the creation of a film was partially controlled by the size of the lining components together with their physical and chemical properties.

Scieszka [45] studied the 'metalisation' of friction materials where a film high in metal content is formed on the contacting surface. This affect is undesirable as lining life may be altered, friction performance reduced and interface temperatures increased at metal to metal contact points. Metallic wear debris is forced into the softer lining material and becomes insulated allowing high temperatures to be achieved. Growth of the particle occurs by collection of further debris or adhesion of disc material plucked from the surface. High temperatures make sintering of the debris into a solid and mechanically resistant polycrystal possible. Rupture of the metallic layer can occur by adhesion onto the disc which will then subject the lining to severe ploughing action. For metalisation to occur Scieszka concluded-

- The temperature of the interface is higher than the degradation temperature of the binder.
- The mechanical properties of the metallic disc surface are reduced.
- The lining material is such that the accretion is trapped and not lost from the system.

Metallic fillers, for example copper and brass, are often introduced into the lining to promote metal transfer onto the disc surface. Adhesion onto the disc occurs followed by shearing of the metal resulting in a thin surface layer. This increases the actual surface area as well both protecting the disc and, for certain lining compositions, increases the friction performance.

Borjesson *et al* [46] studied the transfer film formation in braking situations subject to low contact forces representing off-brake wear. Above a critical force or temperature the transferred friction film of certain linings may have a wear inhibiting property, thus explaining the often surprisingly high off-brake wear rates. When examining the worn disc surfaces it was apparent that different mechanisms were working across the wear track. Abrasive wear was the dominant mechanism at the edges with adhesion being more pronounced in the centre of the track. This was explained by the higher availability of oxygen to the edges of the lining material, indeed any film formed on the edges of the wear track was dominated by oxygen content. X.P.S. and ToFSIMS showed the more central film to contain ingredients of the lining material, particularly barytes. Linings devoid of this material suffered higher wear rates. It was suggested that asperities of barytes and organic material are torn from the lining and deposited on the hills of the rough disc surface, the following wear mechanism then being adhesion between the surface of this film and the lining. The critical pressure forcing a change between abrasive and adhesive wear was explained by protruding steel fibres being pressed back into the pad and thus reducing the abrasive 'brushing' effect.

The study of D.T.V. and film chemistry was taken further by Hermansson *et al* [38] who confirmed earlier work suggesting thickness variations are more likely to be created in situations where the proposed suggesting that film thickness had a critical value due to the inclusion of abrasives. Above a critical pressure the film thickness increased and the affect of the abrasives was much reduced. Thus it was concluded that the size of abrasive particles in the lining material must be chosen according to the thickness of transfer film to ensure uniform disc wear.

Various authors [1, 47] have shown a connection between the lining wear rate and the degree of film coverage observed on the rotor. Rhee *et al* showed that the wear rate increased exponentially as the transfer film was gradually destroyed with increasing temperature. Conversely the wear rate dropped as the transfer film was allowed to recover with reducing temperature. This wear variation may well be more affected by the pyrolysis of the organic binders than film coverage. However, surface analytical techniques used by Wirth *et al* in less severe temperature situations have shown clearly an increase in film coverage on a cast iron surface was associated with a decrease in friction material wear rate. Thus compounds are often added into the lining specifically to aid in the formation of a film [48].

2.5.4 Surface Roughness.

Much work has suggested that the surface roughness of the rotor has an affect on the coefficient of friction and lining wear and in promoting film formation. Rhee *et al* [1] showed how the lining wear is strongly dependant on rotor roughness and suggested that there may be an optimum for speeding up film formation and retention. However, no value was proposed and it is likely that optimum roughness for different lining materials may vary considerably. Unexpectedly very smooth disc surfaces are poor at retaining a film although this may be dependant on the adhesive strength of the film material to the disc surface. This theory fits in well for the film being formed from debris collection on the rough surface as opposed to adhesion. Rhee and Thesier [49] showed how disc roughness is essentially limited as either wear occurred or the roughness was filled in by film material.

The wear of friction materials has been shown to increase parabolically with increasing surface roughness of the counterface [39, 50, 49]. This theory holds true for both organic and semimetallic linings although increasing roughness has less affect on semimetallics most likely due to the more resistant nature of the steel fibres. Wear of the lining material is also noted to increase significantly as the roughness tends towards zero. This wear is probably dependant on adhesion and shear mechanisms and perhaps more importantly, three body abrasive wear caused by hard particles trapped between the mating surfaces. Oxidised and hardened particles are known to adhere to, or be embedded in the disc material. Rhee [39] suggested that adherence of calcined asbestos debris to a very smooth disc was responsible for increased ploughing of the lining material and an associated increase in friction coefficient. With no surface roughness on the disc in which hard debris can fall and be 'hidden', the pad will be subjected to ploughing from the full cross-section of the debris.

2.5.5 Transfer film composition.

Presently there is much evidence to suggest that the performance of a friction couple is at least partly dictated by the chemical composition of the transfer film. The actual lining material and the wear mechanisms involved will dictate the composition as described earlier. For example, in a relatively abrasive environment the film may consist of high proportions of both disc and pad material whereas more adhesive mechanisms may lead to transfer films made up of almost entirely of lining elements. Also the film may consist of a combination of ground lining components or alternatively just a small number of the lining compounds adhering to the surfaces.

Early work by Gatrell and Schreiber [51] using asbestos based friction linings showed the film forming on both pad and drum surface was made up of mainly decomposed or 'calcined' asbestos. They also discovered the addition of previously decomposed asbestos to the lining actually improved friction performance. Similarly, friction performance stabilised during break in where a char layer of partly decomposed asbestos formed on the pad surface. Liu *et al* [34], using Auger Electron Spectroscopy, also showed how asbestos was a major contributor to the film material but also confirmed the presence of fragmented particles of iron oxide and carbide originating in the disc. For the material tested the film thickness on the disc was between 1 and 2 µm with this increasing with test severity.

Much of the literature [38, 46] has compared the wear mechanisms and film chemistry of two or more compositions of friction material in order to isolate the affects of individual elements. Borjesson *et al* [46] showed how filler materials consisting of mainly barytes were important in forming a stable film, the wear mechanism observed was generally adhesive. When the filler was excluded from the lining the film was unstable with the prevailing mechanism being abrasive wear. Similar results were obtained by Hermansson *et al* [38] who noted that for linings with a high content of steel fibres the films consisted generally of iron based flakes, much of these from the shearing and oxidation of the fibres. The adhesion of these flakes to the disc surface is likely to be very strong such that there is no viscosity of the film and abrasive wear alone. For a similar material with lower steel fibre content the film was more organic based and believed to be viscous during running. Also observed was a decrease in disc wear with increasing lining pressure, this being a result of increased film thickness. Filip *et al* [21] showed that as steel fibre content in the pad increased the steel content in the film also increased. Above 40% the film was almost entirely composed of steel and hence the role of other components was significantly shielded and depressed. Holinski [44] showed that the film on the disc did not consist of a total composite formulation but of selective elements from the lining. In particular he noted the presence of metallic additions such as copper, tin and zinc.

Work by Wirth and Whitaker *et al* [48] has shown that with varying temperature there may be compositional changes within the transfer film that can influence the performance of the friction couple. A series of investigations were conducted using various surface analytical techniques including Energy Dispersive X-ray spectroscopy (E.D.X.) and X-ray Photo-electron spectroscopy (X.P.S.).

In order to study the affects of both film composition and film coverage with different lining compositions a base formulation was derived into which eight different additions were included separately. Each formulation was tested on a standard F.A.S.T. machine. The affects on lining wear compared to the base are shown below.

Black iron oxide	- Increase
Lubolid	- Increase
Molybdenum disulphide	- Decrease
Antimony trisulphide	- Decrease
Copper powder	- Decrease
Lead sulphide	- No change
Graphite	- Decrease

Base material consisted of-
Steel fibre
Vermiculite
Phenolic resin
Barytes

Elemental analysis of the transfer films showed the major constituents to be oxygen and iron together with magnesium, aluminium, silicon, sulphur, barium and the additive elements, basically almost everything that exists in the lining material. Carbon from the resins was not included in the film in any great amounts although appeared to increase in concentration towards the interface [47].

Although the lining wear rate was not altered with lead sulphide addition the film analysis showed marked variation in the lead signal across banded layers of film indicating either non-uniform transfer or premature removal of the film. Characterisation of the film using X.P.S. techniques indicated the lead sulphide had transformed into lead sulphate or lead oxide [47]. The material previously considered to be a lubricant had changed into a more abrasive compound and as a consequence the film was continually being destroyed. Thus it was concluded that lining additions should be carefully controlled to avoid compounds that decompose upon heating to an abrasive product.

The scope of this work was extended by testing selected samples on a full scale dynamometer [76]. Additions of black iron oxide (Fe_3O_4) significantly reduced film coverage with lining wear increased indicating abrasive action. There were no dramatic changes to the friction performance compared to the base material. This is in contrast to the expected result that abrasive addition would increase performance and the work of Kayaba and Iwabuchi [52] who found a dramatic increase in friction coefficient with the formation of Fe_3O_4. However the transformation of lead sulphide to an abrasive product was later shown to have little affect on friction levels despite its destructive property on the transfer film [53]. It would appear that for some materials at least, the nature of the transfer film is not the only factor describing friction performance.

Iron oxide additions caused almost entire disc coverage in oxide despite there clearly being sections uncovered by transfer film. This is due to the bulk temperatures of the disc being high enough to rapidly oxidise any exposed iron.

Additions of Molybdenum disulphide to the base formulation, although forming a continuous transfer film, caused a significant increase in friction coefficient during dynamometer testing [76]. This is surprising as the compound is generally considered to be a solid lubricant. Examination of the transfer films [54] showed no retention of molybdenum sulphide indicating that it had decomposed to MoO_3, and that the increase in coefficient was most likely due to the formation of an iron oxide at the interface.

$$3MoO_3 + Fe_2O_3 \rightarrow Fe_2(MoO_4)_3$$

Although the decomposition products of molybdenum disulphide have a higher friction coefficient they are not particularly abrasive as witnessed by the low lining wear rate and continuous film [42].

The affect of molybdenum disulphide additions were investigated further in later studies. F.A.S.T. testing showed a clear and significant drop in friction performance in the early stages of the test. Examination of rotors showed the fade resulted from the retention of disulphide lubricant at the interface. As the test progresses and temperatures increase the lubricant begins to break down with a corresponding increase in performance. The higher temperatures encountered during dynamometer testing effectively bypassed the point where the lubricant is retained.

Eggleston *et al* [55] studied the affects of abrasives on friction performance, wear and transfer film characteristics. Although abrasives increased friction levels for all samples the friction material contained 2% molybdenum disulphide. During the relatively low temperature F.A.S.T. testing retention of this lubricant with the base material may have affected this result. Hence, it is difficult to be sure if performance is increased by temperature affects or abrasion mechanisms.

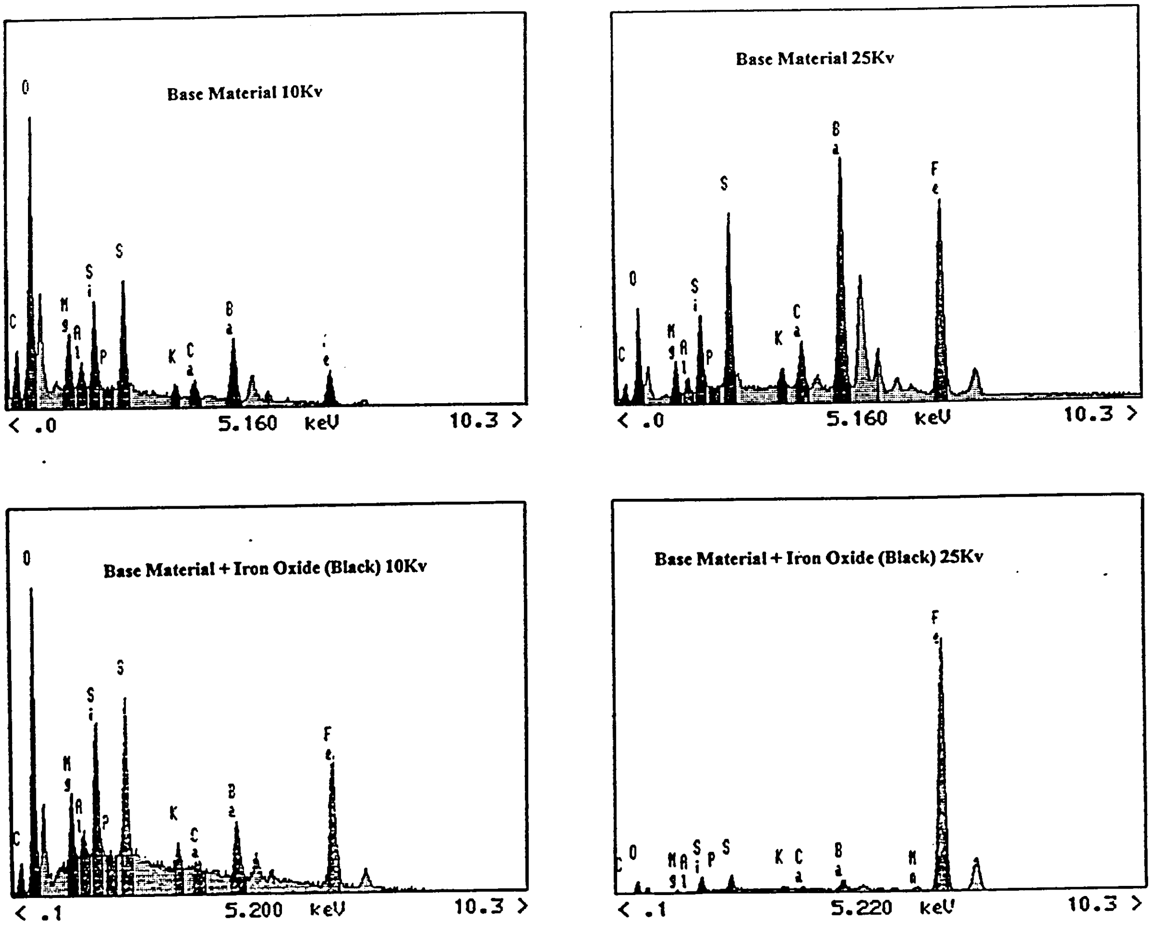
The decomposition of sulphide lubricants was investigated further by the inclusion of 10% antimony trisulphide to the base material [47]. This material acted in a similar way to molybdenum disulphide although the decomposition products were more abrasive to the transfer film.

Retention of lubricants on the surface is particularly significant during wet braking as water will act as a coolant drastically reducing the interface temperatures and prevent decomposition. Additionally, because MoS_2 is a layer lubricant, water separates the crystal structure and reduces friction coefficient.

In another investigation Wirth *et al* [53] showed how increasing the steel fibre content increased the friction material wear rate. This was due to continual destruction of the transfer film by protruding steel fibres. With lubricants such as graphite or molybdenum disulphide thickness variation in the film were observed but rarely was the iron surface of the disc exposed. There was however no mention of performance increase due to the abrasive action of the fibres.

With copper powder additions a transfer film was created over the majority of the disc surface although analysis did indicate some thickness variations in the film. This was also explained by the ploughing action of steel fibres. At low temperatures copper is transferred into the film as copper metal but with increasing temperatures oxidation may occur with a corresponding drop in friction coefficient [55].

Although not commented upon by the authors in their paper on film chemistry [76] examination of the spectra from the film formed with the base material indicates a high degree of coverage with lower levels of iron. Barium and sulphur are major constituents of the film, even at high penetration beam energy the peaks are very strong as indicated in the figure below. In contrast for the linings tested with various additives the barium and sulphur peaks at high beam energy are relatively weak with iron being detected predominantly. At lower beam energies (10 kV) barium and sulphur have strong peaks for all tested formulations. It could be concluded from this data that the film from the base material is thicker than that formed by the other materials. There appears to be a 'base' film composition which the additives are not greatly affecting. They do however control the thickness of the film and may of course be themselves included. Barium and sulphur peaks are from barytes, this forming between 25 and 35% of the lining composition. The retention of this material is due in part to its very inert behaviour and may be linked to a high adhesive strength. Wirth [42] showed that with sufficient temperatures, and particularly if graphite is present, the sulphate in barytes can be reduced to sulphide.



Base Material 10Kv

Base Material 25Kv

Base Material + Iron Oxide (Black) 10Kv

Base Material + Iron Oxide (Black) 25Kv

Figure 2.5.7. X-ray analysis of friction films. (Duplicated from ref. 76).

Wirth *et al* [55] used X.P.S. and E.D.X. techniques to extensively analyse the friction films formed on cast iron surfaces and the following conclusions were drawn [55].

- Friction performance is independent of film thickness.
- Friction performance is independent of film topography.
- Lining wear rates and friction coefficient were not necessarily interrelated.
- Abrasives may either destroy or stabilise the film without significantly affecting performance.
- Film chemistry is independent of abrasive morphology and mechanical properties.

Of the above conclusions that concerning friction performance and film stability being not necessarily related is one of the most repeated in the literature. For the majority of investigated situations whether the film remains intact or is repeatedly created and destroyed often has little affect on performance. The overall friction coefficient appears to be more affected by film chemistry than stability although stability often has a large effect on lining wear.

It has been argued that variations in friction coefficient during braking are the result of varying surface contact area and that all transfer films have the same coefficient. Contact area cannot be disregarded and in many situations may play a dominant role but much of the published evidence suggests the chemistry has a large influence on performance. It is likely that the conclusions reached by various authors are specific to their test specimens and may not be compatible for other lining formulations. This has proved a complex problem when sifting through the published work, attempting to connect every mechanism is a difficult process. Specialisation in a specific area of performance and wear mechanisms will most likely lead to a greater understanding when developing a lining material and corresponding transfer film.

3.0 Experimental Procedure

Throughout the duration of the project the aims have been to observe and document the characteristics of various friction couples and through analysis of the worn surfaces attempt to gain an increased understanding of the mechanisms dictating these factors. All of the practical work covered by the author involves testing of a friction pair on a laboratory based testing facility and analysis of the transfer films formed on both surfaces of the friction couple. The test apparatus used was a 'F.A.S.T.' Machine (Friction Assessment and Screening Test.) The testing and analysis work covered during the duration of the authors involvement at Sheffield Hallam University can be divided into three distinct parts:-

F.A.S.T. Testing. Various experimental friction linings were tested to gain an understanding of both the transfer film and the friction characteristics of linings coupled with cast iron. The experimental materials were designed with a minimum number of components in order to highlight the affects of certain additives.

F.A.S.T. Testing against copper coating. A coating material of metallic copper containing dispersed abrasives has been developed and patented by Plasma Coatings Ltd. This coating was applied to an aluminium friction disc and tested on the F.A.S.T. rig to investigate an alternative to cast iron rotors. Of particular interest at this stage was the development and optimisation of a suitable friction lining to be coupled with the copper coating. For comparison purposes a cast iron disc was also manufactured and coated with copper for testing on the machine.

Analysis of Industry Tested Components. The above sections of work ran along side Plasma Coating's own rigorous testing and development schedule. Much of this testing employed both full-scale dynamometers and specially equipped road-going vehicles. Many of the worn components were transferred to Sheffield Hallam for analysis.

3.1 Friction Material Testing.

Before the introduction of a friction material into the market it is essential that its performance is well understood. The material must be tested under any imaginable conditions before it can be safely matched to a specific duty. Before the development of testing machines standard road-going vehicles were used although this proved both costly and time consuming. Machines were developed to accurately examine and characterise the response of a friction material to a range of conditions thus allowing lining development to continue as far forward as possible before on vehicle testing commenced. Manufacturers do however still require extensive vehicle-based trials particularly in the latter stages of development. Such tests typically cover expected driving patterns such as urban or country driving as well as more intensive and safety critical investigations.

During the development of a friction material a whole range of test equipment may be used varying in complexity and similarity to a real vehicle system. Comparison of results from different test machines is often difficult although many fundamental characteristics of a given lining formulation for example friction coefficient, wear rate and work rate per unit area may be compared directly with sufficient knowledge of the test equipment. In many cases the tests may bear little resemblance to the on-vehicle braking demands, however valuable information on how the material may react to specific conditions can be collected. Results tend to be very reproducible and hence the machines can be used satisfactorily for quality control. Table 3.1 compares some of the commonly used test machines.

Machine	Test time (hours)	Shoe	Lining (sizes in inches)	Disc
Dynamometer	10	Original	Original	Original
Chase Link	7.5	Holding unit	Lining section 1x1	Special casting
F.A.S.T.	7.5	Holding unit	Lining section 0.5x 0.5	Special casting
Ranzi Cuna	9	Holding unit	Lining section 1.1x 0.8	Special casting
Ranzi LRC	7	Holding unit	Lining section 0.1x 0.3	Special casting
ATE krauss	3	Original	Original	Original

Table 3.1 Comparison of test machines.

Dynamometer.

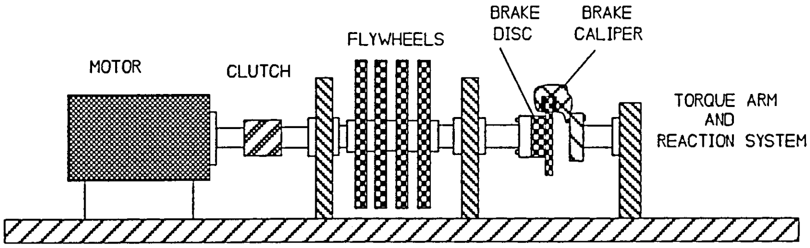


Figure 3.1. A single end dynamometer.

The dynamometer is one of the most common methods for lining development because actual commercial brake components are used allowing many road test procedures to be reproduced. Bedding-in, high-speed stops, frictional behaviour tests and Alpine decent conditions are all within the scope of the apparatus. A typical single-ended dynamometer is shown above in figure 3.1. As with vehicle testing, results from dynamometers may vary slightly [83], hence model testing machines are generally employed for quality control. Although full scale components are generally used for dynamometer testing it is also possible to scale down the whole machine.

Chase-LINK machine.

The Chase test machine was developed in the late 1940's by the General Motors Company [3] as a standard laboratory procedure for measuring friction and wear characteristics of brake linings. The S.A.E. standard practice (J661 a) test equipment has changed little over the years and indeed is still commonly used today as a quality control tool [84].

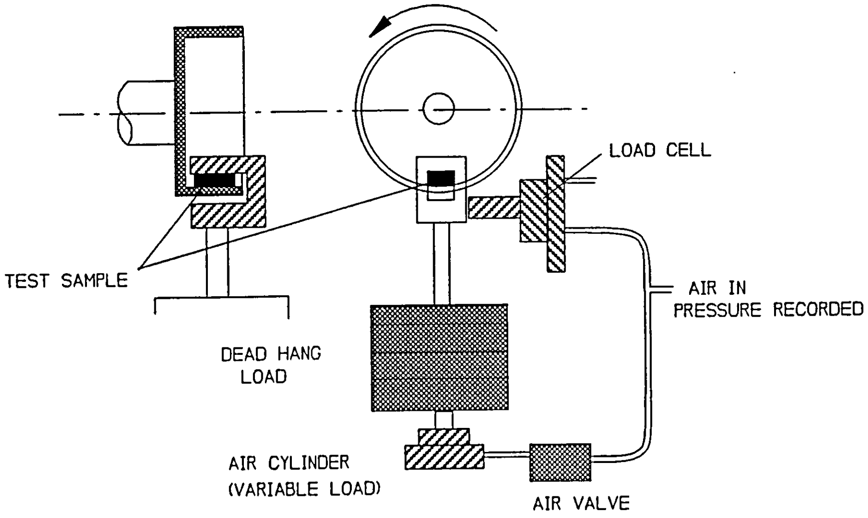


Figure 3.2. Chase test machine.

F.A.S.T. Machine.

The Friction Assessment and Screening Test was conceived and developed in the early 1960's by the research staff of the Ford Motor Company for friction material quality control. The apparatus has become a recognised development tool and is used by lining manufacturers world wide. The machine has an advantage of a very rapid seating of lining to disc (typically less than two minutes) with very simple sample preparation. A F.A.S.T. machine, donated by B.B.A. Friction Ltd. to Hallam University was used throughout the duration of the project and is covered in detail in the following section (3.2).

ATE Friction test machine.

The ATE machine was initially designed in the 1960's by Krauss and then further developed in 1965 by Teves [84]. This machine has the advantage of using full size brake components but a drive unit much reduced in size compared to a full scale dynamometer. The apparatus is fully fitted with test equipment to allow complete screening of a friction material. Such facilities include temperature control and measurement, computer controlled running and data collection, flexible test schedules and contamination tests (sensitivity to water, salt, dust e.t.c.).

3.1.1 Scaling of Friction Components.

When considering performance it is important to note that characteristics will be of the brake system as a whole and not just the lining material. Bearing this in mind scaled systems can generally be used effectively, especially for investigating performance trends under variable conditions. Kuroda *et al* [85] demonstrated reasonable correlation between the scaled dynamometer used by Nisshinbo and full-size systems, however numerical agreement of performance is rarely achieved [86]. This is not surprising considering the values obtained from a full scale dyno are an average of the behaviour occurring over the full contact surface of two brake pads. When comparing brake systems the tribocontact parameter is of importance. This is the ratio of lining surface area to the entire area of the disc wear track [3]. To a large extent the closer the tribocontact parameter of the test machine to that of a vehicle system, the more comparable the results will be.

Test Machine	Parameter
Dynamometer	1 : 6.33 (Example)
F.A.S.T.	1 : 37.8
Chase	1 : 33.8

Table 3.2. Tribocontact parameters.

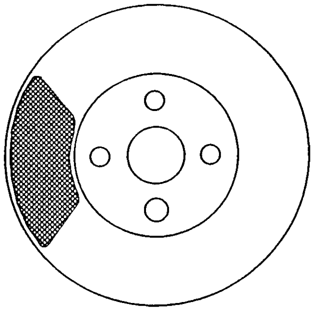


Figure 3.3. Pad to disc tribocontact areas.

3.2 Project Test Equipment - F.A.S.T. machine.

The F.A.S.T. machine was used extensively throughout the duration of the project. Essentially the apparatus consists of a rotating disc with the lining specimen clamped against it. Although the machine was initially developed specifically for lining testing it has been used throughout this project for analysis of the transfer film formed on the disc and lining. For complete operating instructions refer to appendix 1.

3.2.1. Test Modes

The machine allows for two test modes, constant clamping force and constant friction force.

Constant friction force test. This mode of operation is useful as the velocity will also remain constant throughout the test. Referring to figure 3.4, from the fundamental friction law,

$$\mathbf{F} = \mu \mathbf{N} \qquad \text{where } \mu \text{ is the dynamic friction coefficient.}$$

For constant friction force (F), the clamping force (N) and the friction coefficient (μ) will vary in a reciprocal relationship. That is, if the friction coefficient were to drop for some reason during the test (e.g. fade) the clamping force would increase to compensate.

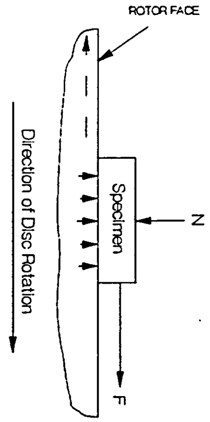


Figure 3.4 Force diagram.

If the friction force and test run time remain constant between tests then the distance travelled by the specimen will be the same (constant velocity), this being true for any friction lining composition. Referring to the equation-

$$\mathbf{W} = \mathbf{F} \times \mathbf{S}$$

where **W** is the work done opposing the friction force **F**, and S is distance travelled, it follows that the work absorbed during each test will also be constant. Hence for near identical discs and ambient conditions the temperature rise of the disc will also follow the same pattern.

With so many variables constant it is very easy to compare results between different lining formulations and this is one of the major reasons for the F.A.S.T. machines popularity.

Constant clamping force test. In this mode of testing the machine applies a constant pre-set pressure to the lining specimen. The friction force will alter to compensate for any variation in the coefficient of friction. In this mode velocity, work done and disc temperature are not constant between each test so comparisons between tests is difficult.

Both modes of testing were used during the project, generally at least one test in each mode conducted on each sample material. With the constant values chosen carefully comparing the results from each test mode gave a good indication of the repeatability of the machine. Standard conditions were established which, unless otherwise stated, all materials were subject to, these being 40 psi in constant pressure mode and 80 psi in constant friction force mode. The duration of each test was 90 minutes, this being the industry standard. This time period was also required for the disc bulk temperature to have overcome the initial sharp rise and be starting to stabilise.

Most of the results are from constant pressure tests because the properties of the standard F.A.S.T. discs and the copper coated discs differed. Although with a constant friction force the work done may have been the same the disc temperatures would have been very different, invalidating direct comparisons.

3.2.2 Machine Description.

The figures below show a photograph and a simplified schematic of the F.A.S.T. machine. More detailed drawings of the machine are shown in appendix 1. The major components of the machine are the motor, the friction disc, the load arm with clamping system and the controllable hydraulic system. All of the components are mounted on a solid steel base underneath which is the oil reservoir supplying the hydraulic circuit.

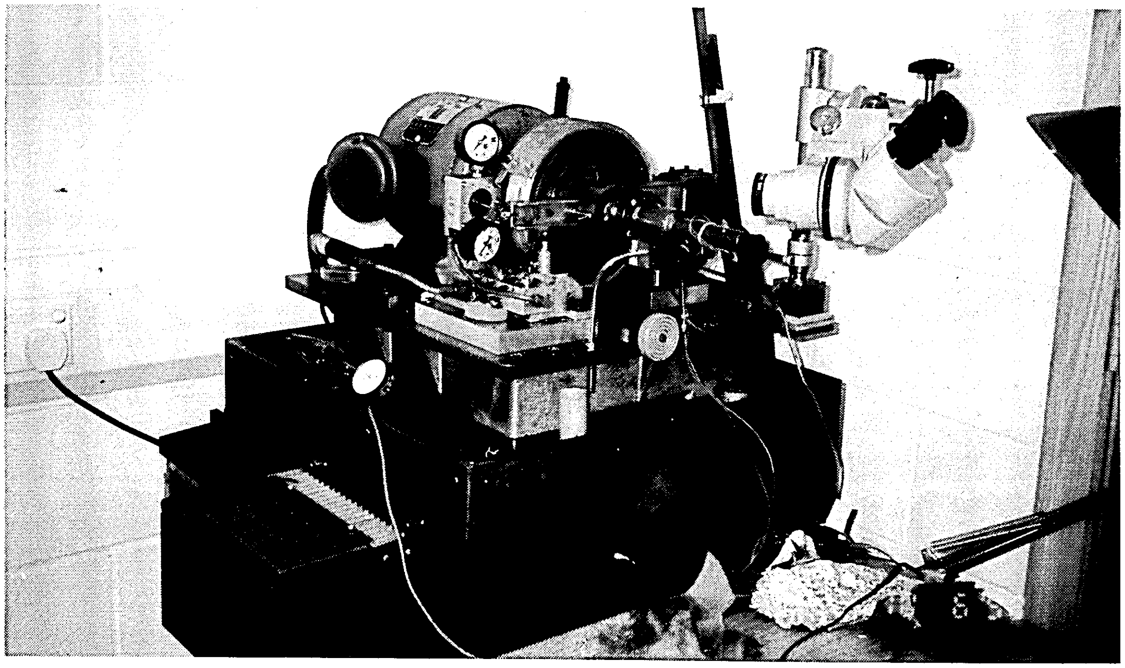


Figure 3.5. Photograph of F.A.S.T. Machine.

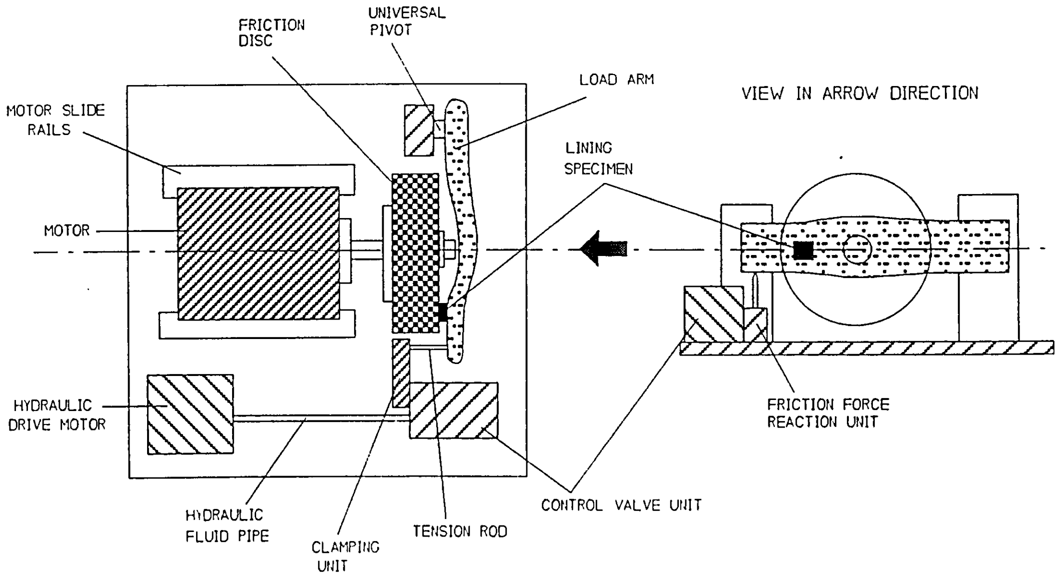


Figure 3.6. Schematic diagram of the F.A.S.T. Machine.

The friction disc is encased, except for the running face, in an insulating cover which forces the disc temperatures to rise sufficiently to investigate fade effects. The initial insulator being made of asbestos was replaced with a different insulating material. The motor itself is located on sliders and its position can be altered to compensate for disc and pad wear with an adjuster screw. The load arm is attached to the test machine base by a pre-loaded universal joint which allows movement in all directions and thus does not effect the test results. The universal joint also allows the load arm to be swung away from the friction disc surface for positioning of the lining sample and for removal and attachment of the disc. Clamping pressure is applied to the load arm via the tension rod from the clamping assembly. This unit contains two moulded elastic diaphragms as indicated in figure 3.7 below. With hydraulic pressure applied between the diaphragms a tensile force is induced on the tension rod due to the different active pressure areas of the two diaphragms. Hydraulic pressure is applied by a motor driven oil pump.

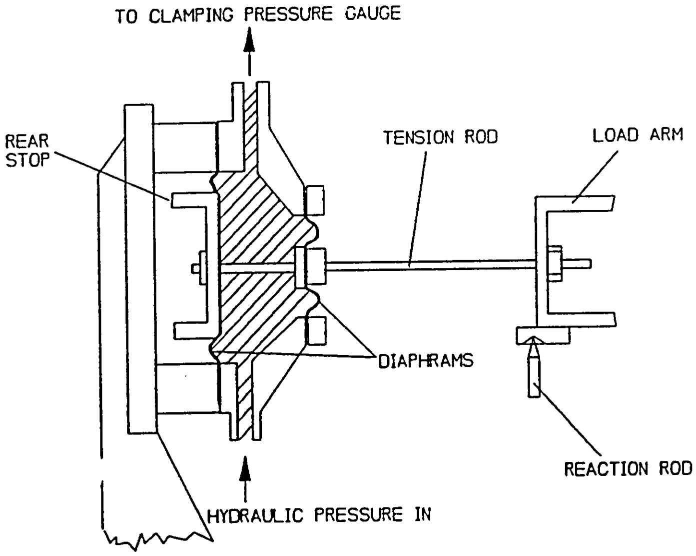


Figure 3.7. Sectioned view of the clamping unit.

The control unit is fixed to the machine base and controls the amount and application of the hydraulic pressure as well as the test mode. A sectioned view of the control unit is shown in the schematic diagram of the F.A.S.T. machine overleaf (figures 3.8a and 3.8b). Constant pressure, either friction or clamping is maintained using two valve spools. The selector valve dictates which pressure is transmitted to the pressure transducer. The transducer, by means of the strain gauge principle, converts hydraulic pressure into an electrical signal which is then fed to the data recorder and processed into meaningful results.

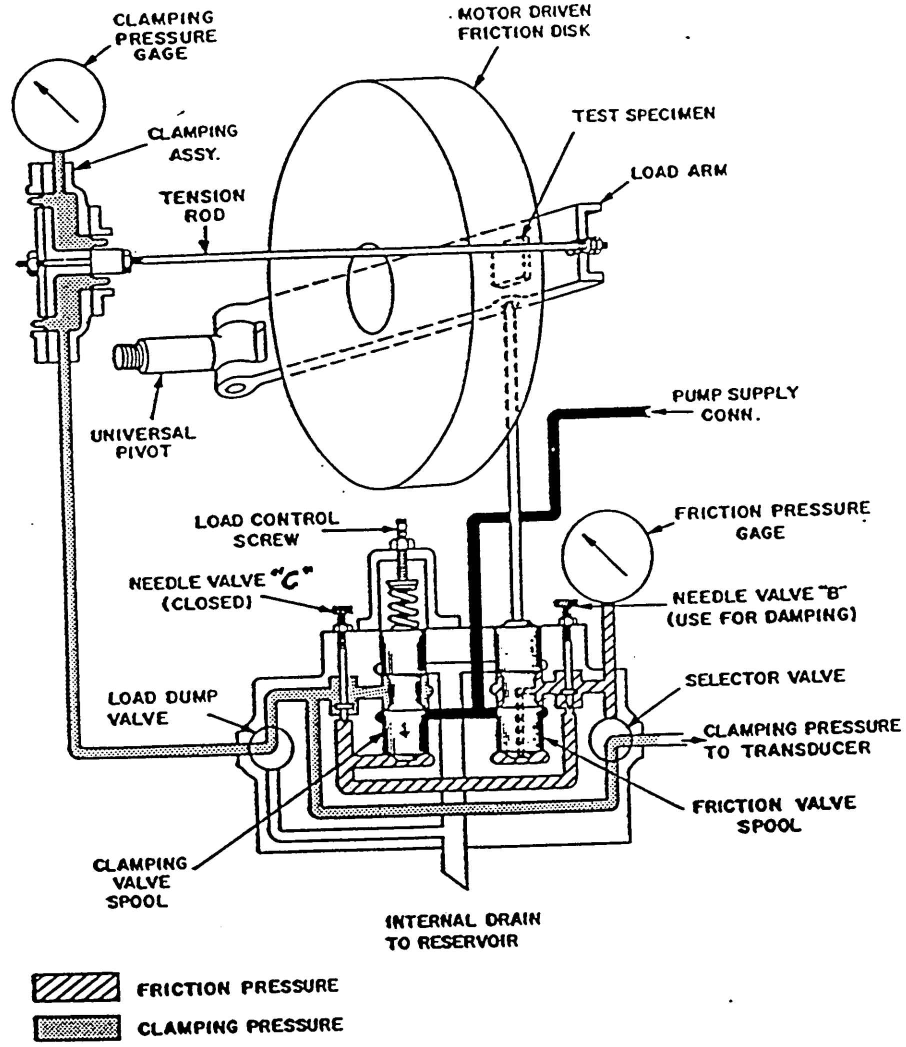


Figure 3.8 a. Schematic diagram of F.A.S.T. machine in constant friction test mode.

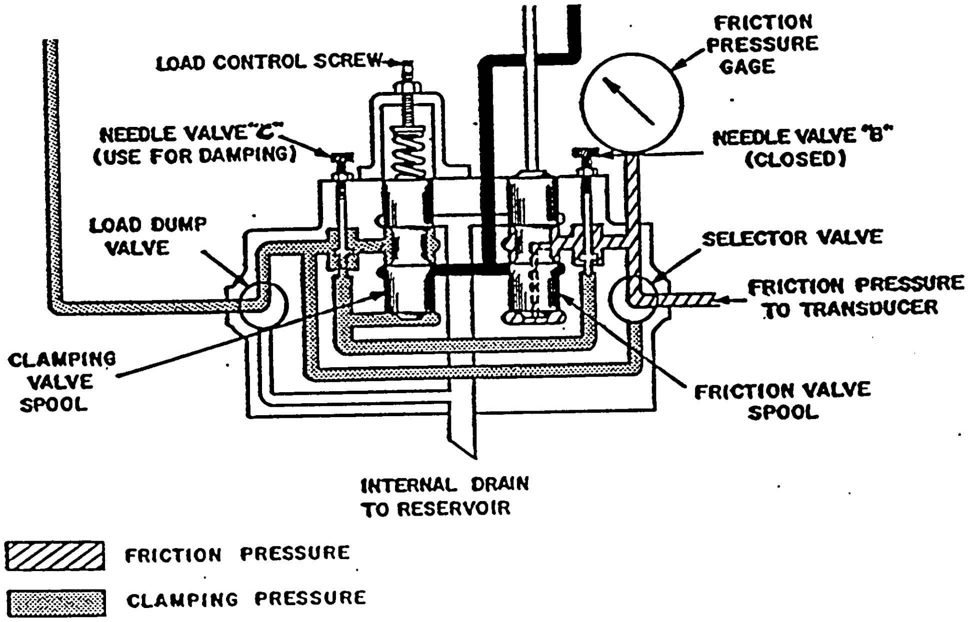


Figure 3.8 b Schematic diagram of F.A.S.T. machine in constant pressure test mode.

3.2.3. Lining Specimen.

The F.A.S.T. Machine allows two sizes of specimen to be used, one inch or half inch square, both sizes by 0.13 inches deep. Throughout the duration of the project and generally within the lining development industry the smaller sample size has been used, the larger size being primarily for clutch material testing. Using a hacksaw a slightly oversized sample is initially cut from standard friction linings taking care to stay a small distance from the lining edges (a few millimetres). It has been suggested that the specimen should only be cut from the very centre of the lining [84] although in the authors opinion the mix of the friction material is relatively homogeneous throughout and such a wasteful approach is unnecessary. Emery paper should not be used for shaping the sample as this may lead to contamination, indeed even leaving fingerprints on the active surface should be avoided. Once roughly cut the specimen is inserted into a specially designed vice which allows simple but accurate filling of the sample to exactly the desired size. Both before and after the test the sample is accurately weighed (to 0.001g) and measured with a micrometer.

3.2.4. Friction Disc.

Three types of disc were used throughout the investigation, standard cast iron F.A.S.T. discs, a copper coated cast iron disc and a copper coated aluminium disc.

All the cast iron F.A.S.T. discs have the same composition and microstructure being cast from automotive pearlitic brake drum cast iron (grade 17 cast iron BSS 1452). The table below indicates the typical percentage chemical composition of the discs, note that the titanium content is not specified as the importance of this addition was not known at the time of development.

Carbon	3.30 - 3.50
Manganese	0.60 - 0.90
Silicon	1.80 - 2.10
Sulphur	0.12 max.
Phosphorus	0.15 max.
Nickel	0.60 - 0.70
Chromium	0.15 - 0.25
Molybdenum	0.20 - 0.30

Table 3.3. F.A.S.T. disc chemical composition.

The disc has a diameter of 179.3mm and an initial thickness of around 38.1mm. Between tests all traces of the transfer film must be removed from the disc. In some cases this can be done using grit cloth although if this is not effective a surface grinding machine is used. Extreme care must be taken to ensure an absolute minimum of the surface is removed and that the upper and lower surfaces remain exactly parallel. Number 400 grit cloth is briefly held against the rotating disc before testing to give the surface an initial roughness. The surface is finally degreased with acetone soaked tissues to prevent contamination before beginning the test run.

Clearly with every grinding operation the disc will suffer an overall reduction in mass and hence heat capacity. With the F.A.S.T. machine operating in constant friction mode the accurate comparison of results depends upon the discs remaining the same. The instruction manual states that the disc must not be used once a thickness of 1.44 inches (36.6mm) has been reached and suggests that each surface may be ground six times. This represents about 0.75 millimetres removed from each face and an overall mass loss of around 2.5 %. With heat capacity being proportional to the amount of material it is unlikely that this small change will noticeably affect results. Due to the accuracy of the grinding equipment employed many more than twelve grinding operations were possible. However, the linings tested were generally low wearing, a heavily wearing or deeply scoring material will obviously reduce the number of times the disc surface can be properly cleaned.

For the copper coated discs grit cloth was generally used for cleaning the surface. It should be noted that the active abrasive of the cloth had to be the same type and size as that contained in the copper coating to prevent contamination. Surface grinding was not commonly used since the coating is relatively thin and any penetration would require the disc to be re-coated. Occasionally, when film removal by polishing proved difficult surface grinding was undertaken. Since the grinding machine table holds the sample by magnetic forces a flat steel base was manufactured and bolted securely to the aluminium disc in order to hold it stationary. The non-coated side of the disc was surface ground first to remove any disc thickness variations, had this not been done the coating thickness would have been ground unevenly across the sweep of the grinding machine.

Often surface cleaning was avoided and the film allowed to build up with progressive tests to investigate how the transfer film stabilises.

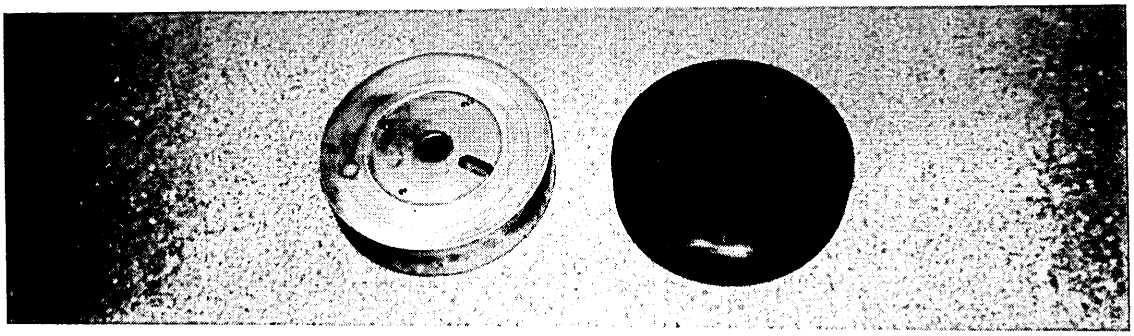


Figure 3.9. Photograph showing a standard disc and the copper coated aluminium disc.

3.2.5. Additions and Alterations to the F.A.S.T. Machine

Speed and temperature recording. Because constant pressure mode was frequently used where speed and temperature vary between tests the monitoring of these variables was thought essential. Temperature recording in particular was introduced to observe the different thermal behaviour of the aluminium disc compared to cast iron discs. For speed monitoring a tachometer generator was attached to the rear of the drive motor which produces an electrical voltage proportional to rotational speed. A copper-nickel thermocouple was used to measure the temperature of the disc. The tip of the thermocouple was electrically insulated and inserted into a pre drilled hole in the disc so that the bulk temperature would be measured. The hole was 1.5mm in diameter, 15mm deep and centrally positioned across the width of the discs outer edge. Despite the relatively simple thermocouple positioning, recording the induced voltage proved difficult as, due to the disc rotation, thermocouple wires could not be attached directly to the data logger. The temperature induced thermocouple voltage 'onboard' the rotating disc was transferred to the stationary data logger via a slip ring unit containing separate rotating contacts immersed in mercury.

Result Logging. The F.A.S.T. Machine initially came supplied with an XY plotter which operated only during the test. In order to upgrade the system a computer with data acquisition and processing packages was employed. The computer package *Work Bench* was used to acquire and store the data. In order to speed up and simplify the data transfer and plotting, and so as not to entirely fill the memory of the 286 computer, data values were collected every one tenth of a second and then averaged over sixty seconds. Thus 90 values were recorded for a one and a half hour run. Figure 3.10 shows the simple *work bench* program used.

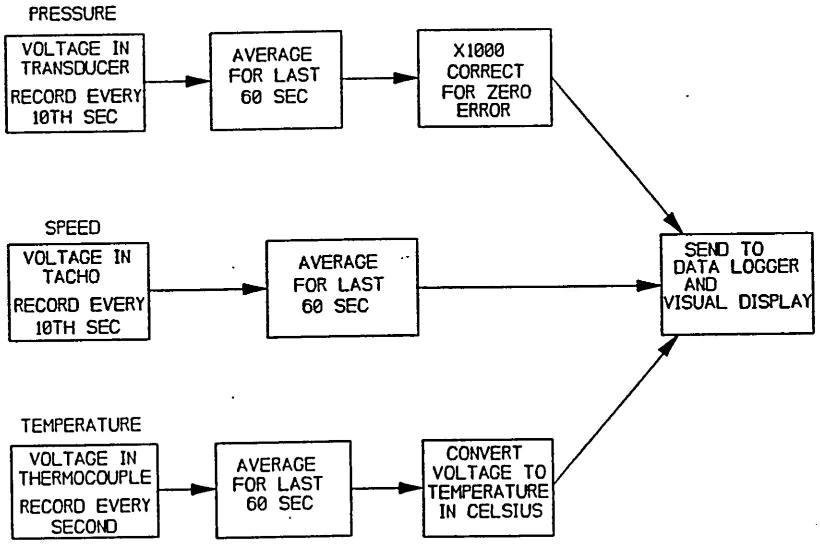


Figure 3.10. Work bench program for data acquisition.

The recorded results from all three variables, pressure, temperature and speed, are in the form of voltages. The voltage output from each device was initially calibrated and conversion factors established for presenting the data in a more meaningful form. To calibrate speed and pressure voltages the output was varied in small steps with the speed or pressure being monitored by accurate external measuring equipment. This allowed a plot of voltage against speed or pressure to be drawn. The computer package already incorporated specific conversions for thermocouple voltages. All three variables have been plotted on the same graph with the pressure curve also doubling as the friction coefficient when set against a different axis.

Stroboscopic illumination. It is difficult to be sure how the transfer film is acting whilst the disc is in motion. Is the film constantly being created and destroyed and does this vary with temperature, speed, pressure or disc or lining material? In order to make a start in the investigation of this matter a system was devised to optically view the disc surface whilst rotating. Stroboscopic illumination was used to effectively freeze the disc in motion. Since film changes were likely to be on a small scale a stereo microscope with a maximum magnification of ×80 was employed. Various clamps and fittings had to be manufactured to hold the microscope body firmly in the correct position. Setting the strobe frequency manually was not effective as, because of very slight variations in rotational speed, a different area was illuminated upon each revolution. To escape this problem a trigger mechanism was built and attached to the rotating motor shaft. The matter was further complicated by the need for high levels of illumination when examining a magnified surface, the existing strobe unit was simply too large to be placed near to the running surface. A remote strobe unit was designed but unfortunately due to expense and lack of time was not built. Thus, the surface was not as clear as it could have been although film changes were visible providing extremely interesting and potentially new information. Only at the higher magnifications could nothing be seen. It was frustrating in that given more time to develop the system the surface mechanisms could have been observed with much greater clarity and the understanding of transfer films taken a step further.

The illumination and magnification apparatus was designed to be used without affecting the running of the F.A.S.T. machine and measuring equipment in any way. Unfortunately at this stage results from this section of investigation cannot be displayed due to the prohibitively high cost of very high speed photography equipment and the required trigger and flash instruments.

In conjunction with stroboscopic analysis 'stop-start' tests were used for more thorough surface analysis. This simply involved stopping the test when desired and examining the surface. These tests were conducted entirely separate from the standard 90 minute runs due to cooling whilst the disc is stationary. Occasionally the surface was of enough interest to warrant ending the test completely and removing the disc from the machine for more detailed analysis.

Cooling and heating apparatus. In order to broaden the scope of investigation electrical fans were used to alter the temperature rise of the disc whilst running. When using this equipment the vastly increased air flow over the running surface will alter the temperature gradient between surface and thermocouple measuring point, this must be kept in mind when analysing results. Occasionally discs were preheated to investigate friction material behaviour at elevated temperatures. The preheating was done in a separate oven and the disc carefully transported to the machine laboratory. Alternatively, at the end of a test, the film on the disc surface is cleaned with emery paper rapidly before the disc cools down.

3.2.6 F.A.S.T. Machine Limitations.

Sample size. Of particular note is the relatively small size of the friction material sample and the corresponding tribocontact parameter. Also it must be observed that the friction material cannot be scaled down indefinitely, the size of the constituents remains fixed. Even with thorough mixing it is likely that there will be inhomogenities especially when large particles are included. Whether the wearing surface contains one or five or ten of these particles may have a drastic affect on the results. Wilson and Bowsher [83] suggested that the largest constituent of a lining material should be at least 100 times smaller than the sample mating surface. Considering the F.A.S.T. sample area is approximately 160mm^2 the constituent size should not exceed 1.6mm^2. Microscopic analysis of the friction composites used throughout the project indicated that all fibres, abrasives and metallic friction modifiers were below this figure but areas of resin and vermiculite came alarmingly close to the limit.

Disc runout. The F.A.S.T. machine handbook states that for a disc run-out of below 63 μm reliable results will be obtained, this being compatible with the flexible diaphragm load system. However a minimum of run-out should be strived for. Assuming each disc is exactly parallel the run-out is introduced either through non-true rotation of the motor shaft or an uneven disc mounting surface. Eight, equally radially spaced high density fibrous pads separate the disc from the hub, these serve both as the mounting surface and spacers to thermally separate the disc form the hub. With extreme care each pad in turn can be sanded with emery paper thus altering the mounting surface until a minimum of runout is achieved. In practice however the runout varied between every tightening procedure and run-outs below 10 μm were rarely achieved. Typically the run-out, measured with a dial gauge, was between 20 and 40 μm.

Pressure fluctuations. With high rotational speeds disc run-out results in friction pressure fluctuations with higher than expected pressures being registered as the peak run-out point passes the specimen and lower than expected pressures at trough run-outs. These fluctuations can be compared with the problem of D.T.V. For run-outs of around 20 μm the pressure fluctuations may be as much as ± 30% of the set pressure. The machine does have a fair degree of damping built into the system and, particularly in constant clamping mode, the fluctuating friction pressure appears relatively smooth at the pressure transducer. With computer averaging no fluctuations are visible in the final results. Large differences in pressure could lead to transfer film variations around the running track. Due to the sampling procedure (section 3.3.1) only one point of the disc surface could be analysed but the entire track was always checked with an optical microscope for any visible differences in the film (very few). Rapid fluctuations in speed and bulk temperature cannot occur due to the relatively large mass of the disc.

Pressure limitations. The maximum pressure the hydraulic motor can produce with any stability is around 140 to 150 psi. This affected the choice of test pressures as the reaction pin will not be able to maintain its equilibrium position at higher friction forces. In constant pressure mode a pressure of 40 psi will induce a friction pressure of 105 psi at a friction coefficient of 0.5. With pressure fluctuations the friction pressure may rise up towards the 140 psi mark and so 40 psi was chosen as the standard test pressure.

Comparison with full size testing. Recent work has indicated that the friction coefficient noted on the F.A.S.T. machine is between 0.05 and 0.1 greater than that observed during dynamometer bedding stops. Also if a friction material fades on the F.A.S.T. machine then it almost certainly will during full scale testing. However, although there are similarities this method of testing is generally used to draw comparisons between different lining materials and is not used to accurately predict performance.

3.2.7 Dynamometer and On-vehicle Testing.

Throughout the development of the copper coating and suitable friction lining, part of the testing has been conducted on both dynamometers and specially equipped road-going vehicles. Although the author has not been directly involved, many of the worn components were forwarded to Sheffield Hallam University for examination. Much of the test equipment was capable of monitoring friction coefficient, temperature, vibration and other variables. This information along with the tested components proved extremely useful in forwarding the development of suitable lining materials to be coupled with the copper coating. Other testing was conducted on non-adapted vehicles with no means of monitoring equipment, the performance of the friction couple was simply assessed by the driver.

3.3 Surface Analysis

The analysis of the friction components has been conducted employing extensive optical and electron microprobe techniques. For optical analysis using various stereo microscopes no sample preparation was required and so this equipment was used extensively. However, with limited means of recording the observed data samples of the worn surfaces were transferred to the electron microscope for photography.

3.3.1. Sample Preparation.

The limited size of the specimen chamber inside the scanning electron microscope dictates that only sections of the disc could be inserted for analysis. Generally this would render the sectioned disc unusable for further testing, this clearly being an expensive and wasteful approach. A removable 'plug', designed and manufactured by the author, has been introduced into all of the F.A.S.T. discs. A simple diagram of this is shown in figure 3.11 below.

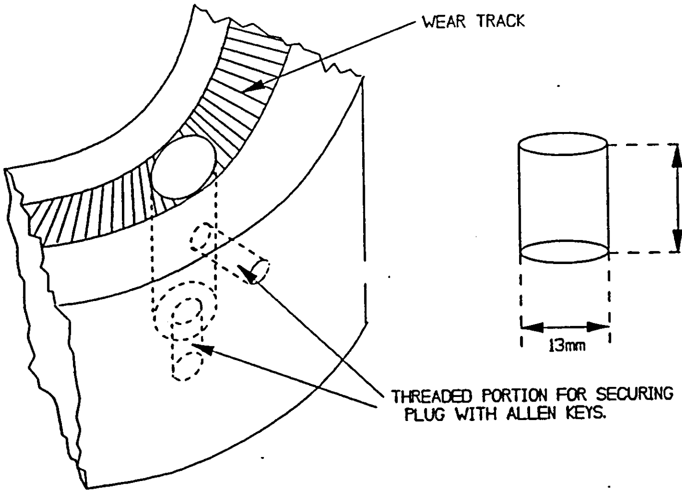


Figure. 3.11 Diagram of the removable plug and position in disc.

The plug is easily removed from the disc after testing and, after cooling, can be placed directly into the vacuum chamber of the electron microscope. In the case of the cast iron discs new plugs were turned on a lathe from the same grade 17 cast iron bar. The bar was turned with a marginal taper such that an interference fit was made between the top of the plug and the drilled hole in the disc. The plug was then secured with the Allen keys. Care was taken to ensure a small amount of the plug stood proud over the disc surface (typically 0.5mm). The disc was then placed on a surface grinder and a minimum amount of material removed from the whole surface as described earlier. For the copper coated discs pre-coated plugs were provided by Plasma Coatings Ltd which were pushed into the hole and secured with Allen keys. The disc was then transferred to the grinder and the new plug made flush with the disc running surface.

Generally no further preparation of the disc plug was required, the conductive nature of the sample being an added bonus for electron beam analysis. In the case of very thick deposition layers on the plug especially those low in iron, some charging of the sample was observed although this was uncommon. Many of the friction materials however were prone to charging as by their nature they are primarily insulating. Some of the materials contained negligible metallic content and the viewed surface rapidly charged making analysis impossible. In these cases the friction material surfaces were carbon coated. No other preparation of the friction material was required with the sample already being small in size.

3.3.2 Analysis Techniques.

Many techniques have been used to examine the worn surfaces of friction couples including Infrared Spectrophotometry, X-ray Diffraction, X-ray Fluorescence and Emission Spectroscopy [51]. The majority of the analysis to date has been conducted utilising Electron Microprobe Analysis techniques. The electron probe MicroAnalyser is well suited to the study of thin surface films as, in addition to affording a magnified view of the surface, information regarding the chemical composition of the film can be gathered. This information is provided by collecting characteristic X-rays emitted from the transfer film. More recently X-ray Photo-electron spectroscopy has been used in the study of transfer films [53, 54]. The table below shows the relative merits of each technique.

Optical Microscopy.	Visual evidence of material transfer and rapid assessment of wearing mechanisms.
Energy Dispersive X-ray Analysis	Elemental analysis and distribution from bulk of transfer film.
X-ray photo-electron spectroscopy.	Chemical state information from uppermost layers of transfer films.

Table 3.4. Techniques used for transfer film analysis.

For a detailed explanation of the scanning electron microscope the reader is referred to the chapter in appendix 1 or the many available reference books [90].

3.3.3 Analysis of Transfer films.

The nature of the transfer film formed on the disc surface depends largely on the friction material. Many of the transfer films have a 'patchy' appearance which may vary considerably in size and may or may not be distributed in bands, this being partially dependant on the wear mechanisms of the lining material. Alternatively films have been observed to almost entirely cover the disc running surface or in contrast, first impressions may indicate a surface devoid of film. For the majority of the materials tested on the F.A.S.T. Machine the transfer film produced was of a patchy appearance. These may be all of the same composition or in some cases may be very different.

Initially the areas of transferred material or 'deposition' can be highlighted using backscattered electron techniques which display a line-scan image on the monitor. Most of the transferred materials for example magnesium, silicon, and sulphur from the lining material have lower atomic numbers than the disc material, be it iron or copper, and thus darker areas of the backscattered image show areas of deposition. In addition preferentially ploughed sections of film by abrasive action will show up bright where disc material is exposed. When interpreting backscattered images penetration effects must be considered as well as the penetration of different materials. Very often the backscattered image will not be simply light and dark but varying shades. This may be a result of different film thicknesses or different film materials, this being complicated further by different materials having different penetration depths as shown in figure 3.12.

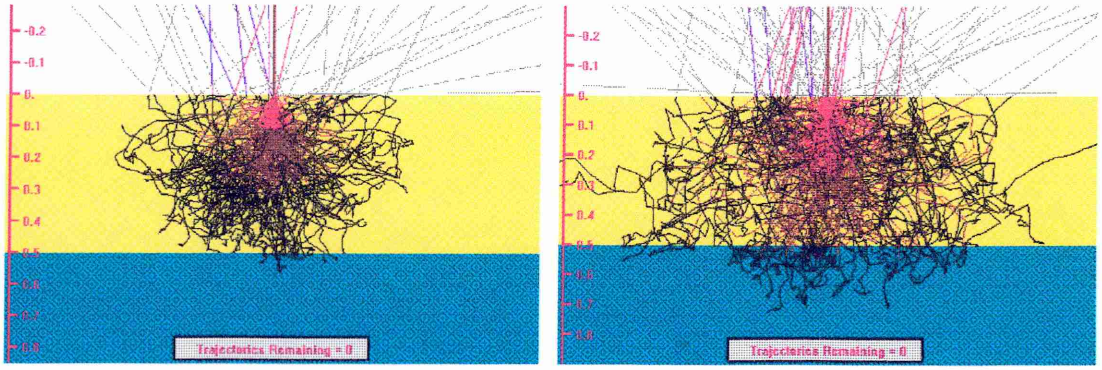


Figure 3.12. Montecarlo simulations of 10 keV beam into Fe_2O_3 (left) and barium (right) films on iron substrate.

These techniques especially combined with optical microscopy provide valuable information on the distribution of the transfer film. Additionally, clues to the wear mechanism can be seen from grooves indicating abrasion or plucked sections suggesting some element of adhesion.

Once areas of interest have been pinpointed they can then be analysed specifically for elemental data. Thus by focusing the electron beam the elements present in individual sections of film can be identified. Problems can arise when penetration of the film occurs such that some of the emitted X-rays are from the underlying disc. If the film thickness is unknown then it is difficult to be sure if the observed copper or iron signals are from the disc or film alone. Montecarlo simulations were performed on a range of possible film materials showing that penetration would rarely exceed one micron when a beam energy of 10 keV was used. Cross-sectional analysis indicated that if a beam of this energy was employed in many cases the film was thick enough to avoid penetration. Hence a beam energy of 10 keV has been used throughout the project unless otherwise stated. This ensures relatively low penetration as well as providing enough X-ray information. Similarly, even if the film is not penetrated there may be differences in the film across its thickness which will not be clear. It has been shown by X.P.S. techniques that the actual contacting surface of the film may be different to the bulk material. Cross-sections of the film also often show a layering affect which may give misleading results.

For many of the films analysed the elemental composition of the patches or bands is similar, clearly the film has been formed from some elements from the pad and perhaps some from the disc by the same mechanisms. However, it is rare for each analysed spot to be identical and as such the methods of calculating 'exact' element composition have been avoided (instrument corrections and use of Z.A.F. techniques). At this stage an estimate of the elemental composition of the films has been calculated by comparing the X-ray signal from the film with that produced by the friction materials themselves. Since the composition of many of the films is similar to the actual pad composition it was felt that the pad itself was a suitable standard. Many individual spectra were taken from the pad material in order to arrive at an 'average' spectra and then, using the known elemental composition of the lining material, efficiency factors for each element were calculated. This allowed an estimate of film composition to be obtained from the film spectra. Of course this method was only possible when the composition of the lining material was known. Comparison of the authors results with those obtained using more sophisticated techniques and a far more advanced microscope (Axis 165 Multi Technique Surface Analysis Instrument) indicated an encouraging similarity.

In addition to spot analysis of the films, X-ray mapping techniques have been used to show distribution. The X-ray map is produced for a chosen area and indicates where individual elements are in high or low concentrations. It should be stressed that the mapping techniques are used for distribution highlighting alone and have not been used to provide any quantitative data. For individual elements the contrast between areas of high and low concentration has been increased for more clear display.

From all of the work covered on the analysis of transfer films it is clear that the film is a very complex layer. The very nature of the friction material, being multi component, means that what the disc 'sees' of the friction material may be quite different across the rubbing track. This is particularly true in the case of the F.A.S.T. machine where the lining sample is much smaller than a real size pad. As such there may be variations in the film that are difficult to explain. Additionally the surface analysed is only that which existed the moment the test was halted. The film may have been viscous during running or formed during the initial part of the test and remained exactly the same. Also due to the temperatures involved, oxidation of the film and in particular any exposed disc will continue after the test stops.

One of the major limitations of the microprobe analysis techniques is the lack of data on the compounds within the sample. Oxygen and iron may clearly be in the film but it is very difficult to be sure which oxides are present. Data of this type can be obtained using X-ray photoelectron spectroscopy, which in addition to providing chemical information is also extremely surface sensitive, providing information from only the top few monolayers. Information from within the film can be obtained by permanently removing some of the surface by ion bombardment or 'sputtering'. Instead of a focused electron beam the sample is exposed to a flux of near monoenergetic X-rays which results in the emission of photoelectrons from the surface of the sample. Emitted photoelectrons are energy analysed and this kinetic energy is plotted against intensity. The position of peaks in the plot are characteristic of elements of the sample surface. From slight shifts in the peak energies chemical information can be obtained. A limited amount of information has been collected using this technique although has not been presented in this work. Although time consuming, when combined with microprobe analysis this technique is likely to provide much information on the actual chemical state of the elements within the film.

When attempting to explain performance and wear characteristics all variable factors occurring at the interface were considered including in particular the wear mechanism. Changes in performance were only attributed to chemical differences after considerable analysis involving many points from over the entire sample.

4.0 Results and Discussion.

The testing and analysis covered in this present section of work can be suitably divided into three sections-

- Specially designed test materials coupled with cast iron.
- Test materials and developed materials coupled with the HIPAC coating.
- Analysis of industry tested HIPAC coated disc / pad pairs.

During the course of the research programme a huge amount of data has been collected, far too much to include in this report. The data presented here is thought to be the minimum needed to explain and give evidence to the conclusions suggested by the author.

When investigating friction couples there are a huge number of related phenomena which must be considered in order to fully understand automotive braking. However, to gain a complete understanding of braking is clearly a lifelong quest. This section of work has remained focused on transfer films and interface mechanisms and how these affect friction performance. As with much of the published literature the research has centred around a small number of lining materials under specific test conditions.

Some areas of work have been touched on only briefly, one area in particular being the friction performance observed during the early stages of pressure application. For some materials the initial performance was high but rapidly dropped to reach a minimum before rising again. This has been attributed to the initial roughness of the disc and pad which is rapidly worn.

Speed sensitivity was not considered at all and, although the affects of different brake pressures were briefly explored, the results have not been included. Wear rates of the friction couples have also been mentioned only briefly. This is partly due to the very low disc wear. Equipment accurate enough to detect the mass difference over a single test was not made available to the author.

4.1 Friction Materials coupled with Cast Iron.

Three friction materials known as 1/41, 1/43 and 1/45 were designed and mixed by B.B.A. Friction Ltd. The materials are fairly simple with a minimum number of components in order to highlight the affect of abrasive additions and to simplify the analysis. The only difference between the three materials is the fibres as shown below. Each material was also prepared with no abrasive addition (known as the base material) for comparison purposes. The composition of the materials by volume is as follows-

• Resin (p41)	40%
• Barytes	26%
• Vermiculite	20%
• Molybdenum disulphide	2%
• Copper powder	5%
• Fibres	5%
• Abrasives	2%

Material 1/41 - Steel fibres
Material 1/43 - Kevlar fibres
Material 1/45 - Stainless steel fibres

Abrasives - Fused Alumina in a size range donated-

1200 - 2-4 μm
800 - 8-10 μm
500 - 20-25 μm

Also tested was the addition of 20 μm diameter chromic oxide abrasive, this being in two different shapes, angular and spheroidal. The version of material 1/43 containing chromic oxide abrasive was denoted material 1/44. However, the majority of the testing and analysis was concentrated on the alumina abrasives.

The elemental content of the materials (by weight) is listed in appendix 2.

4.1.1 Materials 1/41 and 1/45.

These materials can be described together as there were only subtle differences in both the performance and surface analysis. This was expected considering the only difference in the two is the type of steel fibre. The similarities in the worn surfaces are shown in appendix 2 (figure A2.5). In a more corrosive environment over long time periods the stainless fibres may well indicate useful advantages.

The complete test traces including disc temperature and speed are shown in appendix 2. As can be seen from the performance traces for material 1/41 below (figure 4.1.1) the coefficient for the base material was initially fairly low at around 0.3 but steadily climbed to around 0.4 where it remained relatively stable for the duration of the test. The addition of abrasives of all sizes induced a much higher initial coefficient, typically around 0.48. This is as expected with the performance increasing with increasing ploughing action as reported by Crosia [26]. Then, as the test progressed, the performance fell considerably, particularly with the large abrasives. Following this some recovery was made with the friction coefficient towards the end of the test being similar to the base material

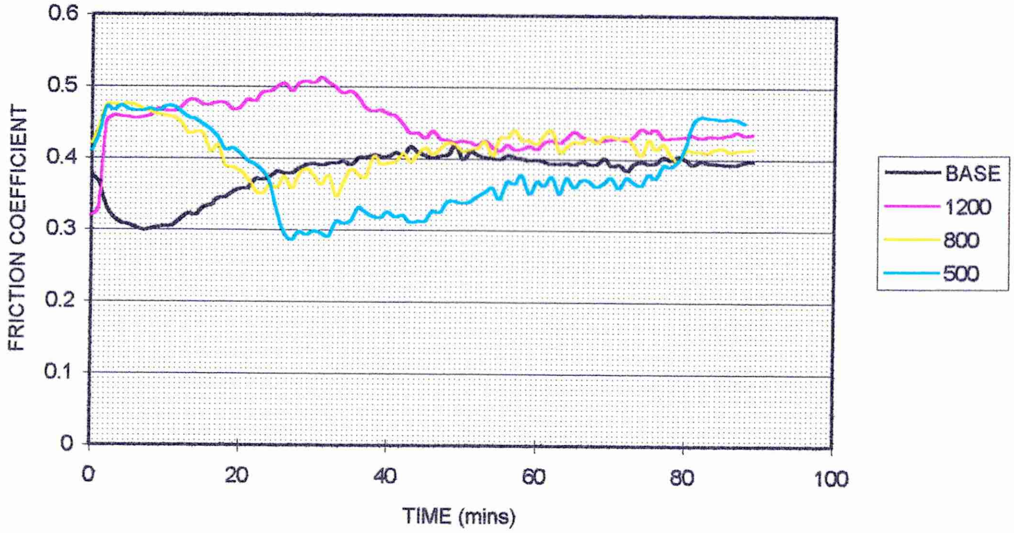


Figure 4.1.1 Friction coefficient variation with various abrasive sizes in material 1/41.

Stop-start tests indicated that during the early stages of testing the abrasive materials were inducing adhesive wear on the disc surface as well as abrasive scoring. There were many 'chipped holes' in the iron surface with wear scars originating at them and continuing in the direction of rotation. These scars will be partly from the removed metal being scratched over the surface. (See figure 4.1.2. overleaf.)

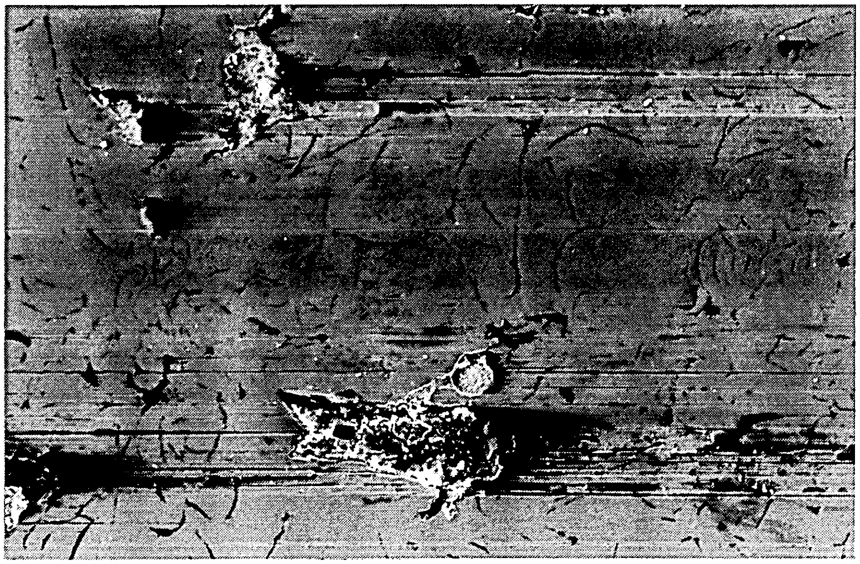


Figure 4.1.2. Chipped holes and wear scars on disc surface.

Occasionally a flake of metal, no doubt from the steel fibres, was seen adhered to the cast iron although this was quickly removed. This is probably the cause of the surface chipping shown above. Debris was noted to be collecting in the holes and then, once hardened or grown to a certain point, also be pulled out or torn away. With all abrasive sizes there was very little film noted on the disc, any seen by stroboscopic analysis to start forming was quickly abraded away. The amount of scoring appeared to increase with increasing abrasive size although it is more likely that the larger abrasives produced more visible grooves. The performance traces for all abrasive sizes were similar at the start of the test indicating that larger abrasives and thus deeper ploughing is not responsible for higher friction (this being in contrast to that reported by Crosia [26]). Since the abrasive concentration is fixed, the overall amount of ploughing may be similar Alternatively it may not be the ploughing affect of abrasives that is dictating performance. The mechanism of abrasive wear is likely to be microcutting.

In contrast to the abrasive materials the base mix suffered much less adhesive 'plucking' and within a few minutes there was evidence of some transfer film. The low levels of scoring on the surface was probably from the steel fibres. It appears that the high friction levels with the abrasive materials during the early stages of testing are due to the action of both adhesive mechanisms and abrasive ploughing by abrasives, fibres and removed or adhered debris. In the absence of abrasives it is likely that a film is formed quickly on both the disc and fibres in the pad reducing adhesive wear.

For all lining materials a thick film was noted on the disc at the end of the test. For the base material this formed relatively quickly with stable coverage after around 35 minutes which remained similar for the remainder of the test. For the abrasive linings the film took longer to form. At a certain point depending on both temperature and fatigue of the lining the adhesive strength between disc and pad material will be greater than the cohesive bonds within the pad resulting in transfer. As seen from the performance traces the friction coefficient for the base material stabilised at around 0.4. In the absence of abrasives this friction level is probably the result of adhesive mechanisms occurring within the film, interlocking with the rough thick film and ploughing of harder components on the couple surfaces (for example the fibres) through the softer film. This would explain the increase in performance as the film grows and the eventual stabilisation. Additionally the performance may rise partly due to the increasing adhesive strength of the lining material with increasing temperature.

The first stages of transfer film formation with both the base material and abrasive linings appears to be the formation of a dark 'glaze' on the cast iron. Following this the film thickens and forms a characteristic patchy appearance and a 'matt' grey colour when viewed optically as shown in figure 4.1.3 and in the micrographs in appendix 2. The top surface of the thick film appears to be constantly flaking off in tiny pieces, this gives the patchy appearance. The matt appearance is due to the rough, unworn surface remaining after a flake of glaze has been removed. Sometimes the removed flakes expose the oxidised iron disc. This is shown by lighter patches on the back-scattered images of figures A2.5 and A2.6 in appendix 2.

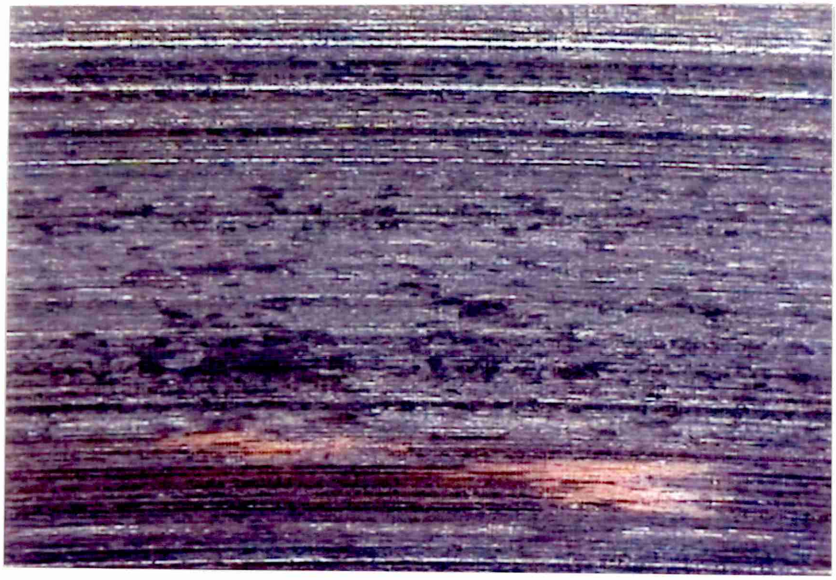


Figure 4.1.3.
Optical photograph
of disc surface.
1/41 + 500 alumina
90 mins x50.

Cross-sectional analysis shown overleaf (figure 4.1.4) and in appendix 2 (figure A2.7) indicates the film to be upwards of 3 or 4 μm thick. Within the early stages of the test when the glaze is relatively thin, bands of film are often removed completely and re-grow in different places but as the film thickens they remained fairly static. When scratched with a scalpel the thick film comes away relatively easily but a glaze remains on the disc which is much more resilient. The thin glaze cannot be seen in cross-section and when analysed appears to be made up of iron oxide with traces of transfer elements.

Figure 4.1.4 Cross-section of film formed with material 1/41 + 1200 alumina.

Where there is little 'thick' film on the disc, patches of deposition of a similar nature and elemental content can be seen on the lining surface. These flakes, often greater than a millimetre across, cover many different components in the pad and are probably formed in a similar way to metalisation. This suggests that there is a film between disc and pad for the majority of the contacting area such that the friction performance will be dictated by this layer. Often the flakes are only very loosely attached or appear to be fractured as shown below in figure 4.1.5. Softer sections of the lining material will offer little support to the flakes. The harder components of the lining for example the steel fibres and copper powder are generally film covered.

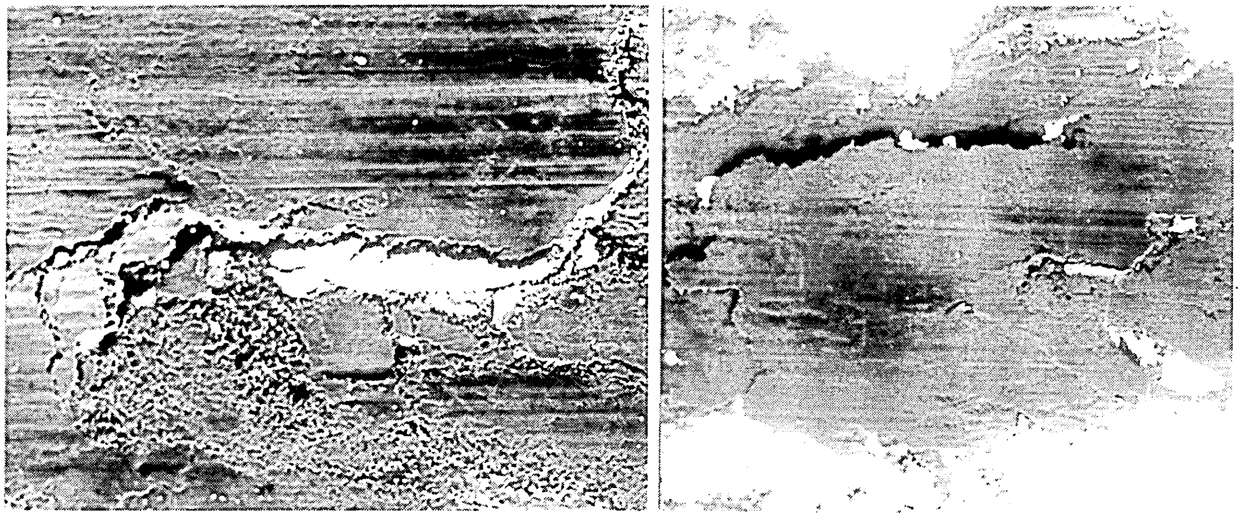


Figure 4.1.5. Flakes of deposition on the surface of material 1/41.

Clearly there is a question as to why the friction level falls with the abrasive inclusions. The fade may be the result of a low friction coefficient oxide film. This is under investigation by Wirth *et al* [87]. High asperity temperatures encourage the formation of a complex iron oxide by reaction and reduction of the iron with the lining components. Because the asperity and interface temperature will increase with abrasive size the oxide will form and performance fall earlier with the largest abrasive. As the performance began to drop a film was observed as shown below (figure 4.1.6.). Initially the film was in occasional isolated bands, then gradually the film thickened in a similar manner to the base material as the performance began to slowly recover.

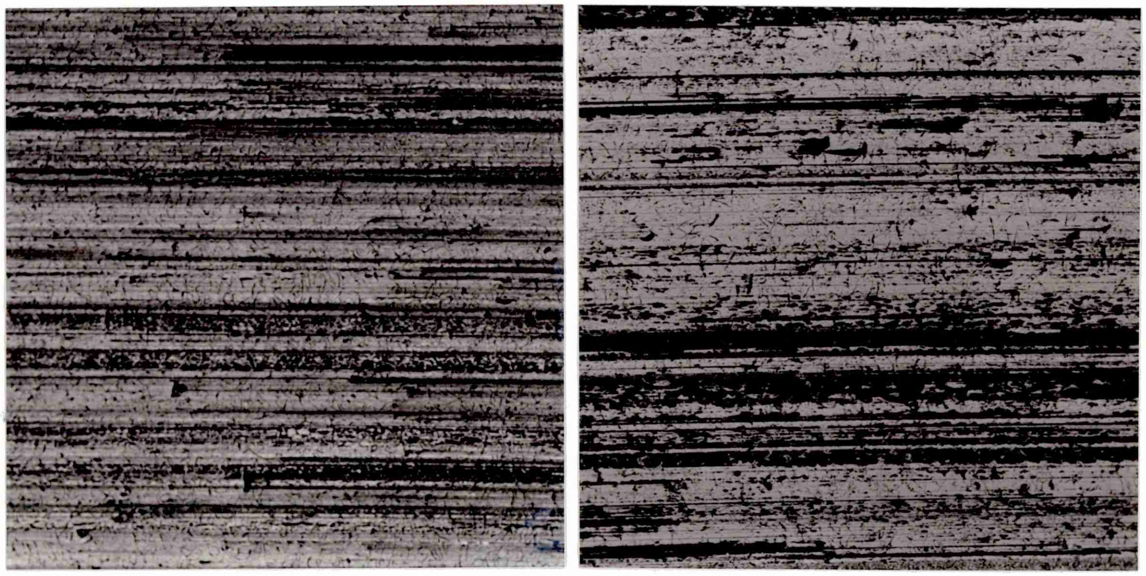


Figure 4.1.6. Disc surface with 1/41 + 1200 alumina after 35 mins. (left) and 45 mins. (right).

This development of film is likely to be at least partially dependant on temperature. High temperature start tests with 1/41 + 1200 alumina and the disc bulk temperature around 200°C showed the friction coefficient to be initially high but immediately fall with a corresponding transfer of material. After only a few minutes the film was much thickened and covered the majority of the wear track. With the base material a film was rapidly formed with friction levels quickly reaching those observed as stable in the standard tests. Clearly temperature effects the film formation. Abrasive particles are likely to raise the interface temperature further suggesting an earlier transfer of material than with the base mix. However, as discussed earlier, the nature of the abrasives inhibits film formation.

It is likely that there is a combination of affects, the abrasives begin to lose their effectiveness and the film becomes more adherent as the temperature increases. Also the disc surface may change with oxide formation altering the friction performance and adhesive nature. Evidence of this 'cross-over' point was seen using stroboscopic illumination. Initially the bands of deposition were seen to be constantly forming and then being destroyed, this occurring on a time scale such that the bands appeared to be slowly moving. Gradually the bands became more static and acted as catalysts for further deposition. The abrasive nature of the pad may reduce with increasing temperature as the pad softens and the abrasives and trapped debris are squeezed inwards as opposed to protruding from the surface.

Once the performance has fallen it then tends towards that of the base material as the transfer film thickens and contact between the pad and the oxide layer is reduced. Hence, as with the base material, it is the thick film that dictates the friction coefficient. As would be expected the coefficient is slightly higher than with the base material due to the abrasives within both the pad and film. This considerable increase in film thickness is likely to much reduce the affects of three body abrasive wear as all the smaller abrasives will be contained within the film. Additionally the ploughing action of abrasives will no doubt be reduced in the softer film material compared to the cast iron. Although there is obviously some abrasive action on the disc surface as shown in the micrographs of appendix 2 (A2.5 and A2.6) it is clear that the cast iron disc surface is rarely exposed.

Testing with material 1/41 containing chromic oxide abrasive demonstrated similar results as with the large (500) alumina. There was no obvious difference in the test results between the angular and spheroidal shaped abrasives. However, although a thick film was formed it had a different appearance to that formed with the alumina abrasive, the disc surface being much more scored (figure A2.6 of appendix 2). This has been attributed to the chromic oxide abrasives cutting through the film surface. Once the abrasive has cut a path in the film there will be little resistance assuming the abrasive retains its position. The contribution to performance from the actual transfer film looks to be relatively low due to the few contact points. This is also clearly shown in the micrographs of appendix 2.

Why the alumina and chromic oxide should act differently on the transfer film is unknown. One suggestion for the lower level of scoring by the large alumina is that it is more easily fractured into smaller particles. There were indeed many similarities between the film surfaces formed with all alumina abrasives adding weight to this. Additionally, unlike the chromic oxide, large alumina abrasives were never observed at the contacting surface of the lining.

Consecutive tests with 1200 alumina (disc and pad cooled to room temperature) showed that the thick film was removed during the first minute or so, this probably being the work of protruding abrasives and steel fibres. However, the underlying and more resilient glaze appeared to be retained and probably dictates the friction performance. The retention of the glaze prevented contact between the fibres and the cast iron. The friction performance, as indicated in figure 4.1.7, was relatively stable throughout the consecutive tests.

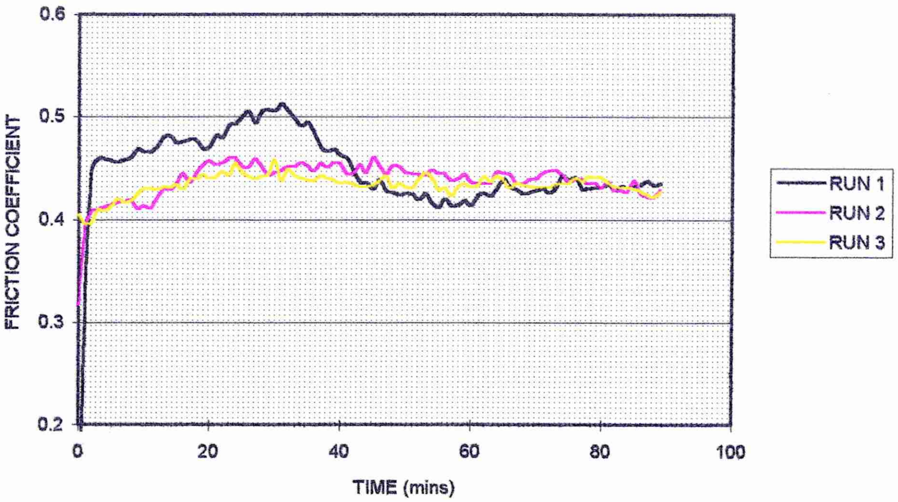


Figure 4.1.7. Consecutive testing of 1/41 + 1200 alumina abrasive.

Consecutive testing with 500 alumina caused the complete removal of all traces of film, this being the work of the abrasives. As a result the friction performance followed a similar pattern to the first test. With the base material there is some removal of the thick film but the film then grows to even thicker levels (up to around 10μm), forming a cracked and patchy glaze over the majority of the surface. This is shown in figure 4.1.8.

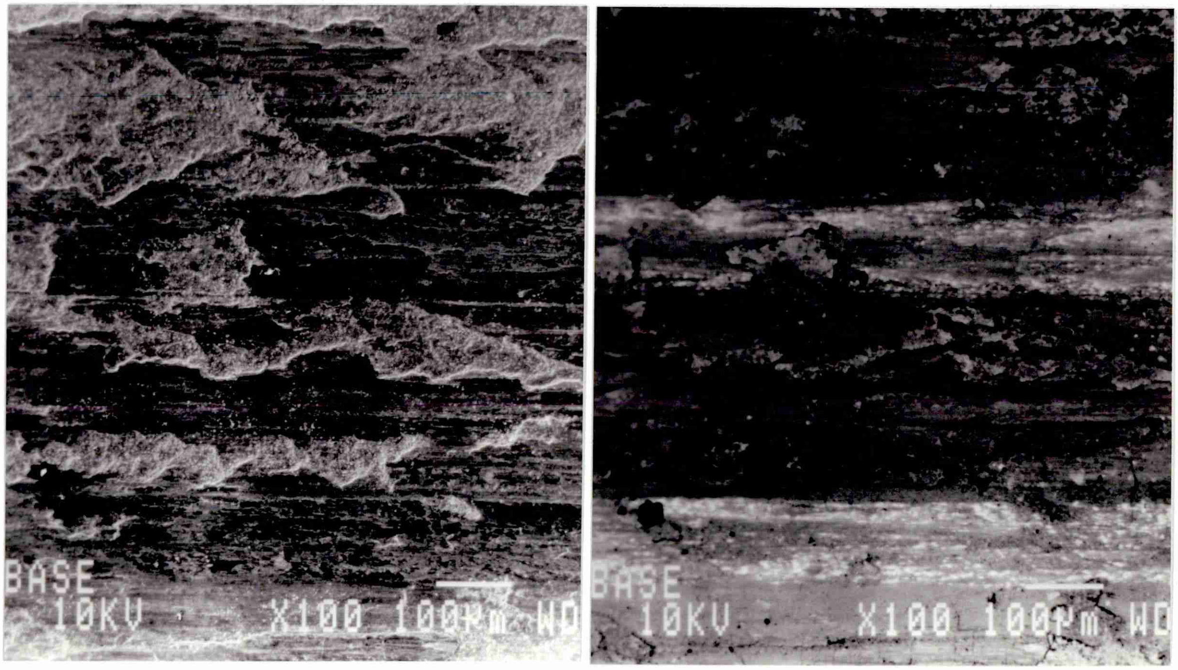


Figure 4.1.8. Secondary and back-scattered images of disc surface ran with base material 1/41. Third consecutive run. 10kV.

With a reduced conductivity on the disc surface the interface temperatures will be increased affecting both the wear and performance of the lining. Once a critical thickness is reached it will break away, this being a major cause of severe lining wear. It appears that the abrasive size is important for both friction stability and film control with repeated braking. For the samples tested the smallest abrasive had the better overall performance once bedded in. Disc clean up occurred upon brake application but a transfer film was retained exhibiting relatively stable friction. It may be that with higher braking pressures thick film formation will be controlled to a greater degree.

Analysis of the Transfer Film.

Cross-sectional analysis of the thick transfer film using E.D.X. techniques indicated the film to have no obvious structure and to be primarily made up of a homogeneous material (figure A2.7, appendix 2). Occasionally spots of iron debris and copper patches were noted in the cross-section but nothing else. However, surface analysis has shown that the film does contain other debris for example abrasive alumina but the chances of finding these in cross section are small. The composition of the film across the worn surface appeared to vary slightly in content for most elements. This however usually followed specific patterns, for example certain patches may have higher levels of barium and sulphur from barytes, and others higher levels of silicon, magnesium and aluminium form vermiculite. This highlights the difficulty of analysing transfer films, the multi-component nature of the lining means that the deposited film on the disc may vary in composition over a distance of just a few microns. If the analyst is not thorough then completely incorrect conclusions can be drawn regarding film composition and related friction performance.

There was no obvious difference in the film content between the tested samples based on 1/41 and 1/45.

Using the elemental break-down of the lining materials (figure A2.1, appendix 2) an estimate of the film content was made, the results of which are shown in figure 4.1.9. This represents an averaging process using many analysed film patches from a specific disc surface.

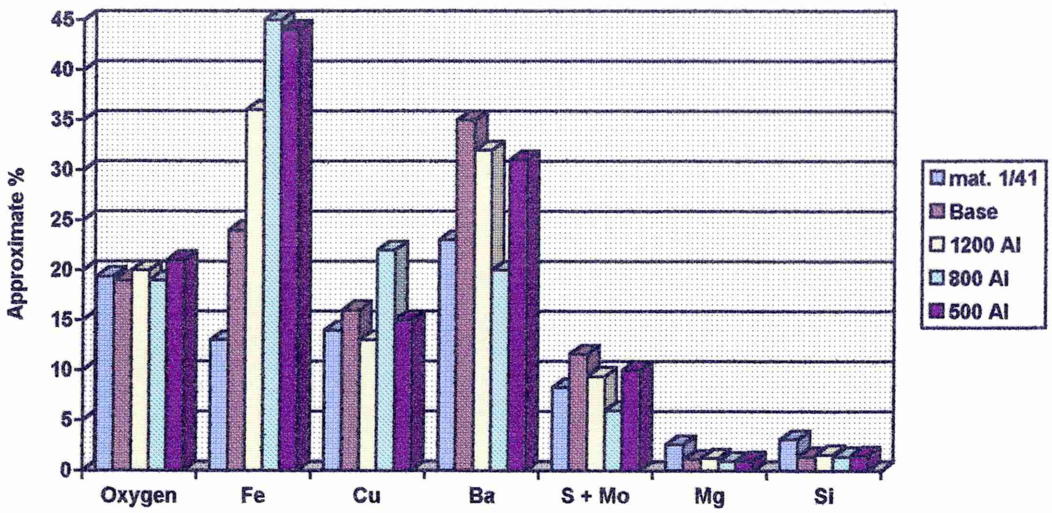


Figure 4.1.9. Estimate of film composition.

The film appears to be made up of most of the materials in the lining and is probably formed from ground material which is then compacted. Barytes and vermiculite are both contained and are likely to remain in their original form given the relatively low temperatures of the test and the stability of these materials. The retention of barytes in the film has been observed by various authors [46] and may well act as a 'binding agent' for the film material. The molybdenum disulphide lubricant is likely to have decomposed as suggested by Wirth et al [54].

Copper was the only material to vary notably in concentration within the film and variations in concentration can clearly be seen in the cross-section maps. It is likely that the copper smeared randomly from the pad onto the disc or into the film.

Iron is the major contributor to the film material originating in both the disc and the lining fibres. The majority of the iron appears to be distributed homogeneously throughout the film and will be tiny particles of oxidised wear debris. It is unlikely that much of the detected iron is from the 'substrate' as the film is generally to thick for beam penetration. The iron content within the film appears to vary with abrasive size and is the lowest with the base material. This correlates with the expected amount of abrasive wear.

Carbon was not clearly detected within the film. This has been observed with many lining materials both experimental and commercial. The carbon resin is likely to have broken down at the interface into a very thin char layer and been lost as debris.

Figure 4.1.10 below shows a typical spectra taken from a patch of film on the disc surface coupled with 1/41 with 500 alumina abrasive. Spectra from all discs indicated similarities with this example.

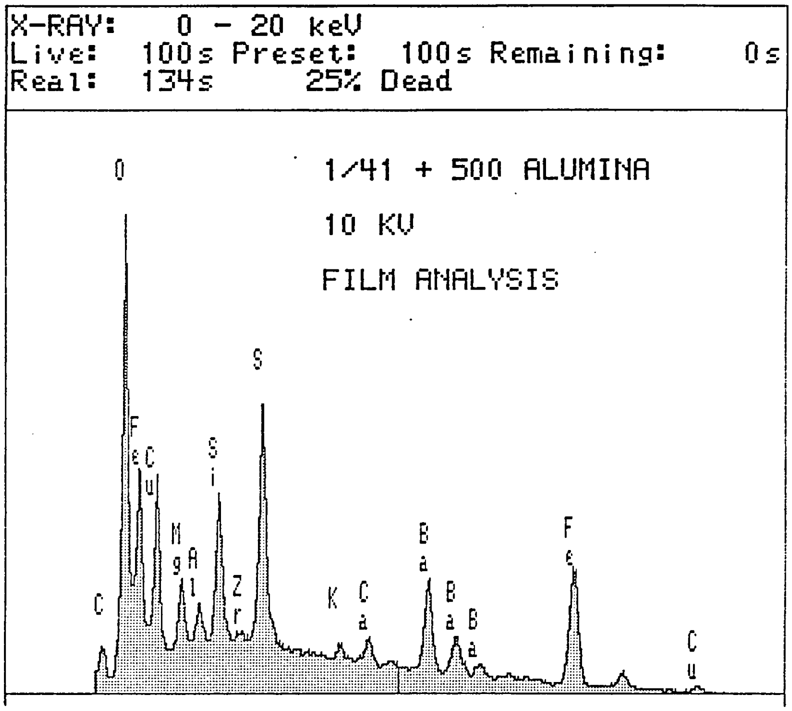


Figure 4.1.10. Typical spectra from disc surface.

Analysis of the glaze formed during the early stages of testing indicated the film to be made up of primarily iron and oxygen. Other pad elements were present although only in small amounts. Part of the iron trace will probably originate in the substrate although reducing the accelerating voltage considerably (and hence the beam penetration) still indicated iron to be by far the dominant element. It is likely that this film is mainly the oxidised iron surface with some transferred elements. Oxidation of the iron will occur due to thermal affects in the very early stages of the test. Much more meaningful results have been collected using X.P.S. techniques [87]. The thicker, adhered and compacted but weaker debris forms on top of this layer.

4.1.2 Material 1/43.

The only difference between this material and the two previously tested was the fibre content, the fibres being kevlar as opposed to steel. This however made some difference to the film coverage and performance as shown below.

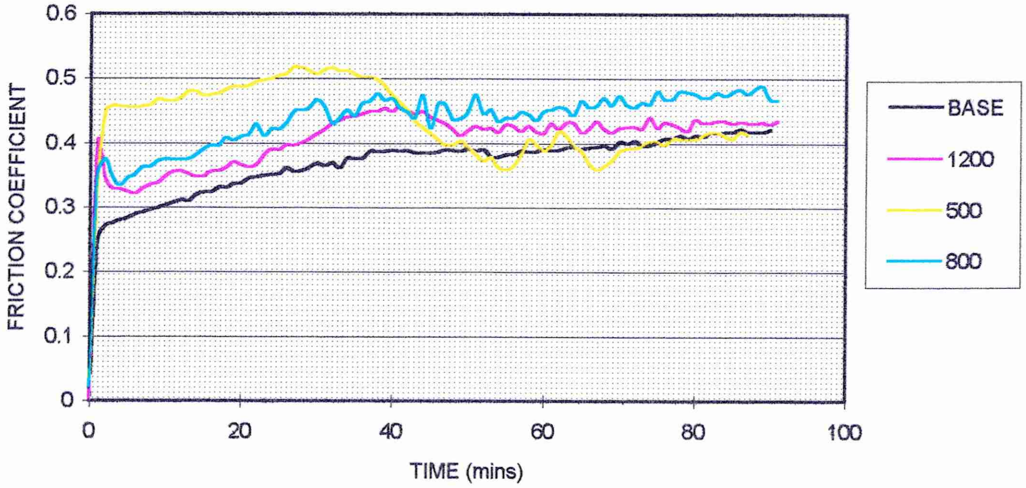


Figure 4.1.11. Friction coefficient variation with different abrasive sizes.

For the base, 1200 and 800 abrasive size linings the friction coefficient was initially relatively low but steadily climbed during the test becoming more stable. As the abrasive size increased so did the performance. The large abrasive size however, had a high initial performance which dropped dramatically part way through the test. Erratic friction followed with some stabilisation towards the end of the test. The full test traces are shown in appendix 2 (figure A2.4).

With the base material a faint film was evident after 5 minutes or so which gradually but steadily thickened. There was little evidence of surface scoring but just some polishing of the iron. Interestingly the friction levels are similar as for the steel fibre base material indicating that it is not the fibres but other components of the material combined with the transfer film that are dictating performance. Also the thick film forms in a similar manner suggesting that abrasive action of steel fibres is not the explanation for the slow build up. The micrographs in appendix 2 (figures A2.8 - A2.12) indicate the nature and extent of the film coverage.

For the abrasive materials stop-start and stroboscopic analysis of the surface as the tests progressed showed that, as with the steel fibre materials, a film was slow to appear but towards the end of the test had thickened considerably. There was however, no signs of adhesive plucking on the disc surface which may explain the lower initial friction levels. It appears that the base 1/43 material running against the disc or transfer film dictates performance with the extra ploughing effect of the abrasives superimposed upon this. As the abrasive size increases, so does the friction level, this being in contrast to that observed with 1/41. From this it may be deduced that in the early stages of testing with 1/41 the friction performance was increased by the steel fibres in contact with the cast iron.

As with material 1/41, the drop in performance has been attributed to the formation of a complex iron oxide at the interface. With 1/41 however, all sizes of abrasive caused fading, with 1/43 this only occurred with the largest. Since temperature is likely to be of primary importance is was assumed that the extra scoring from the steel fibres would induce a higher interface temperature. With material 1/43 the performance drop occurred later in the test adding weight to this theory. With the smaller abrasives the oxide may not be formed at all. A very similar affect was noted when the alumina was replaced by the large angular or spherical chromic oxide abrasives (known then as material 1/44).

The lining wear increased with the abrasive size as shown below in figure 4.1.12. However, there appeared to be two wear rates, this being most apparent with the large abrasive. Almost all of the wear occurred in the first half of the test with the wear rate then becoming similar to that of the base material. A heavily scored disc coupled with excessive pad wear suggested severe three body wear in the first half of the test. For the large abrasive the fall in wear rate coincided with the fade in performance, for the smaller abrasives the wear rate was reduced as deposition occurred. The abrasives will lose some of their affect due to pad softening as well as possible fracture and capture within the film.

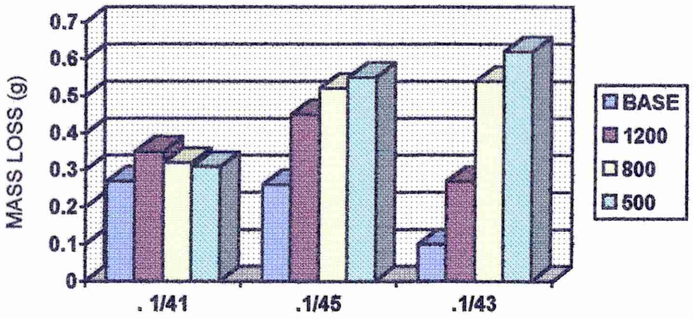


Figure 4.1.12. Pad wear after 90 minutes.

The nature of the thick film which builds up during the test with 1/43 is very similar to that which forms with 1/41. Bands of deposited material cover the disc surface with the uppermost layer having a glazed appearance. In many places the glaze has flaked off to leave the underlying deposition material or in some cases the iron disc. The only real difference between the films is the extent of the coverage, with 1/43 there are many bands of un-coated iron between the deposition. This is clearly shown in the micrographs in appendix 2, particularly those of 1200 and 500 alumina (figures A2.11, A2.12). However, except for the 500 alumina abrasive, the majority of the surface is film coated and this probably dictates the friction performance. The nature and content of the film and the friction levels are similar to materials 1/41 and 1/45 suggesting that once bedded in, the different fibres are not altering performance.

The explanation for the lower disc coverage, especially with 500 abrasive for 1/43 compared to the steel fibre materials is unknown at present. The lack of steel fibres suggests that the abrasives may be acting on the disc and they have not become inaffective due to pad softening. Alternatively the film may have been removed by adhesive wear although this was not so apparent with 1/41.

Spot analysis of the thick deposition showed that elementally it was similar to that formed with the steel fibre pads. Again cross-sections revealed the film to be generally homogeneous. The film is made up of mainly barytes, vermiculite, copper and iron oxides. The major component in the film is barytes as opposed to iron, with higher levels of vermiculite. This is due both to the lower wear of the disc as well as there being no iron debris from the fibres. Again carbon levels within the film are very low.

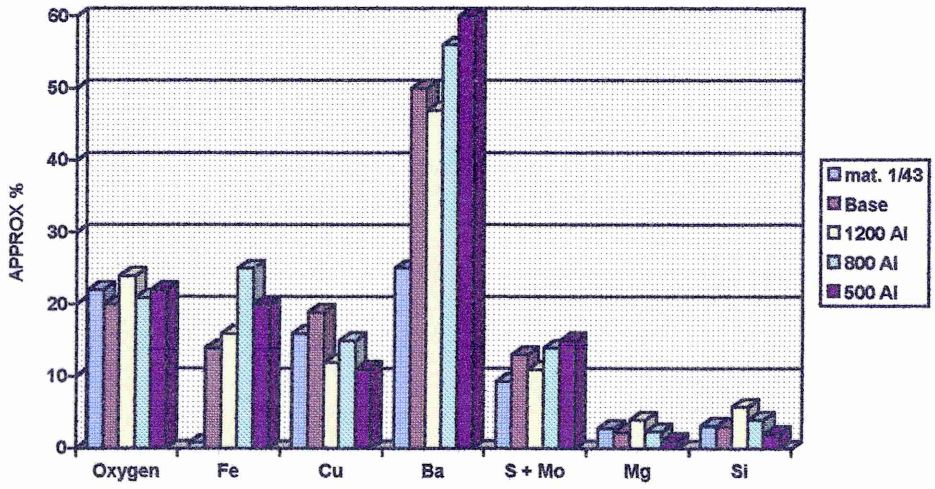


Figure 4.1.13 Estimation of elemental content of deposition with 1/43 + 1200 alumina.

In the early stages of the test before heavy deposition occurred thin bands of copper were observed on the disc surface, this being most apparent with the smallest abrasive and the base material. This was not apparent with the steel fibre pads suggesting that the copper deposition is inhibited by abrasive action. Once the copper has adhered to the surface it remains fixed and forms part of the transfer film with transfer elements and more copper adding to the band. These bands are clearly visible in the maps in appendix 2 (figures A2.10 and A2.12). Occasionally a small section of the band is missing, no doubt removed by adhesion back onto the pad, and the iron disc is revealed. Copper is introduced into a friction material generally to increase performance by increasing the contact area and altering the interface material. There does not appear to be much difference in the final friction levels whether the copper bands are formed on the disc or not.

Figure 4.1.14 below shows the spectra from a typical area of deposition on the disc surface. When compared to that formed with material 1/41 (figure 4.1.10) the main difference is the iron oxide content. Because this is much reduced all other elements appear in greater amounts.

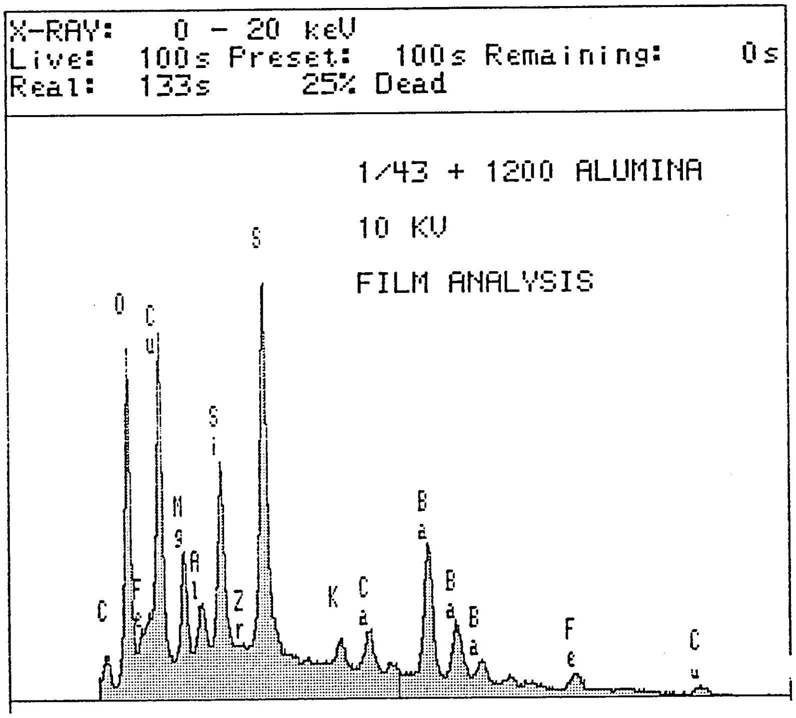


Figure 4.1.14 Typical spectra from deposition.

4.1.3 Conclusions - Cast Iron Discs.

The conclusions drawn by the author are specific to the individual materials and testing regimes.

- The mix of binders, fillers and metallic fillers induced a relatively low friction coefficient against cast iron. This increased with temperature as adhesive forces increased.
- The addition of abrasives increases the friction coefficient by increased ploughing action. The larger the abrasive the higher the performance.
- The steel fibres running against cast iron induce a high performance. Once the fibres are separated from the disc by a transfer film their effect is reduced.
- With increasing interface temperatures a complex iron oxide may form on the disc which results in a fading of friction performance.
- By their nature abrasives can prevent the formation of a transfer film.
- The temperature of the lining effects the performance of the abrasives. With increasing temperature the pad will soften and the abrasives be pushed back thus losing their effectiveness.
- With increasing temperature deposition of material occurs more readily.
- With all materials a thick build up of deposition occurred towards the end of the test. For most materials this film dictated the performance since the disc and pad were entirely separated.
- The filler material barytes was the main component of the transfer film. However most of the lining materials were included in the film. Carbon was the only material which did not appear to be part of the deposition.
- Abrasives may be required to control the build up of very thick deposition layers.
- Chromic oxide abrasive appears to control the deposition better than alumina although induces a fading in performance, again related to interface temperature.

4.2 Coatings Project.

One of the main aims of the project was to study the tribological response of various friction materials when coupled with a HIPAC coated disc. HIPAC is the name given to the process of applying the coating to a substrate, this procedure is Patented by Plasma Coatings Ltd. The work covered by the author has concentrated specifically on wear mechanisms, transfer films and performance characteristics of various friction materials against the coating. There has been no involvement whatsoever in the development of the coating.

4.2.1 Analysis of Copper Coating.

HIPAC is the method of thermally spraying, densifying and mechanically bonding a material to a substrate. The coating is metallic copper with inclusions of silicon carbide abrasive. The abrasive content is around 5% by weight or 11% by vol in the raw material mix. The size range of the abrasives is wide, varying from sub micron to 15 μm. Larger abrasives may increase the friction coefficient by protrusion from the surface or by being included in transfer films. Smaller abrasives orient themselves around the grain boundaries of the copper during the HIPAC process. This reduces the wear rate of the copper by increased resistance to abrasive ploughing.

A brief analysis of the copper coating was conducted prior to testing. The 'as provided' ground surface was clearly visible under S.E.M. conditions as shown below in figure 4.2.1.

Figure 4.2.1. As provided surface of HIPAC coating.

There is evidence of the ploughing action of the grinding process with much plastic flow of the copper. Inclusions or voids within the coating are visible, these being identified by their smooth nature. Presently the coatings are surface ground as opposed to tool machining due to the difficulties imposed by hard inclusions within a relatively soft material. Cutting tools suitable for copper would quickly be blunted by the carbide particles and harder cutting edges capable of coping with the carbides would tend to ball up resulting in poor machining performance. Presently Plasma Coatings are developing a tool machining process specific to the spray coatings.

Silicon carbide particles are easily identifiable within the copper coating although tend to be at least partially covered with copper as a result of plastic deformation during surface grinding. When the surface is polished the carbides are much more clear, their size, shape and distribution indicated in the micrographs shown in figure A3.1 (appendix 3). Diamond paste was used for polishing to avoid contamination. From the high magnification micrograph of the silicon carbide particles it is possible to see how the coating has been shielded from polishing due to the carbides standing slightly proud of the surface.

The micrograph below (figure 4.2.2.) shows a cross-section of the interface between the coating and the aluminium disc. Prior to coating, the substrate is roughened to increase the bonding area and mechanical strength of the interface. Evidence of splat quenching in the copper is clearly visible.

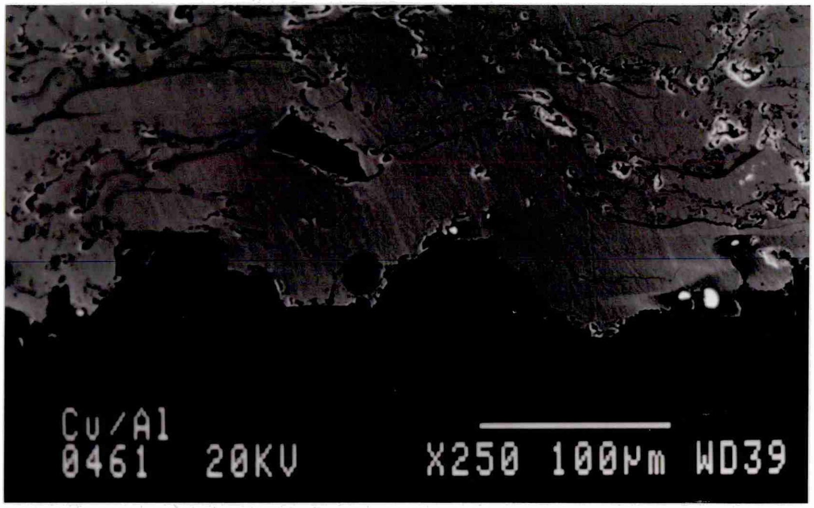


Figure 4.2.2. Interface between aluminium substrate and HIPAC coating.

Although the mix of materials was carefully considered the coating applied to the friction discs has at this stage has been dictated to some extent by the raw material provided to Plasma Coatings Ltd. The coating is still in the early stages of development, this being the first composition tested.

Materials Coupled with Copper Coating.

It is well understood that lining materials incorporating large amounts of steel fibres can be rather hard wearing to aluminium metal matrix discs. Many friction material manufacturers have a range of specifically developed materials using alternative fibres for use with these discs. On-vehicle testing (section 4.3), indicated that the copper coating also responded unfavourably to linings containing steel fibres. As such the testing and development work covered by the author was centred around friction materials containing no steel fibres.

Although material 1/43 was developed for use against cast iron it's simple, non-steel fibre range of constituents made this a suitable test material to couple with the coating. The use of this material allowed the affects of abrasive additions to be investigated in a similar way as with the cast iron discs.

In addition to 1/43 some other materials mixed by Ferodo Ltd. were briefly tested for completeness. These materials were made with a similar composition to 1/43 such that comparisons could be drawn.

Other non-steel fibre materials made by Ferodo Ltd. were also tested. These materials were already fully developed and available commercially for automotive use. Two materials were tested fully, these being denoted 4042F and M9238. Due to commercial sensitivity exact information regarding the content of these materials cannot be disclosed.

4.2.2 Material 1/43 Coupled with HIPAC Coating.

Initially both the coated aluminium and the coated cast iron discs were tested to compare the affect of different disc materials on performance. Both discs were tested in the same way with the range of alumina abrasives in material 1/43. The performance traces for each disc are shown overleaf in figures 4.2.3 and 4.2.4. As expected there was little difference in the overall friction performance between the two discs since the coatings are identical. The differing properties of aluminium and cast iron did however lead to higher bulk temperatures being achieved in the aluminium disc as shown by the complete test traces in appendix 3. This may explain the slight fall in coefficient with the aluminium disc towards the end of the test end which does not happen so much with the iron disc. Considering the relatively low work input into the discs during F.A.S.T. testing, any comparisons made between the discs concerning temperature should not really be attempted. This should be left to full-scale testing where the superior thermal conductivity but limited heat capacity (per unit vol.) of aluminium over cast iron can be investigated fully.

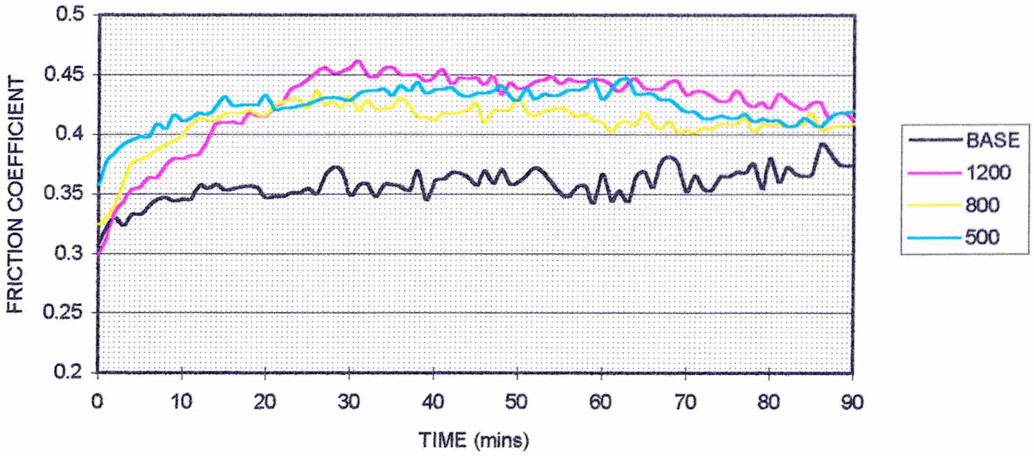


Figure 4.2.3. Copper coated aluminium disc coupled with 1/43.

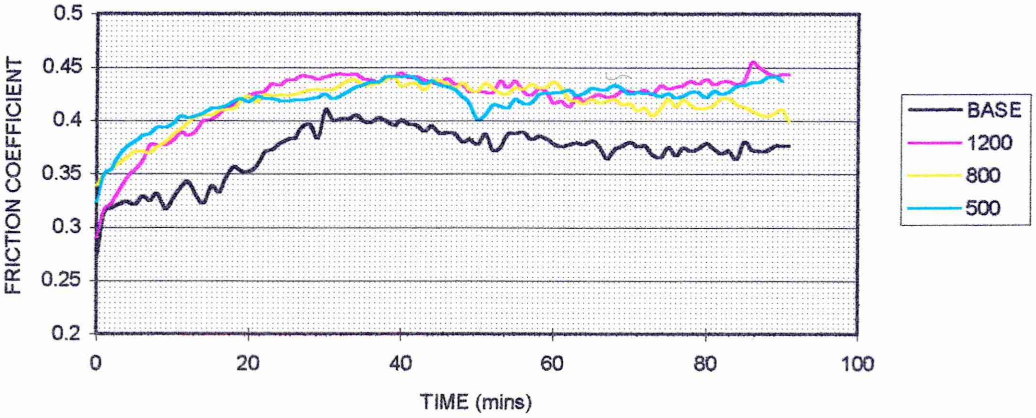


Figure 4.2.4. Copper coated cast iron disc coupled with 1/43.

For material 1/43 there is an initial rise in coefficient for the first thirty minutes or so where a peak value is reached followed by a slight drop. The addition of abrasives appears to be increasing the performance for the entire test suggesting that the affect of the abrasives is superimposed upon that dictated by the base material. On average the base material gives a friction coefficient of between 0.35 and 0.4 and the abrasive additions push this up to between 0.4 and 0.45.

During the early stages of testing the disc surface is polished by the lining with very little transfer of material. There is some scoring of the disc especially with the large abrasive size but generally the surface appears to lose much of the original roughness introduced during the surface preparation (rubbing with 400 grit paper). The friction coefficient is due to a combination of abrasive ploughing, interlocking and adhesion although the adhesive mechanism is not leading to material transfer. A contribution to the performance will probably be made by the larger embedded abrasives within the HIPAC coating. Friction levels achieved with the base material show there is some contribution of interlocking and adhesion to the performance. It is unlikely that the embedded abrasives embedded are responsible entirely for the base friction levels.

For the first minutes of the test the largest alumina abrasives induce the highest friction coefficient, this probably being due to increased ploughing action. A similar observation was made with the standard cast iron discs. Fairly quickly the affect of abrasive size decreases and the friction coefficient noted with the different sizes then follow a similar path. This may be due to pad softening as the interface temperature increases allowing the abrasives to be pushed back into the lining. Also, once an abrasive has 'cut a path' in the disc its individual affect will be reduced. An explanation could also be found in the fracturing of the abrasives as they plough through the silicon carbide reinforced copper disc.

From the performance traces it appears that the smallest abrasive addition actually has the highest performance for the majority of the test. This may be due to individual tests since differences are small and examination of the worn surfaces formed with all sizes showed few variations (see figure A3.4, appendix 3). However, it may be possible that the higher performance is due to a more abrasive transfer film. Whitaker *et al* [15] reported that abrasives incorporated within the transfer films formed on aluminium MMC's were critical in dictating friction coefficient. The smaller abrasives are much more likely to be incorporated within the film where as larger abrasives remain within the lining. The film thickness of around 8 to 10 μm would support this. Mapped areas of the film show occasional small spots of alumina but never anything larger than a few microns. Because the percentage of abrasive in the lining is fixed this means there will be many more of the smaller abrasives available for inclusion within the film.

As the tests progress lining material is noted to collect in any depressions on the disc surface. After thirty minutes or so the friction performance reaches a peak and patches of deposition appear on the disc. At first the deposition is unstable with material constantly being deposited and removed, this often tending to occur within a specific banded area. Gradually the patches become more stable and grow, eventually covering the majority of the disc surface.

The gradual increase in friction level may be due to an increase in the adhesive properties of the lining as the temperature increases. This reaches a maximum when the adhesive bonds are greater than the cohesive bonds within the lining resulting in material transfer. As noted on the cast iron discs the abrasives tend to slow down the formation of the film compared to the base material. Greater adhesive forces will be required to overcome the abrasive action. The performance traces show that adhesive forces alone do not dictate the friction levels otherwise the base material would reach a similar friction coefficient to the abrasive materials.

In order to investigate the affects of temperature a disc was preheated to around 200 C prior to testing. The friction coefficient rose sharply and deposition began almost instantly. After a few minutes the friction level had reached a maximum and then remained relatively stable, falling slightly, but following similar trends to those noted in the standard tests. This experiment shows that the adhesive strength of the lining increases with temperature.

Oxidation of the copper will occur during testing. With the abrasive linings the friction coefficient peaked and material transfer began as the un-worn copper coating just aside from the wear track began to adopt a distinctive pink/red colour (due to oxidation). With high enough surface temperatures any un-oxidised copper exposed by ploughing will be oxidised as fast as it is uncovered. The formation of copper oxide may alter both the friction coefficient and the adhesive properties leading to the friction variations as seen. The inclusion of oxidised copper in the transfer film has been reported to reduce the friction coefficient [55] which may account for the performance peak.

The abrasive mechanism is almost certainly microploughing leading to wear by microfatigue. Evidence of this can be seen in many places over the surface although varies considerably in scale. Some areas of the surface, and particularly within the early stages of testing, have small wear grooves probably from the polishing action of the abrasives (see figure 4.2.5).

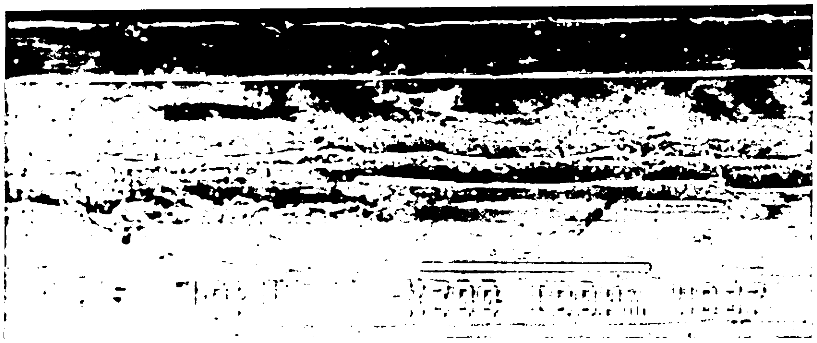


Figure 4.2.5. A thin groove in the copper surface formed during the early stages of testing.

Other sections of the surface, noted more towards the ends of the test, have deep grooves where the surface has apparently adopted a new shape. Occasionally the groove may even have a 'bow wave' at each side due to the deformation. The disc and pad surfaces tend to have the inverse grooved surface showing that they are wearing to fit each other. The grooved surface of the disc towards the end of the test is rougher than would be expected on a cast iron disc. Talysurf results overleaf (figure 4.2.6) show a typical trace taken from the coated cast iron disc ran with 1/43 and 800 abrasive. (Trace length of 5mm.)

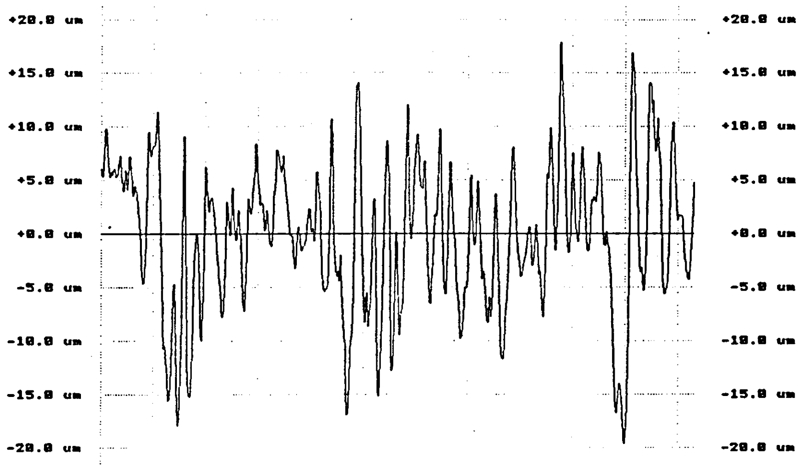


Figure 4.2.6. Talysurf trace from copper coated cast iron disc coupled with 1/43 + 800 alumina.

The surface noted at the end of the test was generally more grooved than the point at which deposition began to occur. This suggests that the ploughing action actually increased as the test progressed. These grooves are clearly not due single abrasives alone but have been attributed to hardened conglomerates of material collecting in the lining. As the test progresses more and more wear debris is created allowing these conglomerates to grow.

The mechanism of film formation is a combination of debris compaction and adhesion. Lining material will initially transfer and back transfer between disc and pad due to adhesion during which time mixing occurs. The material eventually settles on the disc or pad due to a combination of adhesion and interlocking with asperities. Once established the patch can grow with copper debris being smeared into it and further lining components adhering. This continues resulting in separation of the disc and pad surfaces. At the end of the test the majority of the disc surface was covered a thick film, the thickness of which is indicated in figure 4.2.7 below.

Figure 4.2.7. Film on HIPAC surface.

It is likely that for given conditions a critical thickness of the film will be reached upon which it will flake away. This was regularly observed with all the test linings towards the end of the test. The micrographs in appendix 3 (figures A3.5 and A3.6) show areas of the film that have broken away to leave a clearly unworn surface. The removal of the flake does not appear to expose the copper disc but material from inside the film indicating that shear has occurred within the film. This is shown in the mapped areas and the backscattered images of appendix 3 (see particularly figures A3.6 a and b)

When running consecutive tests without disc cleaning the traces were very similar with an initial rise in performance but no real peak in coefficient but more of a levelling out as shown in figure 4.2.8. At the start most of the thick flakes of deposition were quickly torn away although the actual copper surface was not revealed. The film which remained may have been that formed in the early stages of deposition in the first test. The initial adhesive bond between lining material and the copper surface is likely to be stronger than the bonds holding together successive layers of deposition as discussed earlier. Also any areas of the copper surface uncovered by deposition are likely to be highly oxidised. Thus the actual HIPAC surface is not in contact with the lining and this prevents the peak in coefficient.

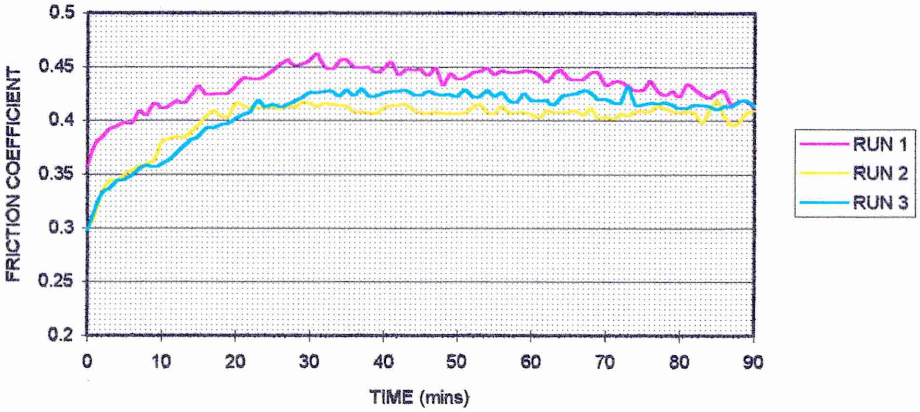


Figure 4.2.8. 1/43 + 1200 alumina. Consecutive runs against coated aluminium disc.

The figure above (4.2.8) shows consecutive runs with 1/43 + 1200 alumina, the results were similar for the other abrasive sizes although as the size increased the performance in the early stages of a consecutive test was closer to that observed in the initial test. This has been attributed to the extra ploughing affects exposing more of the original copper surface and abrading away any retained deposition. All consecutive runs show a gradual rise in performance at the start of the test regardless of the surface condition.

Once the film has become established then a completely new running surface has been created. This will dictate the friction properties of the couple. This new running surface is apparently not unlike that noted just after the friction performance peaks and deposition begins to form on what is likely to be an oxidised copper surface. When viewing the disc surface under S.E.M. conditions it appears that the original copper surface is partly covered with patches of deposition. This is most clearly shown in figure A3.7b of appendix 3. However this is actually the top of the film, the original copper surface is completely covered. The copper may be included as debris in the film by being trapped in depressions as shown below (figure 4.2.9)

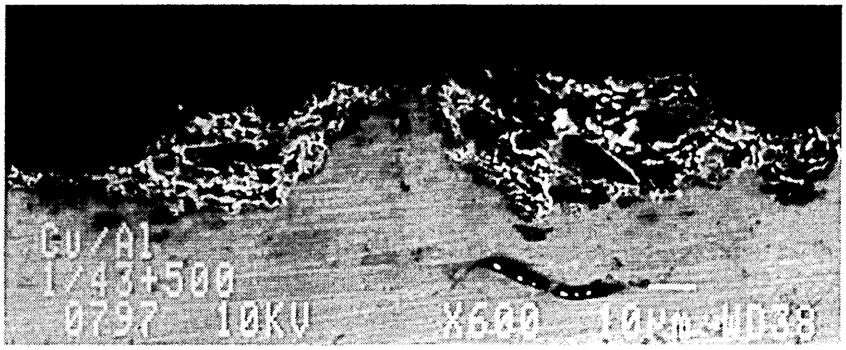


Figure 4.2.9. Film building up around an asperity.

Copper also appears to be smeared onto the film material where it adheres as shown in figure 4.2.10. The result is a random layering affect as clearly indicated in figure A3.7c of appendix 3. The contacting interface is smoothened out and forms a surface which has the appearance of patches of deposition on a copper surface.

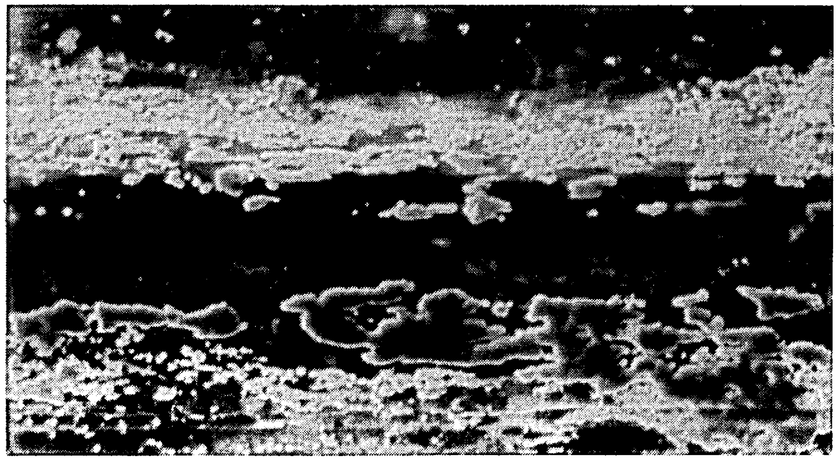


Figure 4.2.10. Copper smears on top of film surface.

Copper within the film will have originated both in the disc and pad. The surface temperatures will have no doubt oxidised much of the copper to either the cupric (CuO) or cuprous (Cu_2O) form. Copper can be removed from the lining material by adhesion or abrasion (from hard particles in the disc or film) or even escapage of a copper dust particle. Disc debris formed through wear by microfatigue or adhesive plucking will be re-used in film building. The relative amounts of copper in the film from the disc and pad is unknown, however the importance of the copper within the friction material was demonstrated with further test materials mixed by Ferrodo Ltd.

Comparing copper free to five percent copper content in the lining the initial rise in performance was about twice as slow although the thick film then built up more slowly. The nature and composition of the film at the end of the test was similar for both materials showing that some of the copper in the film does originate in the disc. Copper in the pad may increase the rate performance rise by increasing the asperity temperature. There may also be some level of adhesion between the copper in the disc and pad. Once a film is initiated the copper in the pad will no doubt result in a more rapid rate of film growth.

Talysurf traces across the wear track showed a growth of material, i.e. negative wear due to film build up (around 0 to 10 μm). It was only after 4.5 hours of consecutive testing that the wear surface was down to its original level. This shows much of the wear debris is used in the film formation. Most material loss from the disc probably occurs over a very small proportion of the running time at the start of each test when, as described earlier, much of the thick film is removed.

When examining the friction material a layer of film could be seen over much of the worn surface. This was not as extensive as that on the disc surface. The film did not appear to be covering specific components but lay on top of the mix of lining components as shown in figure 4.2.11. (Note, the uniform thickness layer is a wrapping of aluminium foil, not the transfer film.) The E.D.X. map in appendix 3 (figure A3.7e) shows the metalised nature of the lining surface. Friction performance is the result of contact between both the film and protruding uncovered lining components with the disc.

Figure 4.2.11. Film on lining material (1/43).

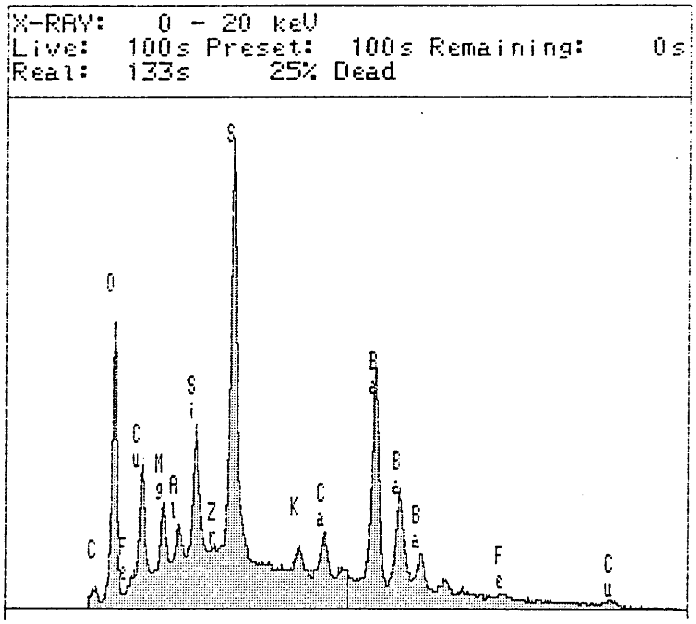
The transfer film on both pad and disc contains most of the constituents of the friction material. Major elements are barium and sulphur, silicon, aluminium and oxygen from vermiculite and copper from both disc and pad. Areas high in barytes and vermiculite correlate but show no obvious particle shapes indicating fine mixing of the materials upon transfer. The film also contains isolated particles of carbon from either the resin or the kevlar fibres and alumina abrasive from the lining. The mix of film components is most clearly shown in the cross-section maps in appendix 3 (figures 3.7 and 3.13).

Molybdenum Disulphide was not individually detected within the film although as described in appendix 1 molybdenum and sulphur peaks in the X-ray spectra overlap. The sulphur content in barytes complicates matters further. To investigate the effect of this lubricant other techniques such as X.P.S. are required. It is assumed that the lubricant will decompose at some point during the testing due to the interface temperatures.

Silicon carbide particles were very rarely observed within the transfer film although they may have been embedded. (note, the silicon carbide particles in the cross-section maps are from the polishing procedure and are embedded in the soft aluminium wrapping). However, the sub micron size abrasives found intergranurally in the HIPAC coating are probably included in the film and may be important in dictating friction coefficient. Film coverage of the protruding abrasives from the HIPAC surface may partly account for the performance peak with their ploughing affect on the pad diminishing.

The slightly lower performance of the transfer film in comparison to the performance of the HIPAC coating may be due to a number of other reasons. Ploughing through the thick film is likely to be easier considering the layered structure. Additionally, as the film coverage is built up on the pad there is less contact of lining components with the disc.

Estimation of the film content is not really applicable due to the mixing of copper metal. Overall the majority of the film material is copper and its oxides. The spectra below is from a low copper area. Rough estimates indicate barium and sulphur represent around 80% of this transferred material, the rest being made up of mainly vermiculite.



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X-RAY:    0 - 20 keV
Live:    100s Preset:   100s Remaining:    0s
Real:    133s       25% Dead
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Figure 4.2.12. Typical spectra from low copper film area.

Alumina abrasive was exchanged for chromic oxide in material 1/43 (known as material 1/44). At the very start of the test the coefficient of friction was noted to be relatively high as indicated in figure 4.2.13 below. This may be explained by the large abrasives ploughing into the disc and 'cutting a path' in the virgin copper surface. However, why this did not occur with the alumina, particularly the 500 alumina which is of a similar size is not known. The performance gradually rises to a maximum and stabilises although the chromic oxide appears to induce a higher friction coefficient than the alumina. The formation of a film follows the same pattern as noted with 1/43 although it grows more slowly and does not cover so much of the surface. These affects can only be attributed to the abrasives as this is the only difference between the pads. Thick build up and flaking of the film still occurs in places as shown in figure A3.8 (appendix 3). With consecutive tests nearly all traces of the old film are removed exposing the copper surface which results in each test following a similar pattern. Although apparently the same size, the chromic oxide appears to be more abrasive to the friction surfaces than the alumina. An explanation for this has not yet been found. Interestingly the shape of the chromic oxide has little affect on performance. At first the spheroidal shape has a higher performance than the angular but these differences quickly diminish.

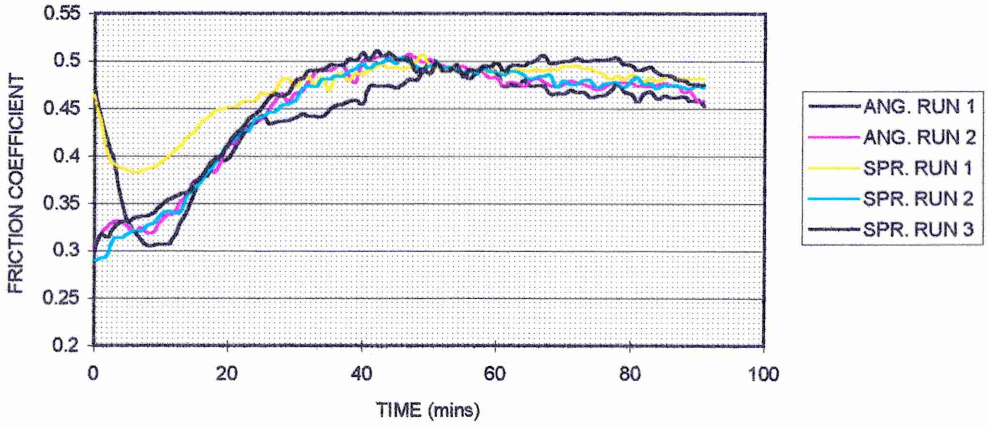


Figure 4.2.13. Consecutive tests with 1/44.

Analysis of the film showed it to be very similar in nature and content to that described earlier with material 1/43. The micrographs in appendix 3 (figure A3.8) show how debris has been smeared into the film. The main difference is the increased levels of scoring on the disc indicating more abrasive action.

4.2.3 Comparison With Cast Iron Discs.

Material 1/43 induced similar levels of friction performance againt both copper and iron surfaces for much of the testing, overall perhaps a little higher with iron. Friction performance is dictated by the base material with the affect of abrasives superimposed. The abrasive wear mechanism is generally microploughing in the copper as opposed to microcutting on the iron.

One of the main differences with the copper coating is the stable friction performance with the larger abrasives, against cast iron a rapid drop in coefficient was observed. This affect did not occur with the coating adding further weight to the theory of iron oxides causing the fade. This phenomena was particularly evident with chromic oxide abrasive. Materials with a similar composition to 1/44 were mixed by Ferodo Ltd. specifically for investigating this affect, the results of which are shown below in figure 4.2.14. The experiment confirm the results noted with material 1/43. This area of work is currently under further investigation.

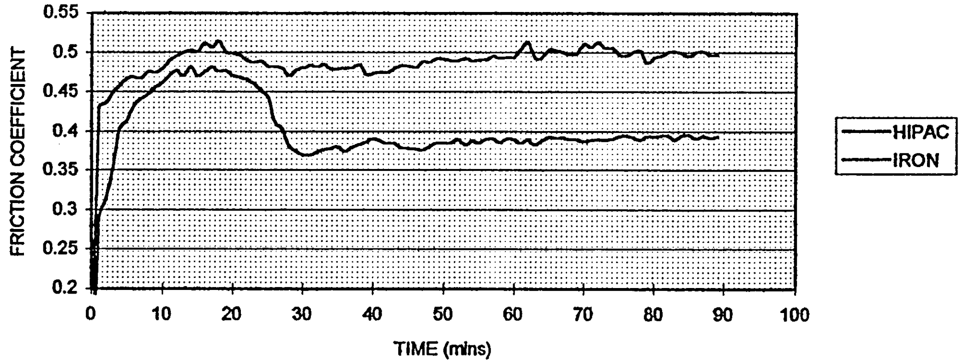


Figure 4.2.14. Chromic oxide inducing fade against cast iron but not against HIPAC.

Although the Ferodo test material and 1/44 were were similar in composition and, as expected, had a similar friction performance against the HIPAC coating, the friction coefficient reached a maximum much more quickly (compare with figure 4.2.13). This affect is of some importance as a slow rise in friction upon each brake application is clearly undesirable. Currently this affect is being investigated.

Comparing the wear of the friction material showed that against the copper coating the abrasive additions made little difference, regardless of their size. The softer copper and thick film build up probably reduce three body wear. Additionally it is suggested that more of the wear debris is retained with the HIPAC coating allowing transfer and back-transfer of film material between disc and lining.

With the cast iron discs much more debris is lost and so as an area of disc passes the pad more material is removed in forming the film on the disc than is transferred to the lining.

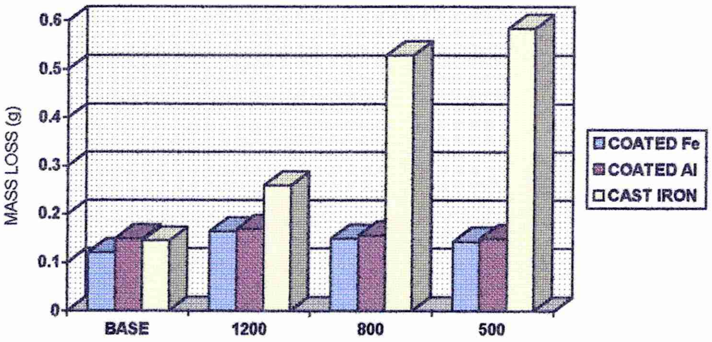


Figure 4.2.15. Friction material wear against cast iron and HIPAC.

Although the differences are small, material 1/43 always had a slightly higher wear rate against the cast iron coated disc compared to the aluminium coated disc as can be seen above. This has been attributed to the higher bulk temperatures achieved in the aluminium disc.

When considering the film on both cast iron and HIPAC coated discs-

- Film formation begins as the friction coefficient reaches a maximum.
- The film grows and thickens considerably to cover a large proportion of the disc surface.
- The film consists of mainly barytes and debris from the disc.
- Flaking of the film occurs when a critical thickness is reached.

With the copper coating the debris from the disc is much larger in size this being due to the softer nature of copper over cast iron. Much of this debris is retained at the interface resulting in a thicker film. For both surfaces it appears that the adhesive nature of the lining is important. This contributes to performance but also results in the thick build up of film material. The copper surface was much more grooved than the iron due to the lower resistance to ploughing by metalised areas of the lining. This affect may increase contact area and add to friction performance.

4.2.4 Friction material 4042F.

This material, made by Ferrodo Ltd. tends to be low wearing to the disc making it a good starting point for testing against the copper coating. Additionally, the material contains similar ingredients to 1/43 allowing comparisons to be drawn. It must be noted that due to commercial sensitivity the exact details of the material components have not been made available.

	4042F	1/43
Binder	31	40
Kevlar fibre	7	5
Ceramic fibre	11	-
Copper powder	7	5
Barytes	10	26
Fillers	20	20
Calcium	12	-
Abrasive	-	2

Table 4.2.1. Content of 4042F (percentage by volume).

One of the main differences in the materials is the fibre content, 4042F contains a proportion (11%) of Rockwool (ceramic) fibres as well as the kevlar fibres. These fibres are high in aluminium and silicon content. The filler materials are not specified and the form of calcium is unknown. The copper powder is in a dendritic form. When analysing optically the characteristic metallic copper colour cannot be seen. An typical spectra from the unworn material is shown in appendix 3 (figure A3.9). This material contained no abrasives.

Testing of this material on the F.A.S.T. machine indicated that its performance was reasonable and that it suffered from no fade problems (figure A3.10 of appendix 3). The friction coefficient was seen to rise at first and then remained relatively stable for the duration of the test. The overall performance did decrease slightly with consecutive tests until about the forth test after which results from following tests were almost identical. Consecutive test results are shown overleaf in figure 4.2.16. The friction coefficient during the first test reached a maximum of around 0.43 and after about four tests began to stabilise at around 0.4. Extended tests indicated that beyond 90 minutes little changes occurred to the friction performance and the temperature levelled out (at approximately 230 °C for coated aluminium disc) when the heat loss equalled the heat input. Friction coefficients of this level, although not high, are not untypical of those used in standard passenger vehicles.

Results from the third test indicated a lower than expected friction performance, out of character with the other tests and un-repeatable. An explanation was not found but this highlights the limitations of the F.A.S.T. Machine. Tests should be repeated to ensure accuracy, especially when results are unexpected.

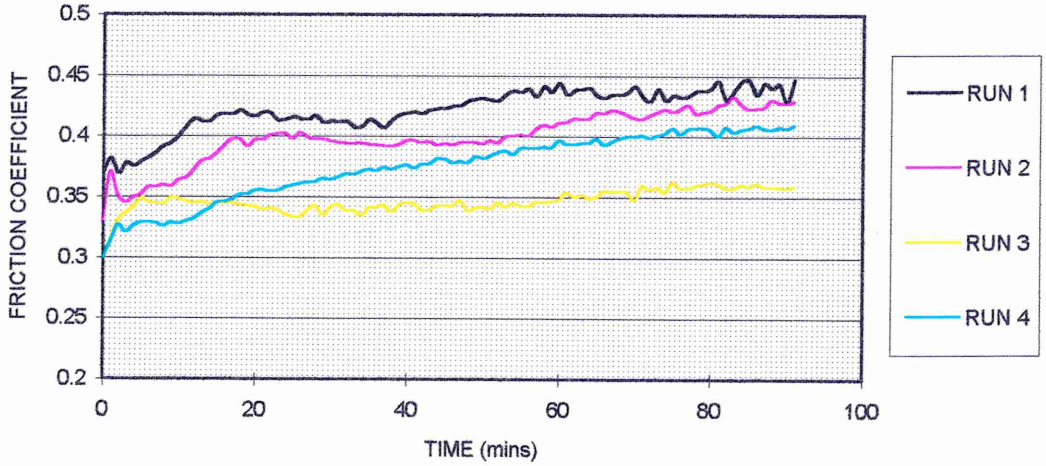


Figure 4.2.16. Consecutive tests, 4042F against coated aluminium disc.

Against standard cast iron discs the friction material performed in a similar manner although the friction coefficient achieved was generally slightly higher.

Overall there were few score lines around the entire wear track indicating the material has a relatively low abrasive nature. This is not surprising considering there are no abrasives or steel fibres in the material. The friction performance of 4042F was similar to abrasive 1/43 materials. From this it could be deduced that the mixture of materials in 4042F has a higher performance than the base mix of 1/43. During the early stages of testing with 4042F there was very little transfer of material onto the disc surface. After around 20 minutes the first signs of deposition were observed in thin bands. The rate at which deposition occurs appears to be related to the rate at which the friction coefficient rises. The ceramic fibres may inhibit film formation in a similar manner to abrasives and allow the lining and HIPAC surface to remain in contact for longer.

In order to investigate 4042F further a proportion of the kevlar fibres (5%) was replaced with glass fibres. Against the copper coating this altered the initial friction performance quite dramatically. After a few minutes the friction coefficient climbed to around 0.5 where it peaked and then soon after began falling as shown in figure A3.10 of appendix 3. The eventual coefficient reached was around 0.42, a drop of almost 20%. Interestingly this friction level is similar to that noted for this material prior to the glass fibre addition. Against cast iron discs the only obvious difference was a slight reduction in the time to achieve stable friction levels.

The glass fibres had little affect on the film build up, however shards of fibre were seen embedded in the copper surface after just a few minutes. A disc surface after 20 minutes of running is shown below in figure 4.2.17 (the embedded fibres are bright due to charging). It is suggested that these particles raise the friction coefficient by ploughing through the lining material. The wear rate of the altered lining material was slightly increased adding weight to this theory. The surface of the standard cast iron disc is too hard for the glass fibres to be embedded explaining why the fibre alteration made little difference.

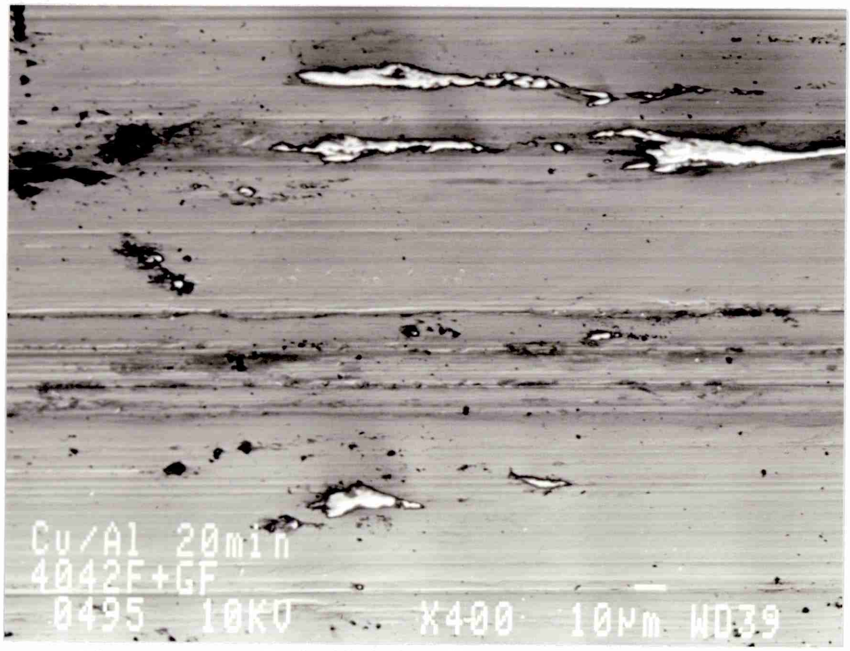


Figure 4.2.17. Embedded glass fibres in worn copper coating.

In comparison to 1/43 the wear rate of 4042F was generally lower by around 30 %. In comparison to all other materials tested this wear rate is relatively low.

During the initial stages of material deposition the film was seen to be unstable, constantly being removed and reappearing in a different place. However this lasted just a few minutes and long before the end of the test the majority of the wear track was covered in a thick film. For the fibre altered lining the formation of the film coincided with the fall in performance. As the deposition thickens the affect of the embedded fibres is reduced and the friction coefficient tends towards that of the standard lining. The transfer film on the copper coating is of a patchy nature not unlike that formed when running with material 1/43. Micrographs and E.D.X. maps of the surface are shown in appendix 3 (figure A3.11).

Cross-sections of the film, as shown in the micrographs and X-ray maps in appendix 3 (figures A3.13a-c), show the majority of the surface to be covered in a thick film. As with material 1/43, towards the end of the test this film is likely to be dictating performance.

For both the standard 4042F material and the glass fibre altered version the film thickness typically measured around 5 microns with some patches being over 10 microns. This film thickness is substantially greater than noted on the cast iron disc. An embedded glass fibre is visible in the cross-section of the film formed with the fibre altered 4042F (figure A3.13c of appendix 3).

Energy dispersive X-ray analysis of the cross-sectioned areas showed the film formed with 4042F to be made up of a high proportion of sulphur and barium. As with material 1/43 the film appeared to be in layers, explaining why analysis of the worn surfaces often indicated different elemental content despite being visually similar. The distinctive patchy shapes are common to other lining materials and in all cases are high in barium and sulphur. It is suggested that barytes (or reacted/oxidised version) has a strong ability to adhere to the copper coating and thus any removed copper back onto it. This high adhesive strength leads to the thick build up and layering affect within the film. Calcium also appears to have a strong correlation with the film material, this is probably a fine ingredient from the fillers. Barium, sulphur, oxygen and calcium all appear as forming a homogeneous film whereas other elements are isolated and are probably trapped debris.

Aluminium and silicon generally correlate together, they are often in particle shape indicating a relative hardness. These particles are from the Rockwool or glass fibres (Glass fibres contain similar elements to Rockwool fibres). The 5% addition of glass fibre has made some differences to the film. Surface analysis revealed a range of elemental content within the film. This varies from being almost identical to that formed with standard 4042F (high in barium / sulphur), to being rich in aluminium and silicon. Spectra from two different areas are shown below in figure 4.2.18.

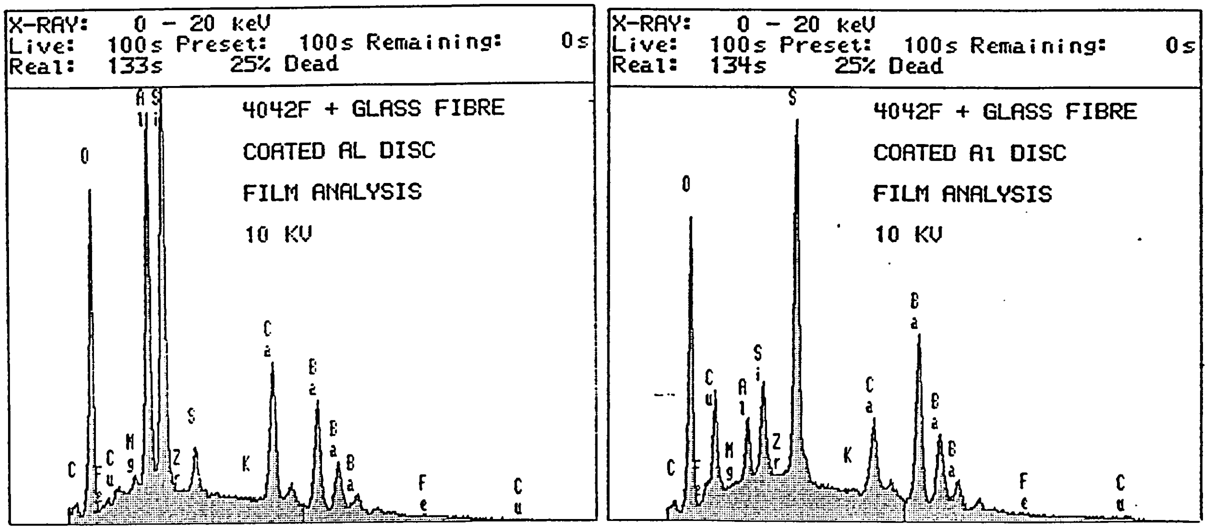


Figure 4.2.18. Film areas with different elemental composition.

Cross-section analysis shows a combination of both obvious chunks of aluminium / silicon and an apparently homogeneous mixing in the film. There is more of this material finely mixed in the film formed with the fibre altered version (figures A3.13 b and c). It is likely that the particles of silicon / alumina are just 'contained' and no chemical alterations have taken place. The stability of Rockwool fibres and glass fibres would add weight to this as well as their brittle nature allowing fracture into tiny pieces. The relatively low conductivity of the aluminium / silicon compound caused some charging of the surface rich in these elements as shown in the micrographs in appendix 3 (figure A3.12). The variation in the film content has been attributed to the amount of mixing of material prior to deposition.

With respect to comparing friction coefficient to film content and distribution between the standard 4042F and the glass fibre version conclusions are difficult to draw. The analysed surfaces were from plugs taken at the end of each test and, as previously explained, at this point the friction levels were fairly similar. Hence it would appear that both types of film have a similar friction coefficient or that the film is not dominant in determining the friction levels. Most likely is that the extra ingredients noted within the film produced with the glass fibres have only a small affect. They are contained within the barium / sulphur / copper film which is more important in dictating performance.

Copper varies in the spectral analysis simply because its content within a given point in the film is variable as indicated by the cross-sectional analysis. The layers of copper within the film are probably debris from the disc or pad. However, as mentioned earlier the copper in the lining is in a very fine dendritic form and may be incorporated in the film in a different way to metallic copper. Copper areas visible in cross-section and making up much of the wearing surface are likely to have originated in the disc. When analysing the film formed on the standard cast iron disc there was no trace of copper as shown in the spectra overleaf (this is also indicated in the mapped areas in appendix 3). The film formed with 1/43 on cast iron, which has a lower content of copper than 4042F but in pure metal form, always contained some copper. Either the dendritic copper is not included in the film or it is more difficult to detect.

The spectra (figure 4.2.19) shows that iron is a major component of the film when standard cast iron discs are used. Although there are some similarities between the film content when testing against iron or HIPAC, the mechanisms of film formation are very different. The iron debris does not build up thick films like the copper and as a result the film is much more sparsely distributed over the disc. The mapped area in figure A3.14 of appendix 3 clearly shows the defined bands of film with the iron disc surface between. Even the graphite flakes and areas of phosphide eutectic can be seen in the iron suggesting that much of the surface is covered in just a thin oxide film.

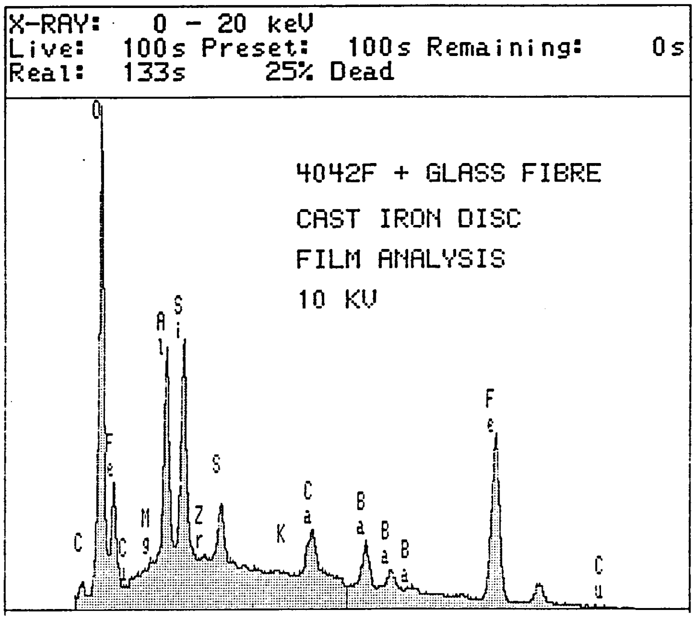


Figure 4.2.19. Analysis of film formed on the standard cast iron disc.

4.2.5 Friction Material M9238.

M9238 is manufactured by Ferodo Ltd. and, like material 4042F, was tested against the HIPAC coating because it is known to induce relatively low disc wear. This material was a step up from 4042F in terms of abrasive qualities as, although containing no steel fibres, it does contain both copper fibres and abrasives. Due to commercial sensitivity the composition has not been made available to the author although some ingredients have been identified and are listed below. The cross-section maps in figure A3.18 of appendix 3 clearly show some of these components.

- Copper fibres.
- Antimony trisulphide lubricant. (see sulphur and calcium map, Ca and Sb peaks overlap).
- Barytes.
- Carbon based resins.
- Magnesium oxide filler.
- Zirconium silicate abrasive.
- Fibres, perhaps ceramic.

The friction level first rose gradually to a peak of around 0.5 and then began to decrease, eventually stabilising at around 0.4. This fade is gradual and although problematical is not critical in that the performance is not lost over a period of minutes or even seconds. Consecutive testing yielded similar trends except the friction coefficient was always slightly lower as shown in figure 4.2.20. The coefficient tended to stabilise at around 0.36 for all tests following the first.

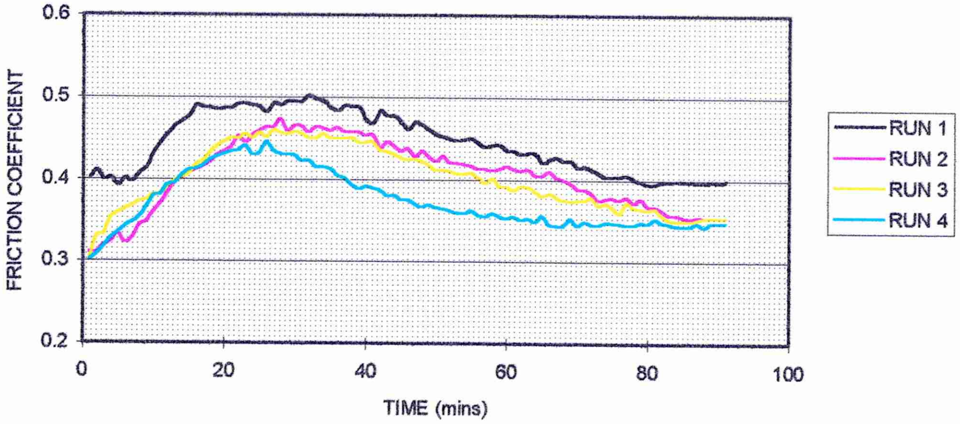


Figure 4.2.20. Consecutive testing of M9238 against coated aluminium disc.

At first the copper surface appeared to be polished although some ploughing was evident, probably due to the abrasives, and perhaps to some extent the copper fibres. Stroboscopic analysis showed that, as with all other tested materials, there was no transfer of material within the first few minutes of testing. The amount of deposition after 17 minutes is shown below in figure 4.2.21.

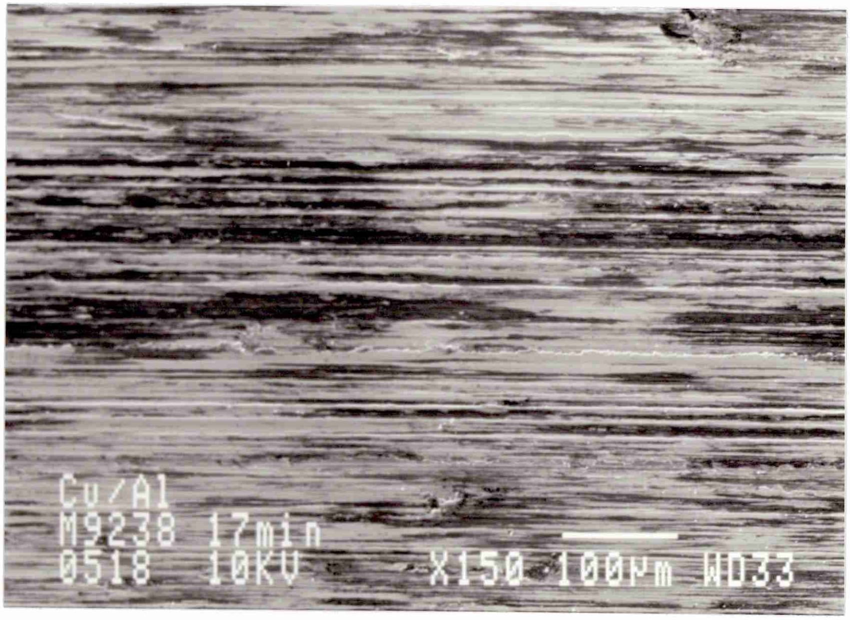


Figure 4.2.21. Coated aluminium disc. Disc surface after 17 minutes.

Observations made with this material support the results noted with those tested previously. The lining running against the HIPAC surface induces a friction coefficient which rises with temperature. With

high enough temperatures deposition occurs resulting in separation of the friction couple and the performance being dictated by the transfer film. The performance has been attributed to a combined effect of interlocking, abrasive ploughing and the increasing adhesive strength.
In order to investigate temperature affects the aluminium disc was re-tested with fans blowing air over the running surface. As a result there was a reduction in the rate of change of friction coefficient suggesting that temperature affects the rise in performance. As expected the rate at which deposition occurred was also reduced by the fan cooling.

Consecutive tests had a similar trend to the first test although the friction performance was always slightly lower as with other materials tested. Although the majority of the thick film was removed during the first few seconds of the test a cleaned copper surface was never revealed. The retained film then affects the performance preventing it from reaching initial test levels. Fading in performance again occurs due to thick film build up although due to the 'head start' the eventual thickness reached is even greater. In many places an apparent critical thickness has been reached resulting in severe flaking and a corresponding reduction in contact area as shown in figure 4.2.22. This may account for the low friction levels towards the end of the test. The abrasives in this material are not controlling the film formation. The mapped area in appendix 3 (figure A3.17) also highlights the flaking and also show the characteristic patchy nature of the contact surface.

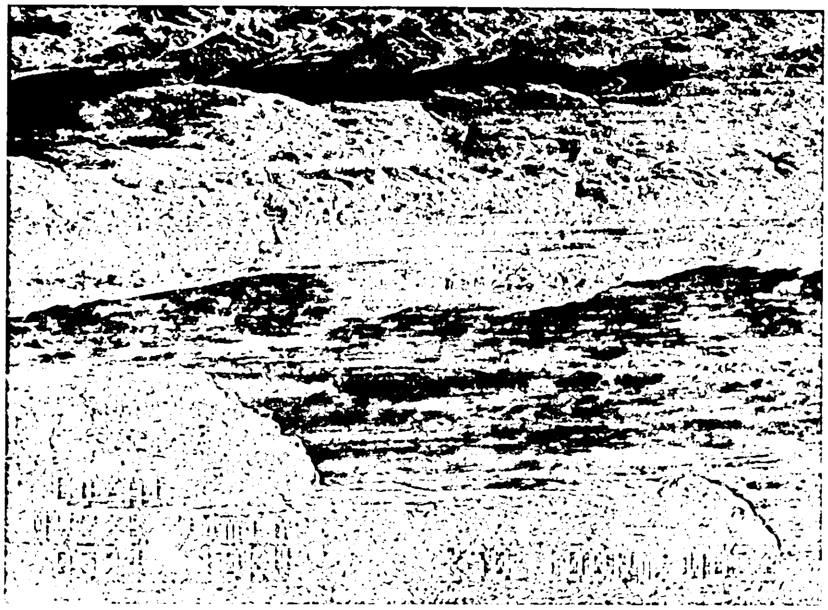
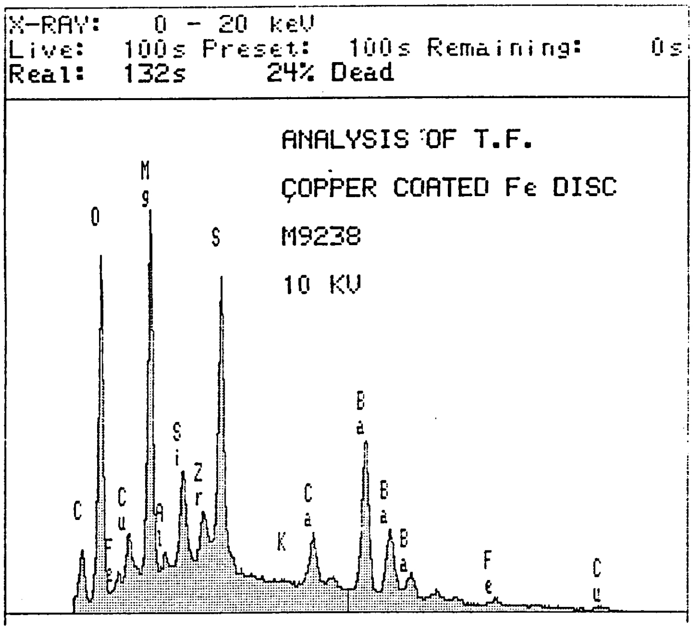


Figure 4.2.22. Severe flaking of the film formed at the end of the third consecutive test.

At this stage it is interesting to note the similarities between the performance of M9238 and that of material 4042F with glass fibre addition. Both suffered a similar rise and fall in friction level. However, the rise in performance for each material appears to be due to different mechanisms. The fall in performance in both cases, and with other materials, is due to the build up of deposition. This lining material however appears to build up a very thick film in a shorter period of time once the deposition has began.

The composition of the film both before and after the coefficient fade appears to be the same indicating that there is no obvious change in the film causing the loss in performance. However, it may be that there are chemical changes occurring that have not yet been detected. This film had a high content of magnesium from the filler. Although the film is certainly rich in magnesium it is not known whether this is in particle form (magnesium and oxygen) or combined with the other components in the film. There are also zirconium silicate abrasives within the film as shown in the E.D.X. maps (figure A3.17, appendix 3) suggesting an abrasive layer has been formed. However, despite this the performance is relatively low. Friction coefficients are lower than with 4042F which contained no abrasives and, after consecutive tests, were similar to the base 1/43 material. For this material to be suitably coupled with the HIPAC coating the build up of such thick films must be avoided. A typical spectra from a low copper area is shown below in figure 4.2.23.



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X-RAY:    0 - 20 keV
Live:   100s Preset:   100s Remaining:     0s
Real:   132s      24% Dead

ANALYSIS OF T.F.
COPPER COATED Fe DISC
M9238
10 KV
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Figure 4.2.23. Typical spectra from deposition on HIPAC coated disc.

As material is transferred and back transferred a film is created on both the lining and disc surfaces. At first there is little deposition due to the lack of material available for film formation. The figure below (4.2.24) shows the film on the lining after 17 minutes. Compare this with the thickness of film on the lining after 90 minutes in figure 4.2.25.

Figure 4.2.24. Thin layer of deposition on lining material M9238 after 17 minutes.

Figure 4.2.25. Deposition on lining after 90 minutes. An E.D.X. map of this cross-section is shown in figure A3.18 of appendix 3.

The nature of the film on the pad varies from compacted and load bearing flakes to debris simply collected within depressions. The figure below (4.2.26) shows relatively loosely compacted debris, the protruding fibres and abrasives will form the running surface. The debris material probably does not contribute greatly to the friction coefficient.

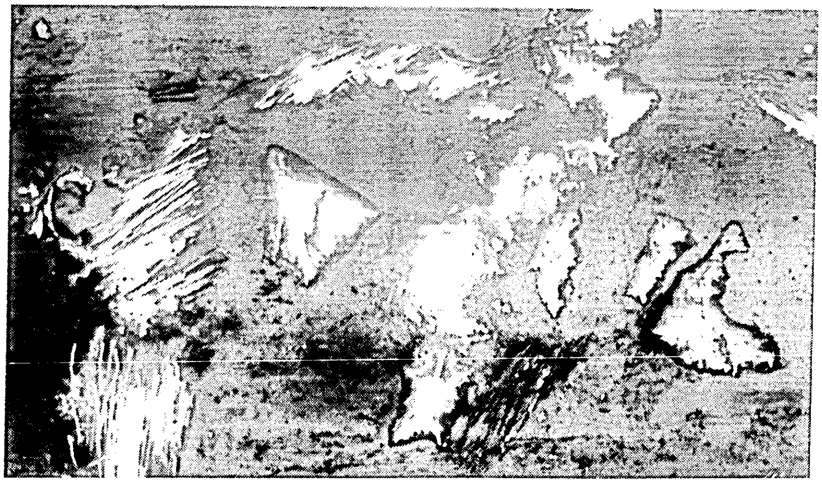

Figure 4.2.26. Loosely compacted debris around lining components.

In contrast, the figure below (4.2.27) shows flakes of load bearing material compacted onto the lining surface, these areas of film will certainly contribute to the friction performance. Many of these flakes appear to be connected to exposed copper fibres and it is likely that the fibres give a foothold for the build up of the film or are themselves spread out slightly across the pad in the direction of rotation. The fibres are film covered in a similar way to the disc.

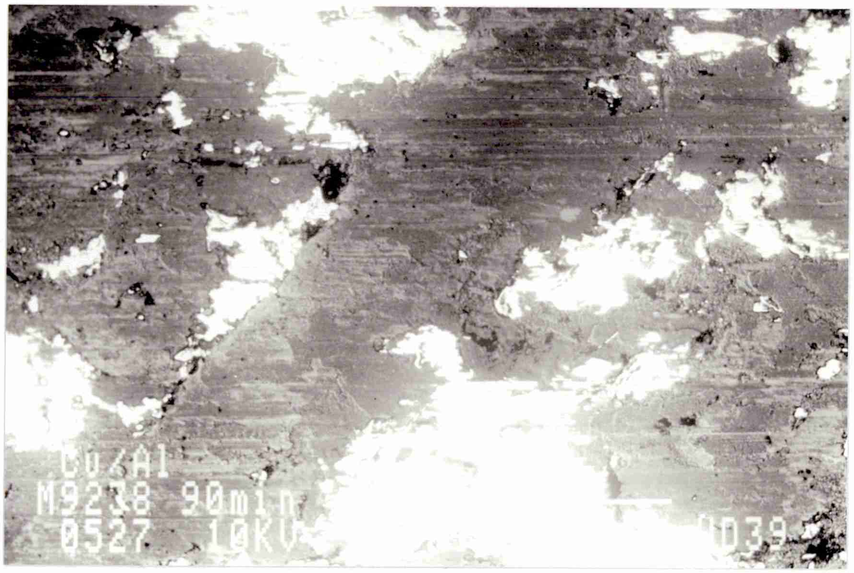

Figure 4.2.27. Flakes of film on lining surface.

The film has the appearance of compacted lumps of debris lying directly on top of the ingredients of the lining. Analysis of the material shows that it is of the same composition to that on the disc which is expected with material constantly being transferred and back transferred. Copper exists in the film although the layering of the metal as seen on the disc was not so common. The loosely compacted debris is probably not solid enough to trap smears of copper.

From examination of the lining surface it appears that friction performance is dictated by the combined affect of protruding lining components and flakes of deposition in contact with the disc surface.

When testing material M9238 against a standard cast iron surface the same overall trend was observed as against the HIPAC coating.

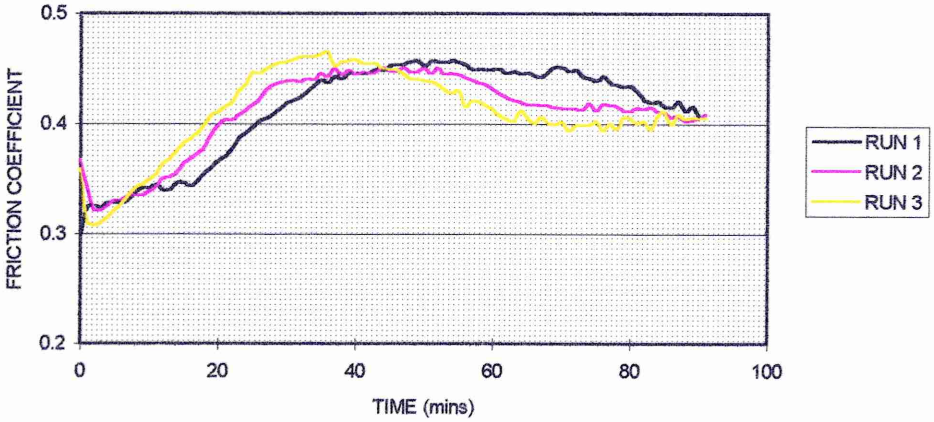

Figure 4.2.28. Consecutive testing of M9238 against standard cast iron disc.

The fade in performance coincided with the build up of a deposition layer. Although never as thick as that noted on the copper coating the film was more extensive than formed with the other materials. The maps in appendix 3 (figure A3.19) show much of the surface to be covered, only a few traces of the iron disc are showing through. The high degree of coverage may be due to the copper fibres. Copper is often added to the lining material because it adheres to the disc and both increases the contact area and changes the interface increasing friction. Indeed copper was noted to be smeared onto the iron disc in thin bands and patches during the test. A situation very similar to the HIPAC coating is then created where material can be deposited onto the copper patches. The micrograph below shows deposition on top of a copper smear on the cast iron disc. The similarities in the nature of this deposition compared to that on the HIPAC coating are obvious.

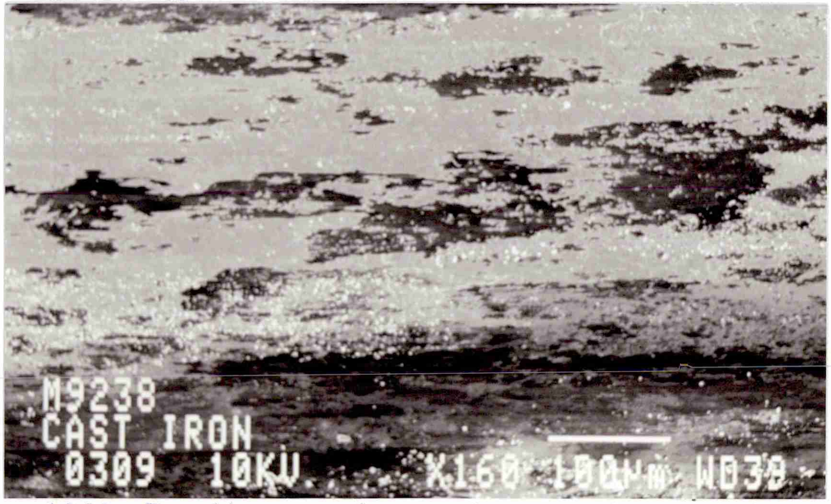

Figure 4.2.29. Deposition on top of a smeared copper patch on standard cast iron disc.

X-ray analysis of this film on the copper patch showed it to be identical to that formed on the HIPAC surface. The copper deposition may explain the differences in the consecutive testing. During the first test the copper is transferred gradually having a corresponding affect on performance. Within the early stages of consecutive testing some of the transfer film was removed although the copper bands often remained on the disc. Hence friction levels build up more quickly. These retained bands now offer a surface upon which a transfer film can be created and as a result deposition and corresponding loss in performance occur earlier.

The main problem with M9238 appears to be the thick film build up. As described in section 4.2.2 the addition of chromic oxide abrasive to material 1/43 increased performance and slightly reduced the film coverage. M9238 was altered by adding 2% of 20μm diameter chromic oxide abrasive. The results of consecutive testing are shown below (figure 4.2.30).

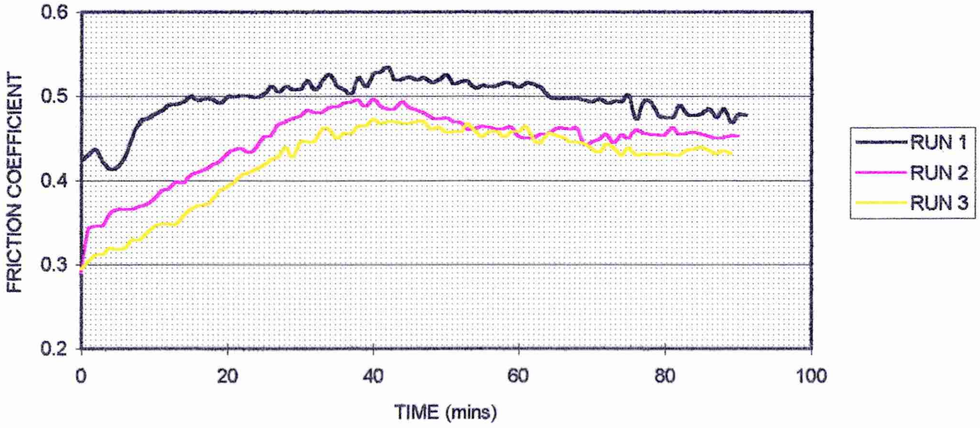

Figure 4.2.30. Consecutive runs against HIPAC with M9238 + 2% chromic oxide.

The chromic oxide abrasives appeared initially to inhibit film formation, faint bands of deposition were noted after 20 minutes or so, but these were quickly abraded away. However, as with all other materials tested so far, a point was reached when deposition onto the disc was faster than the rate of removal. This coincided with a drop in performance. Towards the end of the test the friction levels were lower than the peak value but still fairly high, around 0.45. Examination of the surface revealed that there was less deposition than with the original composition although in places flaking was observed. There was also evidence of ploughing through the film which was not seen with the original lining composition.

4.3 Industry Testing.

The programme of industry testing has been developed primarily by Plasma Coatings Ltd. Friction material testing has been conducted both on dynamometers as well as using on-vehicle test equipment. Much of the results have been made available to the author although they are not presented at this stage. In addition, various specimens have been forwarded to the university for analysis. Of the samples provided the following are discussed in this section of work -

A disc subjected to 'normal' running on a motorbike and achieving positive results.
The disc from a failed test where de-lamination of the coating from the disc was observed.
Worn lining material form an unsatisfactory 'on-vehicle' test.
Dynamometer tested discs and linings.

The majority of the analysis, as with the F.A.S.T. samples, was conducted using the university based Jeol 840a Scanning Electron Microscope.

4.3.1 Motorbike Disc.

The standard front brake disc of a motorbike was replaced by a HIPAC coated aluminium disc. An experienced rider then tested the disc by subjecting it to 'normal' use. The bike was not fitted with any monitoring equipment and hence no results from the testing were recorded. However, the test pilot was 'happy' with the performance indicating that friction levels were adequate, there were no fade problems, and the braking 'feel' was very good. This feedback is as important as any instrument results.

The transfer film on the motorbike disc is different from that observed on the F.A.S.T. discs in both thickness and nature. Much of the transferred material is not part of a deposited and adhered transfer film but powdered lining debris collected in depressed areas of the coating. This is clear in figure A4.1 and A4.2 in appendix 4. These depressed areas account for a large proportion of the disc surface. It is difficult to be sure where the 'holes' have originated, however many of the holes appear to be elongated in the direction of rotation suggesting surface plucking. Clearly this is undesirable as wear rates are increased and the contact surface is reduced.

Unlike that noted on the F.A.S.T. machine the wear debris does not appear to be reused in film formation. The backscattered micrograph displayed in figure A4.1 show the areas of transfer film on the HIPAC coating. It is these patches which appear to be doing the majority of the work. From this micrograph it is clear that the patches are very thin by the relatively low contrast. E.D.X. analysis confirmed this with there being much penetration of the beam into the substrate. Although much of the debris is lost, a thick build up of film has been avoided allowing continued contact between lining and HIPAC coating. This explains the stable performance.

The friction material coupled with the motorbike disc was known as AW2 which contains the same base mix as material 1/43 with chromic oxide abrasive, additional graphite lubricant, and zircon sand combined with a pre-mix. As expected, much of the collected debris was barytes, vermiculite and carbon from the resins. Copper was highly concentrated in the debris no doubt from both the pad and worn disc surface. Analysis of the thin transfer layer was difficult due to the beam penetration although the film was seen to contain mainly copper oxide with some traces of lining materials. In order to collect information from the film alone X.P.S. techniques were employed using the Axis 165 Multi-technique Surface Analysis Instrument based at Sheffield Hallam University. By comparing the chemical shift in the binding energy of the copper peak to copper oxide standards it was deduced that the surface of the disc is covered with Cu_2O as opposed to CuO. Visual examination of the disc confirms this as the surface is very 'copper' coloured and does not appear to have seen a high temperature. CuO is very dark in colour, often referred to as 'black copper oxide', as opposed to Cu_2O which retains the metallic copper colour.

4.3.2 De-lamination Sample.

Standard dimension vented cast iron discs were replaced by solid HIPAC coated aluminium discs on the front of a vehicle and subjected to an E.E.C. fade test. Although the 15 high speed stops were completed the discs failed due to insufficient braking performance towards the end of the test. Examination of the discs revealed the coating on the near-side disc had cracked and almost entirely worn away. The HIPAC coating on the off-side disc, although not as worn, had de-laminated from the aluminium.

The friction material employed for the vehicle test was M9208, known to be of relatively high performance and containing a high proportion of steel fibres. Work by the author indicated the material to be capable of generating a friction coefficient in excess of 0.5. Fragments of the de-laminated HIPAC coating were recovered from the test equipment and forwarded to Sheffield Hallam. Microanalysis of the de-laminated interface revealed melting had occurred by identification of a eutectic microstructure. Figure 4.3.1 overleaf shows this mixture on the de-laminated HIPAC coating in cross section. E.D.X. analysis clearly shows the presence of copper metal within a fine eutectic mixture of aluminium and copper (figure A4.4 of appendix 4). The eutectic microstructure is clear evidence of melting and could not have been formed during the spray coating procedure.

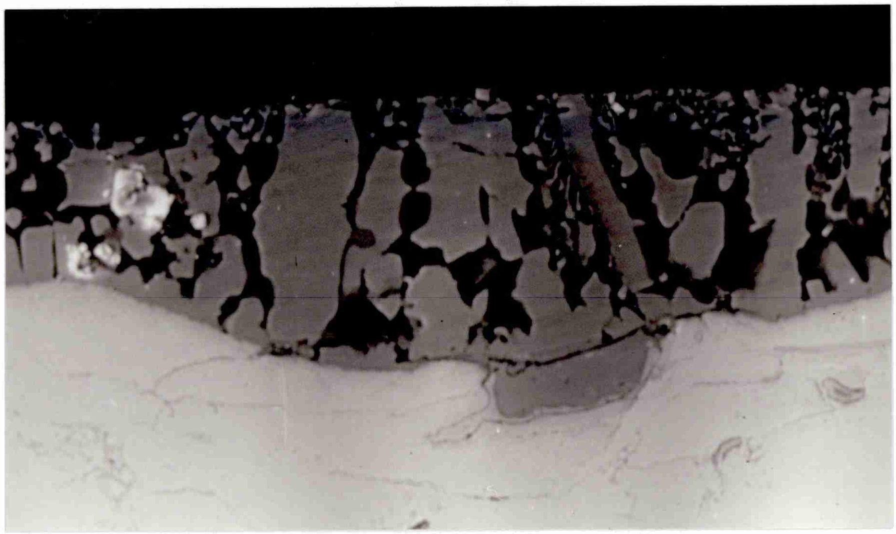

Figure 4.3.1. Eutectic mixture in cross section.

Referring to the phase diagram below (figure 4.3.2), temperatures in excess of 548°C may have been sufficient to form a liquidus state for a eutectic mixture. The presence of copper dendrites indicates the mixture was hypoeutectic with copper being the primary alloy and solidifying earlier than the eutectic. Hence temperatures greater than the eutectic will have been achieved. Although melting has occurred at the interface there is no evidence of melting in the de-laminated sections of coating and only in a few places was previously molten aluminium on the disc observed. As indicated by this mode of failure, the low melting point of aluminium represents one of the greatest problems when introducing coated aluminium discs into automotive braking.

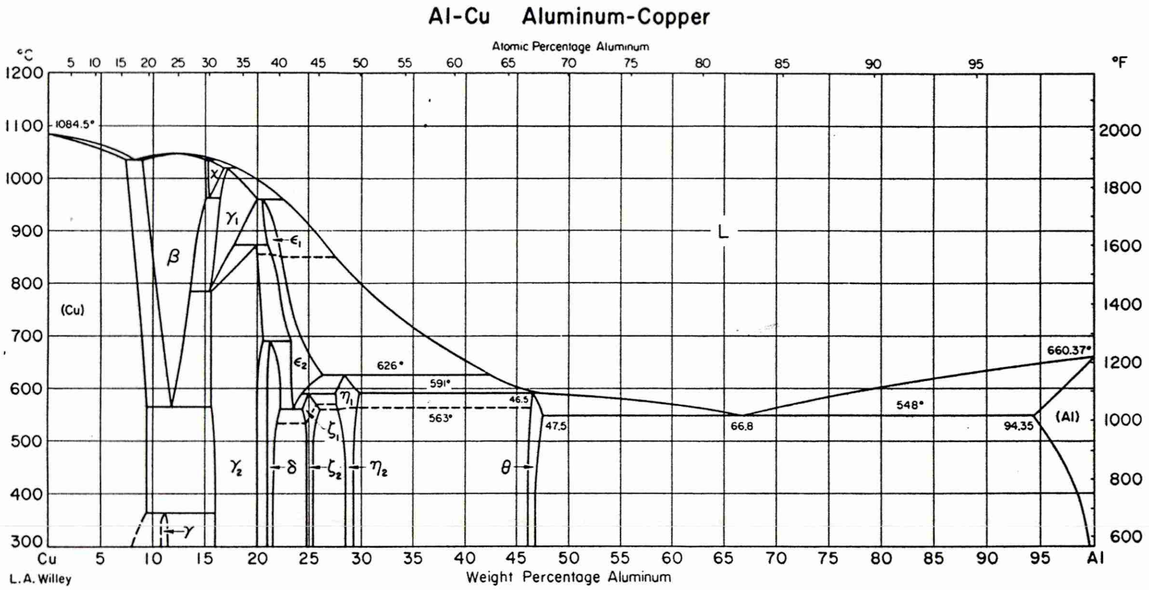

Figure 4.3.2. Phase diagram for aluminium and copper.

4.3.3 Lining material from on-vehicle testing.

Front and rear linings subjected to on-vehicle testing with material 4042F were forwarded to Sheffield Hallam for examination. The discs were not provided and as such the analysis was not conducted in great depth. Both front and rear linings, although worn, had very little evidence of a 'char layer' which is generally noted towards the contacting surface due to the high temperatures. Braking performance during the test had been poor, especially for the rear discs. Analysis of the rear pads showed that severe metalisation had occurred such that there will have been very little contact between the lining materials and the disc. The result is a very thin, highly oxidised and insulated (by the lining) copper surface skating over the disc surface. The large flakes of copper on the lining are shown in figure A4.4 of appendix 4.

In contrast to the rear linings the front pads had only small patches of metalisation. Instead the linings were mainly covered in a black glaze. The glaze was made up of lining material compacted onto the surface. The glazed layer was not a fine homogeneous mix of lining elements, instead it appeared to be made up of a much more coarse mix. This is shown in the E.D.X. maps in appendix 4 (figure A4.5). The glazed layer contained a high proportion of carbon. This layer is probably a compacted 'char' layer.

4.3.4 Dynamometer tested friction couples.

A disc subjected to dynamometer testing with material M9238 was analysed optically. Sectioning of the disc for electron microanalysis was not permitted as this obviously destroys the disc. The test results showed that the friction couple performed satisfactorily.

A transfer film was noted over much of the running surface. This had an appearance similar to that observed on the F.A.S.T. tested samples although was thinner with no signs of film flaking. It could be compared to the F.A.S.T. disc surfaces as the deposition began to appear. This is not surprising as the dynamometer testing consists of repeated stops as opposed to continual running. In some places very rough copper bands were noted, these being uncoated disc material. Examination of the lining showed that these bands matched up with highly metalised and protruding areas of the pad surface. In fact a large proportion of the lining surface was metalised such that the majority of contact will have been from these flakes. Although control of the transfer film is required, this mechanism is not really satisfactory as increased metalisation and disc wear will result. For this test regime the film on the disc has not built up excessively at all, it is the metalisation on the lining which appears more problematical.

5.0 Conclusions.

The conclusions drawn are very specific to the range of lining materials tested. The majority of results have come from the F.A.S.T. machine which bears few similarities to vehicle braking systems. Limited information from dynamometer testing and on-vehicle testing has allowed only brief comparisons to be made.

The HIPAC coating has a similar friction performance to cast iron for a range of lining materials.

Fading of the friction couple as a result of iron oxide formation does not occur.

The abrasive wear mechanism on the copper coating is microploughing which leads to lower disc wear than microcutting observed on cast iron .

Wear debris at the HIPAC interface is re-used in forming a protective film as opposed to being lost from the system. Once the film is formed the wear rates of both disc and lining are likely to be very low.

The separation of the lining and HIPAC coating by a protective film results in the film dictating friction performance.

For the range of materials tested against the HIPAC coating, once the couple was separated the performance and wear mechanisms occurring at the interface were similar.

Barytes adheres readily to the copper coating. Unless film formation is controlled the thickness may reach a critical level and flake away reducing contact area and increasing wear.

Metalisation of the lining materials under severe braking may result in poor braking performance

The overall conclusion at this stage of investigation is that the HIPAC coating has a satisfactory performance against a range of lining materials. Friction levels are comparative to cast iron. However, the transfer film often has a lower friction level than the coating. To maintain high performance either the build up of material must be prevented or more attention paid to transfer film engineering.

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R. Whitaker - Industrial Collaborator, friction material manufacture.

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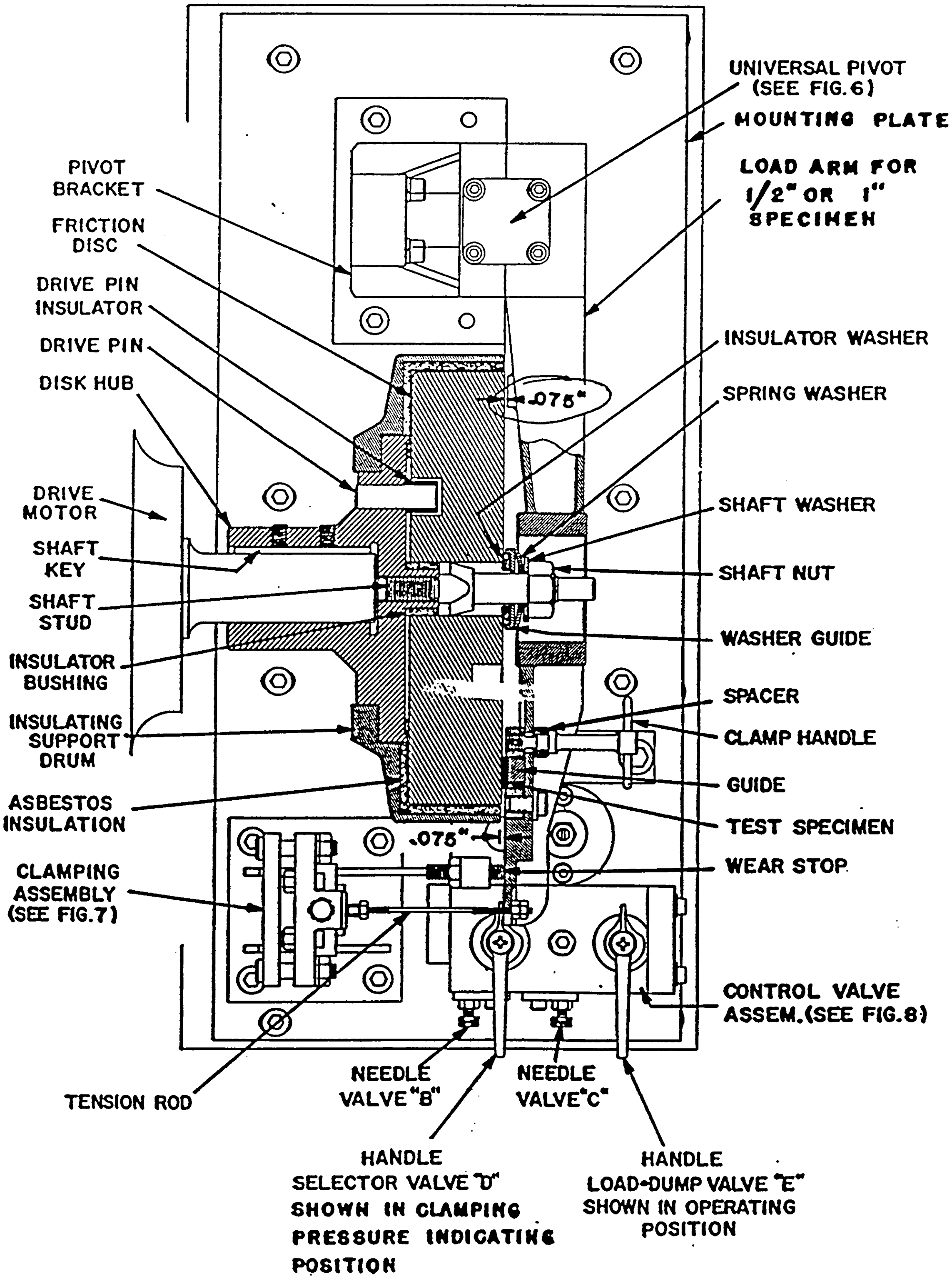
Appendix 1

F.A.S.T. Machine Operating Procedure

- Prepare lining sample. Handle carefully. Weigh and measure and record data.
- Prepare disc. Ensure secure plug, surface grind if required or clean with emery cloth. Degrease, form running surface with 320 grit cloth (avoid with copper coated discs), clean with acetone before running.
- Switch on hydraulic pump and allow to warm up for 20 minutes. The pump should be set to at least 80% of its maximum output. If necessary adjust the allen key valve on the motor such that a minimum of 140 psi is being supplied to the system.
- Switch on computer. In work bench package set for recording of data to floppy disc using pre-programmed data acquisition programme.
- Mount and secure the disc to the motor shaft.
- Check the disc run out at the edge of the disc with a dial gauge.
- Hold the load arm against the disc and adjust the disc/motor unit relative to the arm with the adjuster screw until the arm is parallel to the disc running surface with approximately ½ mm separating them.
- Adjust the stop screw to be up against the load arm in this parallel position to avoid the arm contacting the disc should the lining specimen wear out.
- Insert the lining specimen into the load arm and secure.
- Position the load arm correctly onto the reaction rod.
- Fit the tension rod onto the end of the arm and adjust the nut to be touching the arm. If there is much space (i.e. 1mm or more) between the nut and the arm then the stop within the pressure application unit may be reached before pressure is applied to the arm, alternatively wear of the lining and thus deviation of the arm may lead to the stops being reached and the tension in the arm being reduced. Such a problem is characterised by an apparent huge drop in friction coefficient over a relatively small time scale (e.g. 0.4 to 0.05 in 5 mins)
- Fasten the thermocouple slip ring unit in place and thread the thermocouple wires along the motor shaft. Position the welded thermocouple ends into the pre drilled hole in the friction disc.
- If required set up the microscope apparatus and strobe light instrument.
- In constant pressure mode set the desired pressure by opening the pressure valve (valve E) and adjusting the load screw. If a constant friction force test is to be run adjust the needle valves now for this mode, otherwise leave in the constant pressure mode.
- Set computer to data acquisition mode.
- Turn on the motor and set to pre-determined speed. For the duration of the project the initial speed was always set to approximately 843 rpm (80% mark on the speed control unit). In constant friction force mode the speed would always drop to 760 rpm upon application of pressure.
- Apply the pressure by opening valve E.
- Ensure the desired pressure (friction or clamping) is being read by altering the selector valve, this is obviously the opposite to that which is fixed.
- Occasionally throughout the test alter the selector valve to measure the fixed pressure as a check to monitor its stability.
- After a predetermined time remove the pressure first then switch off the motor and stop the data logger.

Horizontal section of F.A.S.T. machine.



Appendix 1

The Scanning Electron Microscope.

The university based JEOL 840A Scanning Electron Microscope has been employed for the majority of the analysis work throughout this project. A detailed description of the machine and how it functions have not been included in this work.

With the sample chamber of the microscope under vacuum a focused beam of electrons is directed at the sample surface. The electrons are emitted from a heated filament (the source) and accelerated towards an anode through which they pass before striking the sample. The anode is earthed and the source floated at a specific negative charge which dictates the kinetic energy of the incident electrons. Typically the electrons will have a kinetic energy of 10 to 30 keV and will penetrate the sample to a depth of the order of 1 μm, spreading out laterally to a similar distance as indicated in the figures A1.1 below.

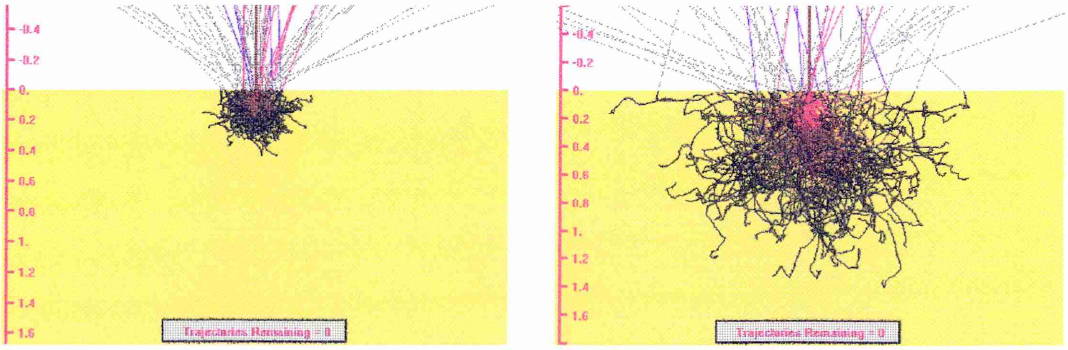


Figure A1.1. Montecarlo simulations of electron scattering in cast iron.
Beam energies 10 and 20 keV. Scale in microns.

Electron images. Backscattered electrons are those from the electron beam that suffer collisions within the sample resulting in their re-emergence from the surface. These may be seen in the simulations above. The proportion of electrons that re-emerge is strongly dependant on the atomic number of the sample, increasing from under 10% for carbon to over 50% for uranium. Hence variations in elemental content across the surface can be observed depending on the relative amount of backscattering. As the figure above suggests with decreasing beam energy the penetration will decrease resulting in increased backscattered resolution. However, this also results in backscattered electrons of lower energy and thus a weaker picture.

individual X-rays with specific energy allows an X-ray spectra to be formed, an example of which is shown in figure A1.3. This spectra was collected from the transfer film formed on a copper coated disc. The beam energy dictates the range over which the X-rays will be emitted, obviously the X-rays cannot have more energy than the electron beam provides.

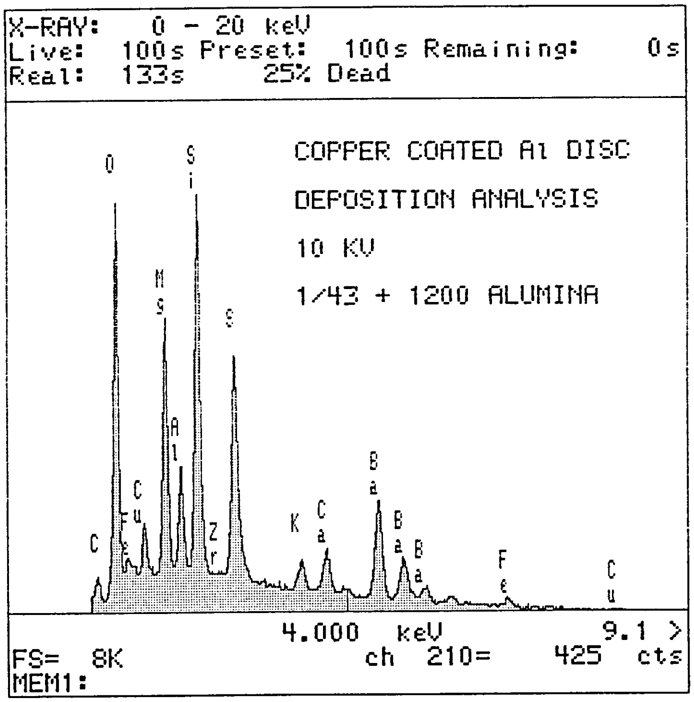


Figure A1.3. Example of X-ray spectra produced from a transfer film.

In simple terms an X-ray is emitted as a result of the transition of an electron between the electron shells of an atom. The energy provided by the incident beam may cause some electrons to be ejected from the atom leaving a vacancy in a particular shell. This is filled by an electron from a greater orbit jumping inwards with the resulting emission of an X-ray photon. For quantitative analysis of individual elements the intensities of the X-rays may be compared with known standards. However in order to arrive at an accurate estimate of elemental content various instrumental and matrix corrections must be applied.

The figure above shows X-ray concentrations or peaks marked with the element from which they have originated. Barium has three peaks due to electrons moving between different energy shells and the emitted X-rays having different energies. Barium, as with most elements, also has more peaks at higher X-ray energy although a greater beam energy is required for their emission. Interpretation of the spectra can be complicated by overlapping peaks. For example molybdenum X-rays are emitted with an energy of 2.29 keV and sulphur X-rays with 2.31 keV. Thus it is difficult to be sure which element is present. In some cases it is possible to distinguish between the elements by using a higher beam energy, Secondary electrons (S.E.) originate in the specimen but have received enough energy from the impacting electrons of the beam to escape. These electrons have low energies, typically below 50 eV which is how the two types of electron are distinguished. Secondary electrons are emitted primarily from the point of impact of the electron beam (as indicated in figure A1.4) as opposed to backscattered electrons which are often spread out considerably before re-emerging due to scattering. Thus the image resolution is greater. However, some secondary electrons are produced by backscatered electrons and hence some of the S.E. signal is generated away from the beam impact point. The variation of secondary electron emission with atomic number varies in a complex manner and as such these electrons are used primarily for topographical data.

Depending on the electrons collected either topographical or compositional differences in the surface may be emphasised. By scanning the beam in a television-like raster information from many points within a specifically chosen area of the sample may be collected. Thus a picture can be built up which is displayed optically on a monitor and a hard copy created if necessary. This allows the user to examine the surface for points of interest. Care must be taken when detecting backscattered electrons that contrast in the image in not due to topography as well as elemental variations. For single detector instruments such as the one employed for this section of work, variations in topography may increase the backscattering in one direction and reduce it in another thus inducing a shadowing effect. Many newer microscopes use two or more backscattered detectors to much reduce this phenomena.

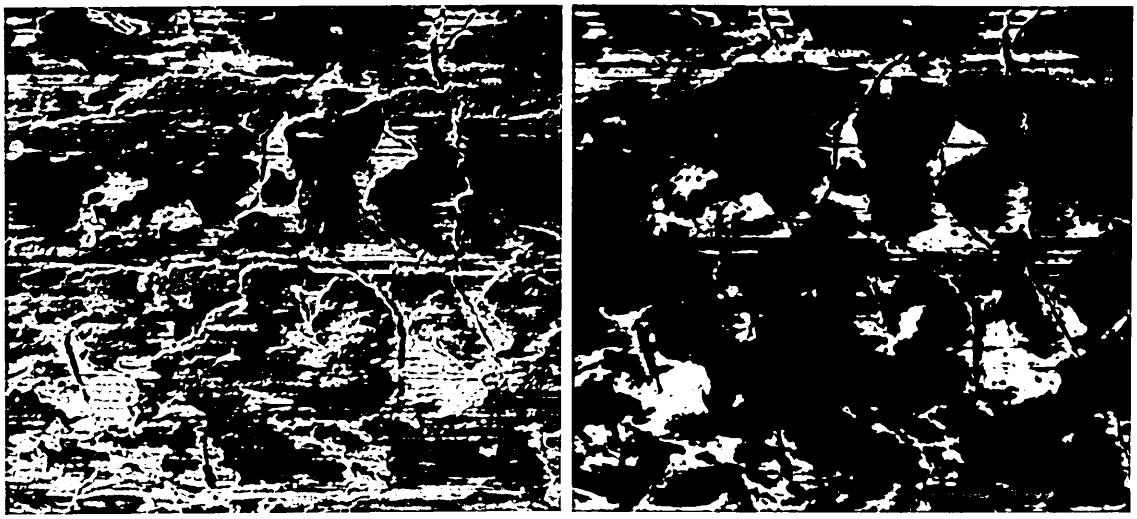


Figure A1.2. S.E. (left) and B.E. images of film on disc surface. The film has a lower atomic number than the cast iron disc and thus shows up darker.

X-ray Spectra. The electron bombardment of the sample generates X-rays which escape and may be detected. The detection of individual elements is made possible because the X-rays have characteristic energies dependant on the element from which they have been emitted. The relative counts of

Molybdenum, for example will emit X-rays with an energy of 17.44 keV and sulphur will not. However the increase in beam energy also results in an undesirable increase in penetration as described below. When examining transfer films there are only a few overlapping peaks to consider even when employing a low beam energy. The overlapping peaks are molybdenum and sulphur; calcium and antimony; and zirconium and phosphorous

Since the electron beam penetrates into the sample the X-rays may originate from a much larger area than the incident electron beam. Hence the resolution, as with backscattered electrons is limited in comparison to secondary electrons. Improving the resolution by reducing the electron beam energy is generally impracticable because the incident electrons must have enough energy for X-ray excitation. Reduction of the beam energy has further implications for the study of transfer films as the depth of penetration is also decreased. For thin films much of the X-ray information may originate in the substrate and so by reducing the penetration an idea of film thickness can be obtained by comparing the relative counts from substrate to film. This however is complicated as the transfer film formed during braking nearly always contains a high proportion of the disc material.

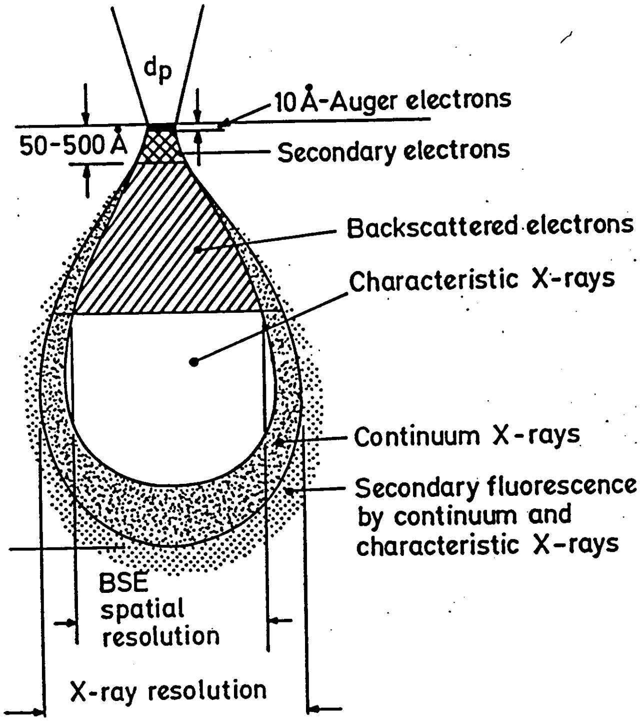


Figure A1.4. Summary of range of spatial resolutions.

Appendix 2

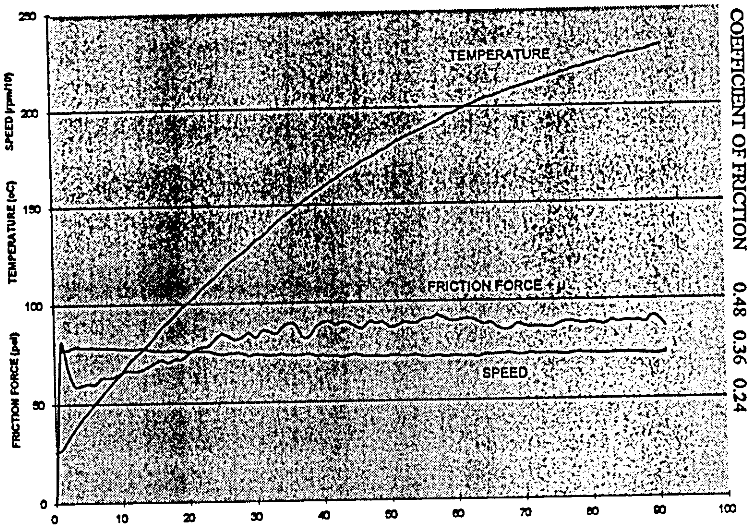
List of figures

Figure A2.1 Compositions of F.A.S.T. Samples.

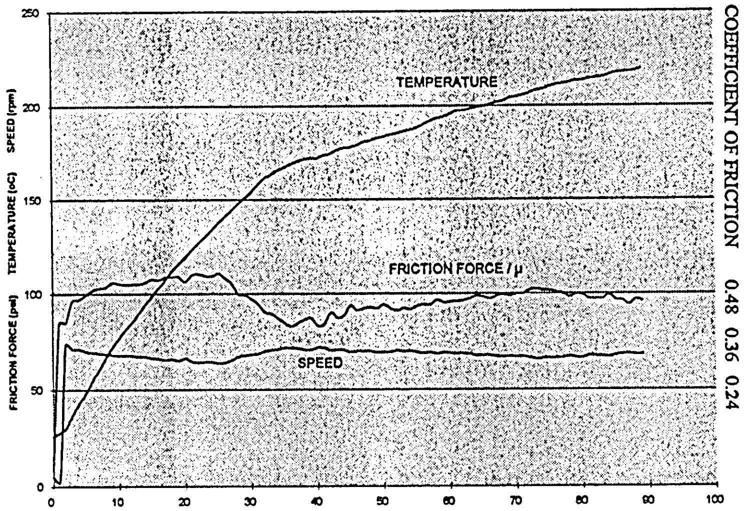
Compositions are for base materials. The addition of 2% by vol of alumina abrasive adds about 0.26% by weight to both the aluminium and oxygen content. Compositions are by weight.

	1/41	1/43	1/45
Al	0.79	0.879	0.79
Ba	22.69	25.12	22.69
Ca	0.07	0.079	0.07
C	12.18	15.33	12.18
Cr	-	-	2.224
Cu	14.11	15.70	14.11
Fe	12.98	0.78	10.558
Mg	2.6	2.896	2.6
Mn	0.10	-	-
Mo	1.81	2.07	1.81
N	0.508	0.87	0.508
O	19.40	21.93	19.40
K	0.69	0.767	0.69
Si	3.104	3.454	3.104
S	6.497	7.227	6.497
H	0.816	1.015	0.816
H_2O	1.71	1.902	1.71

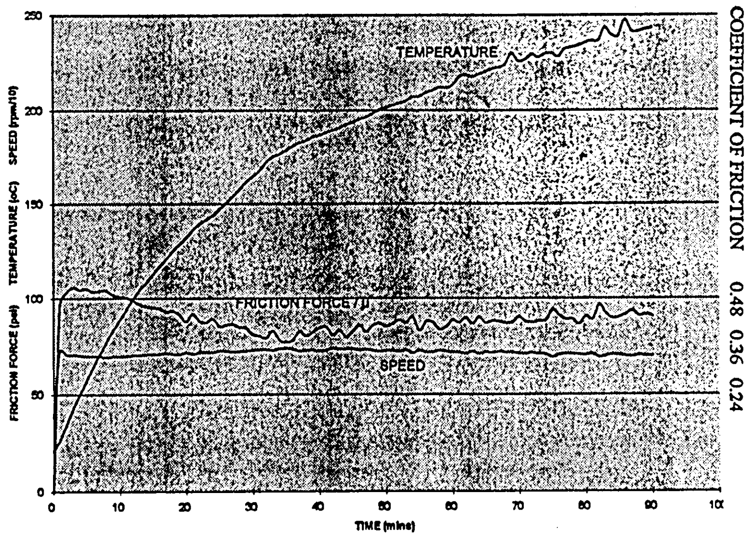
STANDARD CAST IRON F.A.S.T. DISC FRICTION MATERIAL 1/41
CONSTANT PRESSURE 40 psi



BASE FRICTION MATERIAL



1200 ALUMINA ABRASIVE



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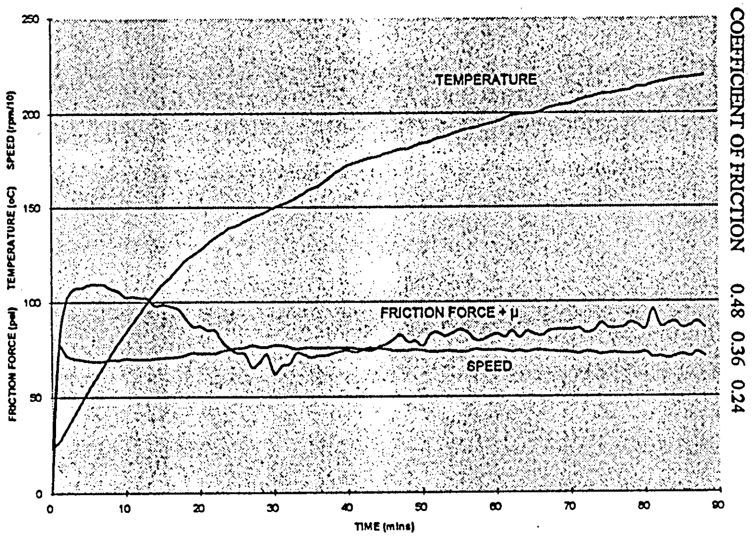
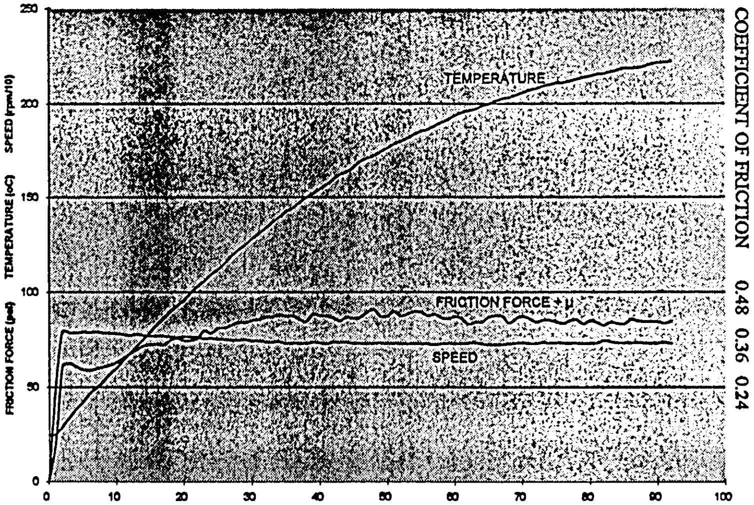
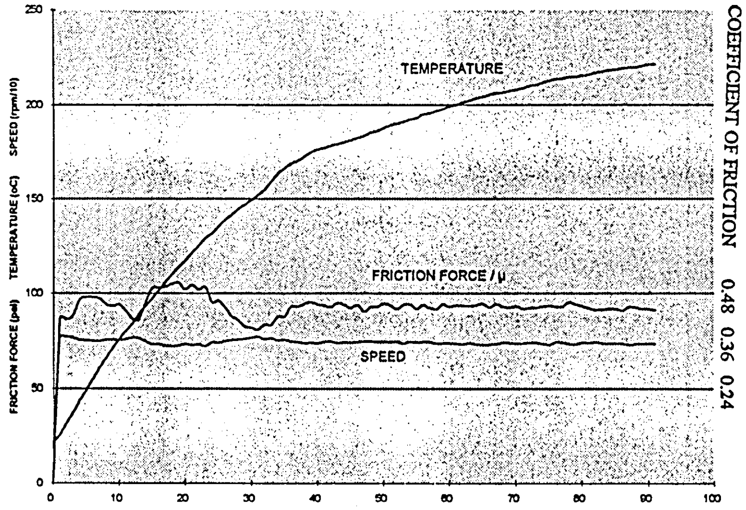


500 ALUMINA ABRASIVE

STANDARD CAST IRON F.A.S.T. DISC FRICTION MATERIAL 1/45
CONSTANT PRESSURE 40 psi



BASE FRICTION MATERIAL



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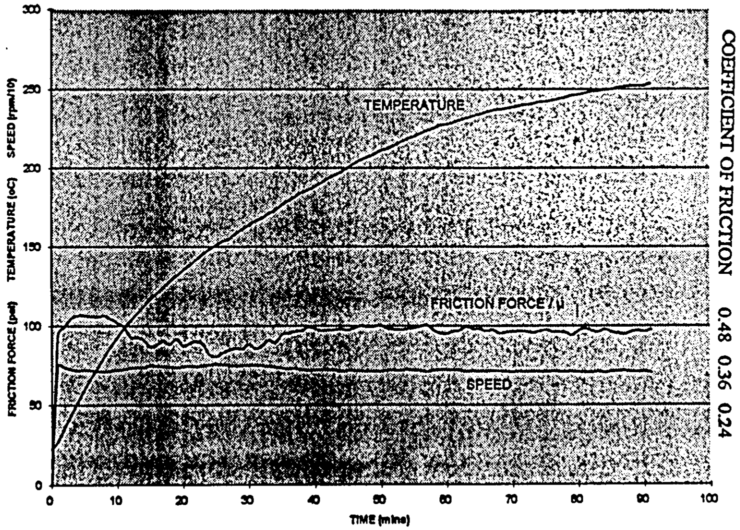

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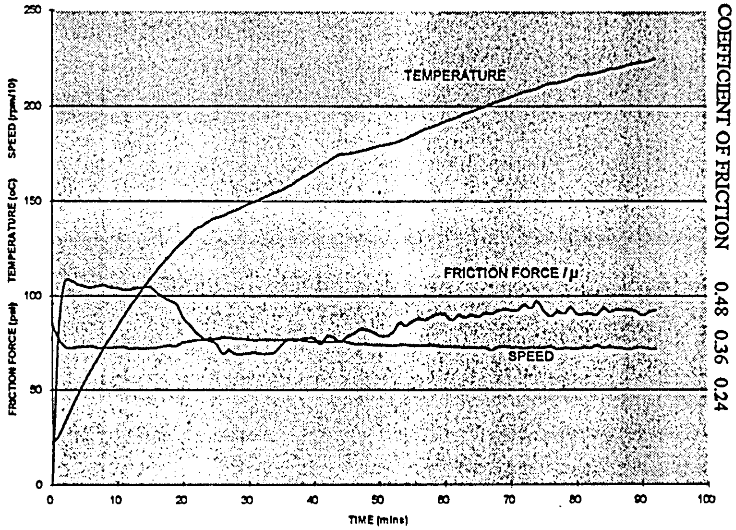
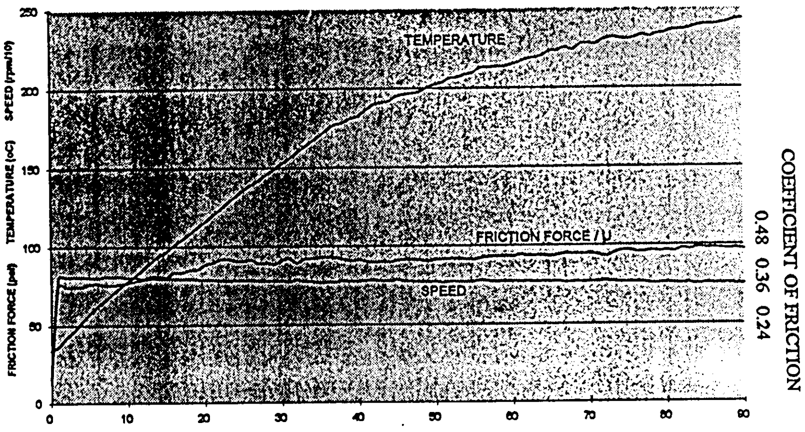
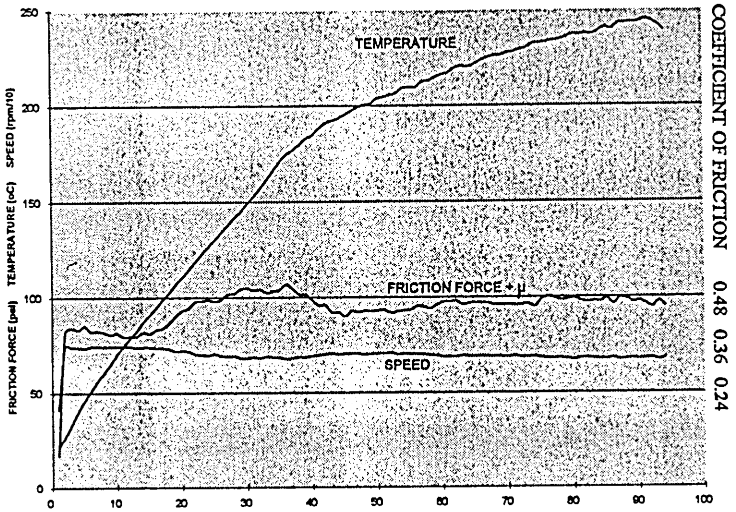


500 ALUMINA ABRASIVE

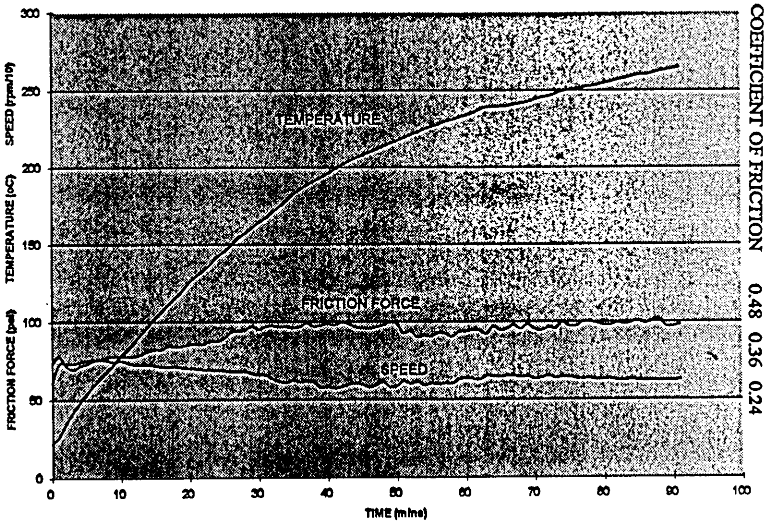
STANDARD CAST IRON F.A.S.T. DISC FRICTION MATERIAL 1/43
CONSTANT PRESSURE 40 psi



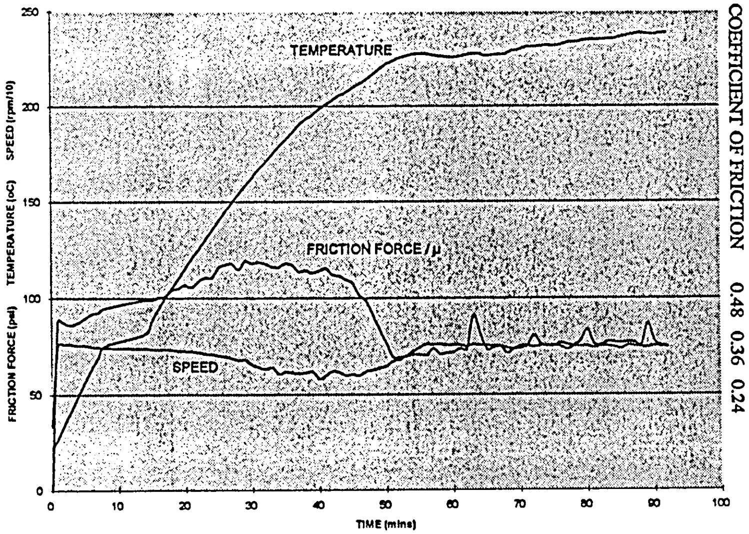
BASE FRICTION MATERIAL



1200 ALUMINA ABRASIVE



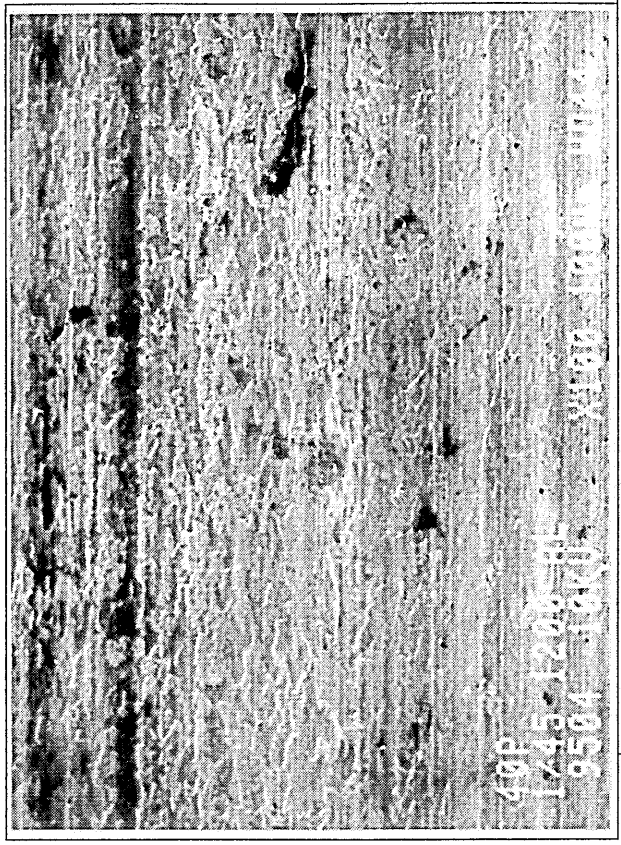
800 ALUMINA ABRASIVE

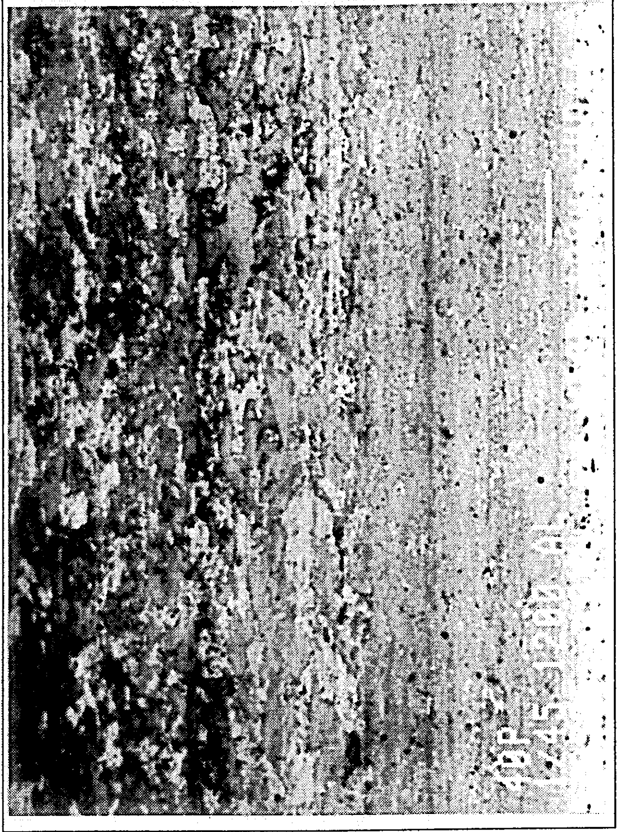


500 ALUMINA ABRASIVE

1/45 + 1200 ALUMINA x100 10 KV

SECONDARY ELECTRON IMAGE

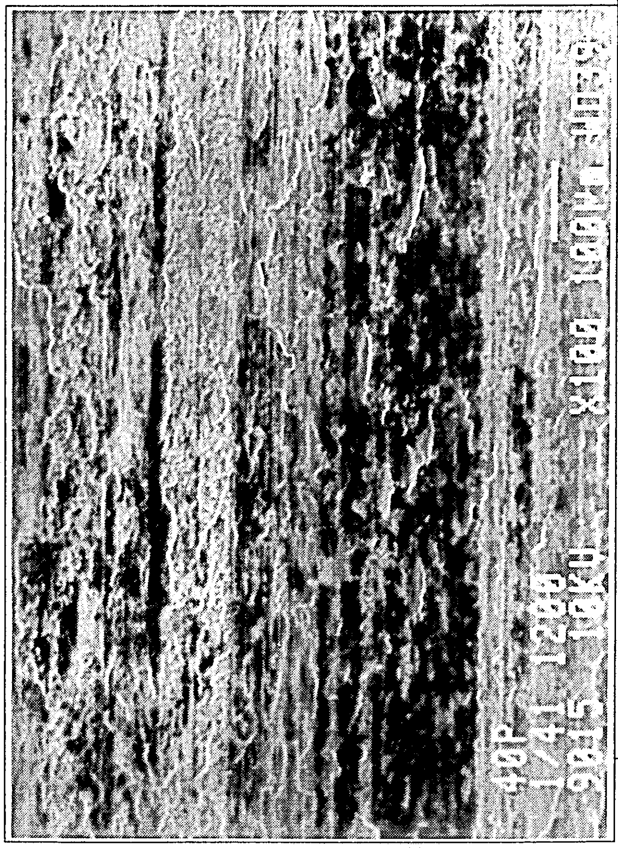




BACK-SCATTERED ELECTRON IMAGE

1/41 + 1200 ALUMINA x100 10 kV

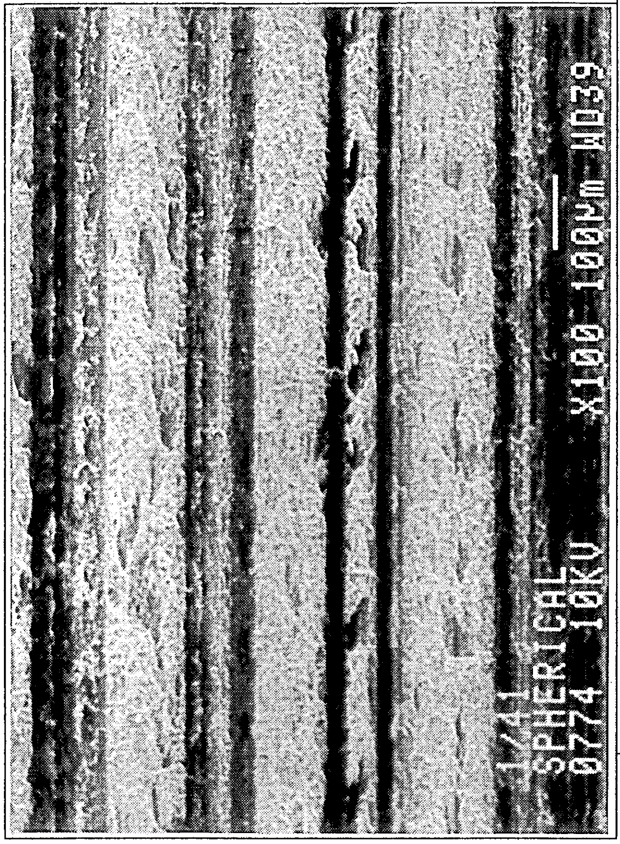
SECONDARY ELECTRON IMAGE

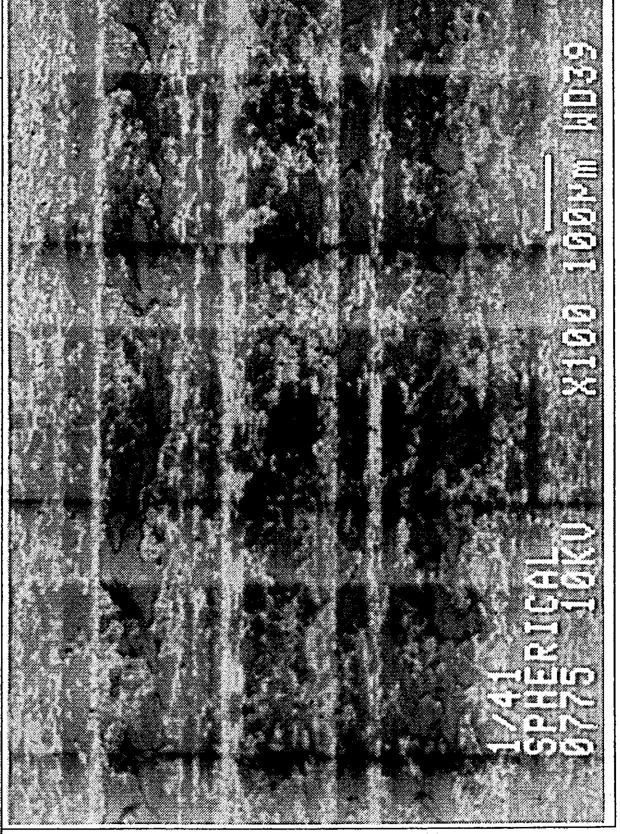


BACK-SCATTERED ELECTRON IMAGE

1/41 + SPHERICAL CHROMIC x100 10 kV

SECONDARY ELECTRON IMAGE

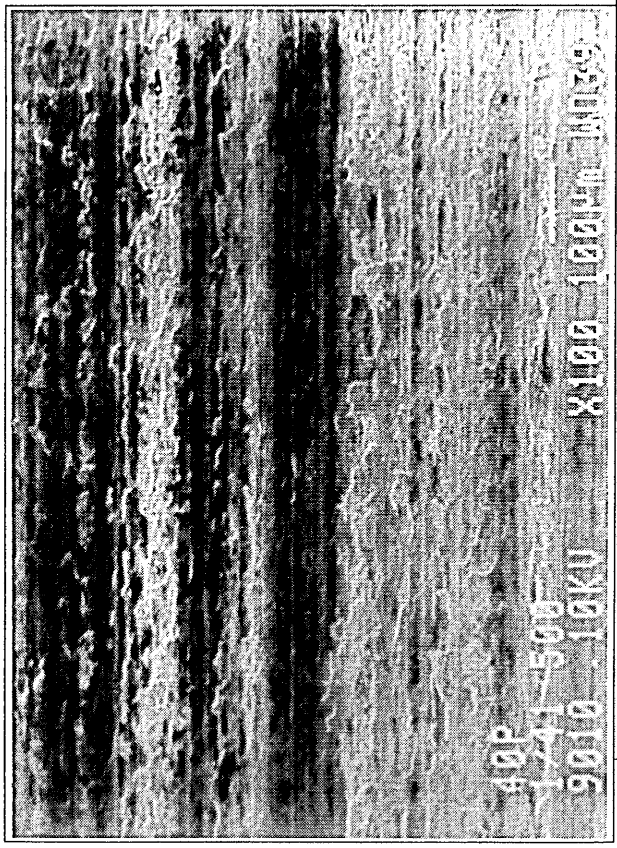




BACK-SCATTERED ELECTRON IMAGE

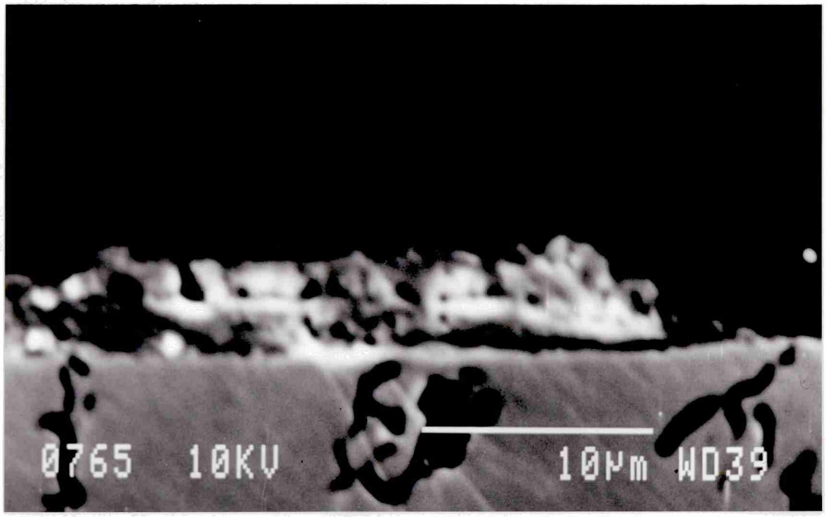
1/41 + 500 ALUMINA x100 10 kV

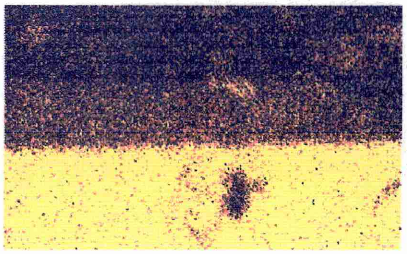
SECONDARY ELECTRON IMAGE

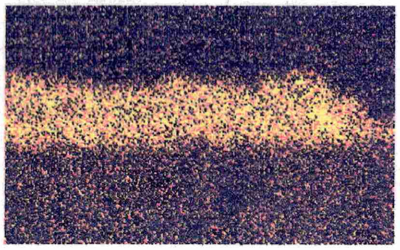


BACK-SCATTERED ELECTRON IMAGE

FRICTION MATERIAL 1/41 + 1200 ALUMINA
CROSS SECTION
10 KV x750




IRON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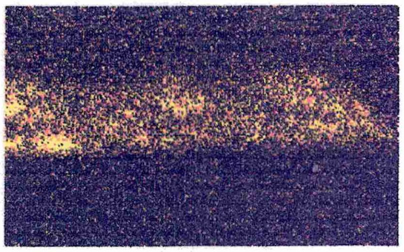
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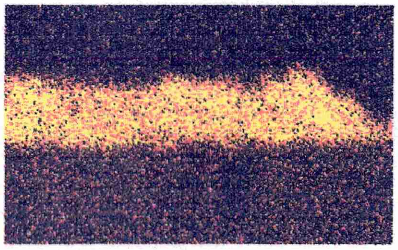
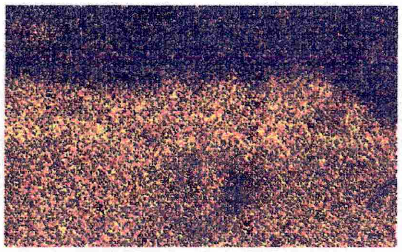
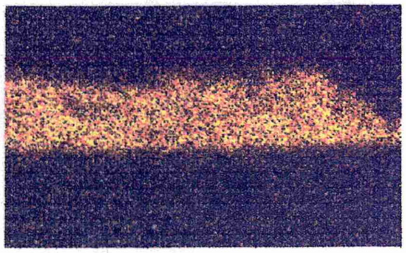
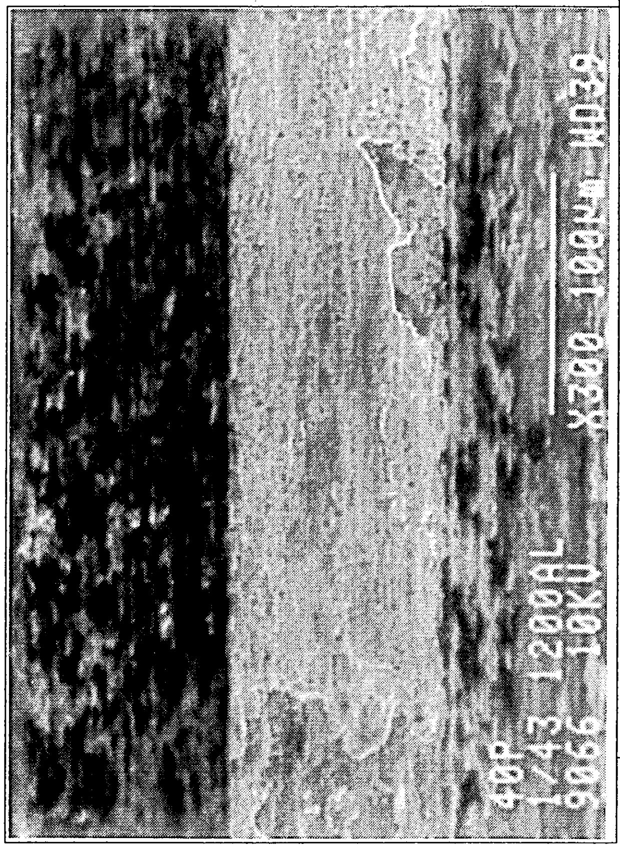

SULPHUR

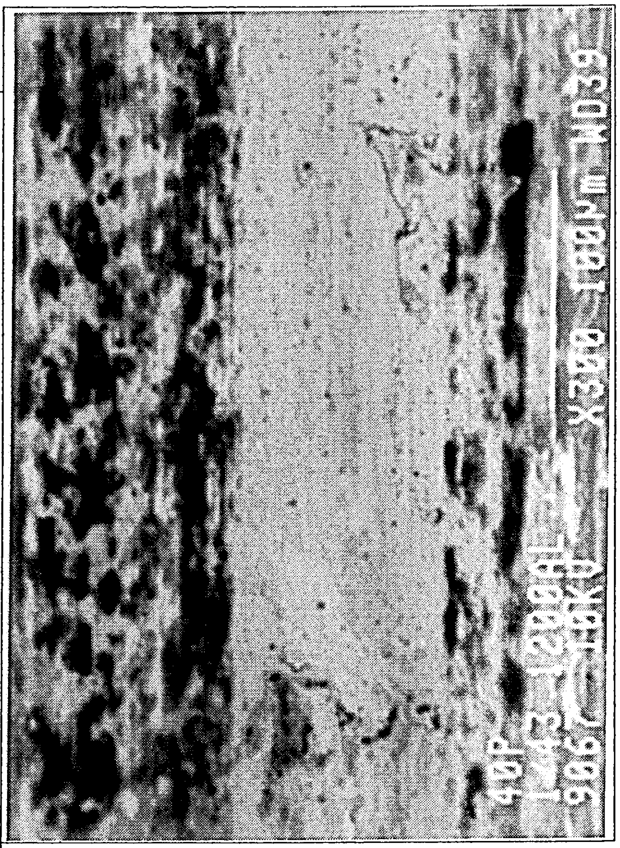

SILICON


OXYGEN

1/43 + 1200 ALUMINA x300 10 KV

SECONDARY ELECTRON IMAGE

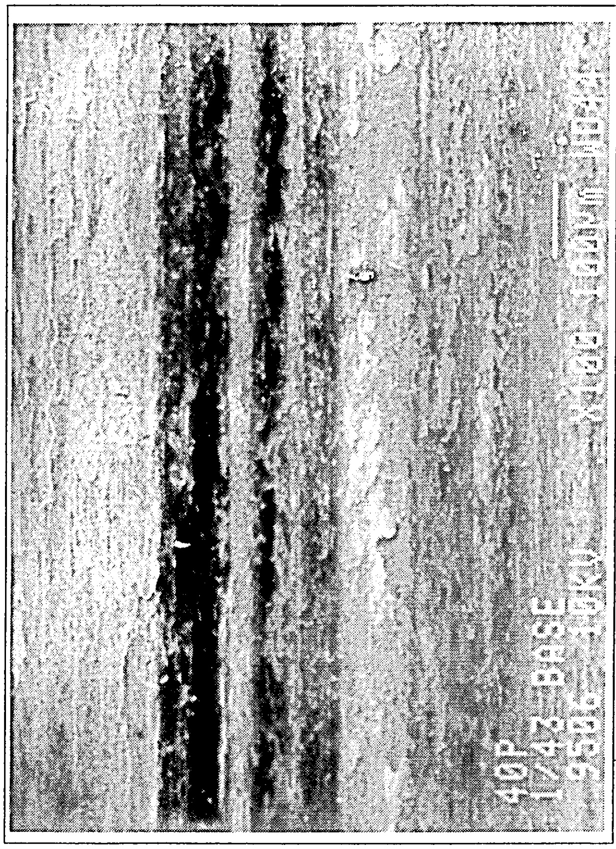


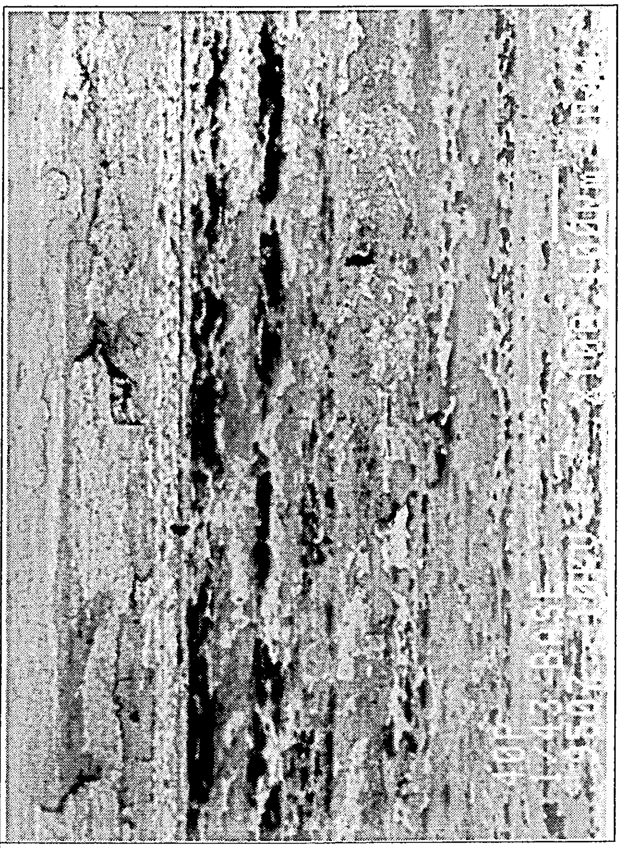


BACK-SCATTERED ELECTRON IMAGE

1/43 BASE MATERIAL x100 10 KV

SECONDARY ELECTRON IMAGE

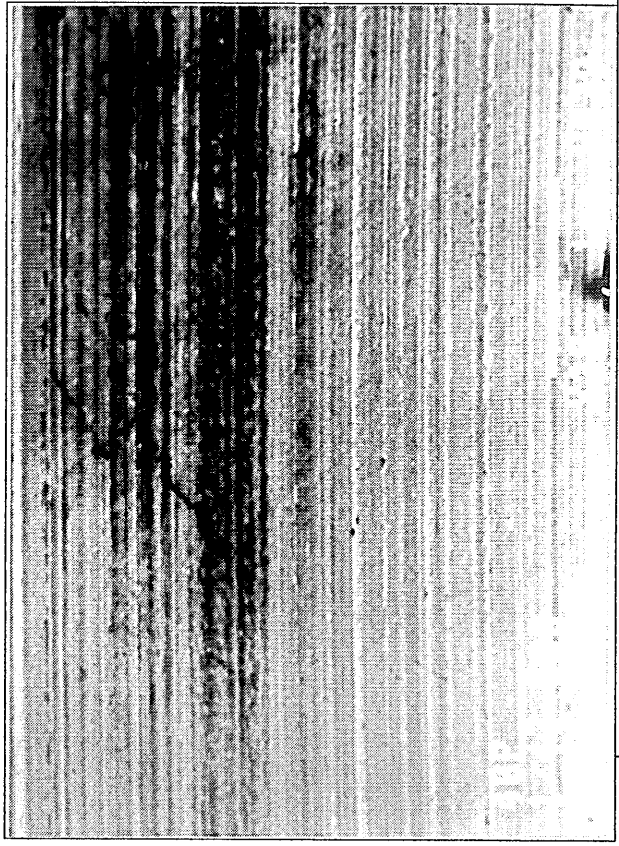


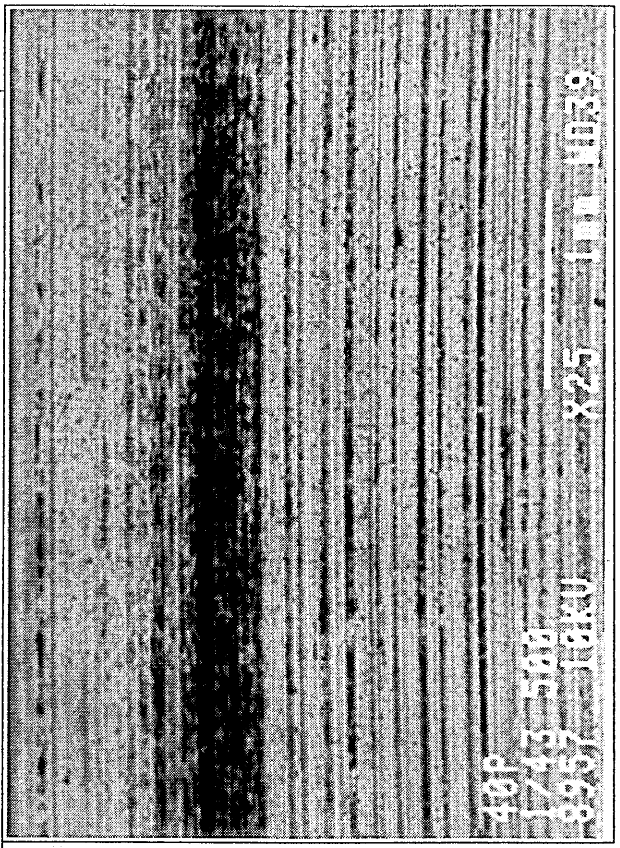


BACK-SCATTERED ELECTRON IMAGE

1/43 + 500 ALUMINA x25 10 KV

SECONDARY ELECTRON IMAGE

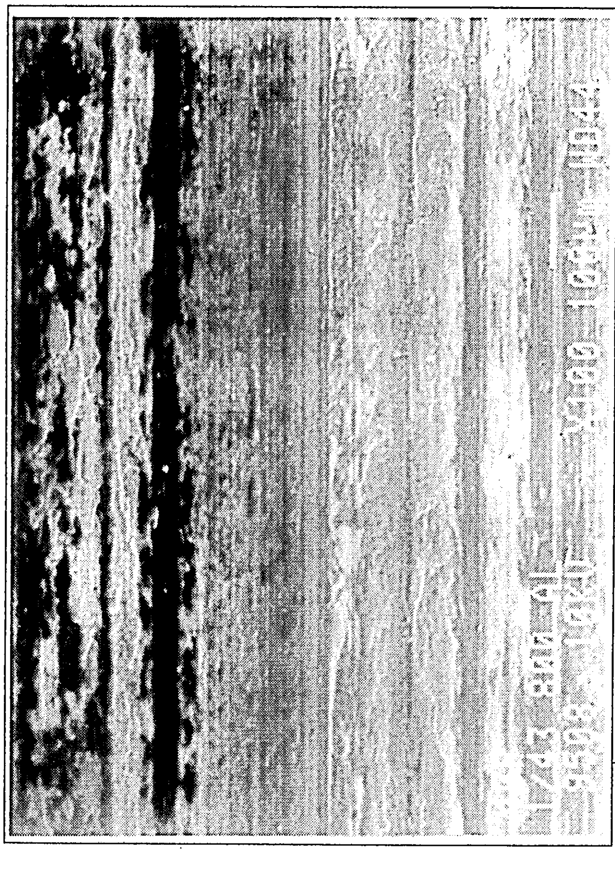


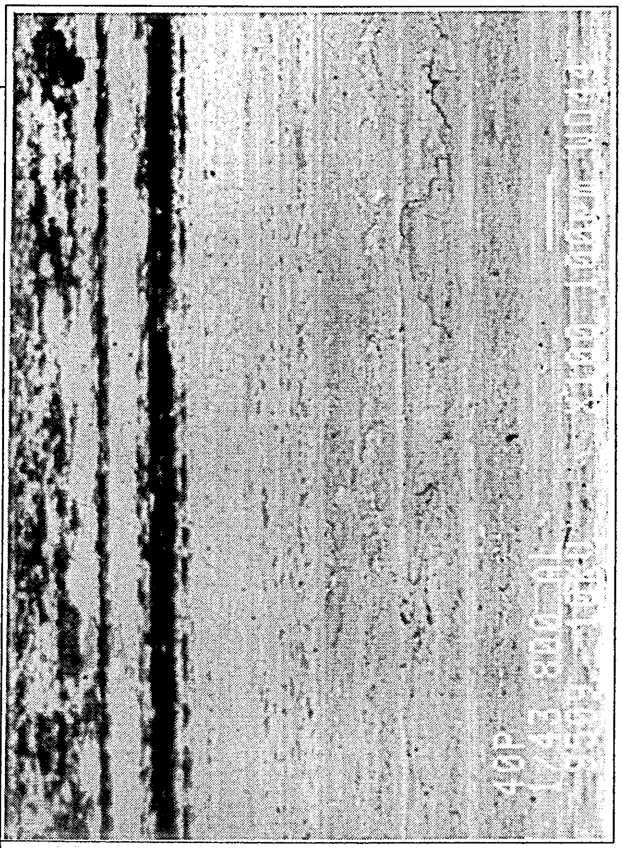


BACK-SCATTERED ELECTRON IMAGE

1/43 + 800 ALUMINA x100 10 KV

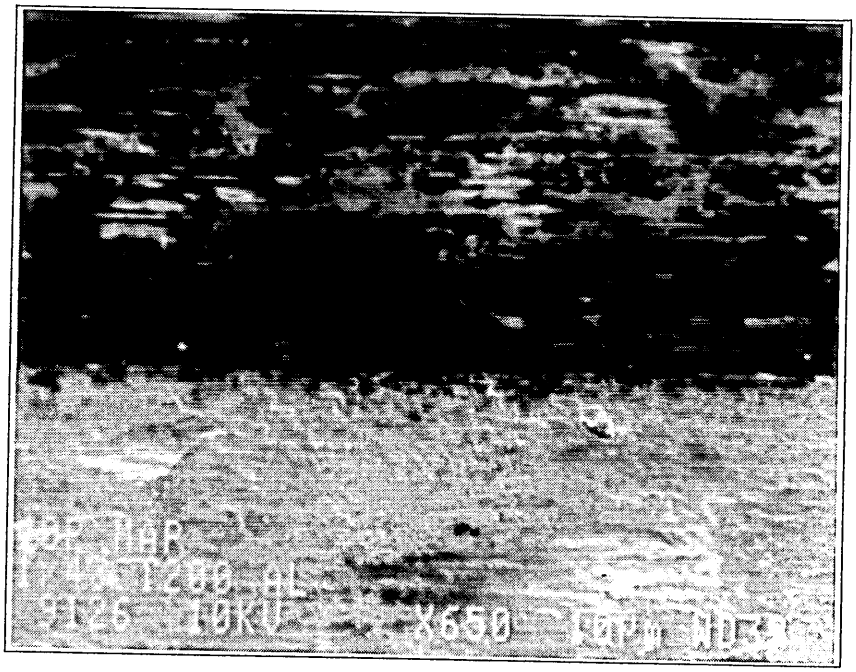
SECONDARY ELECTRON IMAGE



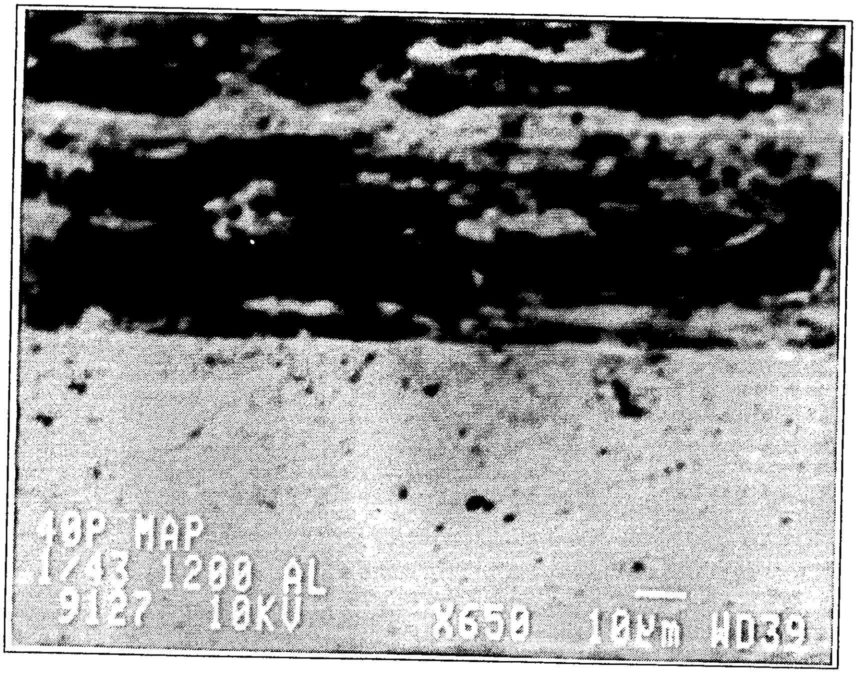


BACK-SCATTERED ELECTRON IMAGE

MATERIAL 1/43 + 1200 ALUMINA
MAPPED AREA
10 KV x650
PHOTO NUMBER 9126

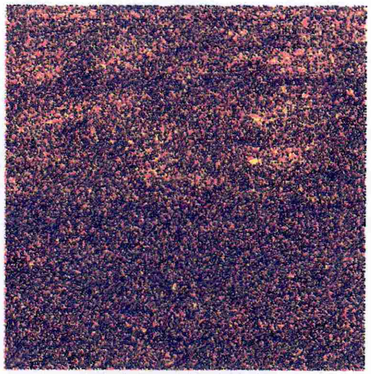


SECONDARY ELECTRON IMAGE

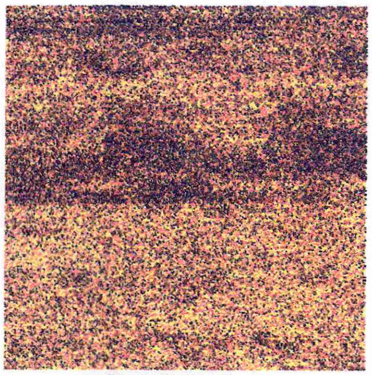


BACK-SCATTERED IMAGE

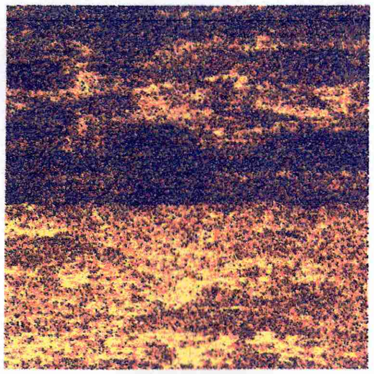
FRICTION MATERIAL 1/43 + 1200 ALUMINA
PHOTO 9126
10 KV x650



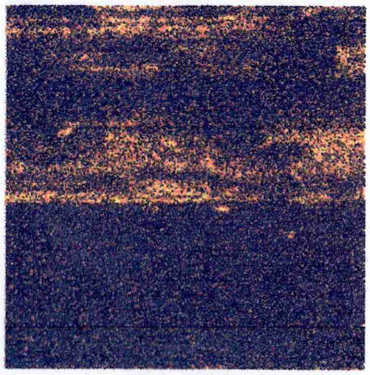
ALUMINIUM



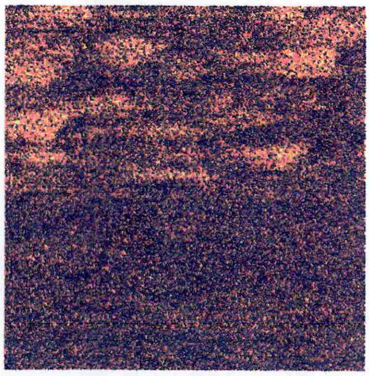
BARIUM



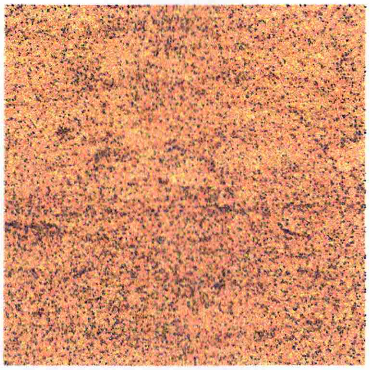
COPPER



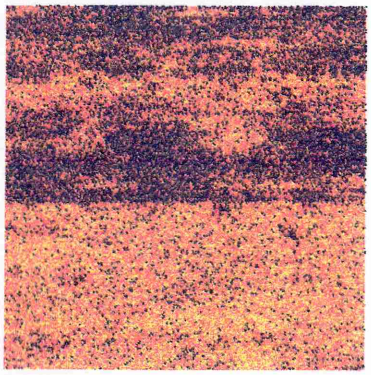
IRON



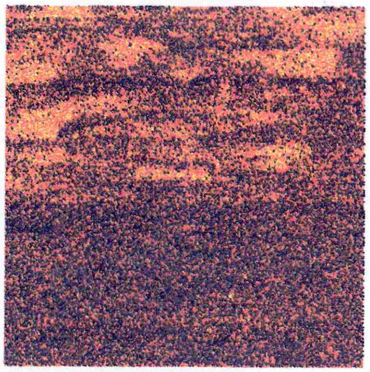
MAGNESIUM



OXYGEN



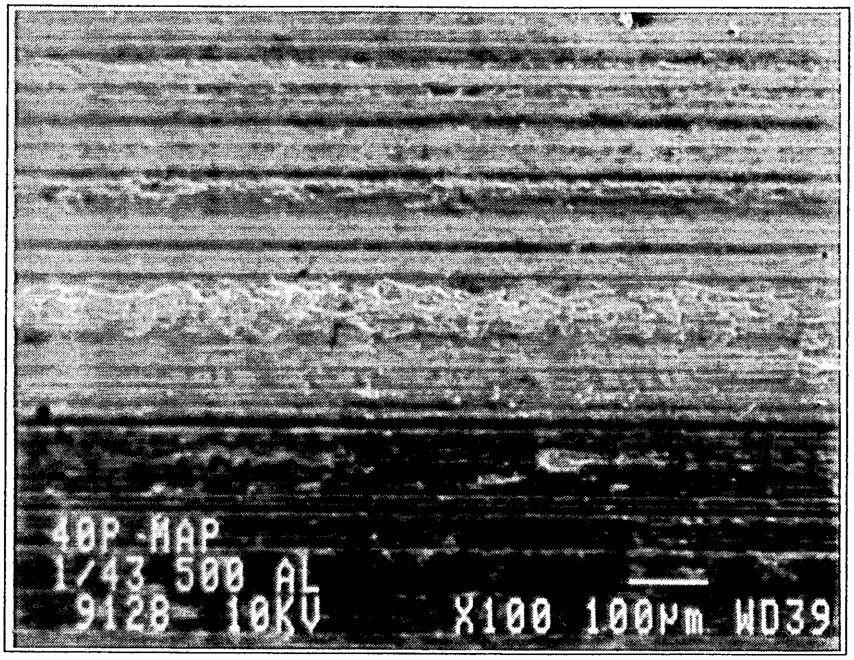
SULPHUR



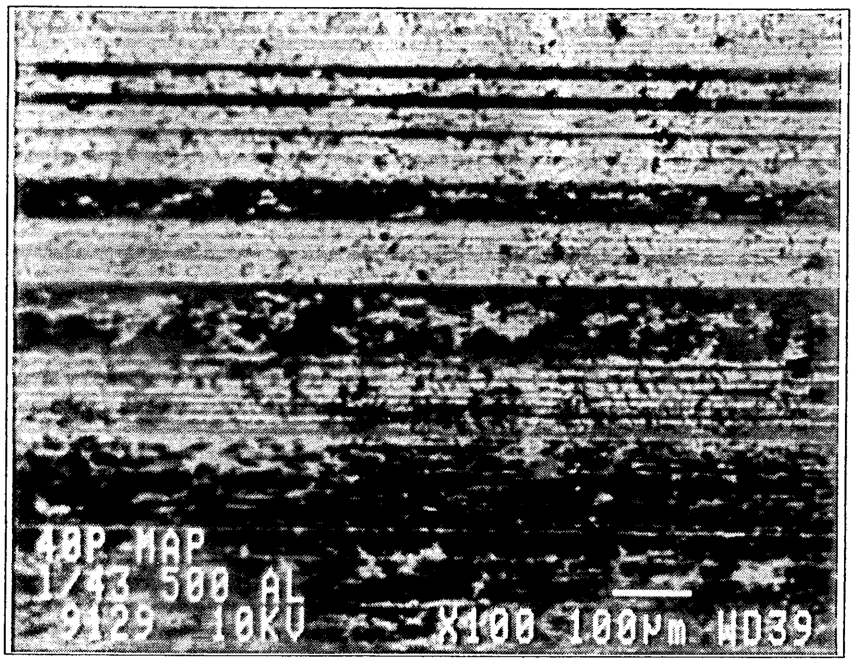
SILICON

A2·10b

MATERIAL 1/43 + 500 ALUMINA
MAPPED AREA
10 KV   x100
PHOTO NUMBER 9128



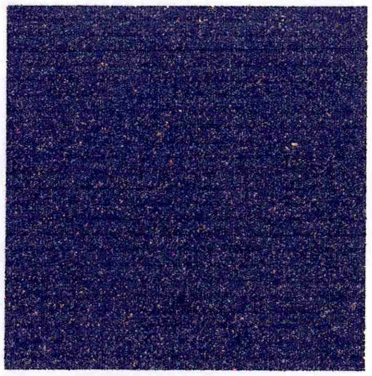
SECONDARY ELECTRON IMAGE

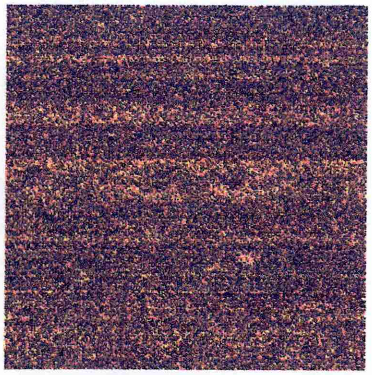


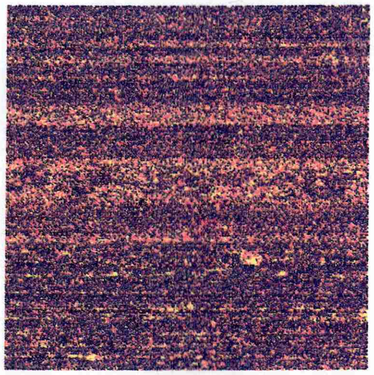
BACK-SCATTERED IMAGE

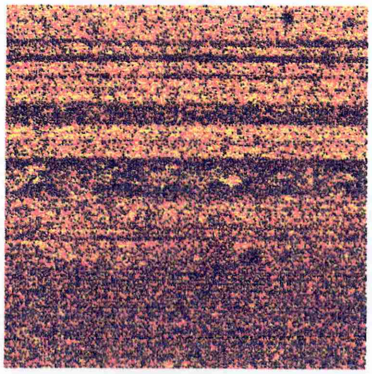
A2.11 a

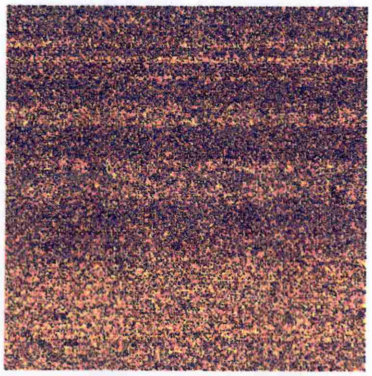
FRICTION MATERIAL 1/43 + 500 ALUMINA
PHOTO 9128
10 KV x100

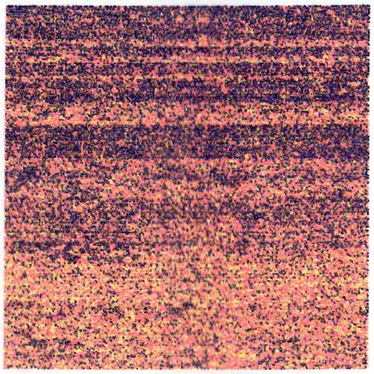

ALUMINIUM


BARIUM


COPPER


IRON


MAGNESIUM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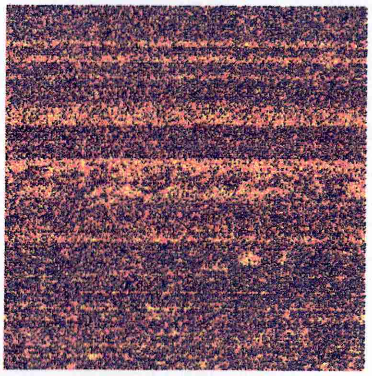
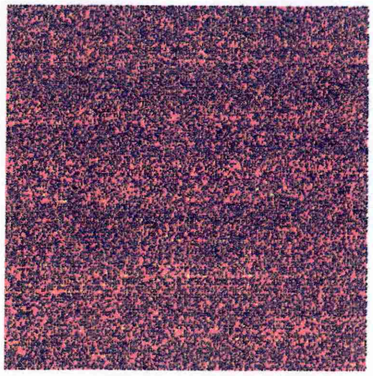

SULPHUR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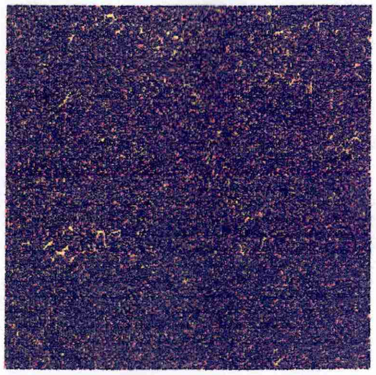
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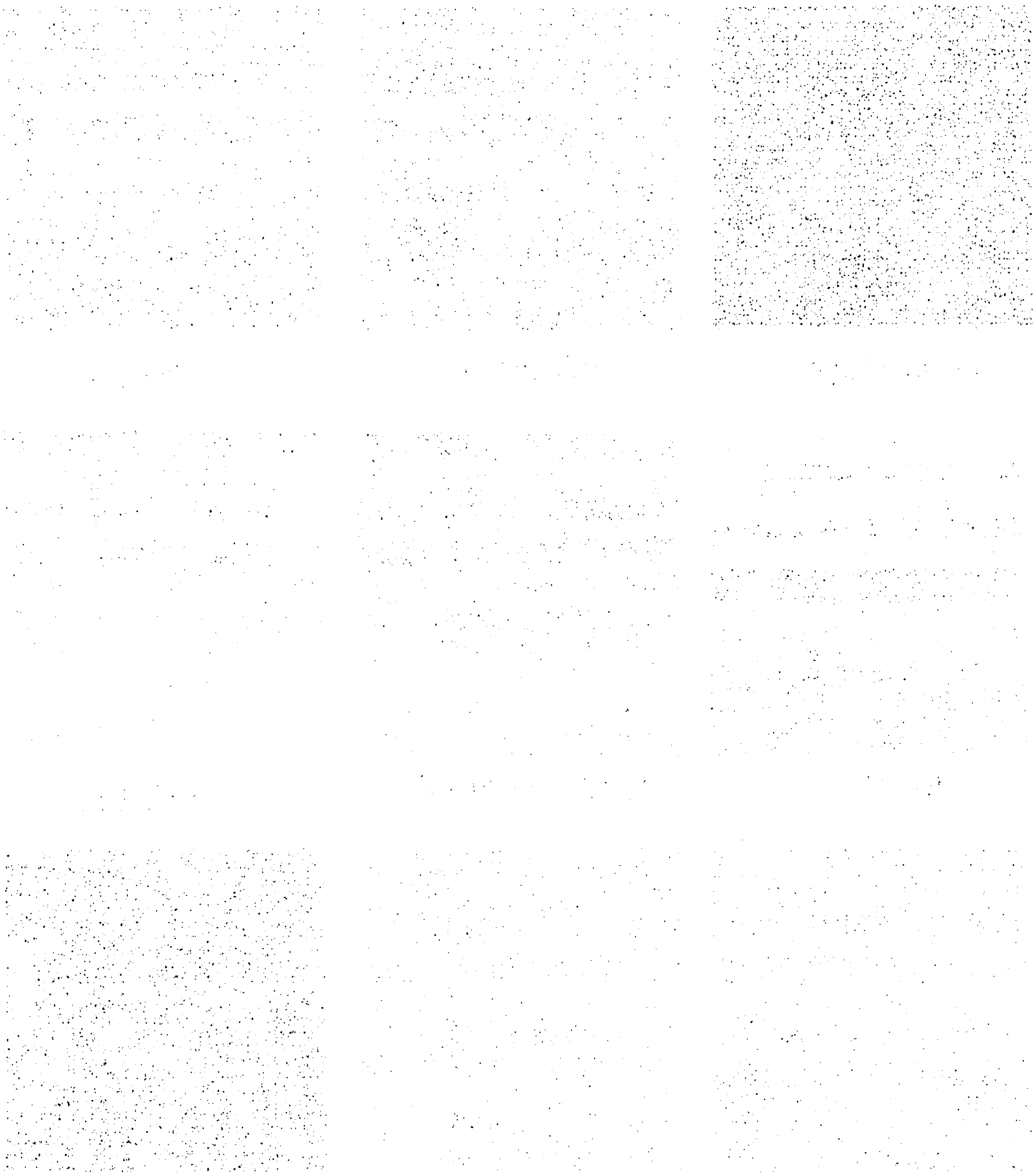
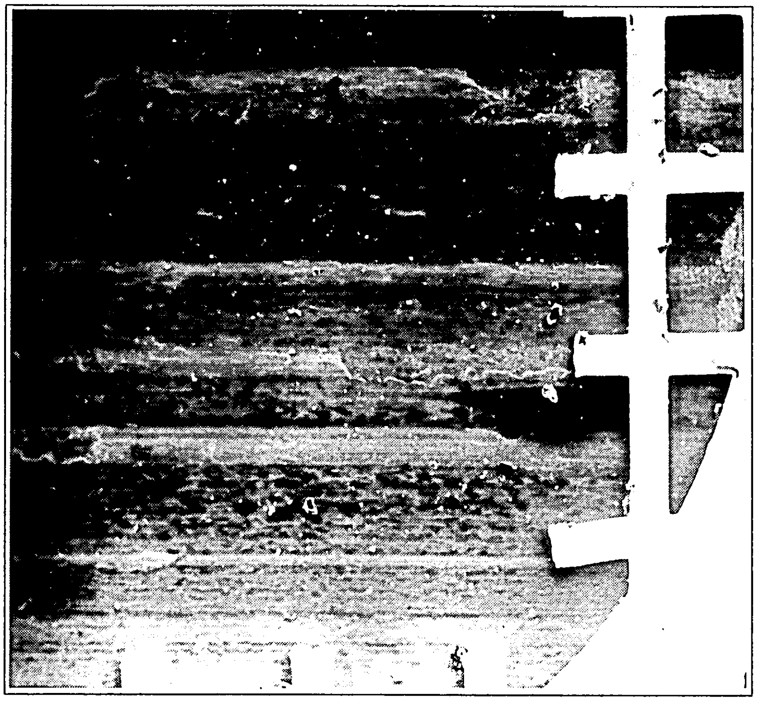


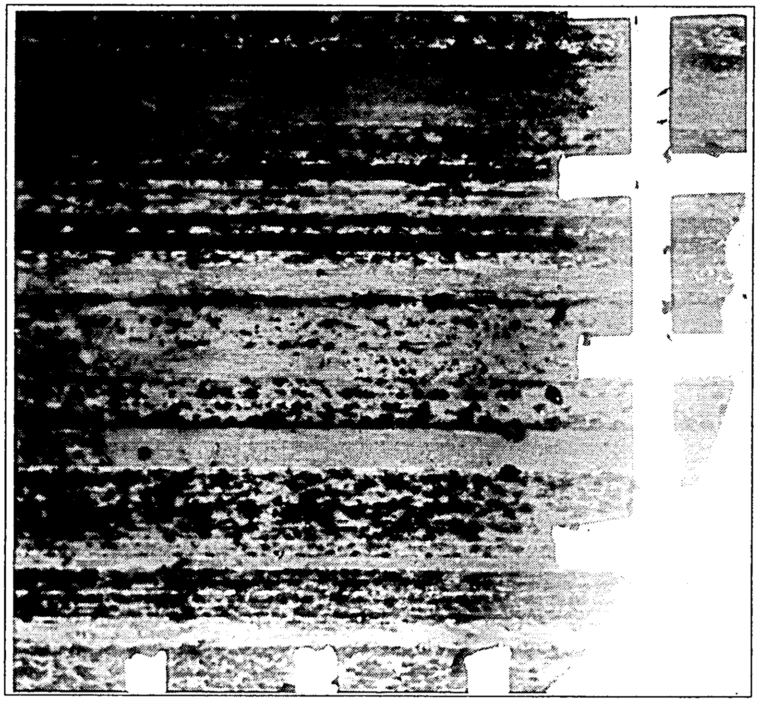
MATERIAL 1/43 + 1200 ALUMINA ABRASIVE

MAP AREA WITHIN GOLD GRID

10 KV x75



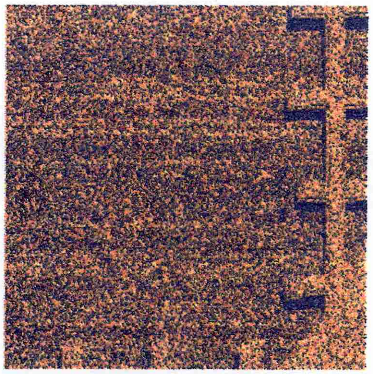
SECONDARY ELECTRON IMAGE

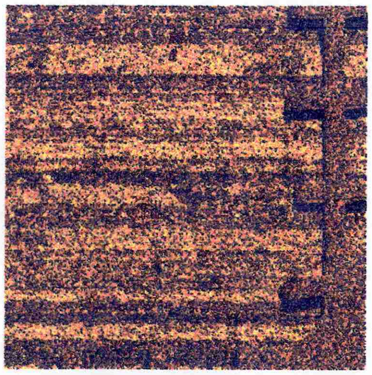


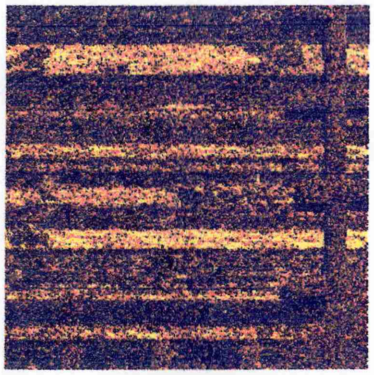
BACK-SCATTERED ELECTRON IMAGE

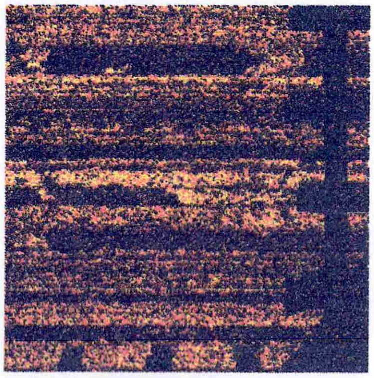
A2·12 a

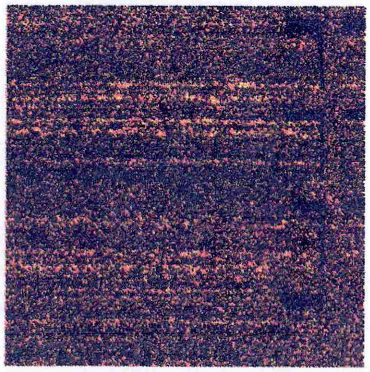
FRICTION MATERIAL 1/43 + 1200 ALUMINA
MAP AREA WITHIN GOLD GRID
10 KV x75

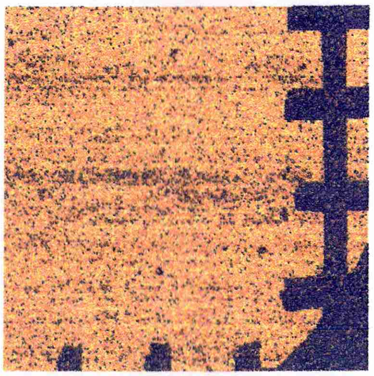

ALUMINIUM

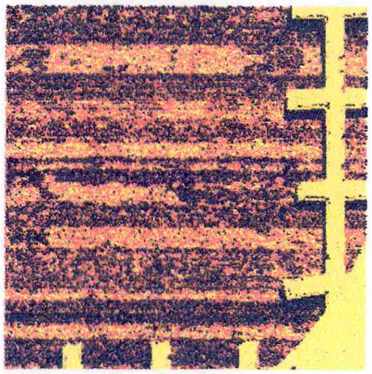

BARIUM

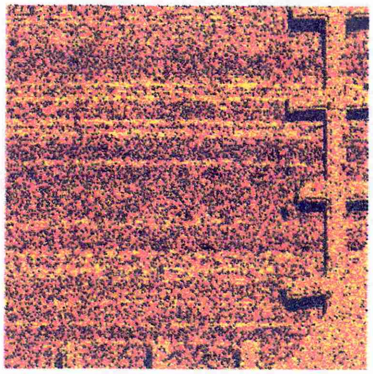

COPPER

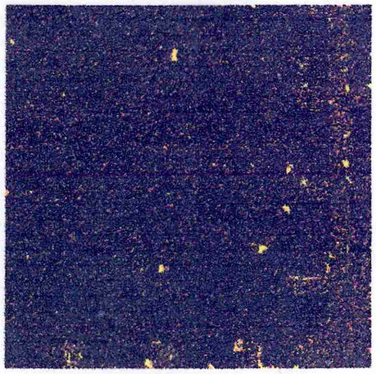

IRON

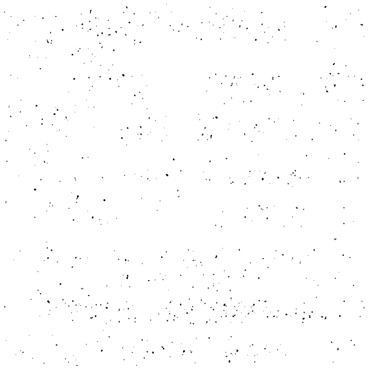

MAGNESIUM

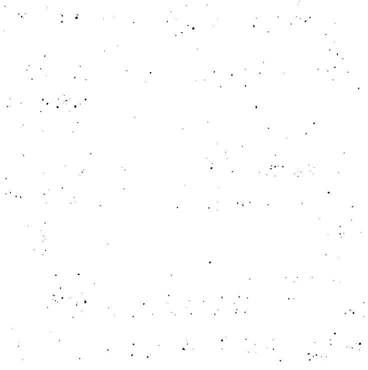

OXYGEN

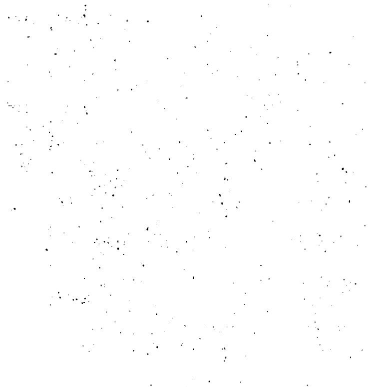

SULPHUR

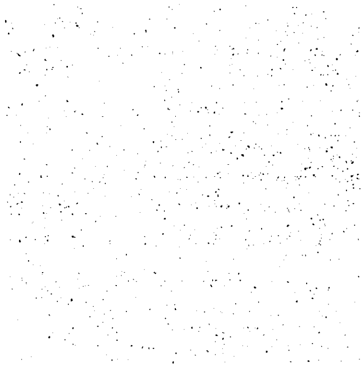

SILICON

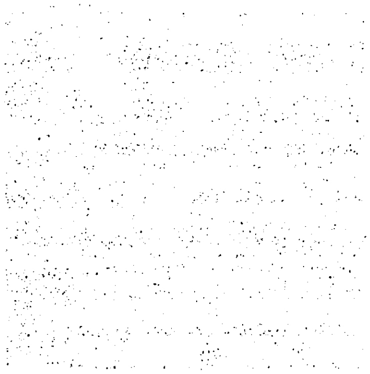

CARBON

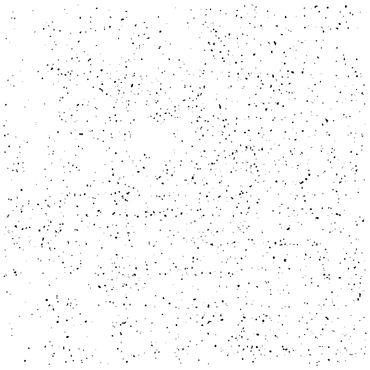


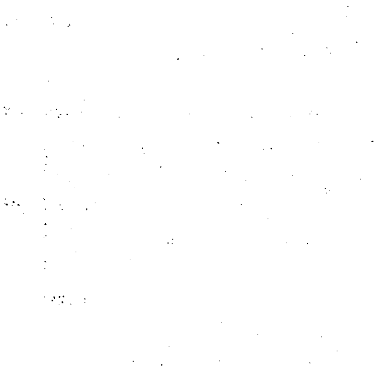










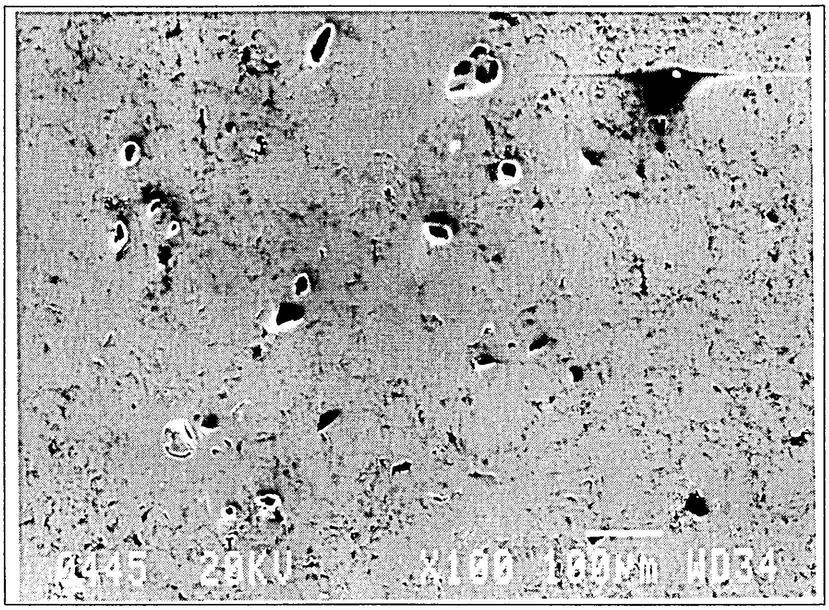


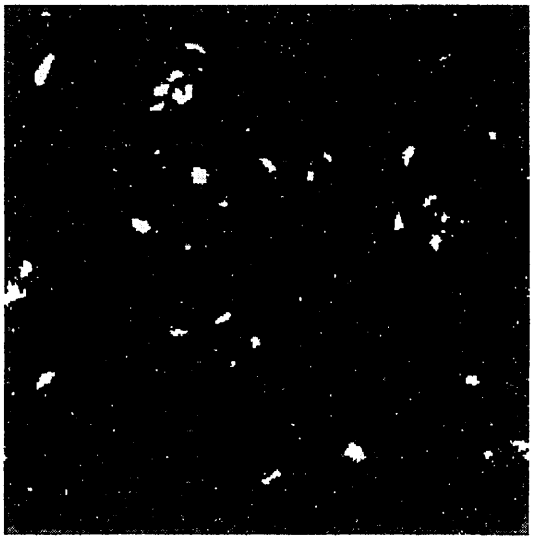
Appendix 3

Section 4.2.2 HIPAC coupled with 1/43

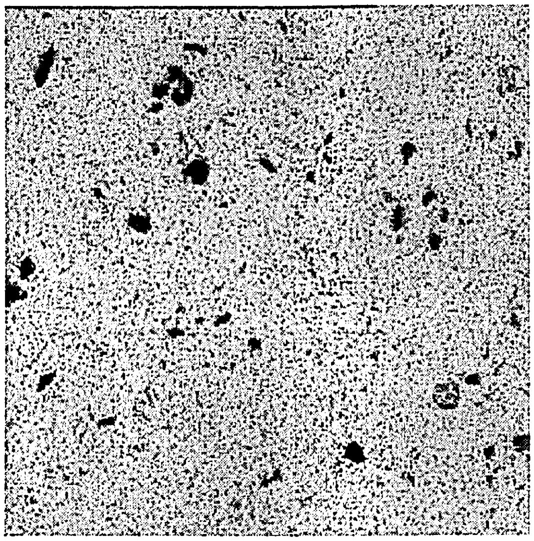
Section 4.2.4. HIPAC coupled with 4042F and M9238.

POLISHED SURFACE OF COPPER COATED PLUG
MAP x100 20 KV PHOTO 0445
POLISHED WITH DIAMOND PASTE

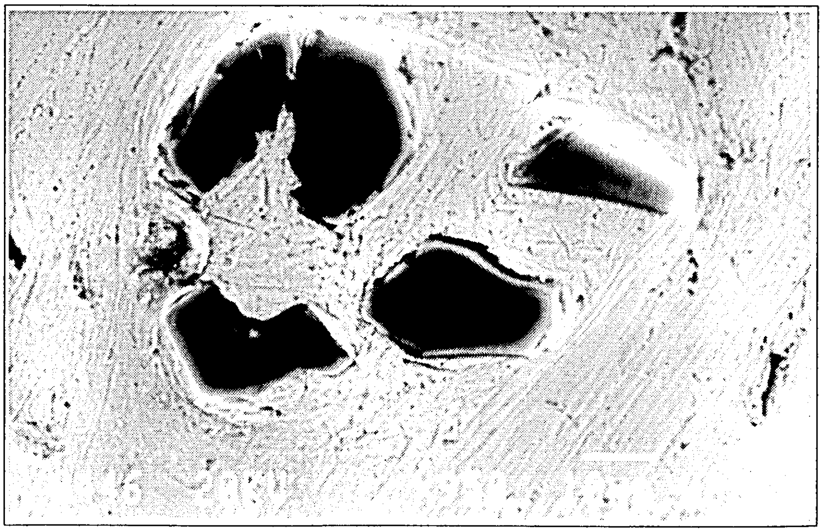




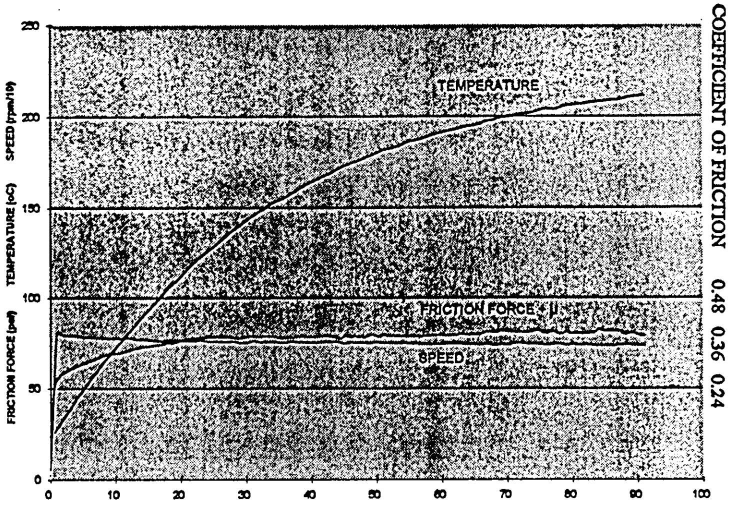
SILICON



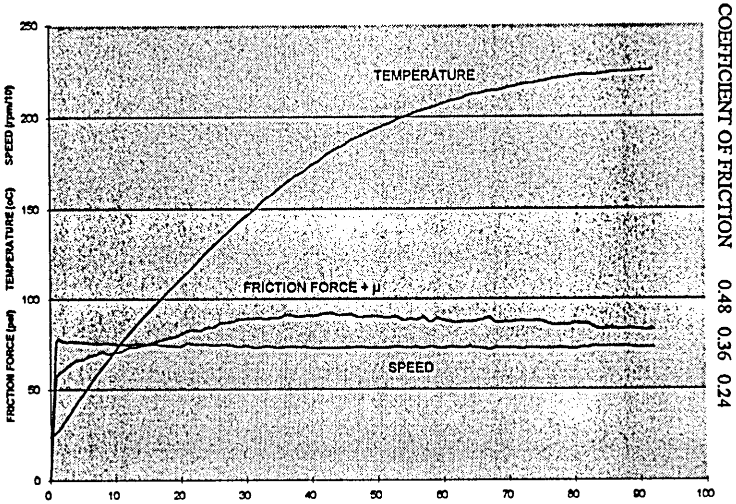
COPPER



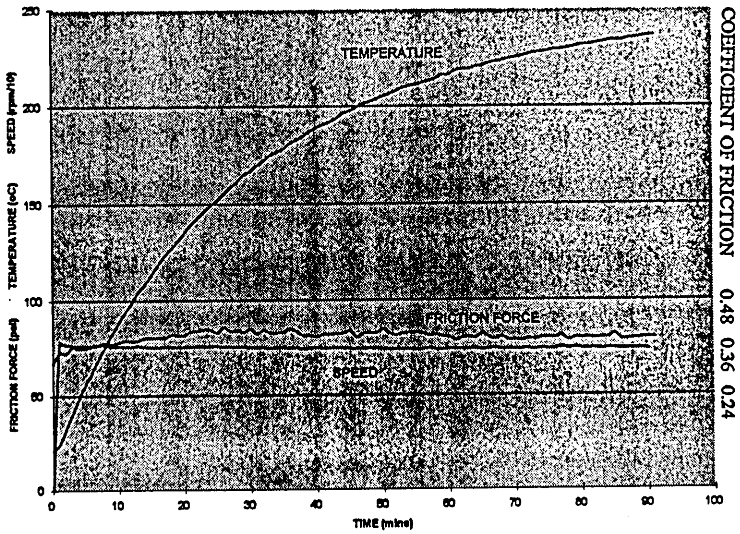
COPPER COATED ALUMINIUM F.A.S.T. DISC FRICTION MATERIAL 1/43
CONSTANT PRESSURE 40 psi



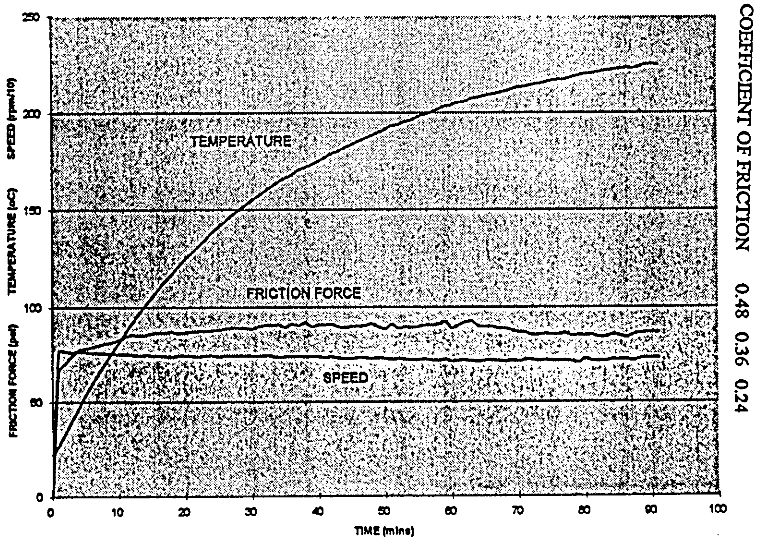
BASE FRICTION MATERIAL



1200 ALUMINA ABRASIVE

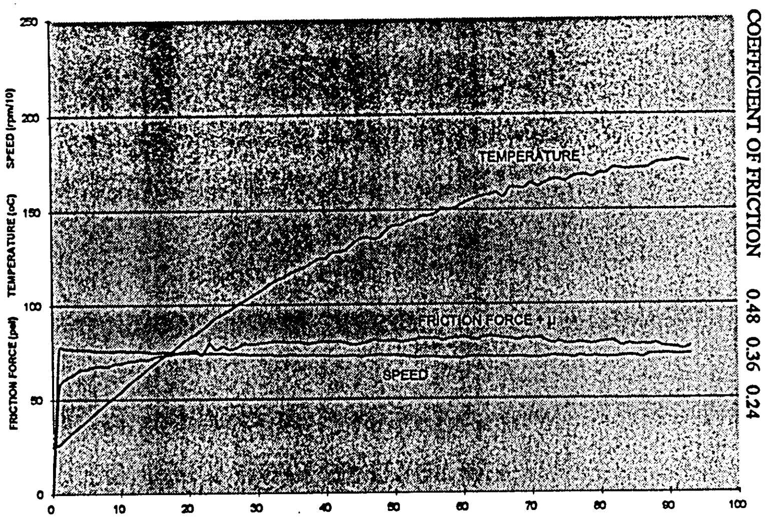


800 ALUMINA ABRASIVE

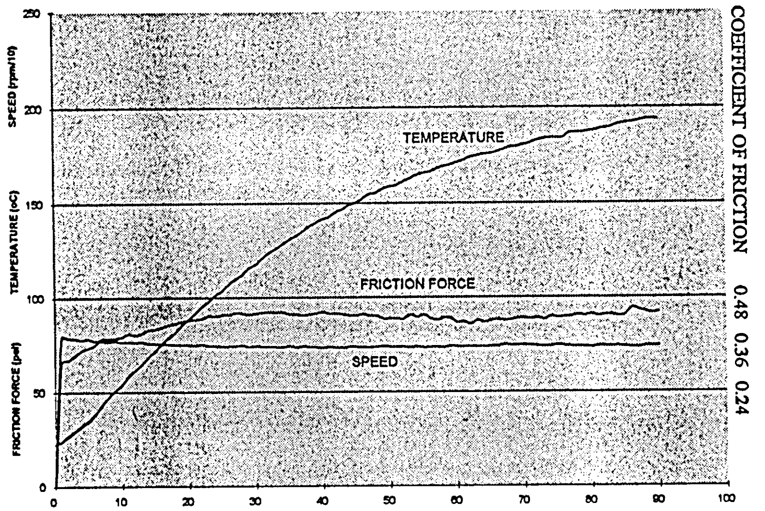


500 ALUMINA ABRASIVE

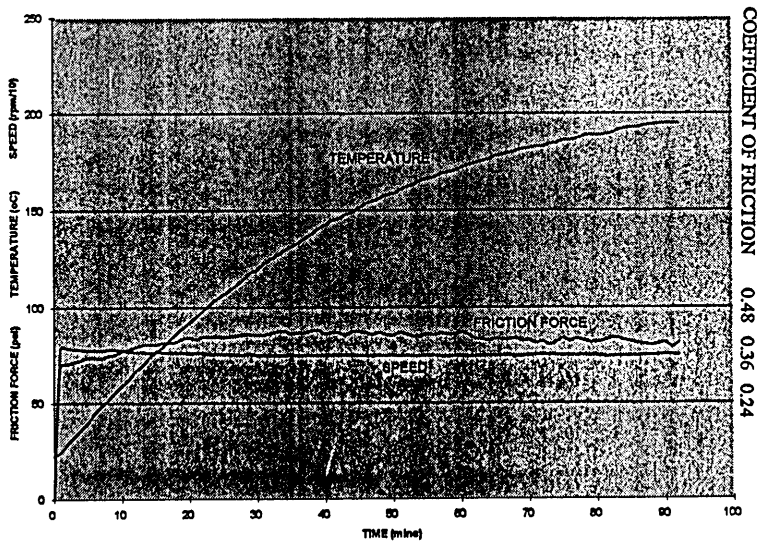
COPPER COATED CAST IRON F.A.S.T. DISC FRICTION MATERIAL 1/43
CONSTANT PRESSURE 40 psi



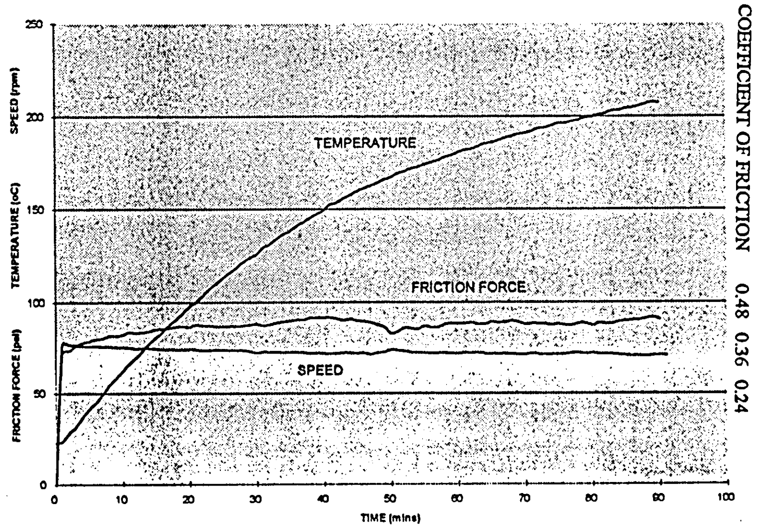
BASE FRICTION MATERIAL



1200 ALUMINA ABRASIVE

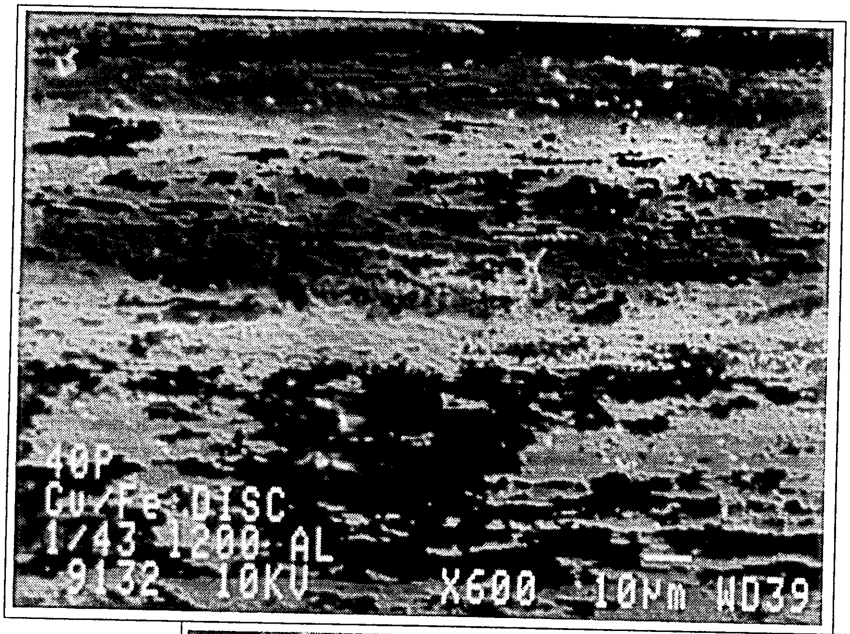


800 ALUMINA ABRASIVE

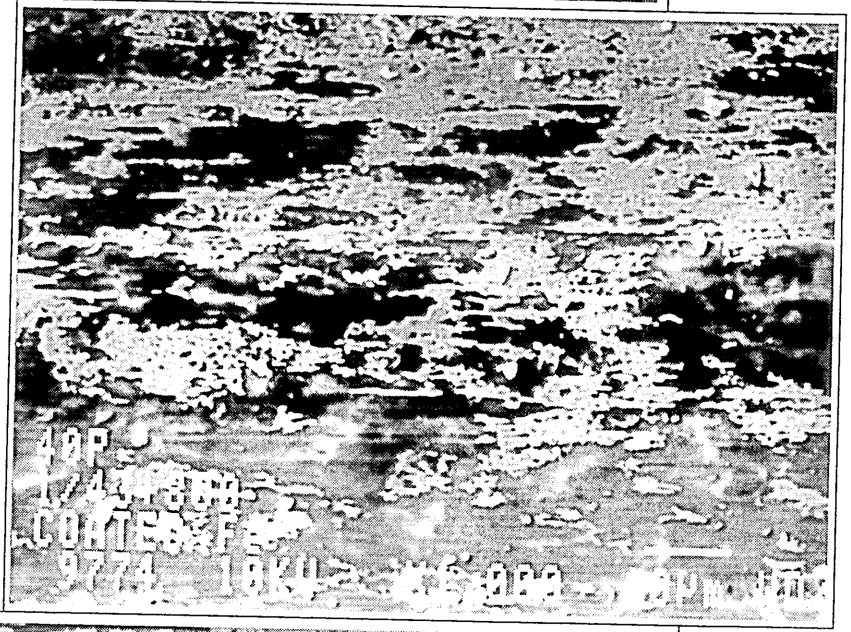


500 ALUMINA ABRASIVE

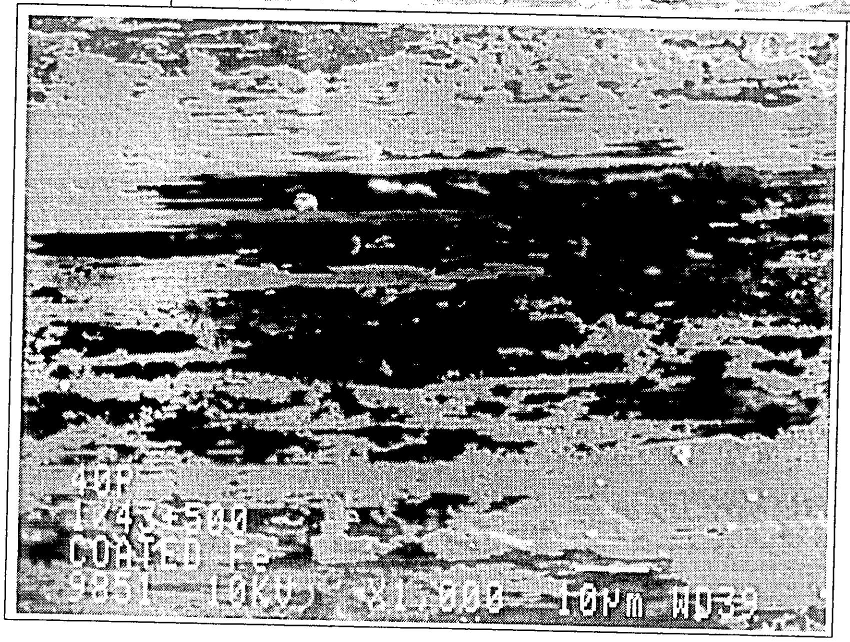
WORN SURFACE OF HIPAC COATED Fe DISC FRICTION MATERIAL 1/43



1200 ALUMINA x 600



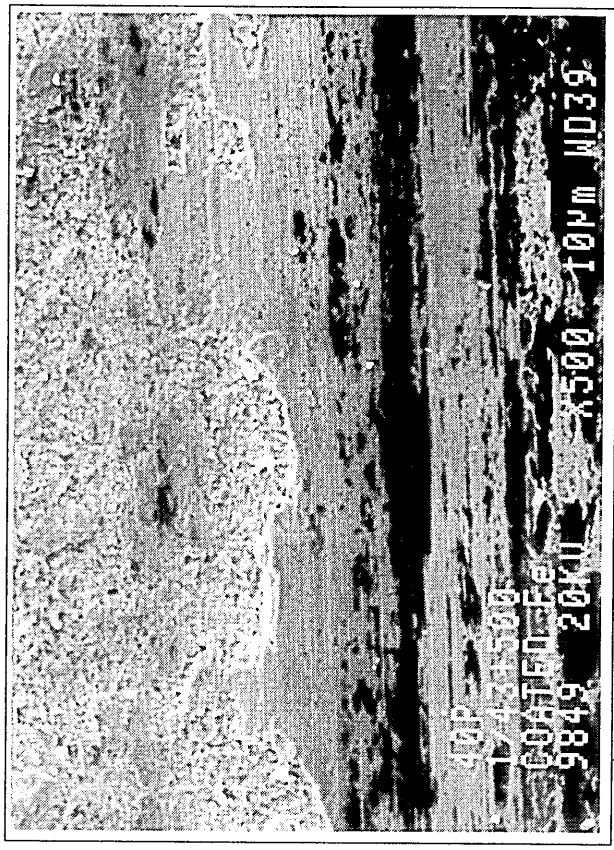
800 ALUMINA x 1000

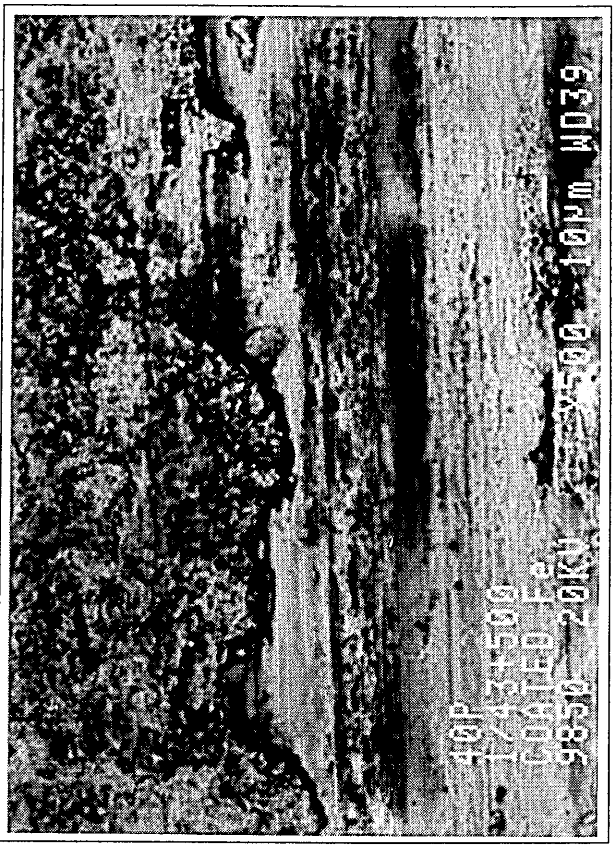


500 ALUMINA x 1000

1/43 + 500 ALUMINA Cu/Fe DISC x500 10 kV

SECONDARY ELECTRON IMAGE

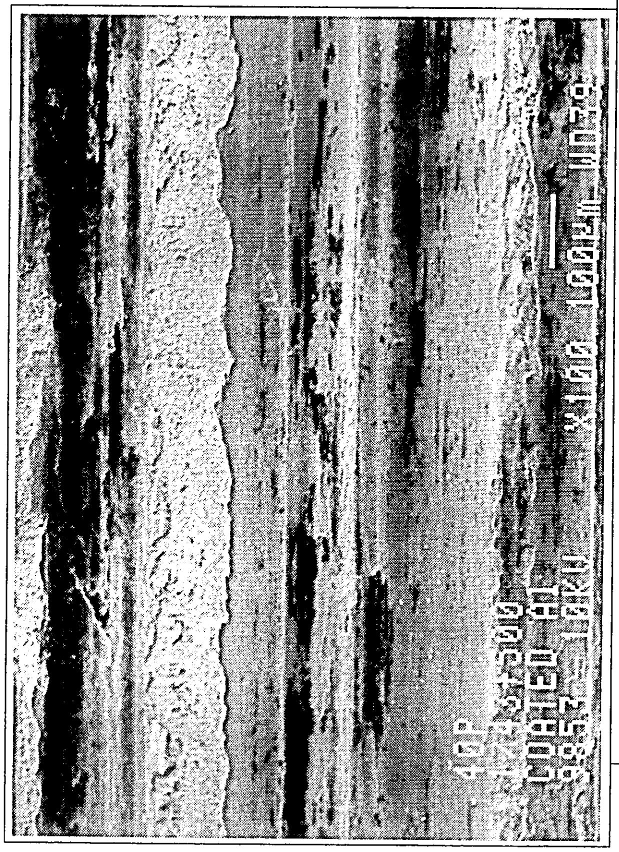


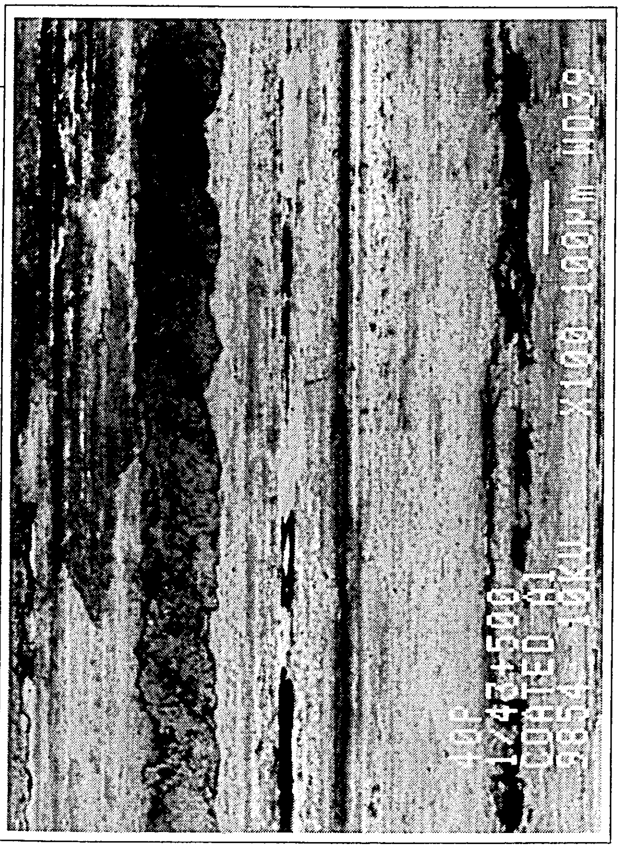


BACK-SCATTERED ELECTRON IMAGE

1/43 + 500 ALUMINA Cu/Al DISC x100 10 kV

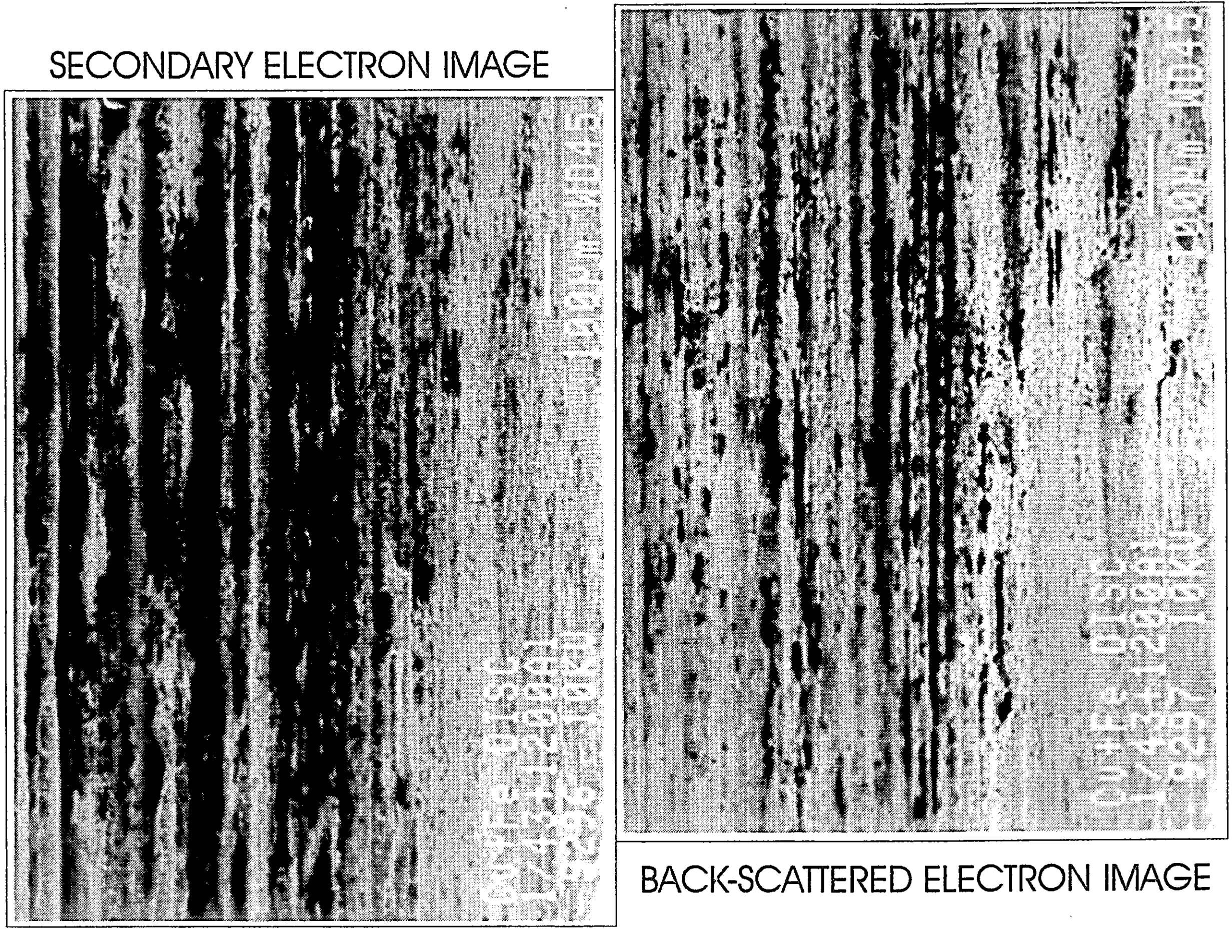
SECONDARY ELECTRON IMAGE





BACK-SCATTERED ELECTRON IMAGE

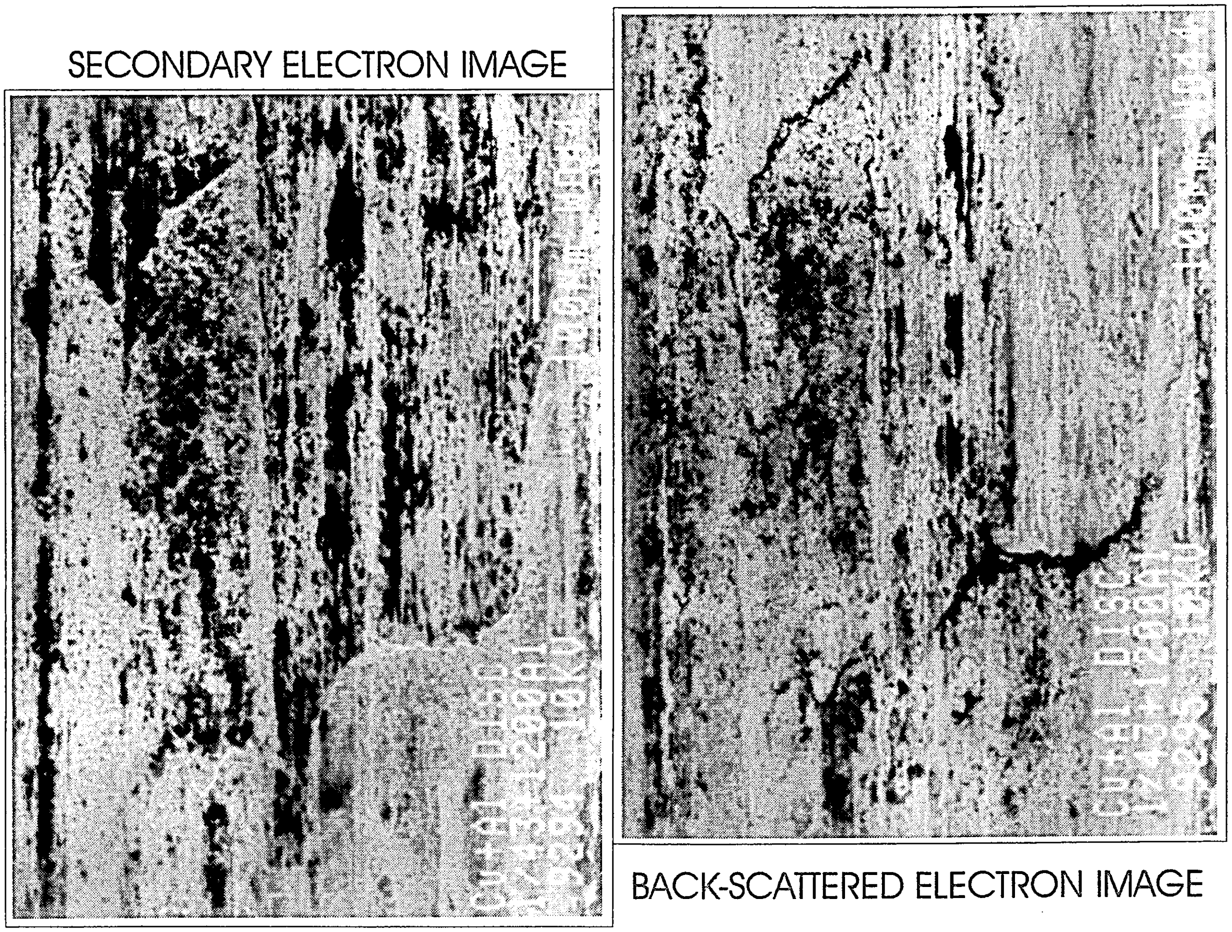
1/43 + 1200 ALUMINA Cu/Fe DISC x100 MAP AREA



SECONDARY ELECTRON IMAGE

BACK-SCATTERED ELECTRON IMAGE

1/43 + 1200 ALUMINA Cu/Al DISC x100 MAP AREA

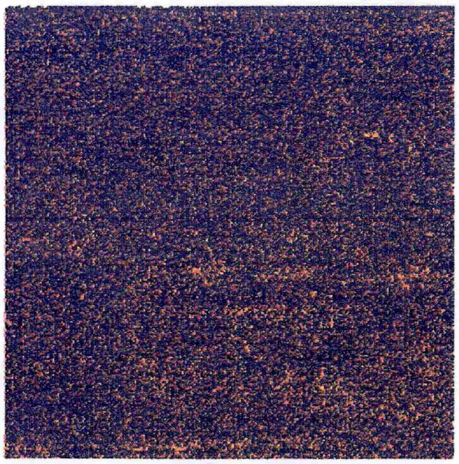


SECONDARY ELECTRON IMAGE

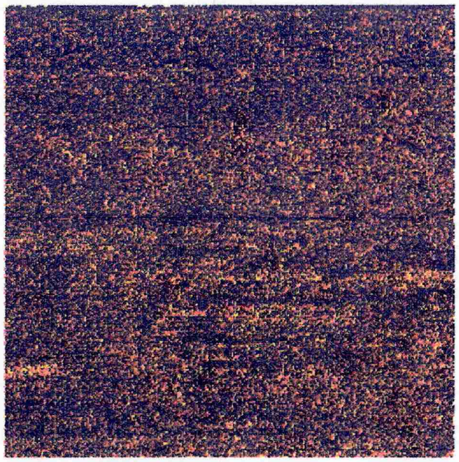
BACK-SCATTERED ELECTRON IMAGE

COPPER COATED ALUMINIUM DISC SURFACE MAP

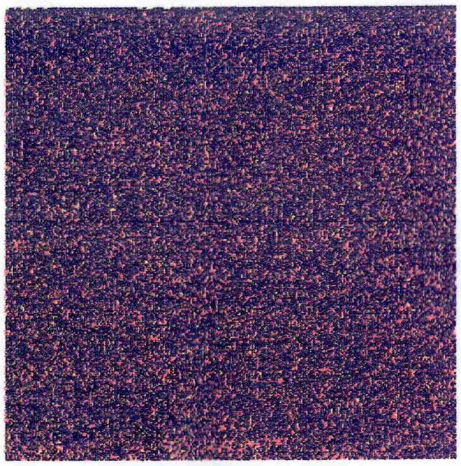
X100 10KV PHOTO 9294 MATERIAL 1/43 + 1200 Al 40psi



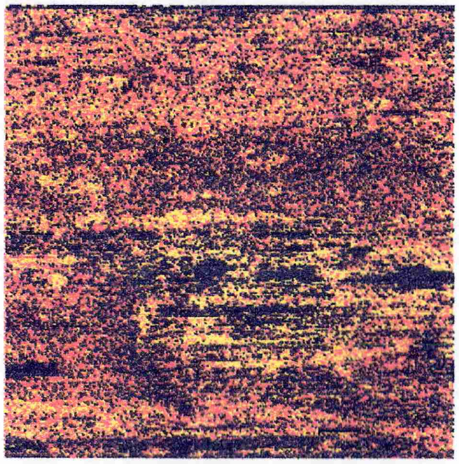
ALUMINIUM



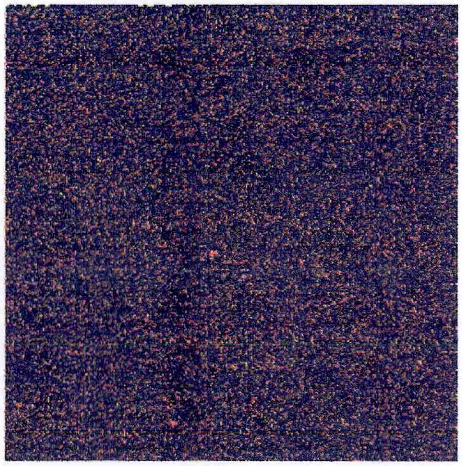
BARIUM



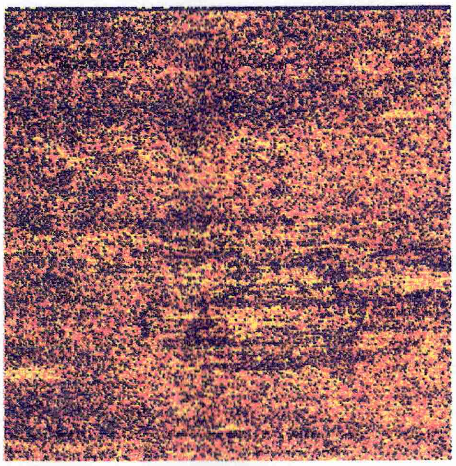
CALCIUM



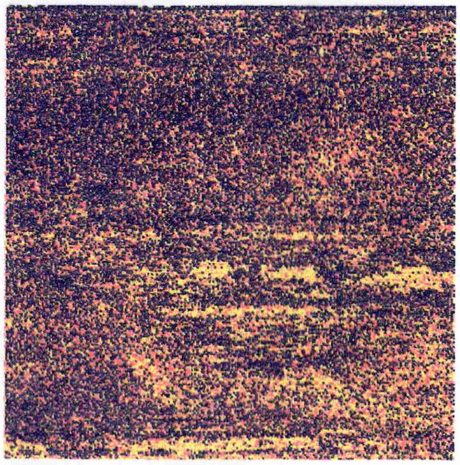
COPPER



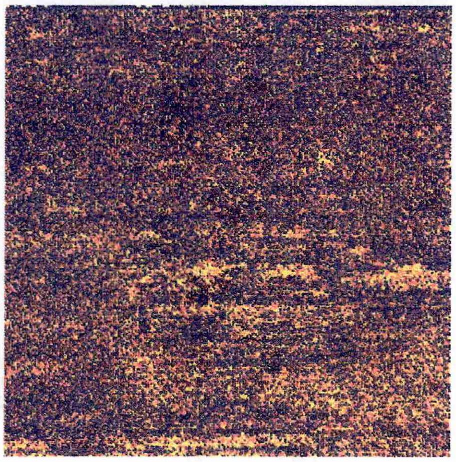
IRON



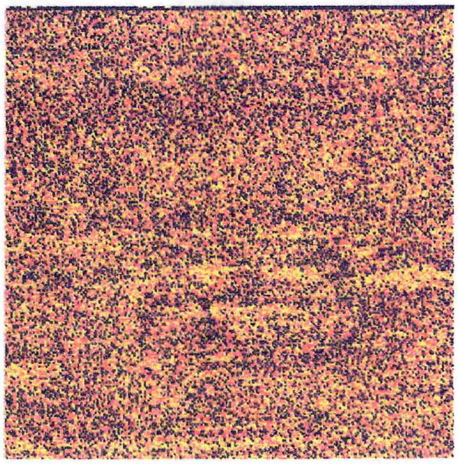
SULPHUR



SILICON



MAGNESIUM



OXYGEN

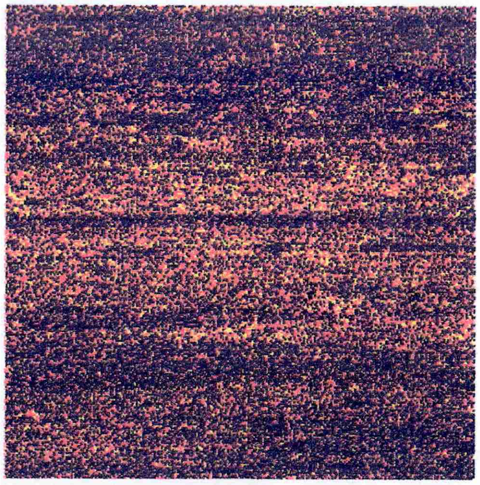
[illegible]

[illegible]

COPPER COATED CAST IRON DISC SURFACE MAP

X100 10KV PHOTO 9296 MATERIAL 1/43 + 1200 Al 40psi

ALUMINIUM



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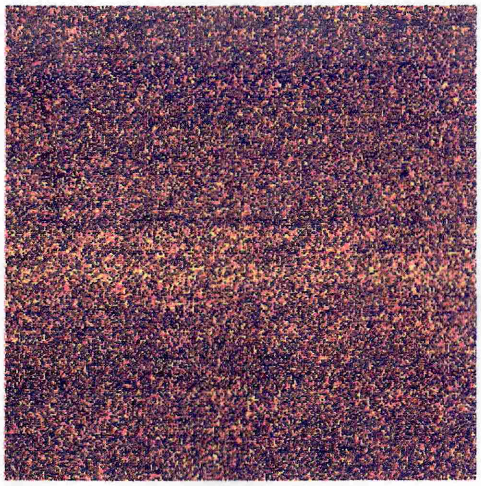
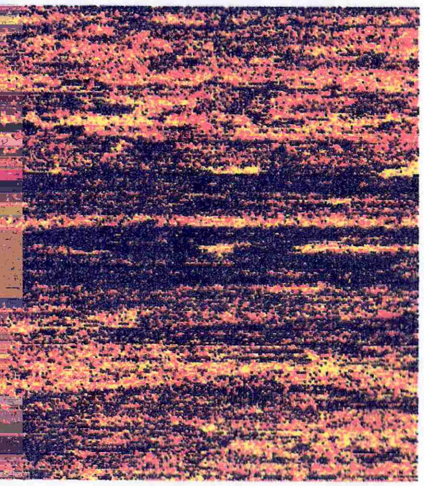
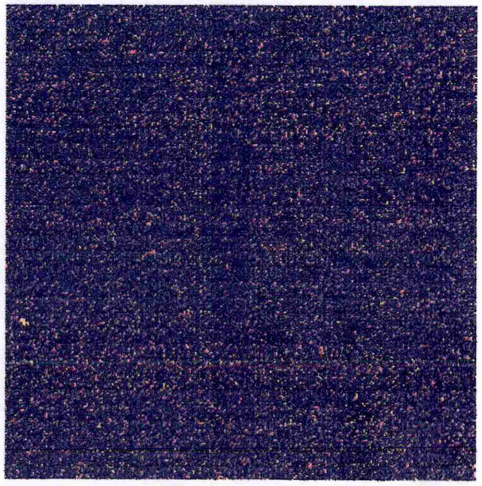


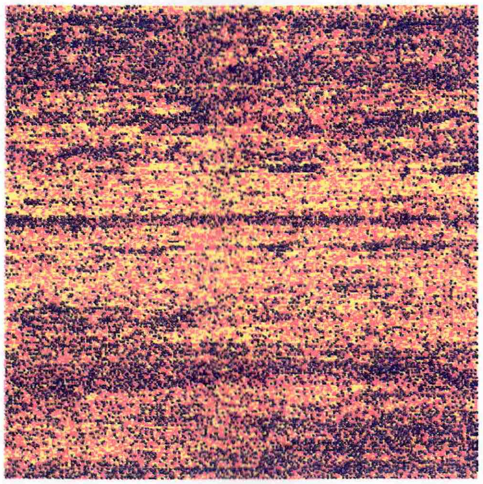
CALCIUM



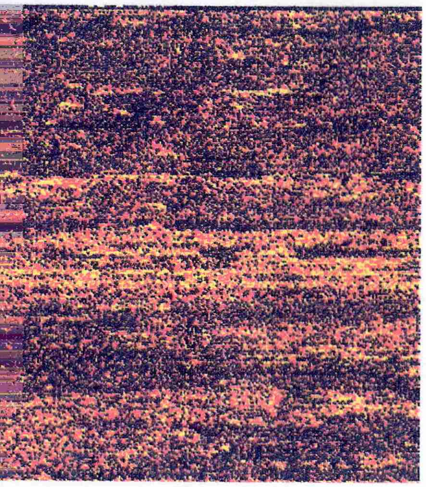
COPPER



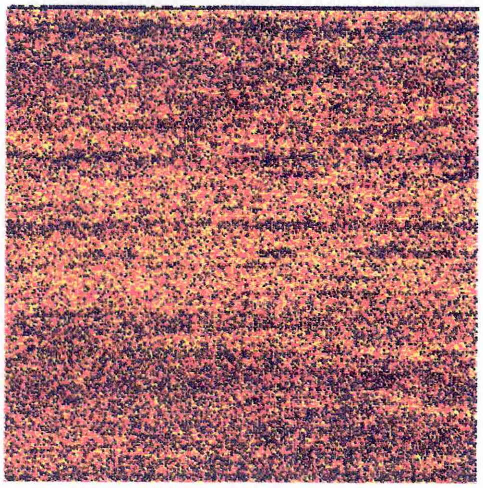
IRON



SULPHUR



SILICON



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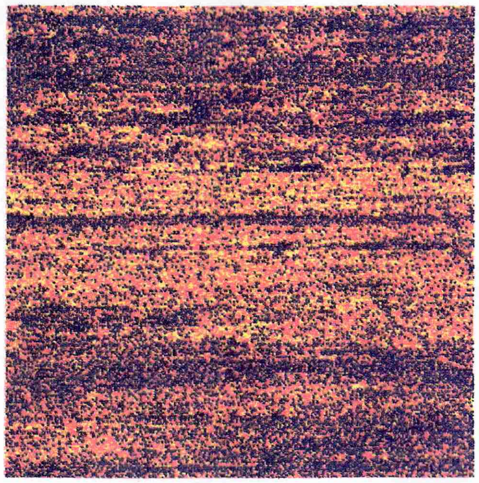
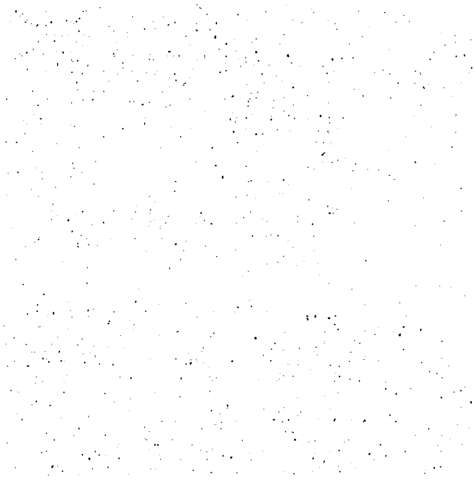
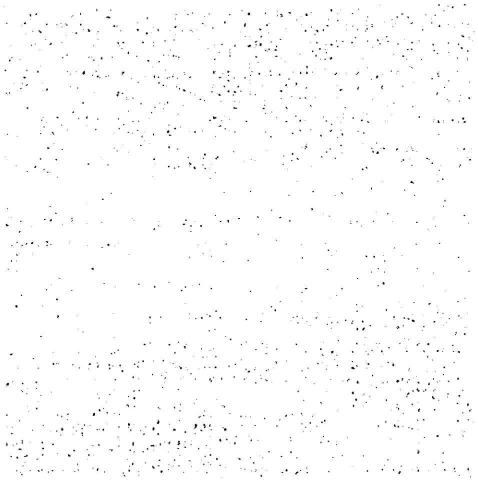
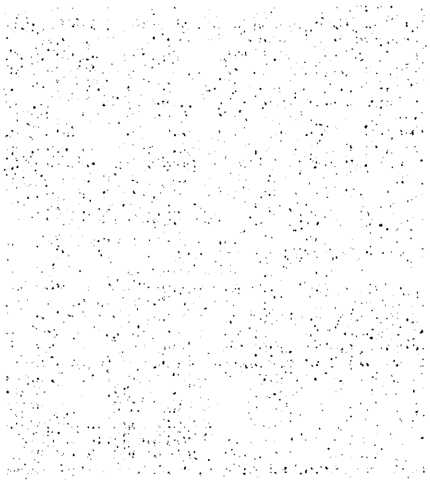


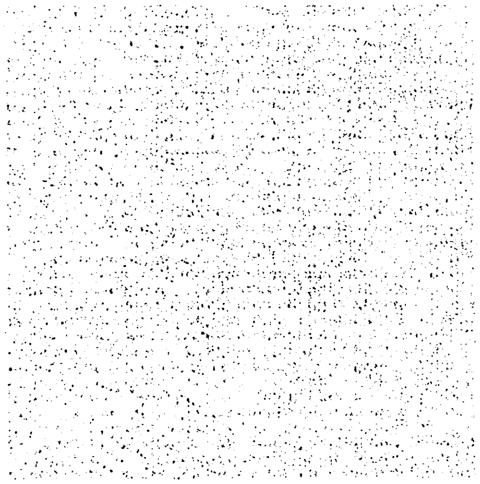
OXYGEN

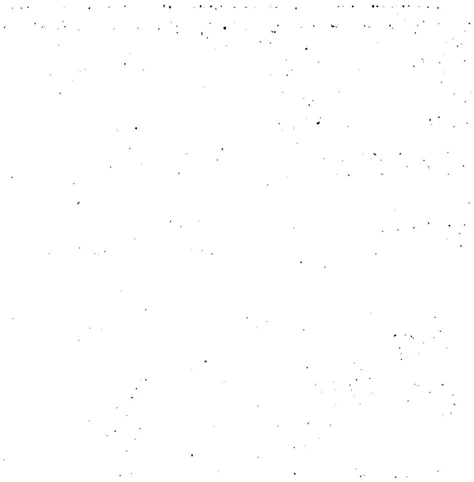
A3·6c



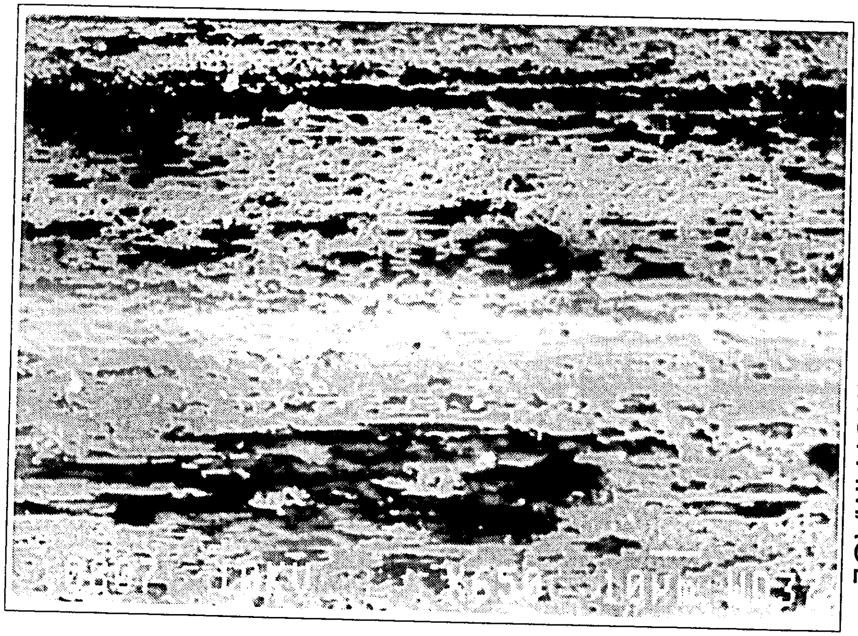








1/43 + 500 ALUMINA Cu/Al DISC x 650 MAP AREA

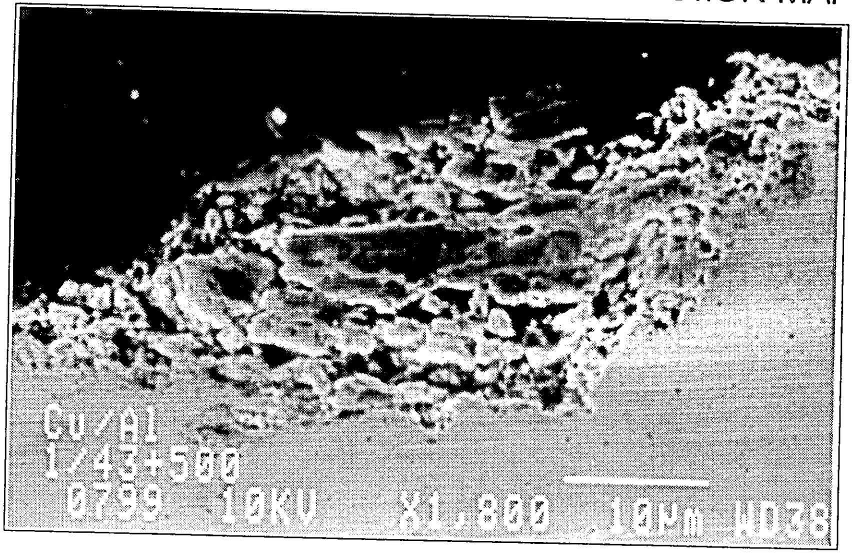


SECONDARY ELECTRON IMAGE

1/44, SPHERICAL x400 10 kV MAP OF PAD SURFACE

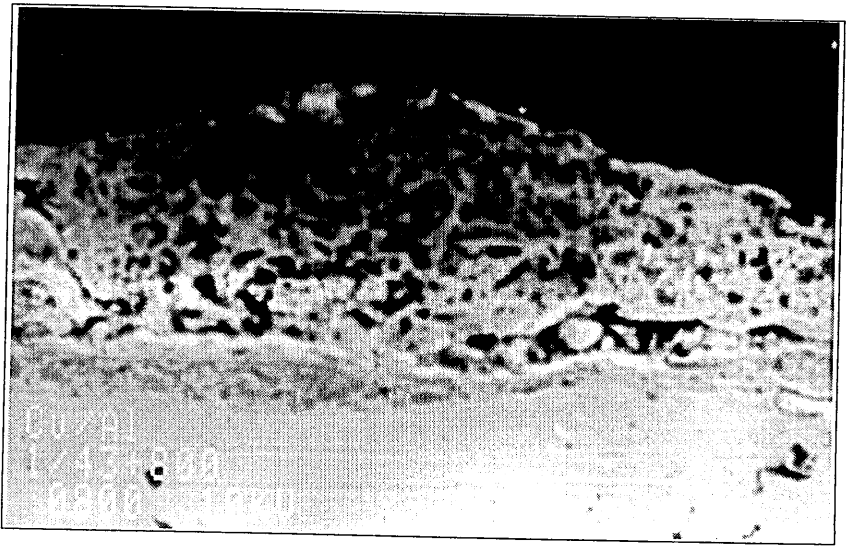
SECONDARY ELECTRON IMAGE

1/43 + 500 ALUMINA x1800 CROSS-SECTION MAP



SECONDARY ELECTRON IMAGE

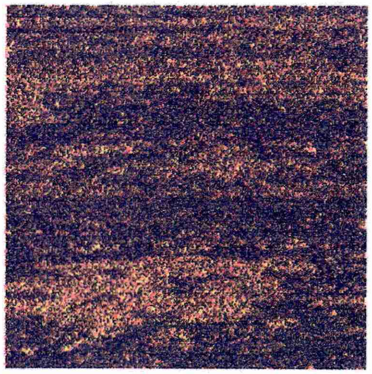
1/43 + 800 ALUMINA x 3000 CROSS-SECTION MAP



SECONDARY ELECTRON IMAGE

COPPER COATED ALUMINIUM DISC
FRICTION MATERIAL 1/43 + 500 ALUMINA

PHOTO 0807 x650 10 kV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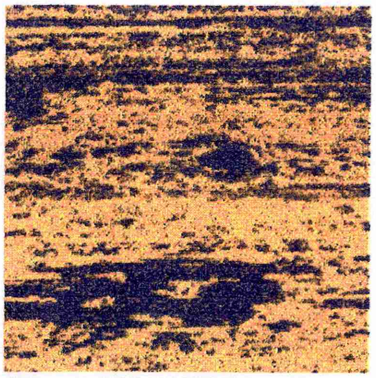
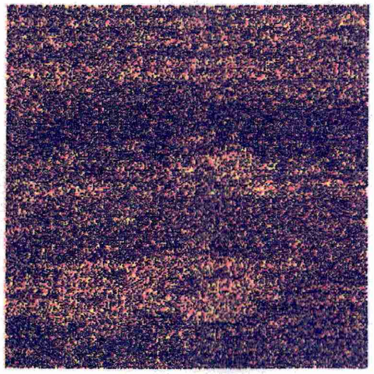
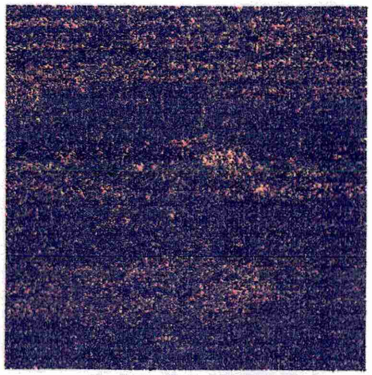
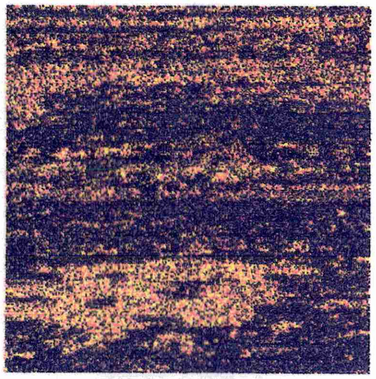
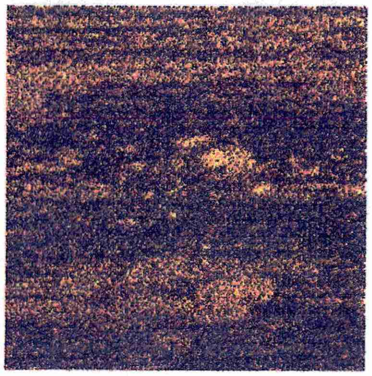
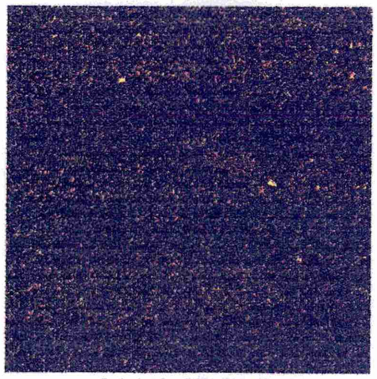

COPPER

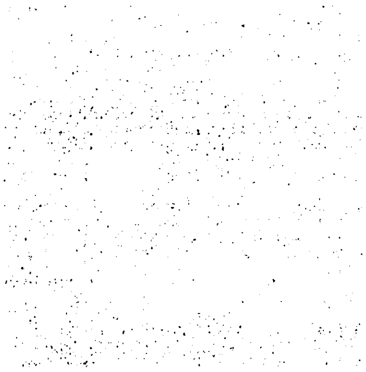
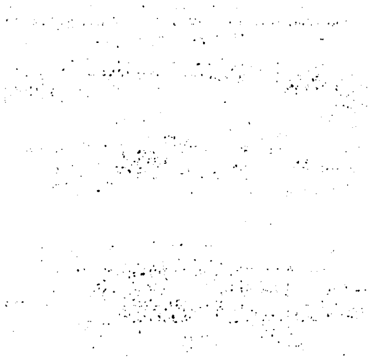
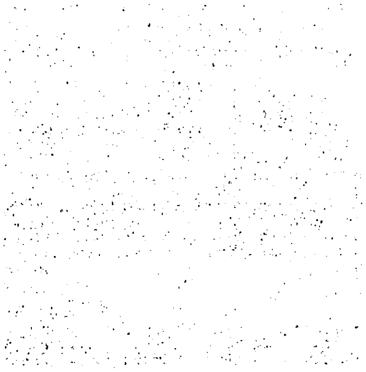
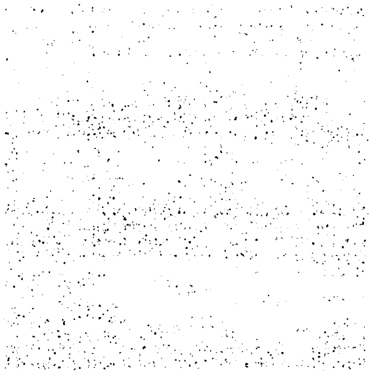
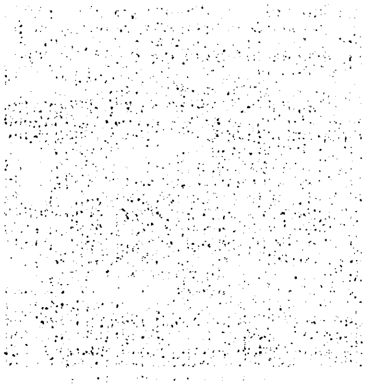
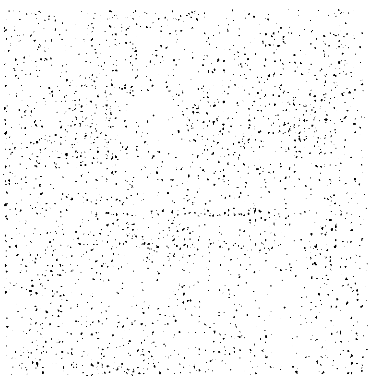
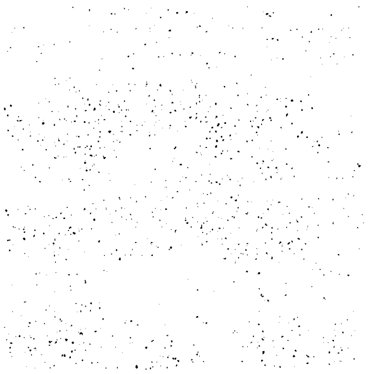

OXYGEN


MAGNESIUM


SULPHUR

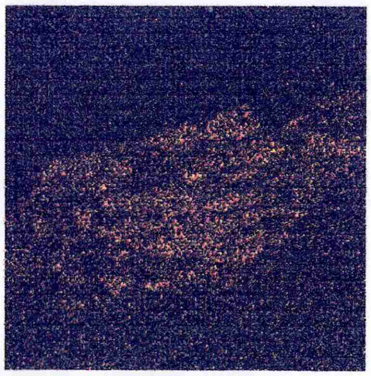

SILICON

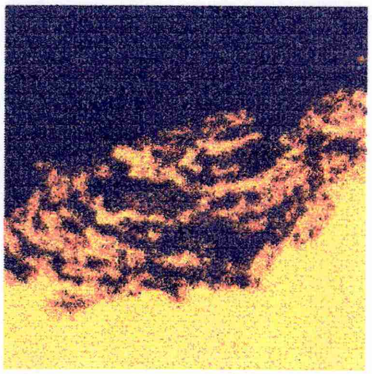

ALUMINIUM

COPPER COATED ALUMINIUM DISC
FRICTION MATERIAL 1/43 + 500 ALUMINA

PHOTO 0799 x1800 10 kV
CROSS-SECTION


BARIUM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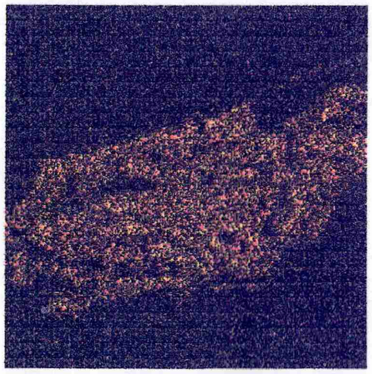
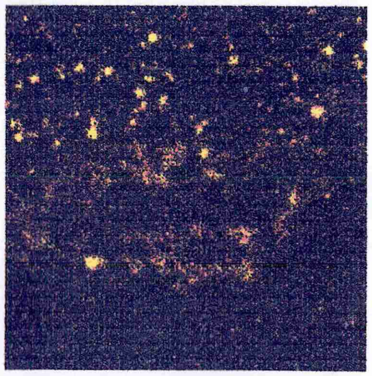

OXYGEN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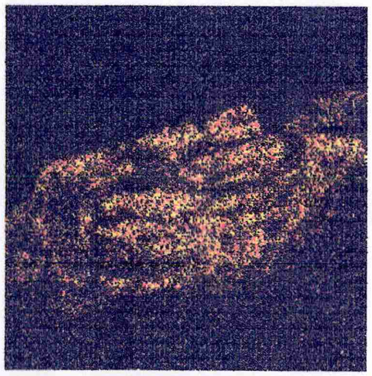
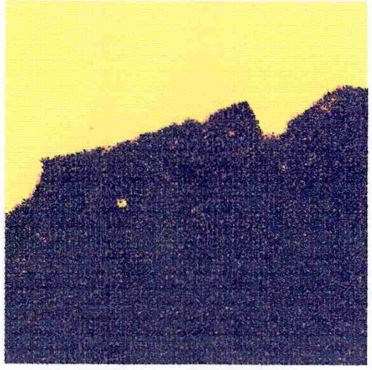
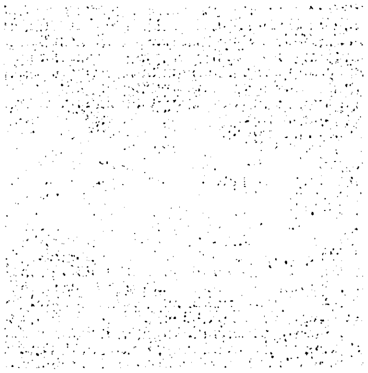
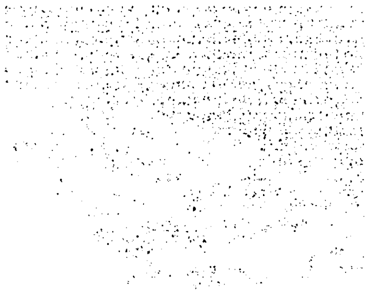

SULPHUR

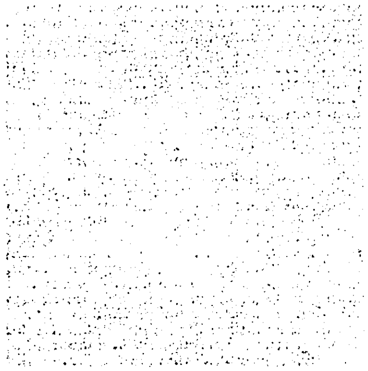

CALCIUM

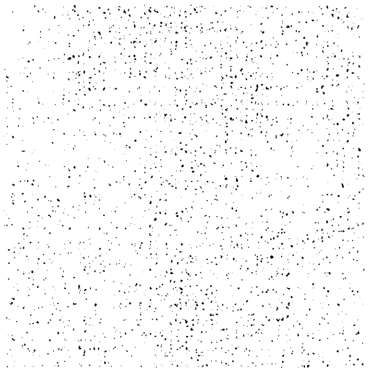

SILICON

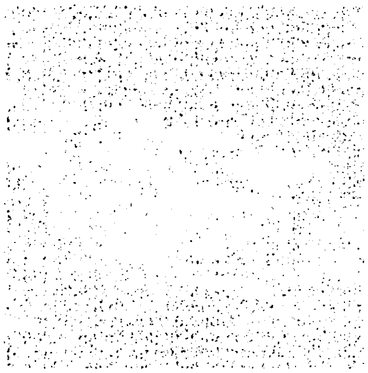

ALUMINIUM

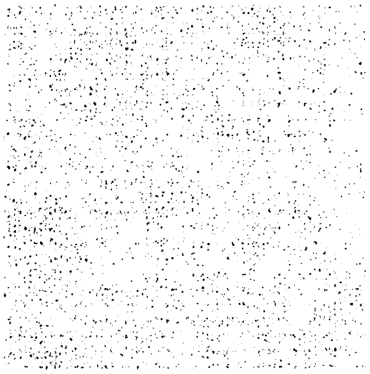


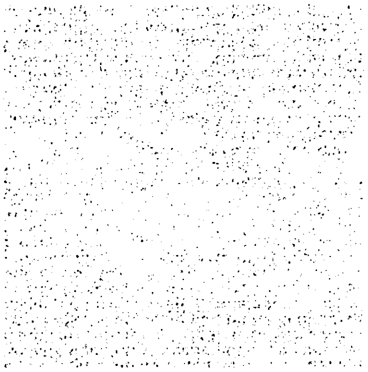






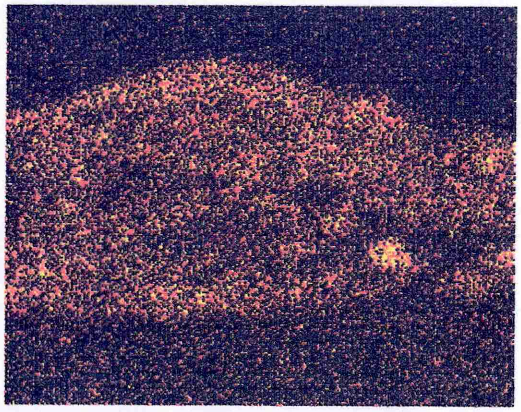


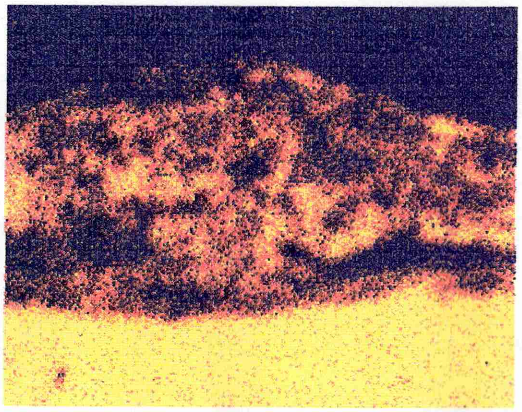




COPPER COATED ALUMINIUM DISC
FRICTION MATERIAL 1/43 + 800 ALUMINA

PHOTO 0800 x3000 10 kV
CROSS-SECTION


BARIUM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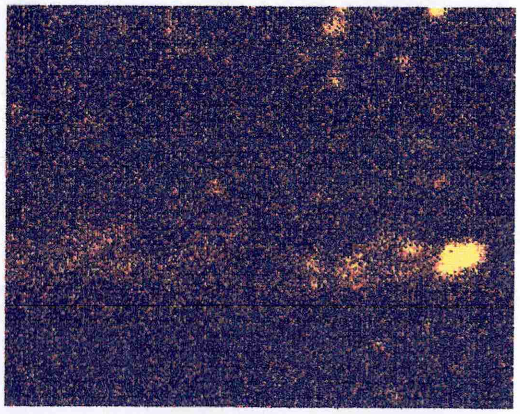
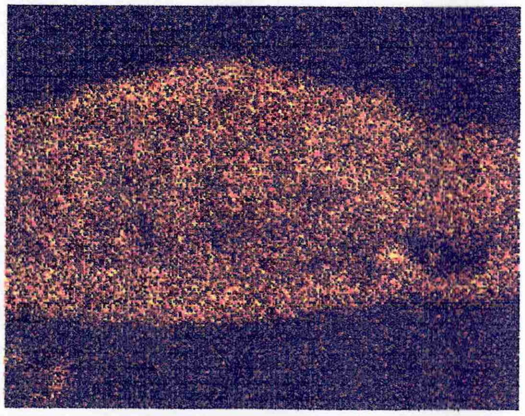
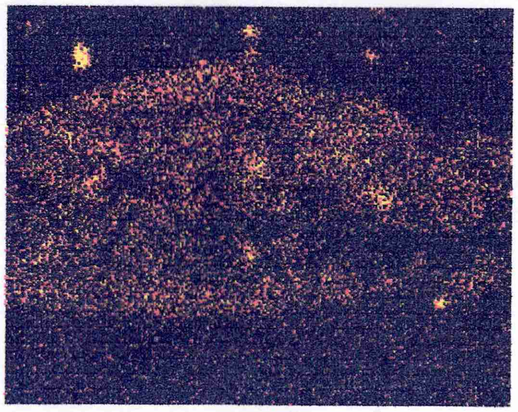
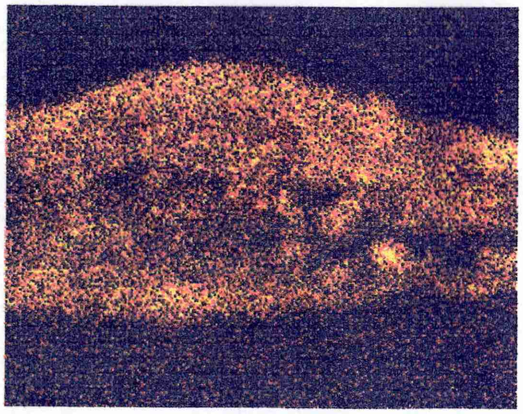
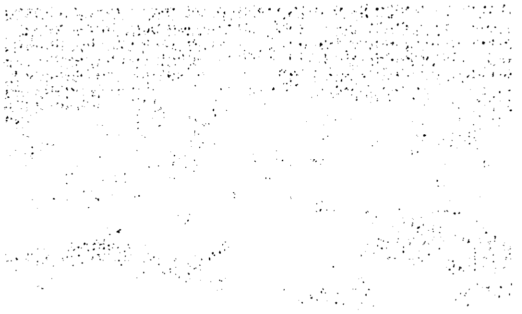

CARBON

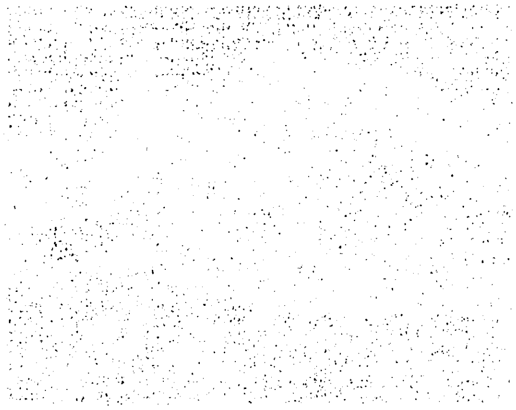

OXYGEN

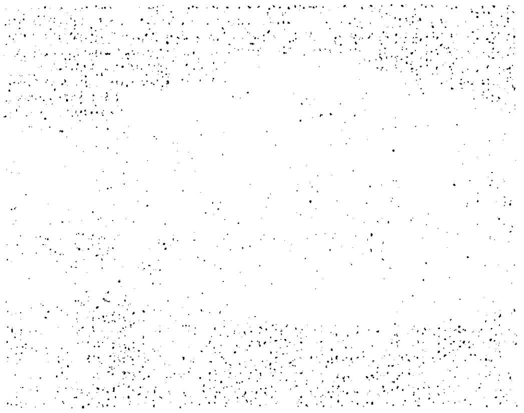

SILICON

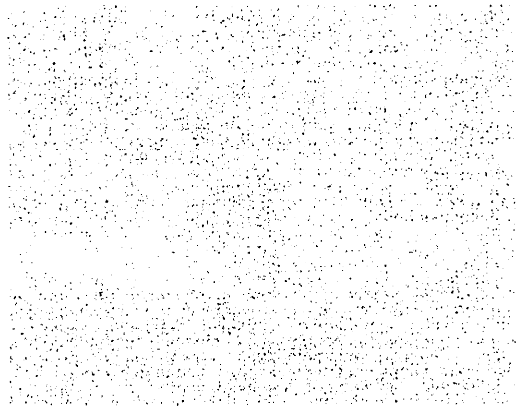

SULPHUR

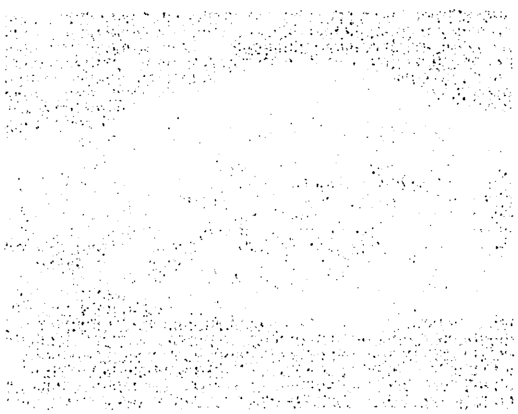
A 3·7d

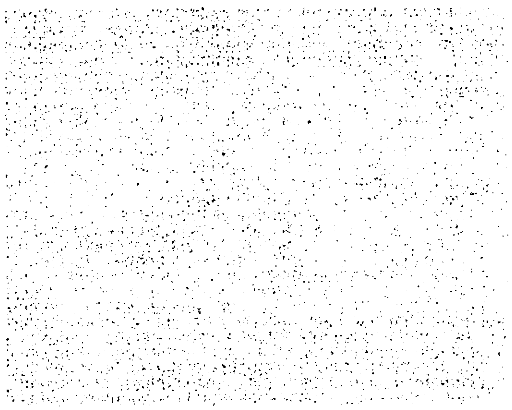






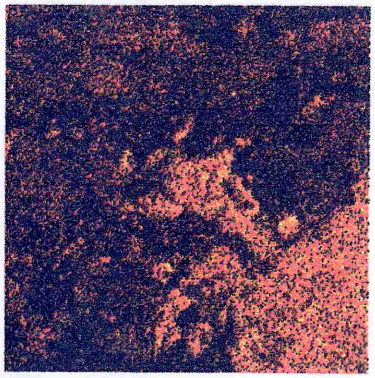


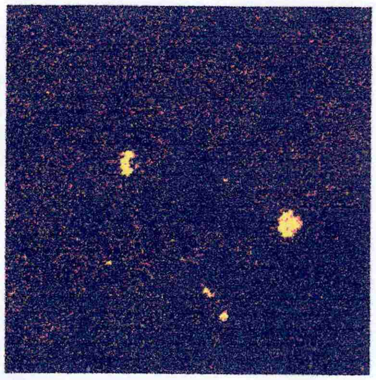




FRICTION MATERIAL 1/44
SPHERICAL CHROMIC OXIDE
GENERAL WORN PAD SURFACE
COATED ALUMINIUM DISC

10 KV x400 PHOTO 584


OXYGEN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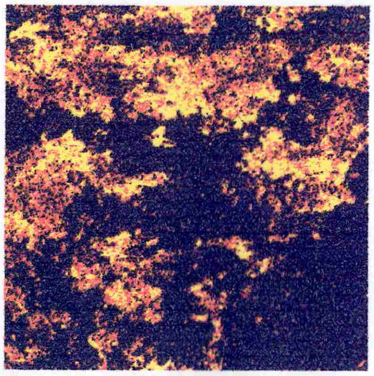
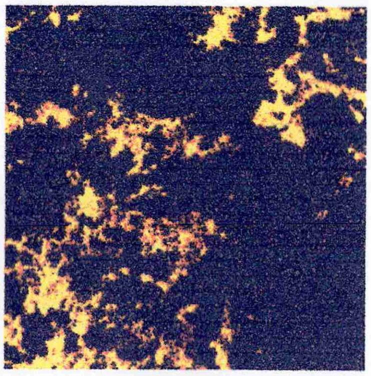
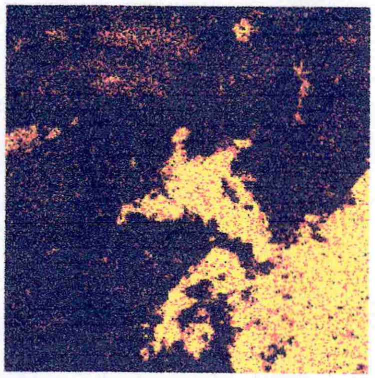
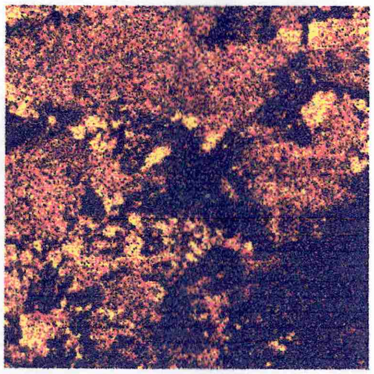
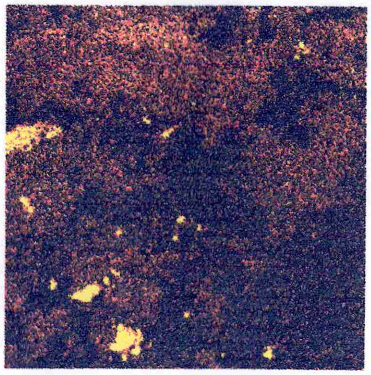
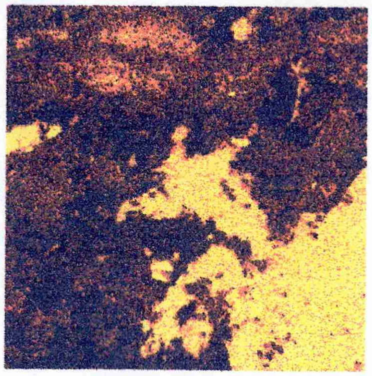

COPPER

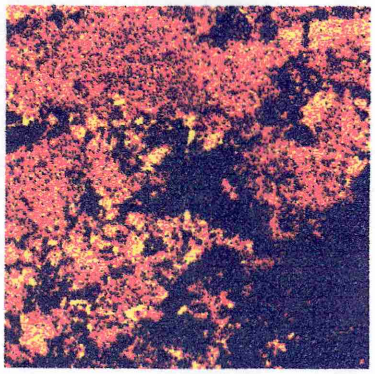

CARBON


MAGNESIUM

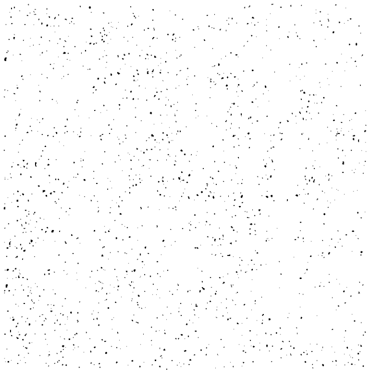

BARIUM

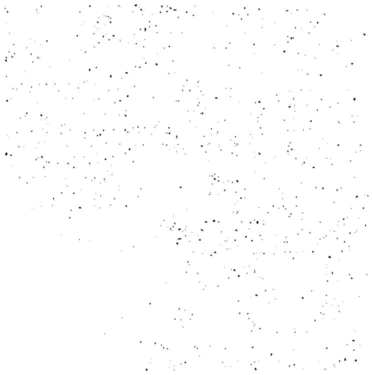

CALCIUM

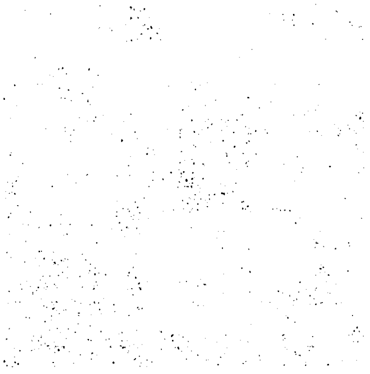

SILICON

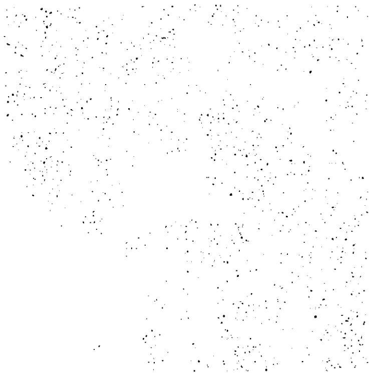

SULPHUR

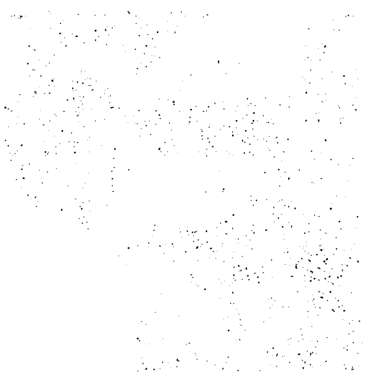
A3·7e

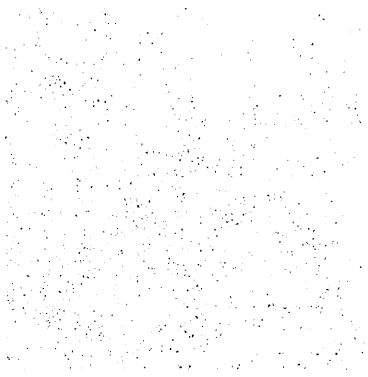






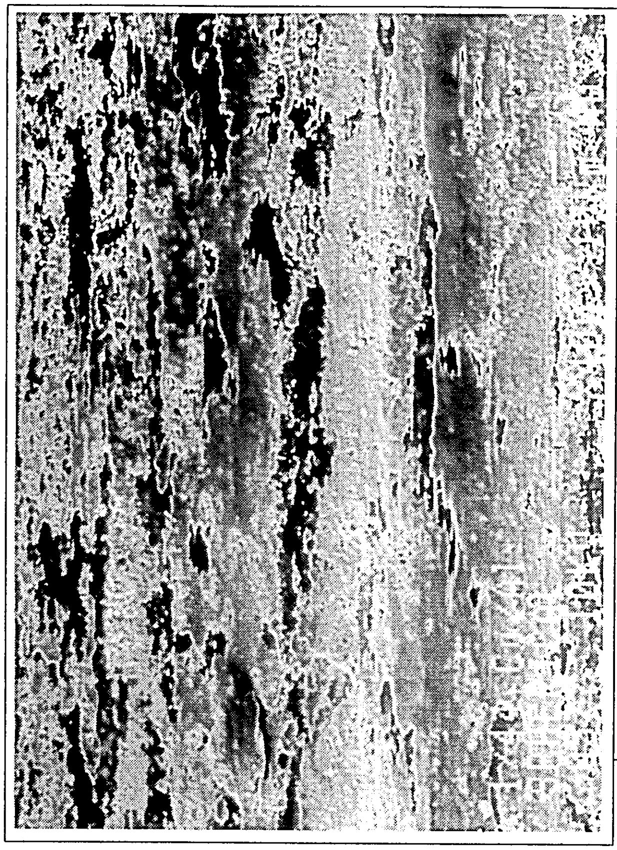


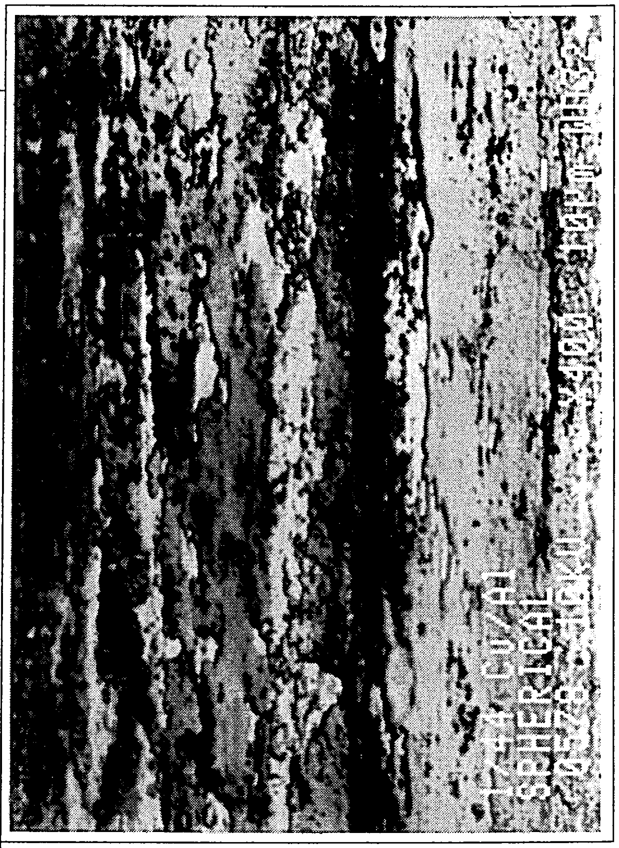




1/44, SPHERICAL CHROMIC Cu/Al DISC x400 10 kV

SECONDARY ELECTRON IMAGE

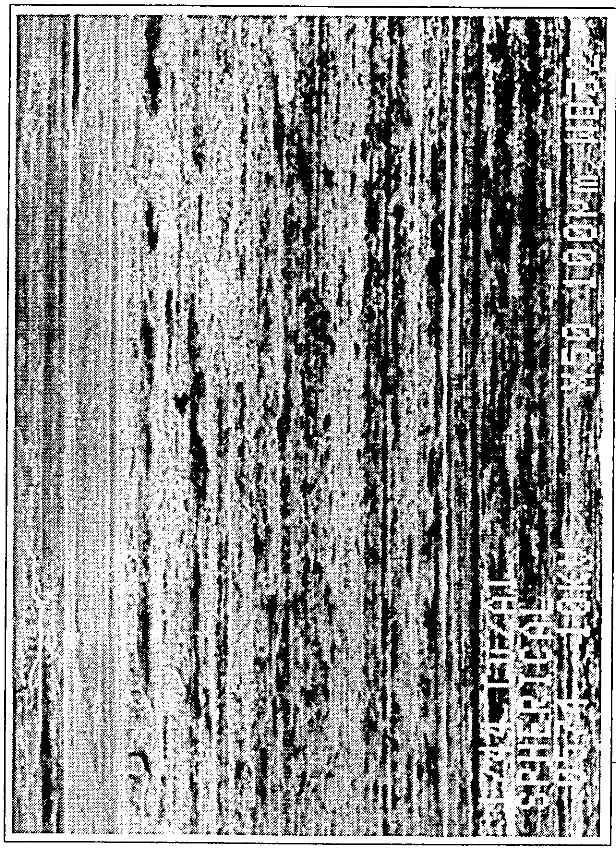


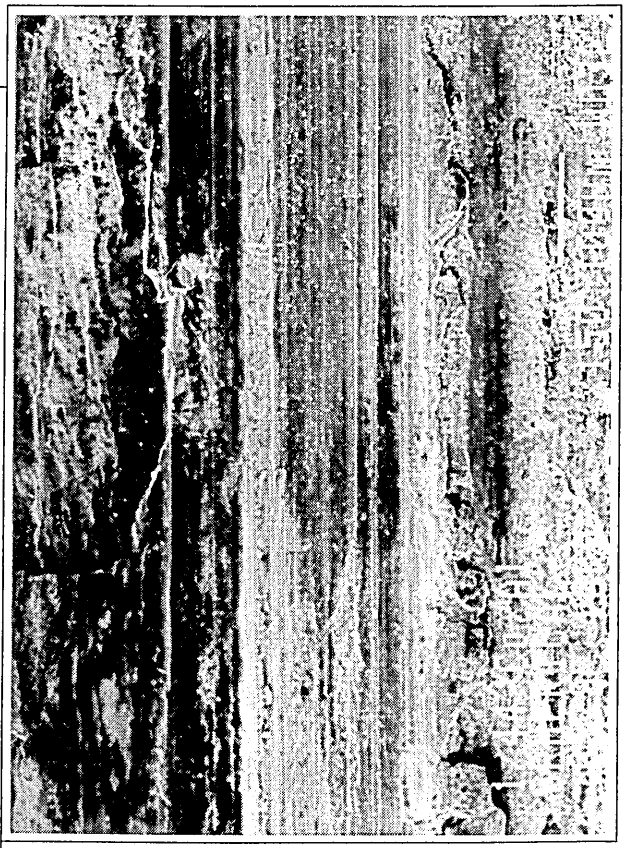


BACK-SCATTERED ELECTRON IMAGE

1/44, SPHERICAL CHROMIC Cu/Al DISC 10 kV

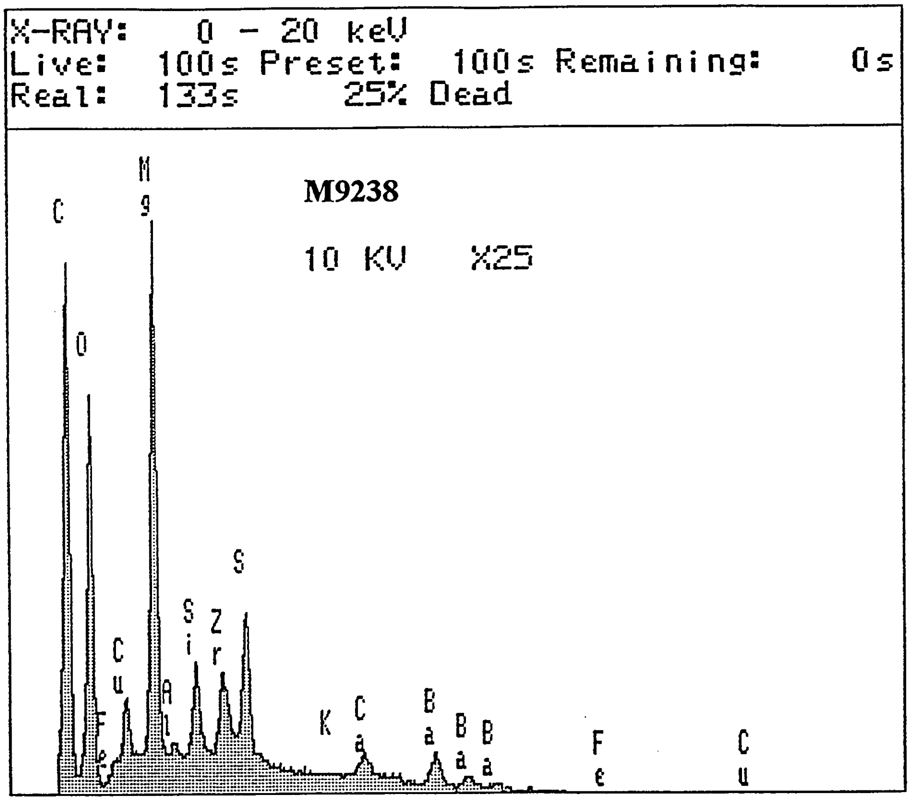
S.E. IMAGE x 50





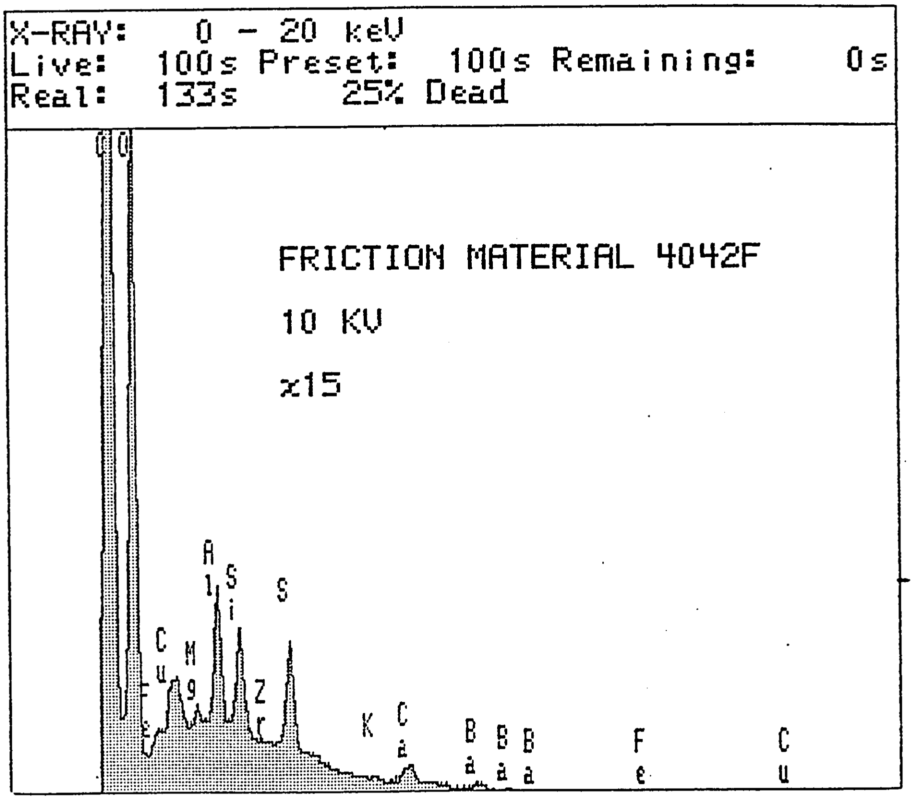
S.E. IMAGE X150

AVERAGE SPECTRA FROM FRICTION MATERIAL
M9238 10 KV



```
X-RAY:    0 - 20  keV
Live:   100s Preset:   100s Remaining:     0s
Real:   133s       25% Dead
```

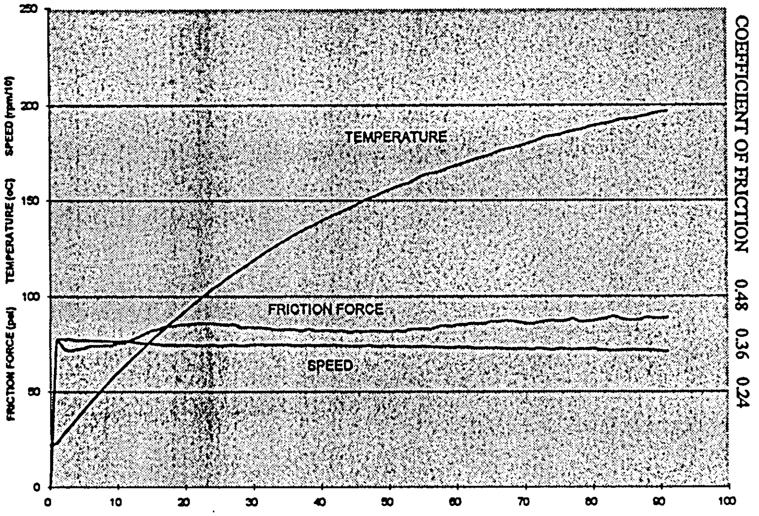
AVERAGE SPECTRA FROM FRICTION MATERIAL
4042F 10 Kv



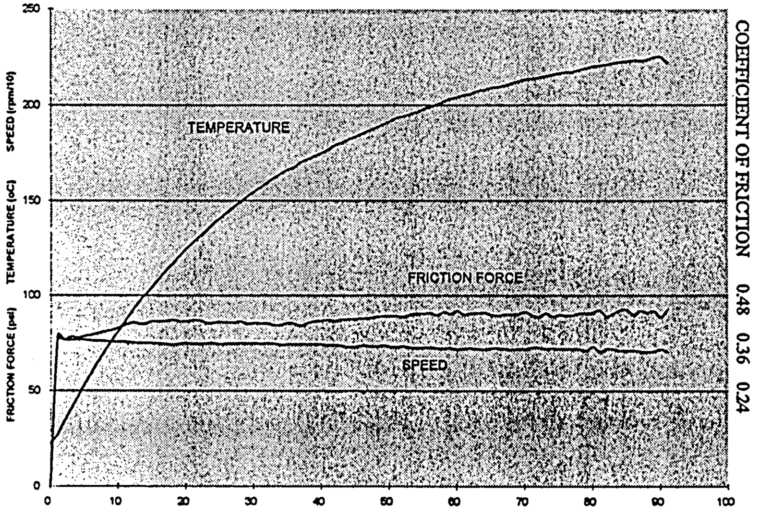
```
X-RAY:    0 - 20  keV
Live:   100s Preset:   100s Remaining:     0s
Real:   133s       25% Dead
```

FRICTION MATERIAL 4042F

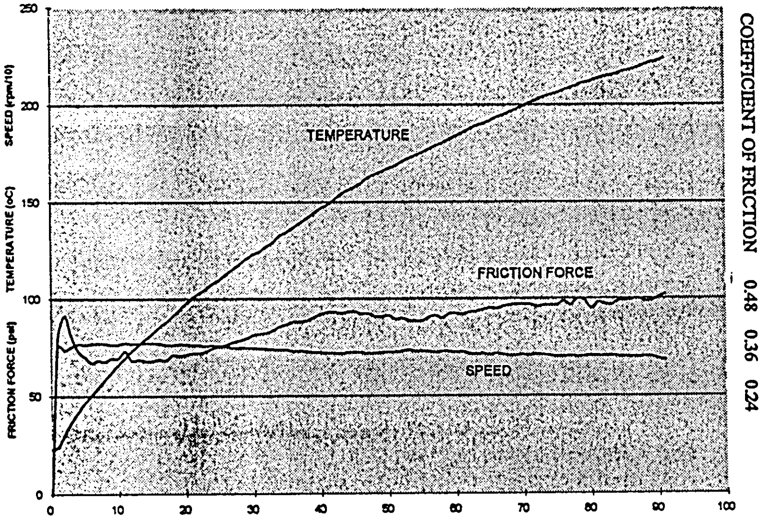
ALL TESTS RAN AT CONSTANT PRESSURE 40 PSI



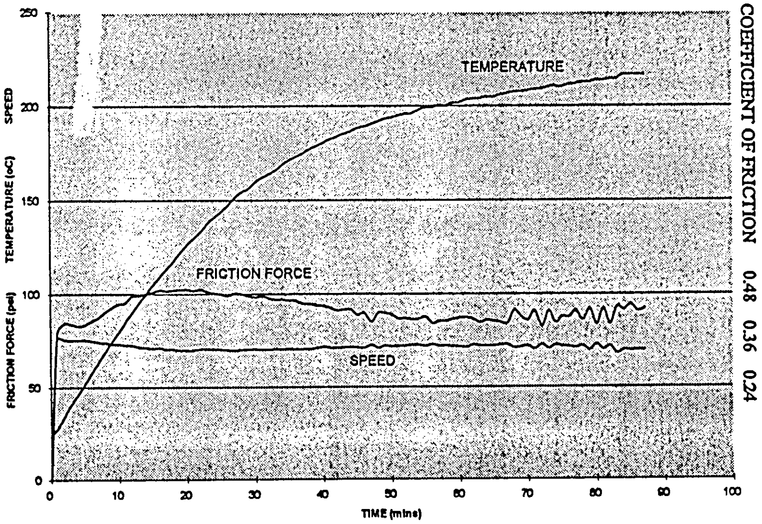
COPPER COATED CAST IRON DISC



COPPER COATED ALUMINIUM DISC



STANDARD CAST IRON F.A.S.T. DISC



DISC. 4042F + GLASS FIBRES

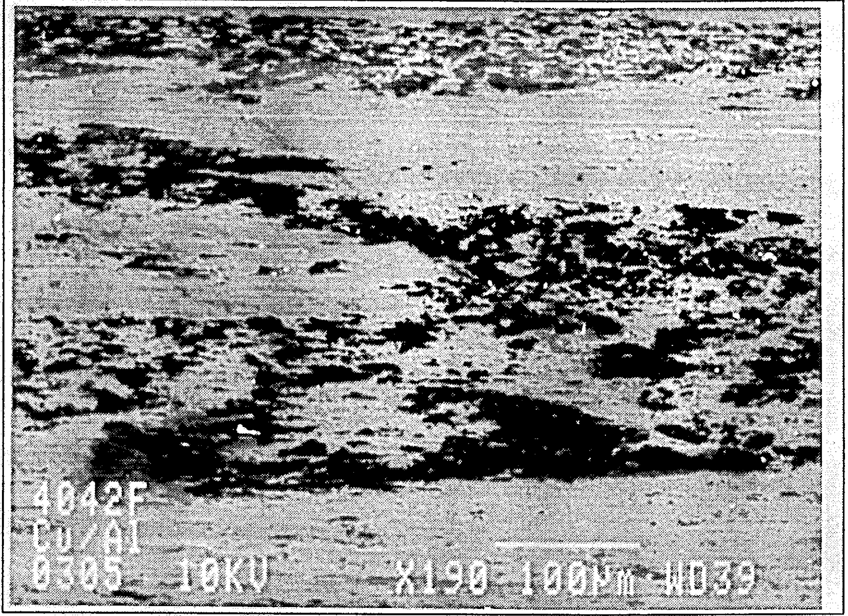
A 3·10

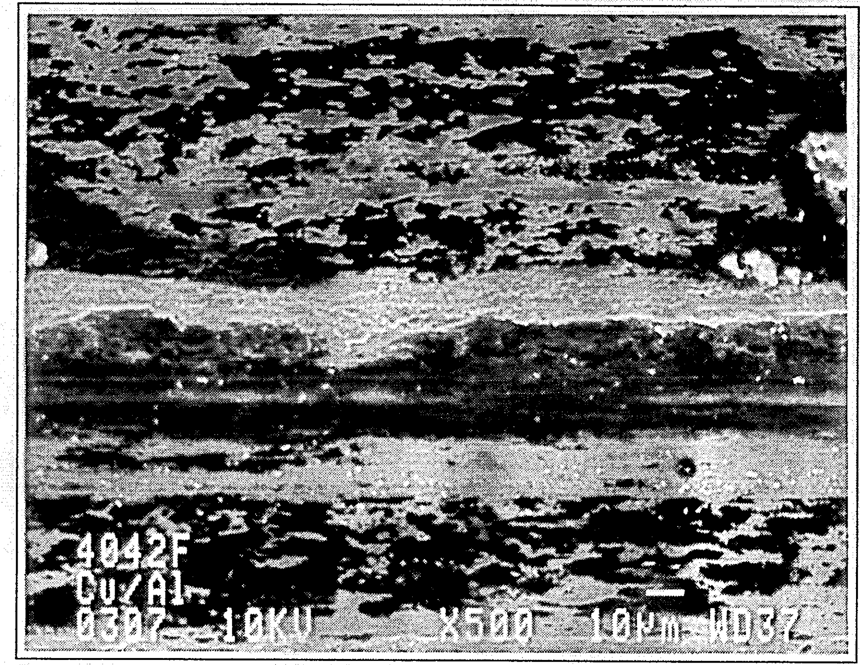
4042F

HIPAC SURFACE
FRICTION MATERIAL
4042F

GENERAL FILM
DISTRIBUTION

S.E. IMAGE

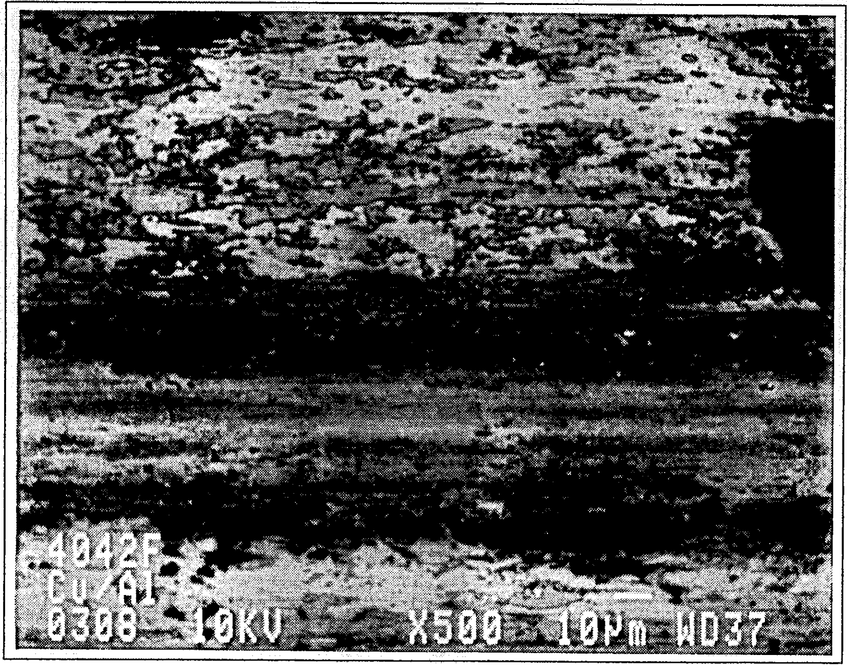




MAPPED AREA OF
PLUG SURFACE

PHOTO 307

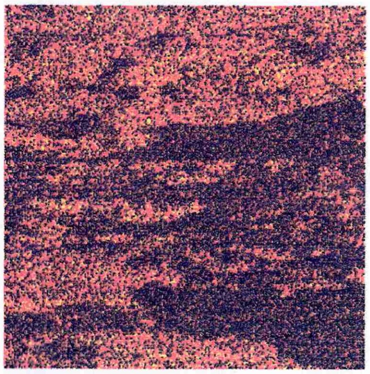
S.E. IMAGE

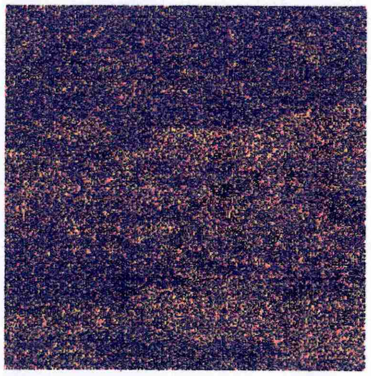


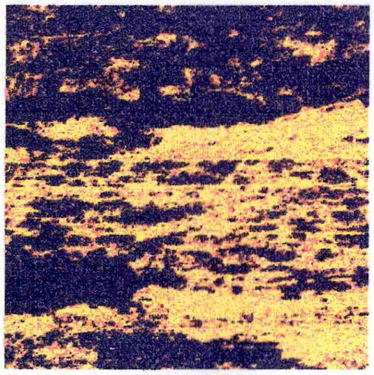
MAPPED AREA
B.S. IMAGE

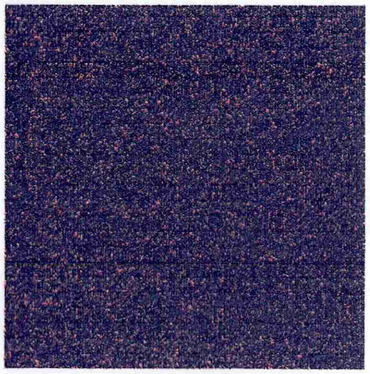
FRICTION MATERIAL 4042F + GLASS FIBRE
COPPER COATED ALUMINIUM DISC
90 MIN RUN CONSTANT 40 PSI

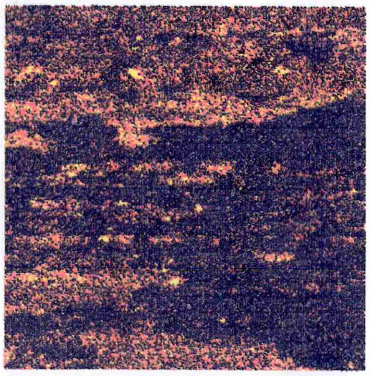
10 KV MAP x350 PHOTO 398

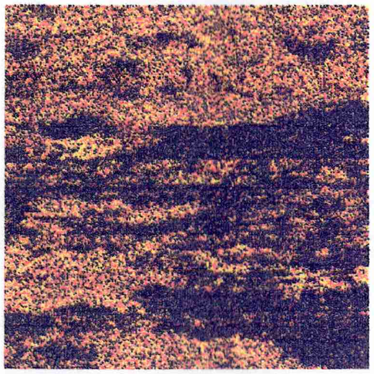

OXYGEN

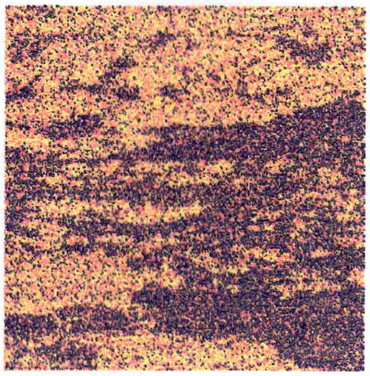

IRON

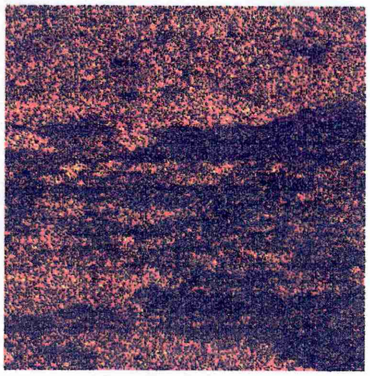

COPPER

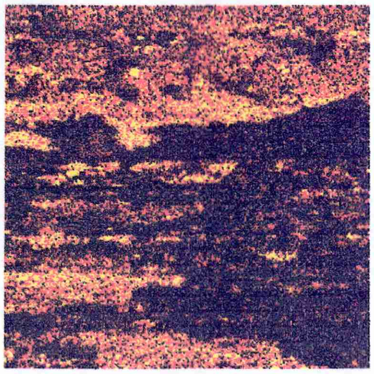

MAGNESIUM


ALUMINIUM


BARIUM


SILICON


CALCIUM

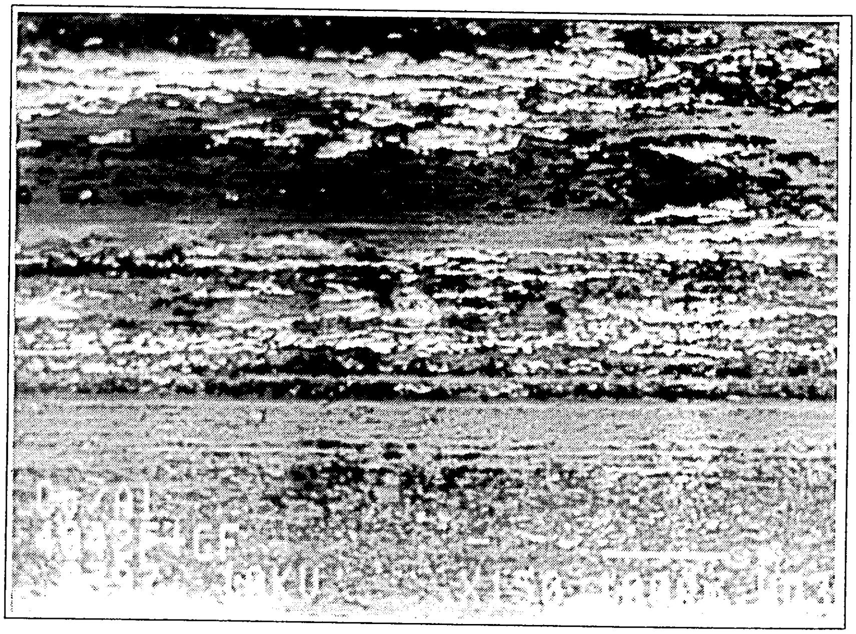

SULPHUR

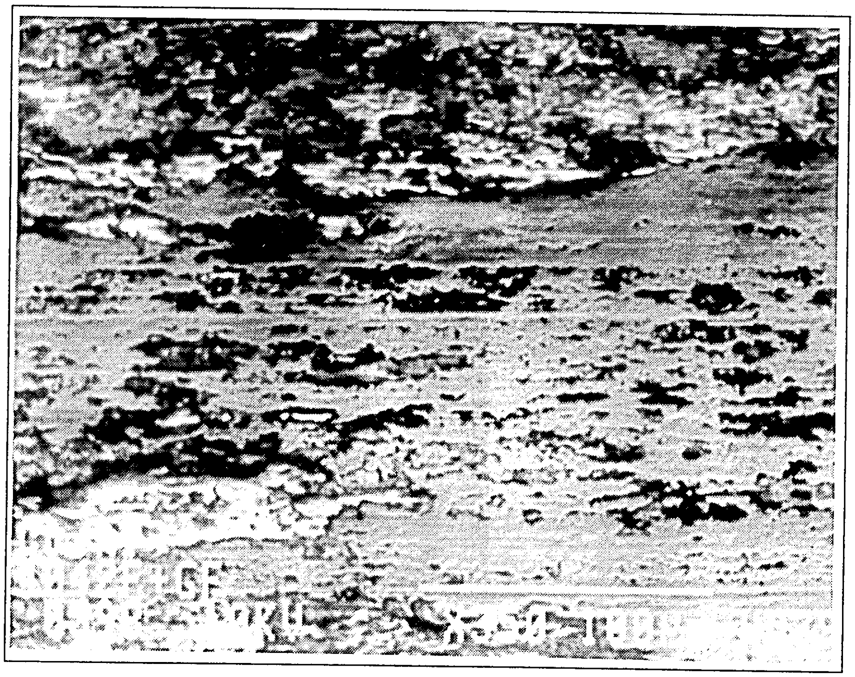
4042F+
GLASS FIBRE

HIPAC SURFACE
FRICTION MATERIAL
4042F + GLASS
FIBRE

GENERAL FILM
DISTRIBUTION

S.E. IMAGE

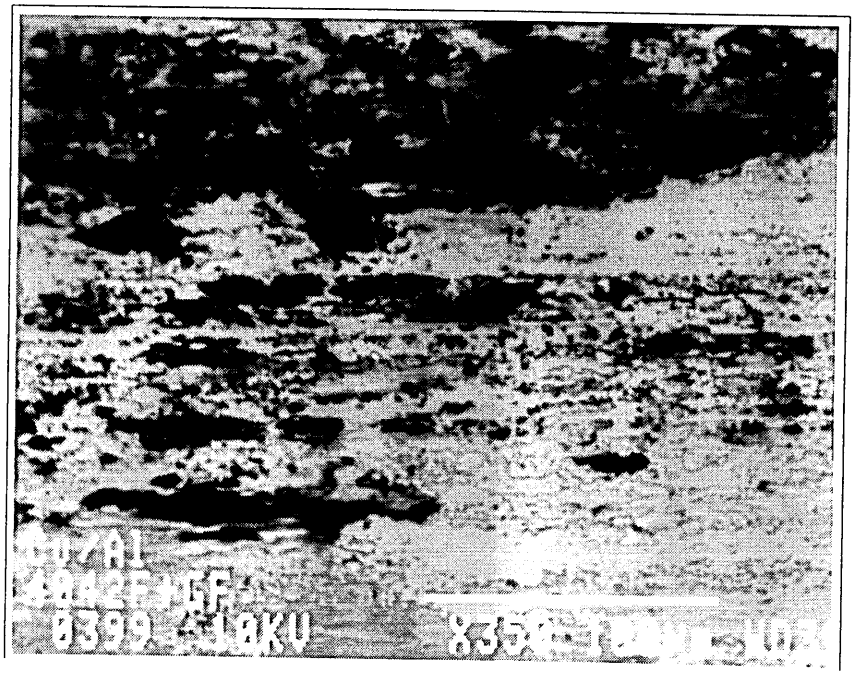




MAPPED AREA OF
PLUG SURFACE

PHOTO 398

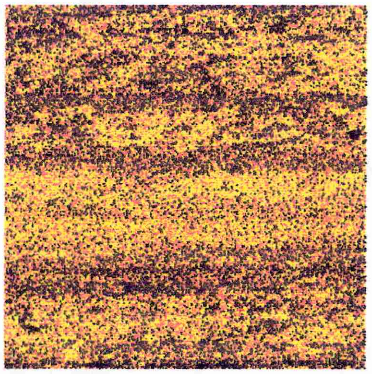
S.E. IMAGE



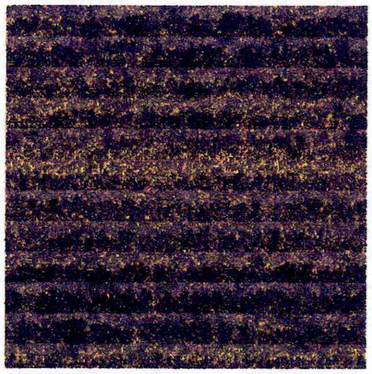
MAPPED AREA
B.S. IMAGE

FRICTION MATERIAL 4042F
COPPER COATED CAST IRON DISC
90 MIN RUN CONSTANT 40 PSI

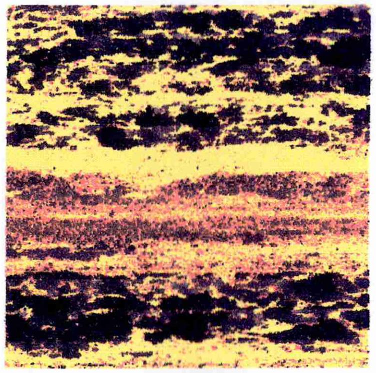
10 KV MAP x500 PHOTO 307



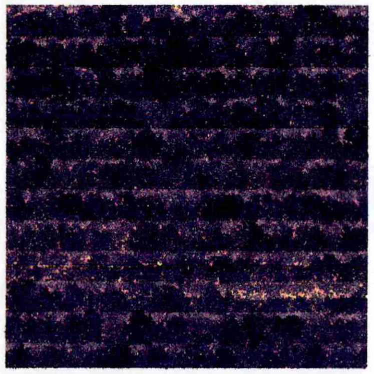
OXYGEN



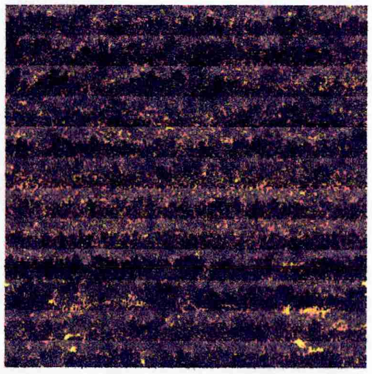
IRON



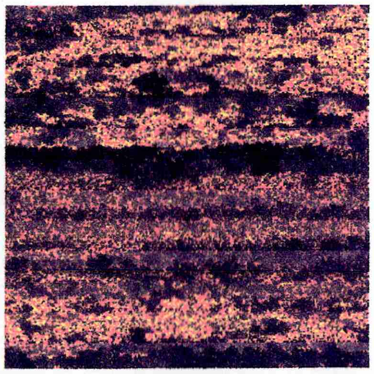
COPPER



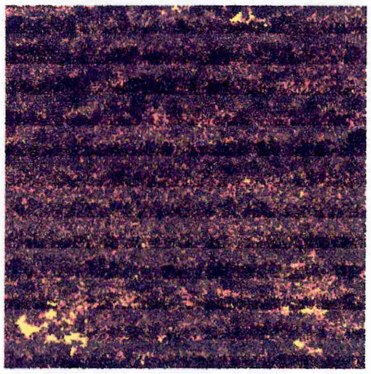
MAGNESIUM



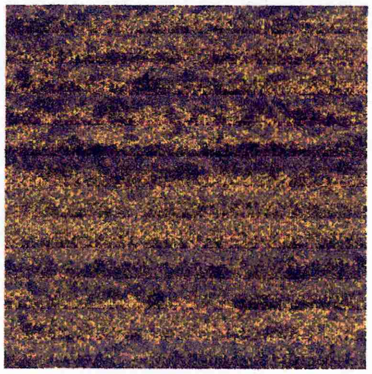
ALUMINIUM



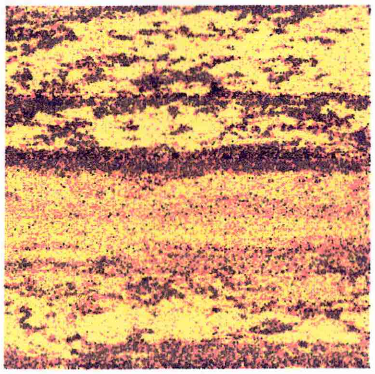
BARIUM



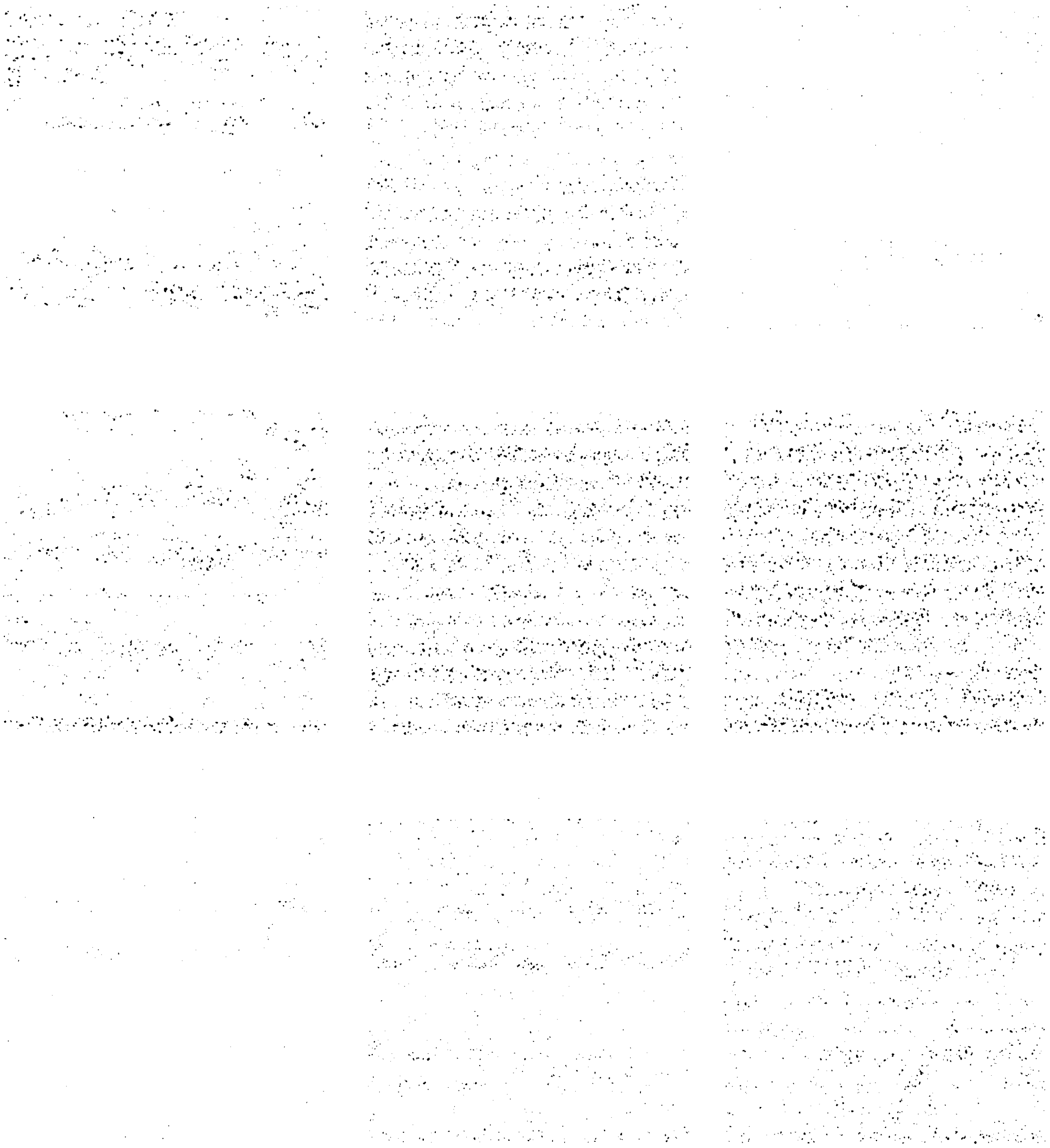
SILICON



CALCIUM

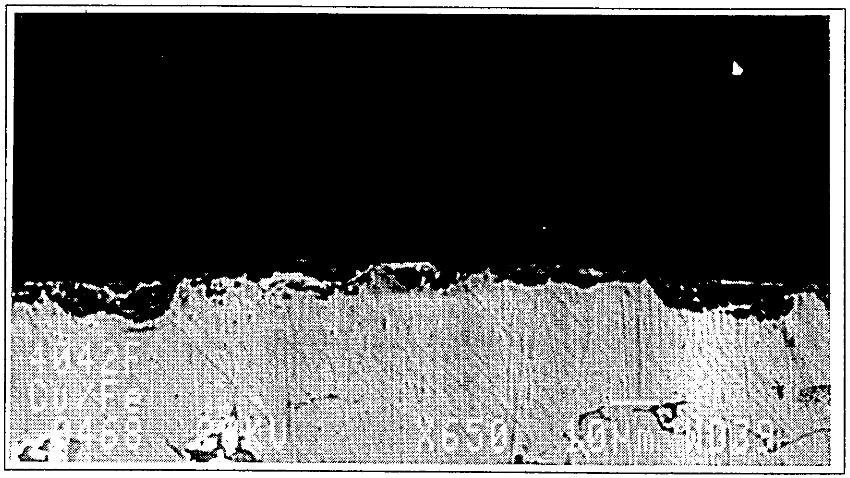


SULPHUR

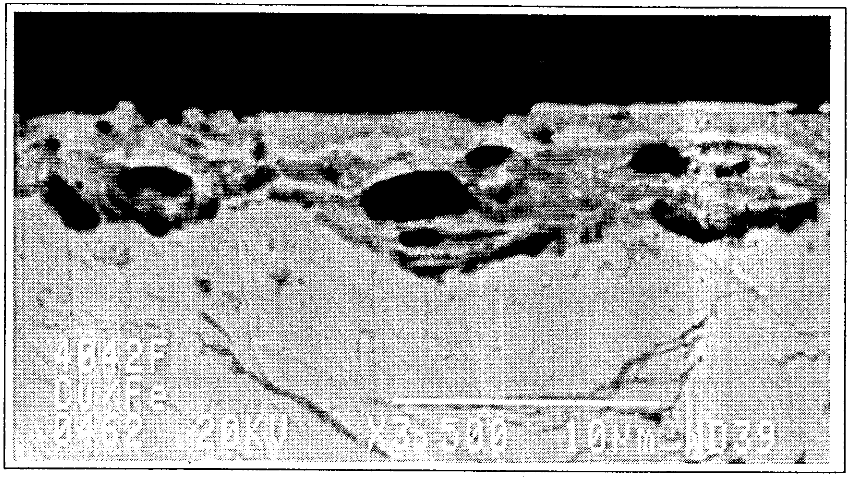


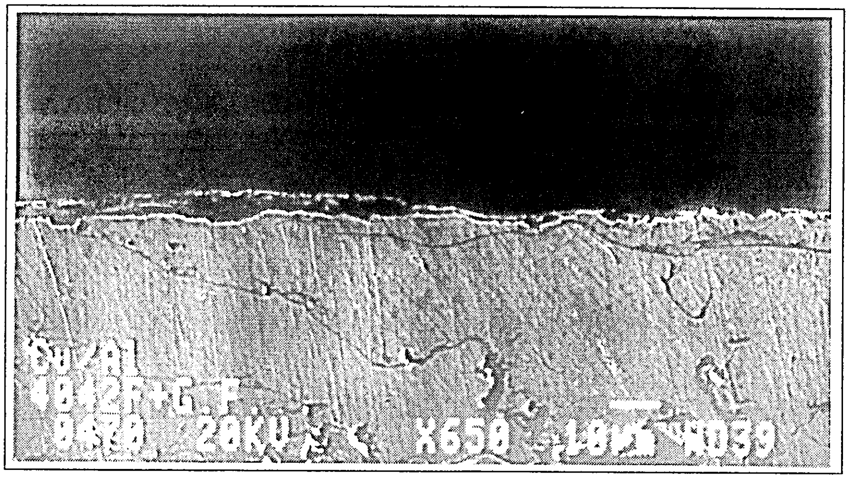
CROSS-SECTION OF
TRANSFER FILM ON
HIPAC COATING

FRICTION MATERIAL
4042F



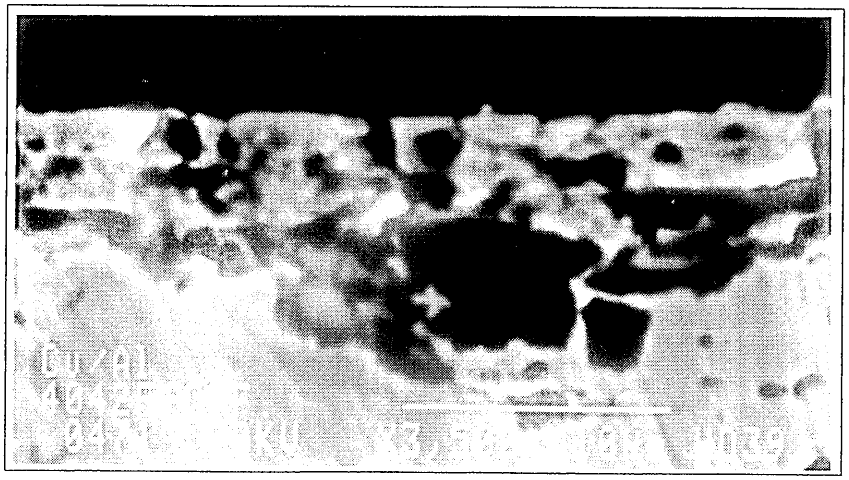
CROSS-SECTION
MAP AREA
PHOTO 462





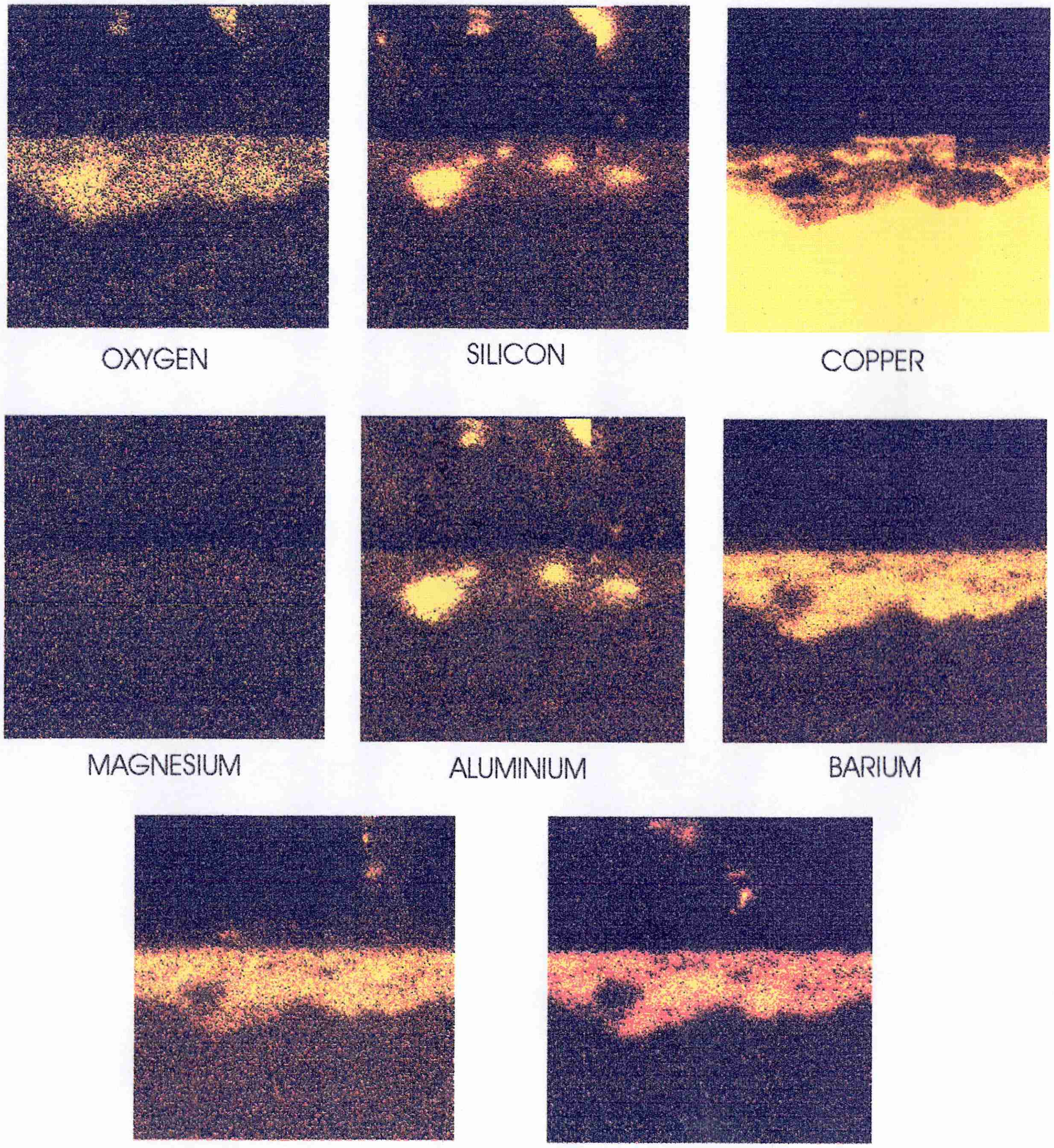
CROSS-SECTION OF
TRANSFER FILM ON
HIPAC COATING

FRICTION MATERIAL
4042F + GLASS
FIBRE



CROSS-SECTION
MAP AREA
PHOTO 471

FRICTION MATERIAL 4042F
COPPER COATED CAST IRON DISC
CROSS-SECTION OF TRANSFER FILM
CONSTANT PRESSURE 40 PSI
10 KV MAP x3500 PHOTO 462



OXYGEN

SILICON

COPPER

MAGNESIUM

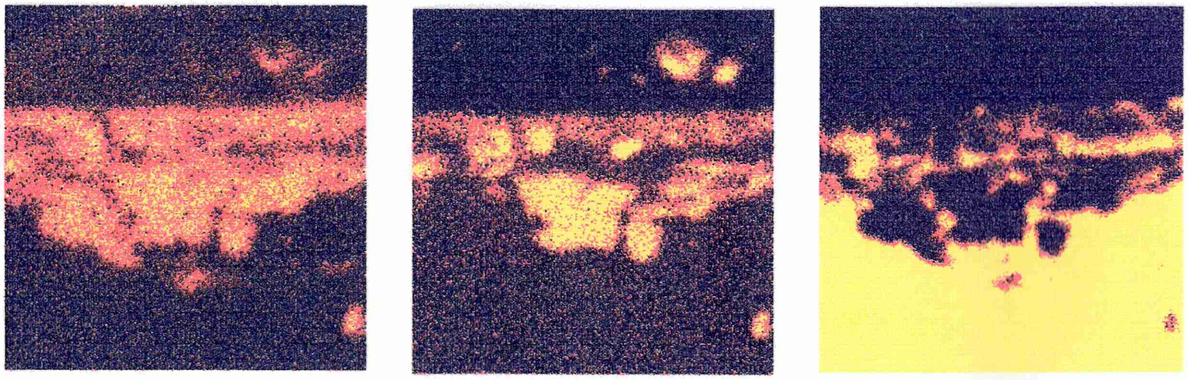
ALUMINIUM

BARIUM

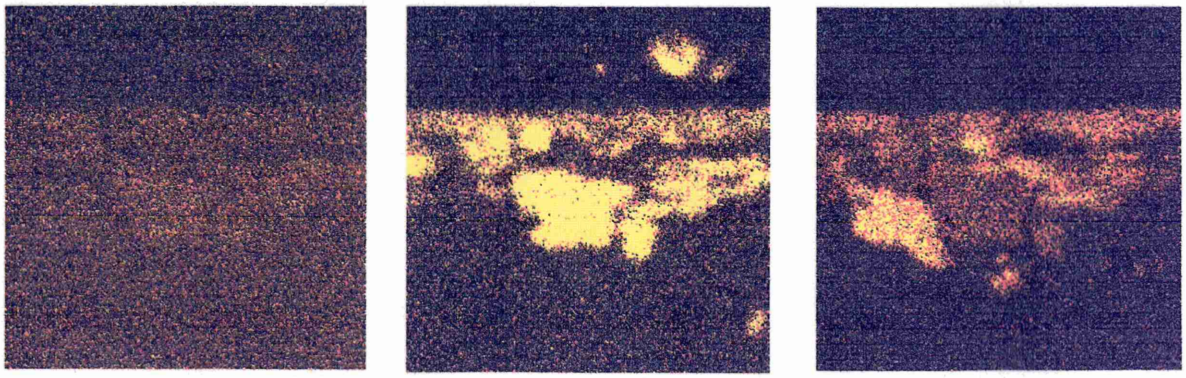
CALCIUM

SULPHUR

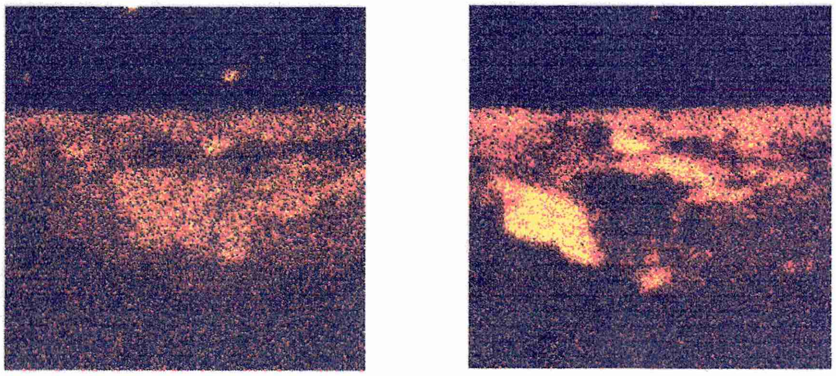
FRICTION MATERIAL 4042F + GLASS FIBRES
COPPER COATED ALUMINIUM DISC
CROSS-SECTION OF TRANSFER FILM
CONSTANT PRESSURE 40 PSI
10 KV MAP x3500 PHOTO 471



OXYGEN SILICON COPPER

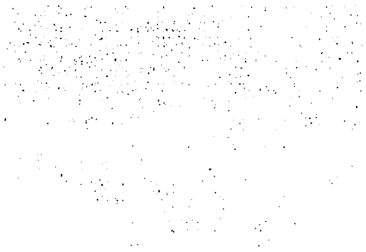


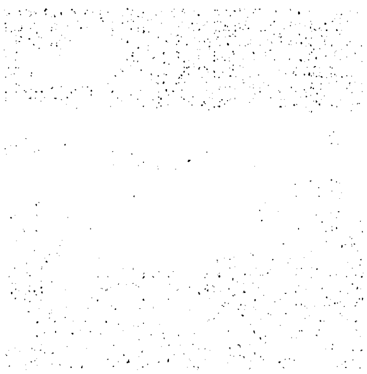
MAGNESIUM ALUMINIUM BARIUM

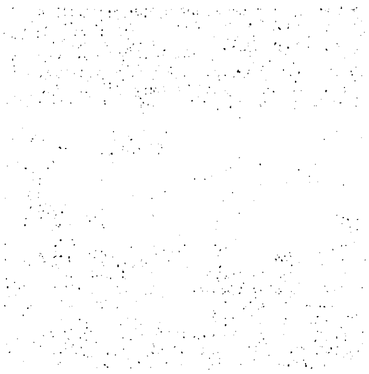


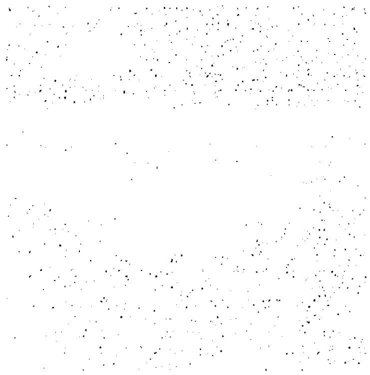
CALCIUM SULPHUR

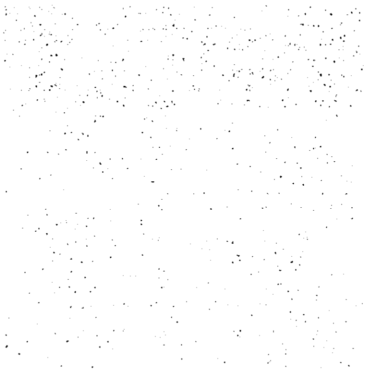
A3·13c

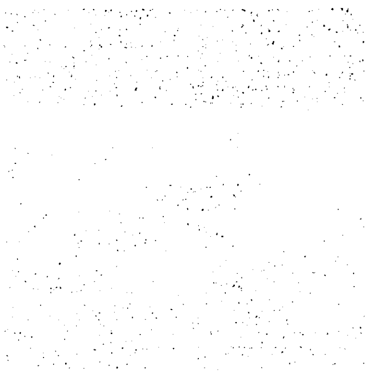


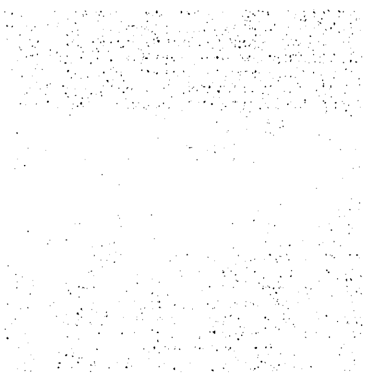




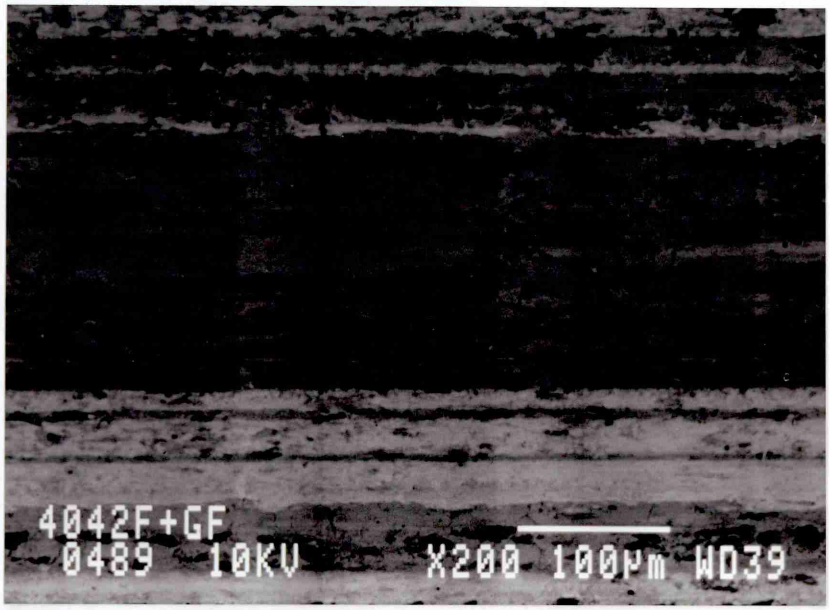




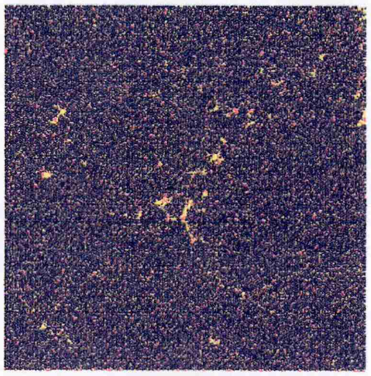




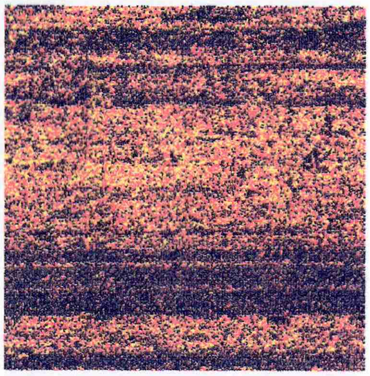
FRICTION MATERIAL 4042F + GLASS FIBRES
STANDARD CAST IRON DISC
CONSTANT PRESSURE 40 PSI
10 KV MAP x200 PHOTO 489



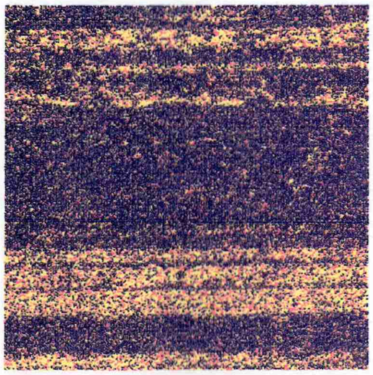
BACK-SCATTERED IMAGE



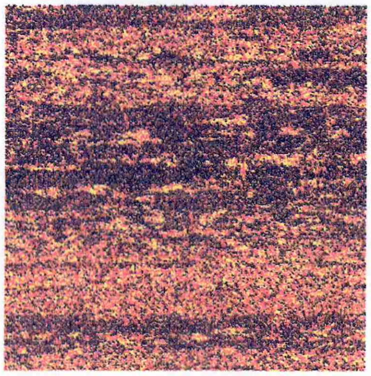
PHOSPHORUS



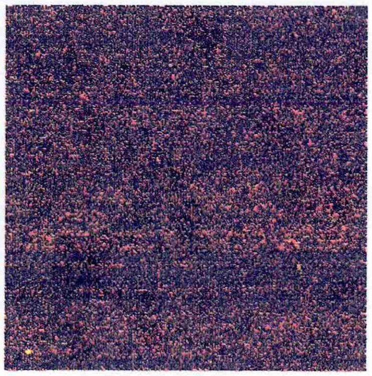
IRON



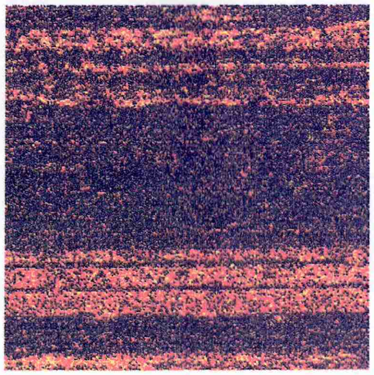
BARIUM



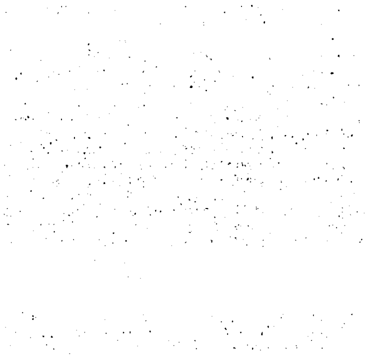
OXYGEN

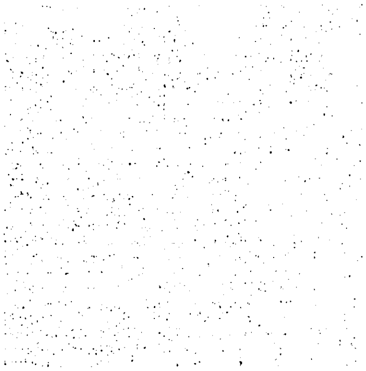


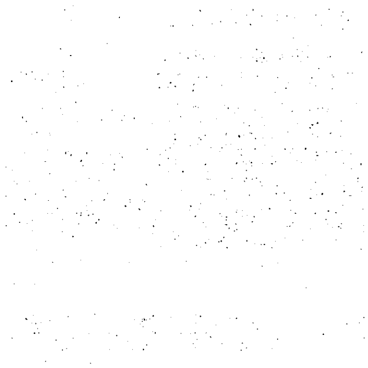
SILICON

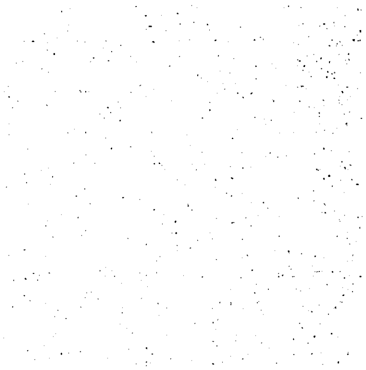


SULPHUR



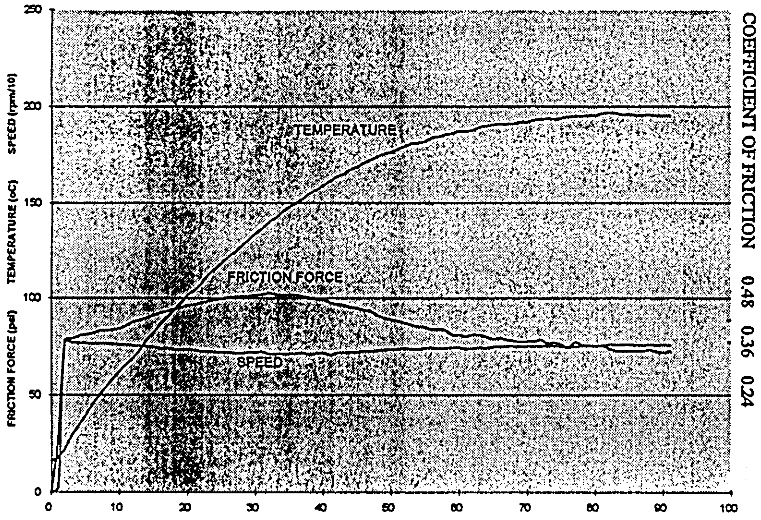




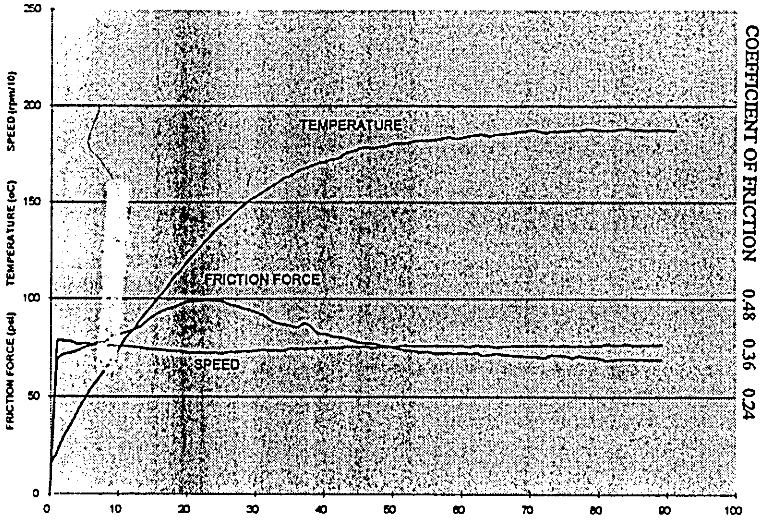


FRICTION MATERIAL M9238

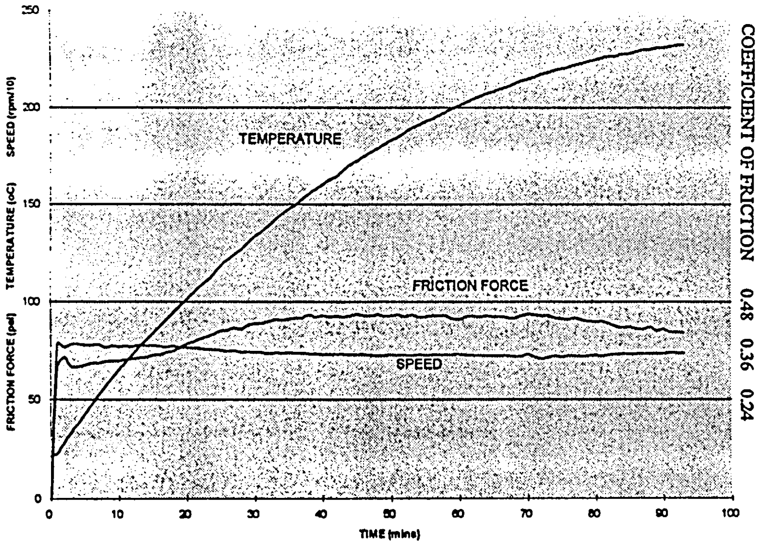
ALL TESTS RAN AT CONSTANT PRESSURE 40 PSI

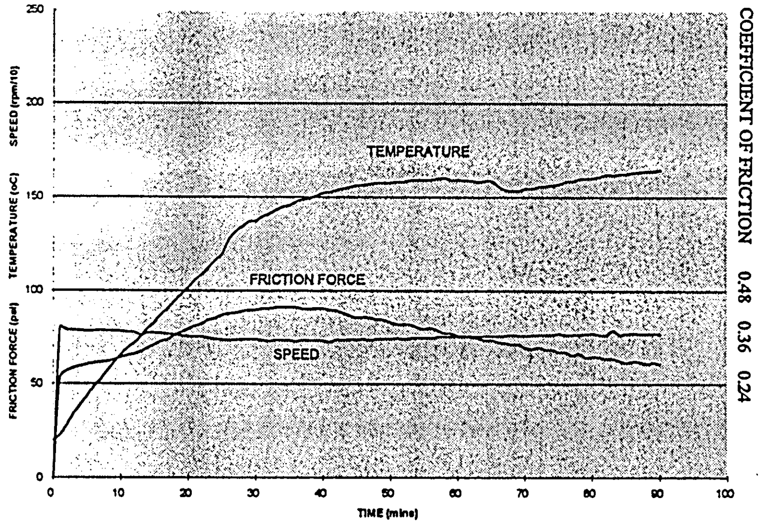


COPPER COATED CAST IRON DISC



COPPER COATED ALUMINIUM DISC





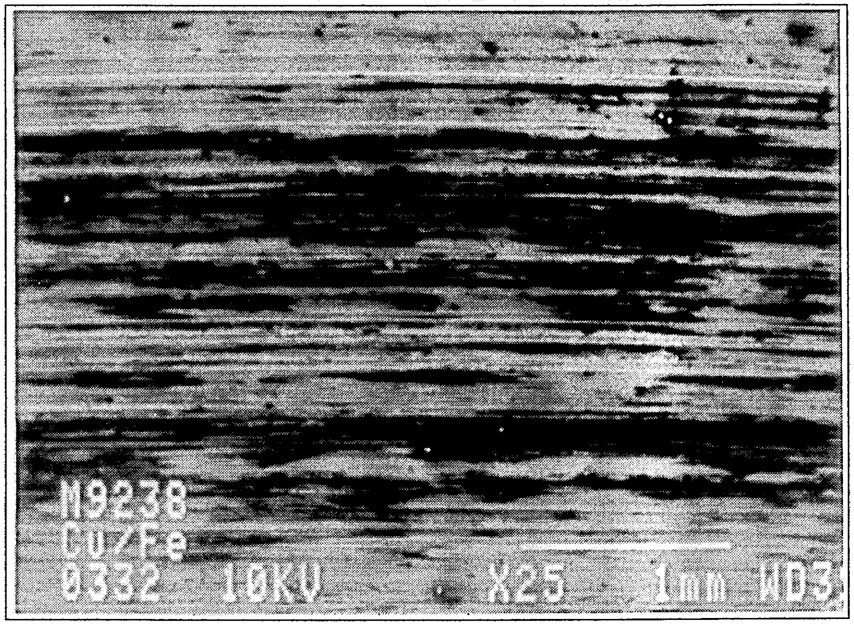
COPPER COATED ALUMINIUM DISC WITH FAN COOLING

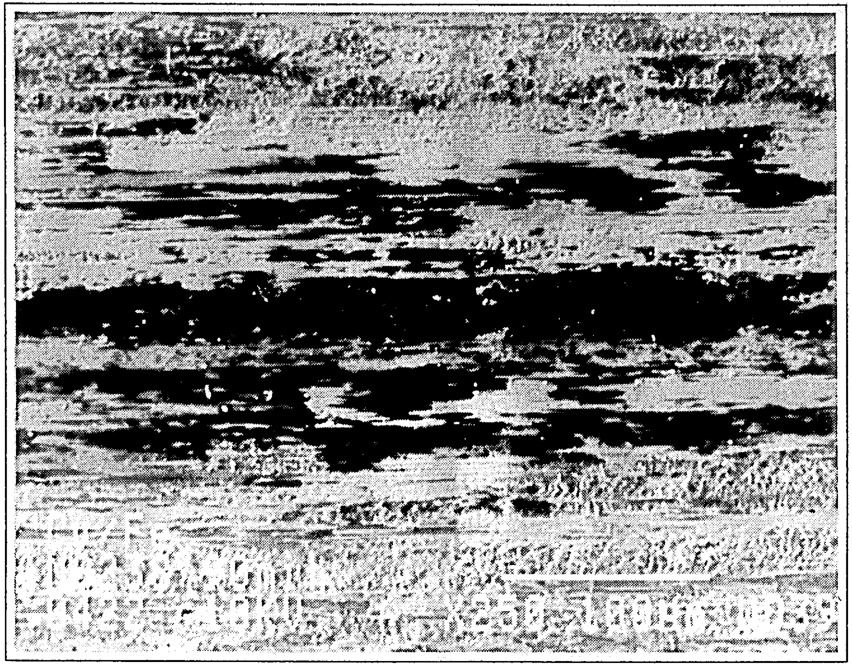
M9238

HIPAC SURFACE
FRICTION MATERIAL
M9238

GENERAL FILM
DISTRIBUTION

S.E. IMAGE

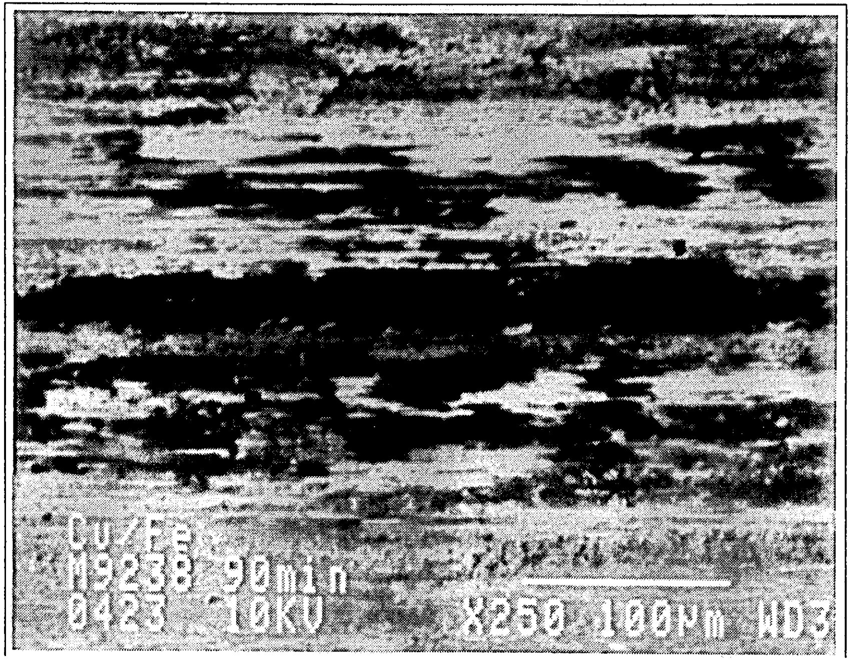




MAPPED AREA OF
PLUG SURFACE

PHOTO 422

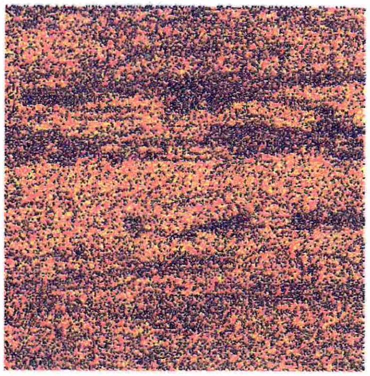
S.E. IMAGE

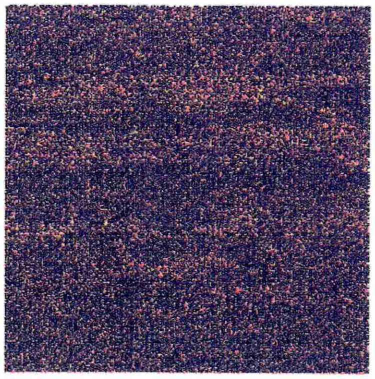


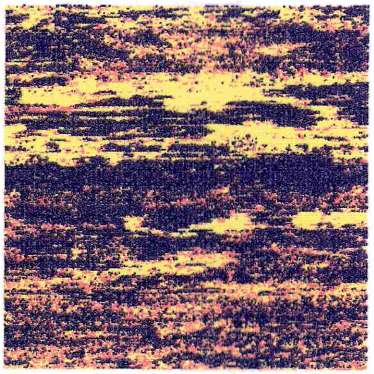
MAPPED AREA
B.S. IMAGE

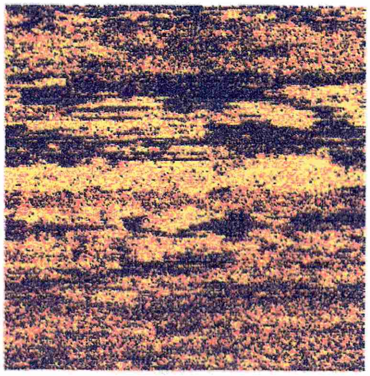
FRICTION MATERIAL M9238
COPPER COATED CAST IRON DISC
90 MIN RUN CONSTANT 40 PSI

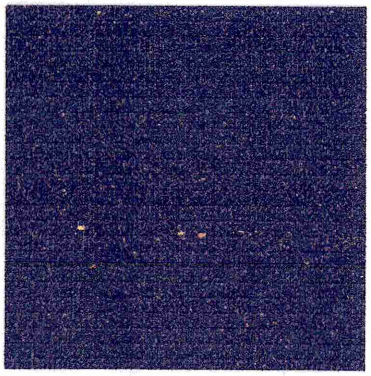
10 KV MAP x250 PHOTO 422

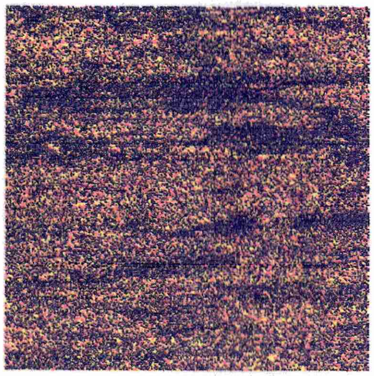

OXYGEN

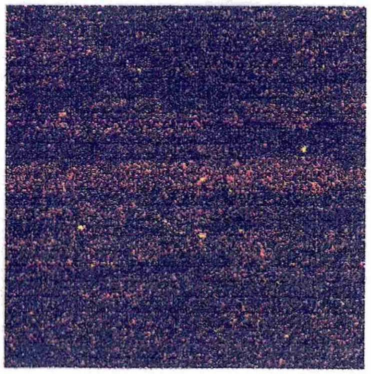

IRON

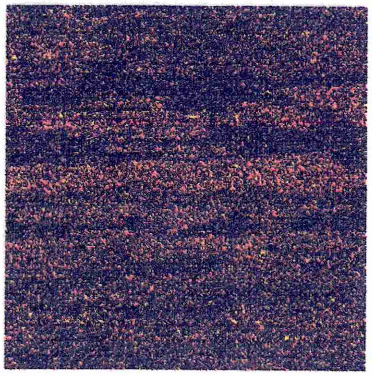

COPPER

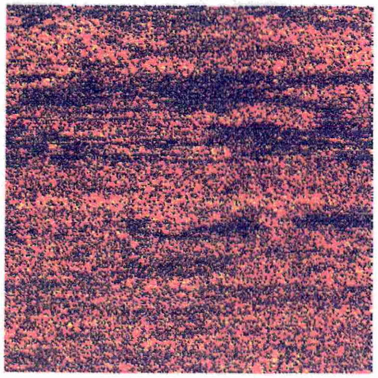

MAGNESIUM

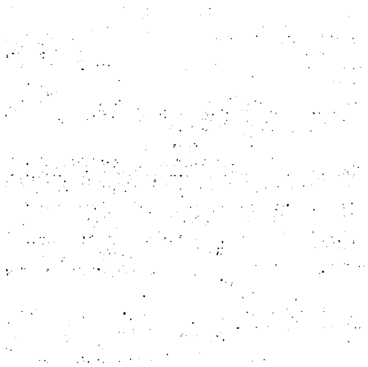
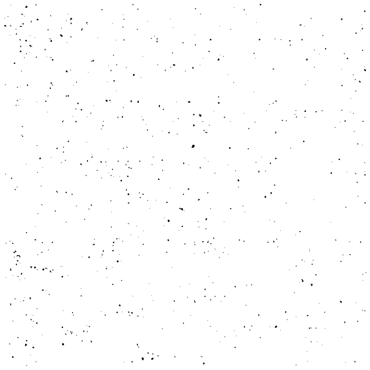

ALUMINIUM

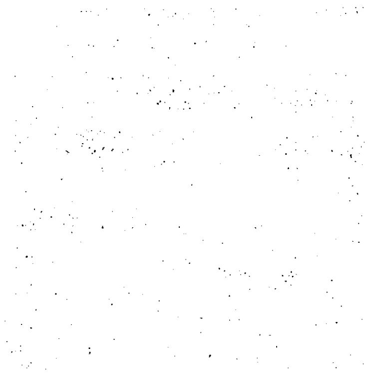
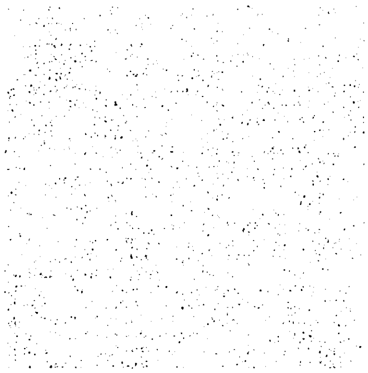

BARIUM

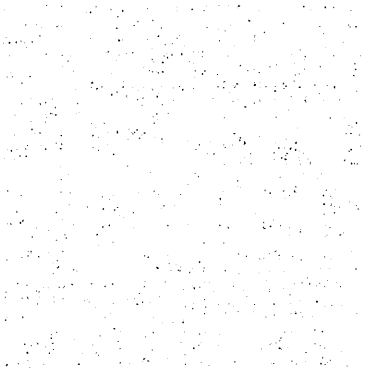
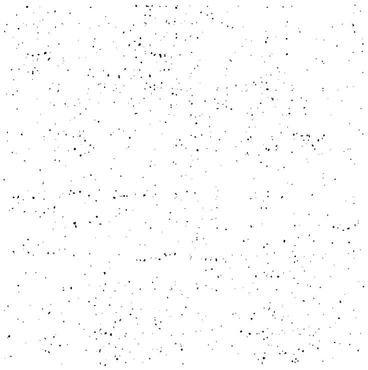

SILICON


ZIRCONIUM

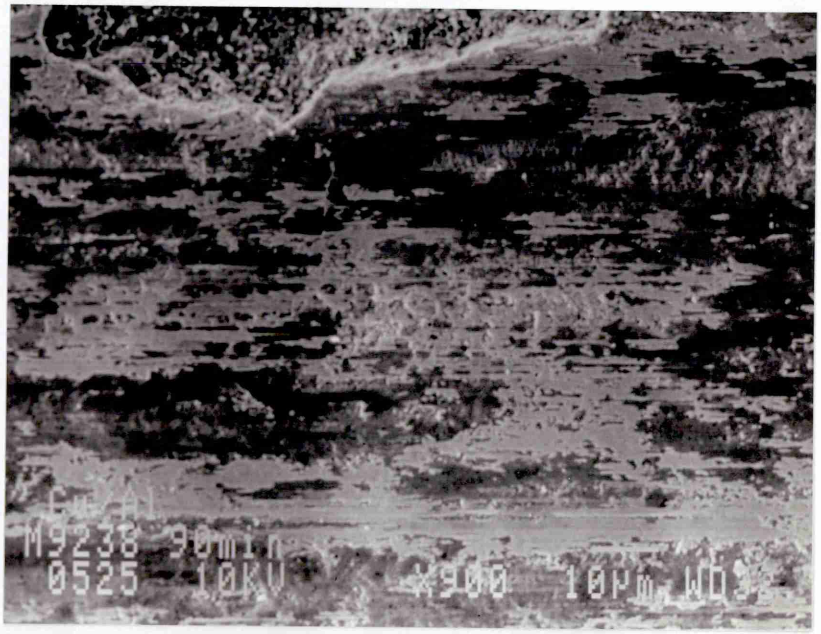

SULPHUR

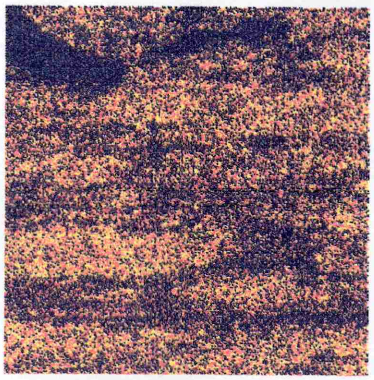



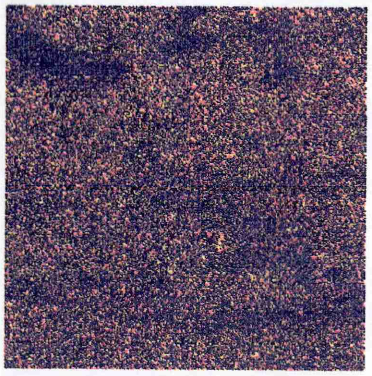



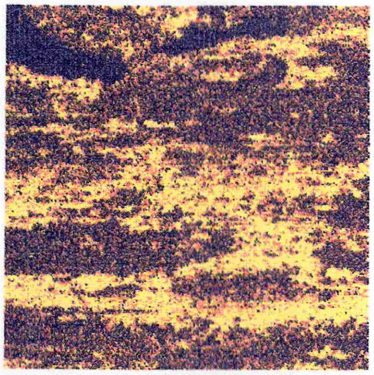




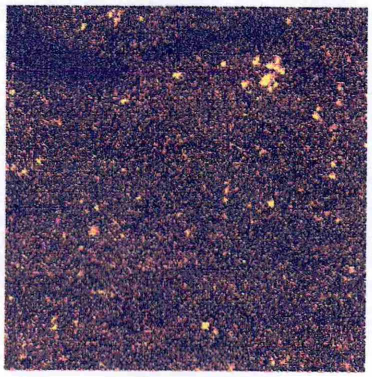
FRICTION MATERIAL M9238
COATED ALUMINIUM DISC
VERY THICK FLAKY DEPOSITION
270 MINS OF RUNNING 40 PSI
10 KV MAP x900 PHOTO 525

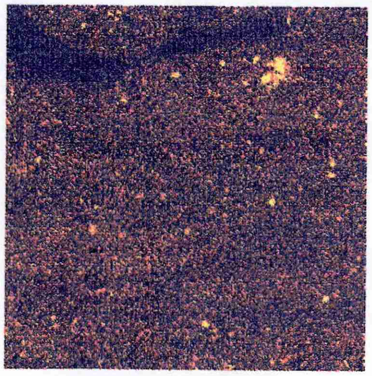


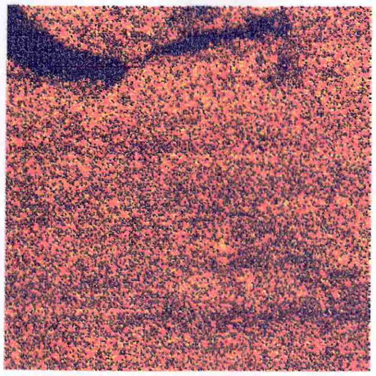

MAGNESIUM

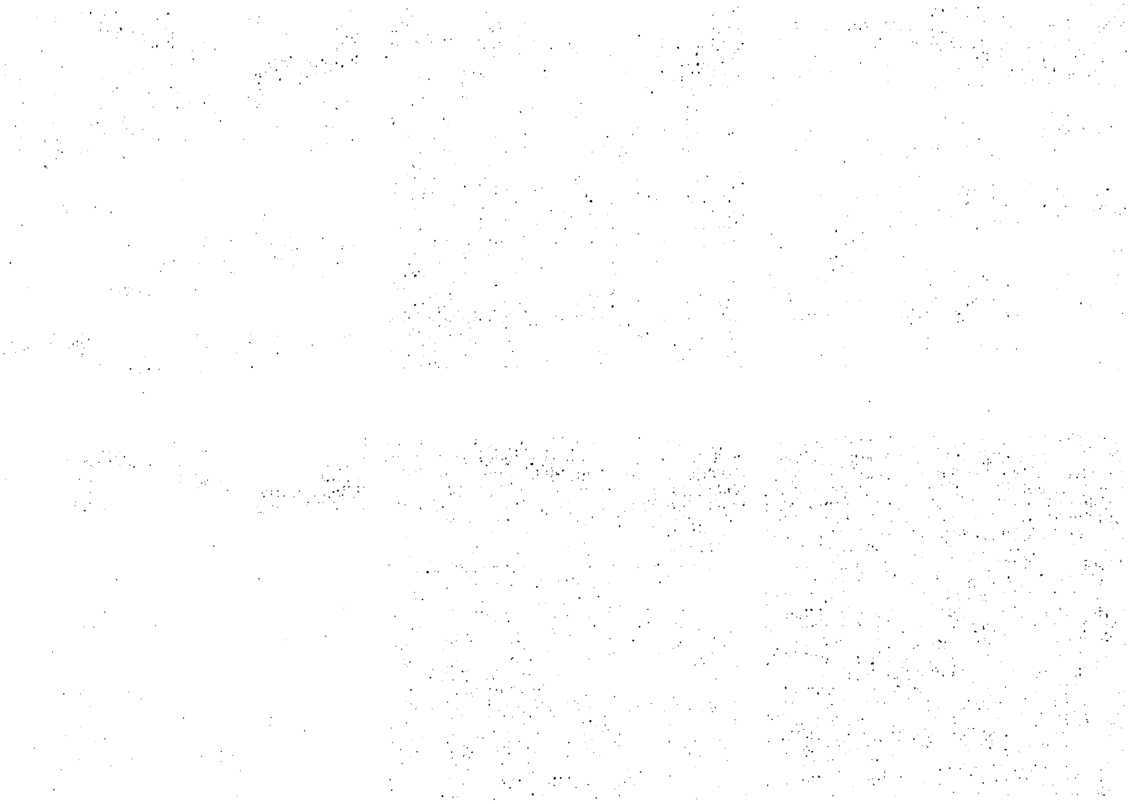

BARIUM


COPPER

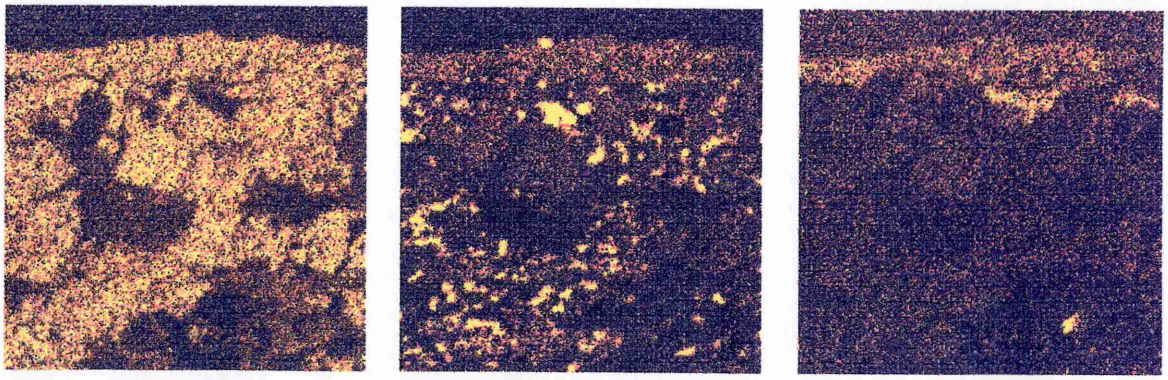

ZIRCONIUM


SILICON

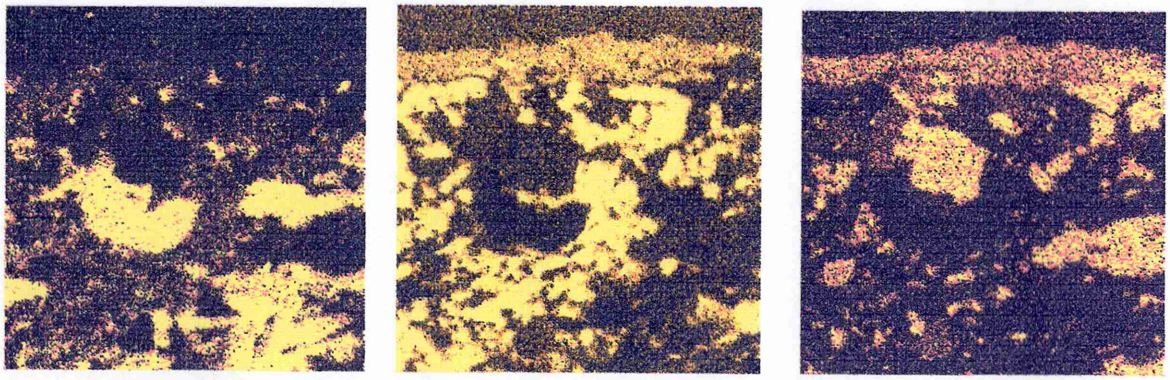

SULPHUR



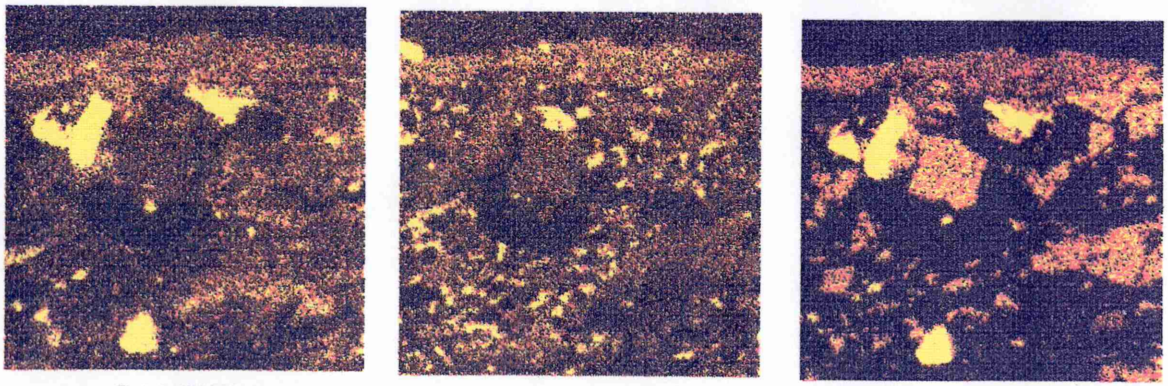
X-SECTION OF FRICTION MATERIAL M9238
RAN AGAINST COATED ALUMINIUM DISC
270 MINS OF RUNNING 40 PSI
10 KV MAP x1300 PHOTO 532



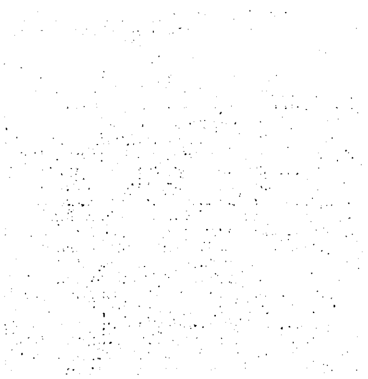
OXYGEN ZIRCONIUM COPPER

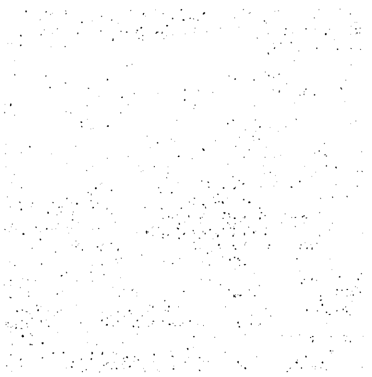


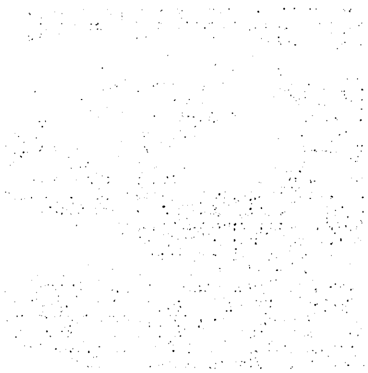
CARBON MAGNESIUM BARIUM

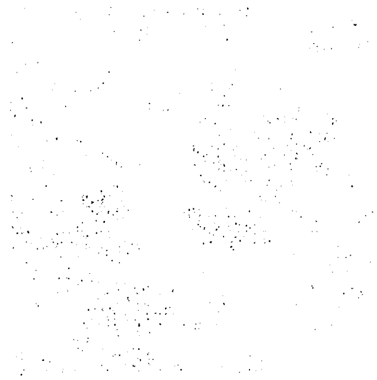


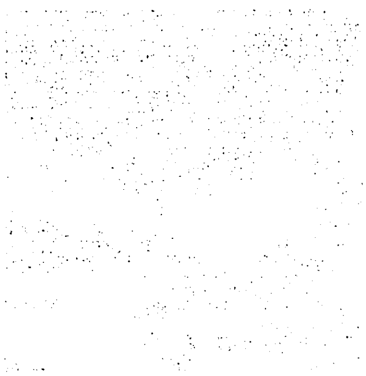
CALCIUM SILICON SULPHUR

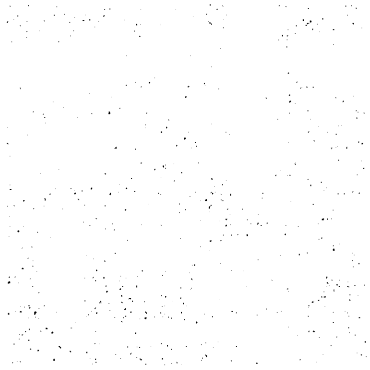


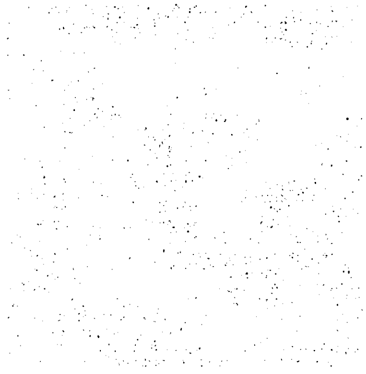










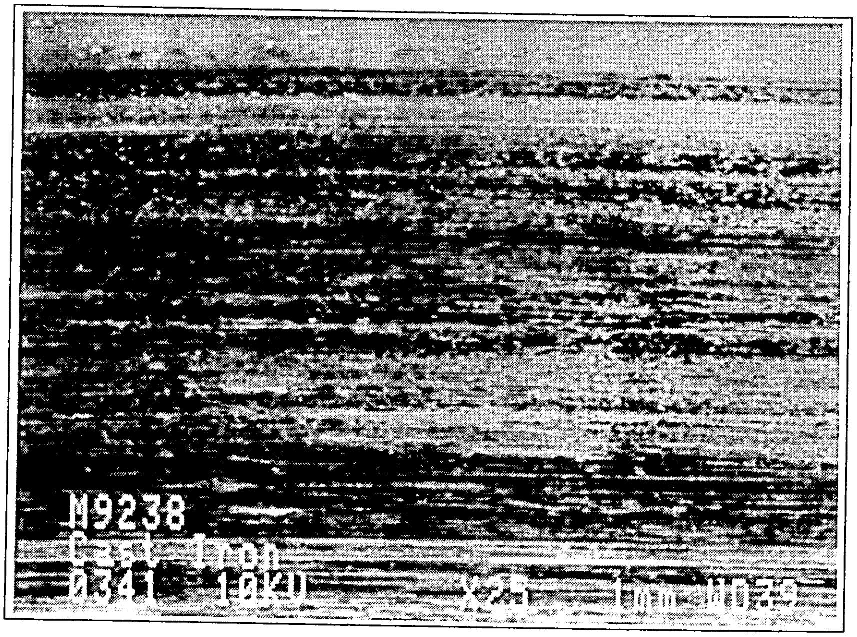


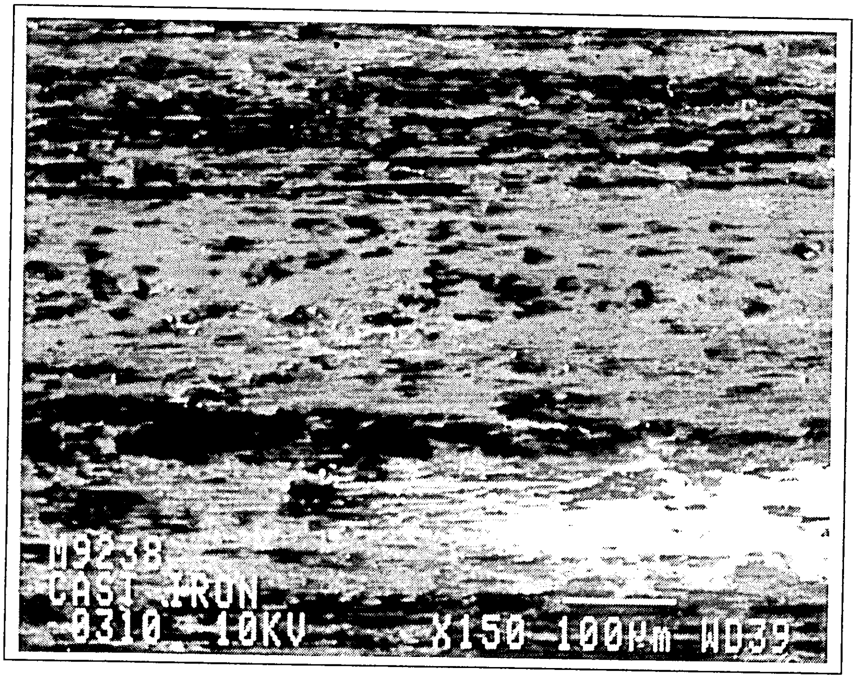
M9238

CAST IRON SURFACE
FRICTION MATERIAL
M9238

GENERAL FILM
DISTRIBUTION

S.E. IMAGE

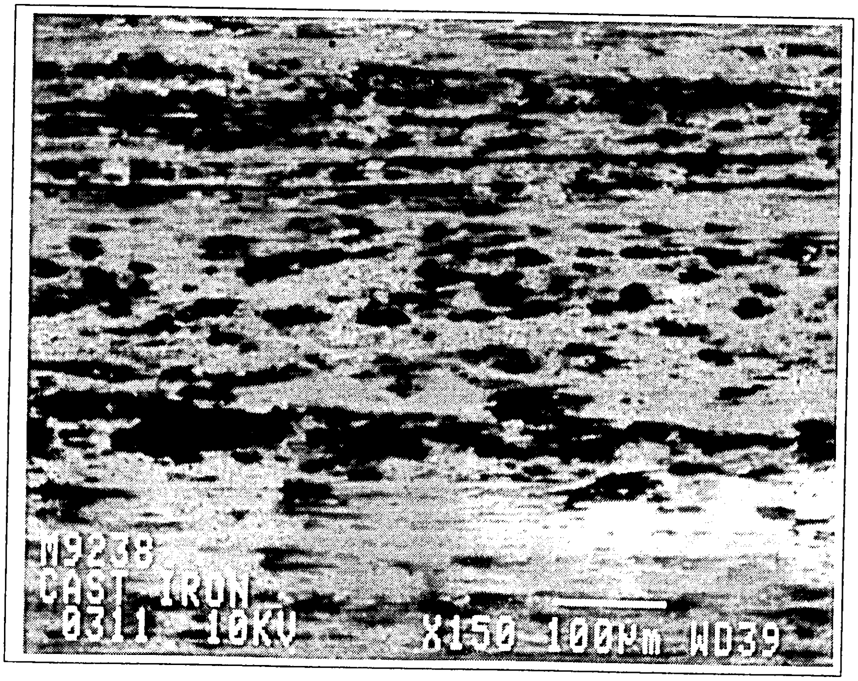




MAPPED AREA OF
PLUG SURFACE

PHOTO 422

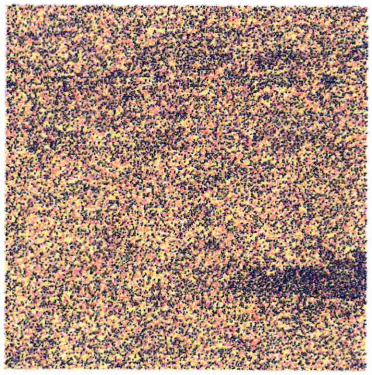
S.E. IMAGE

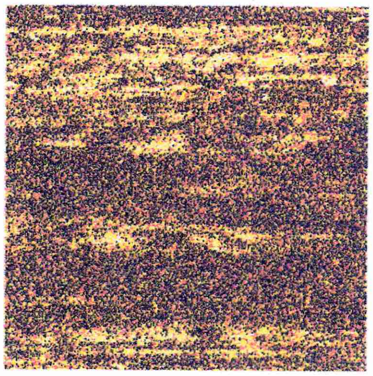


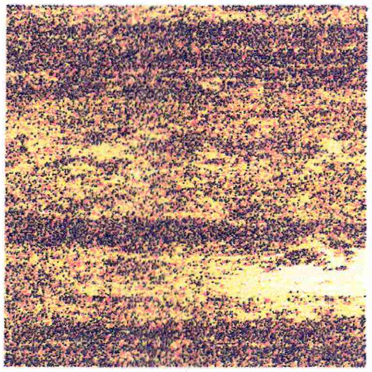
MAPPED AREA
B.S. IMAGE

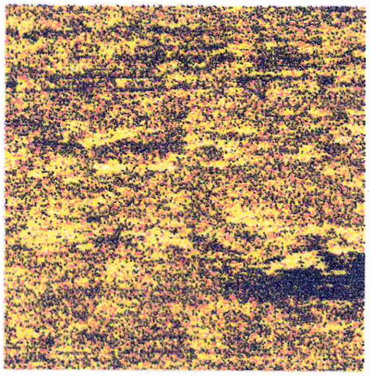
FRICTION MATERIAL M9238
CAST IRON DISC
90 MIN RUN CONSTANT 40 PSI

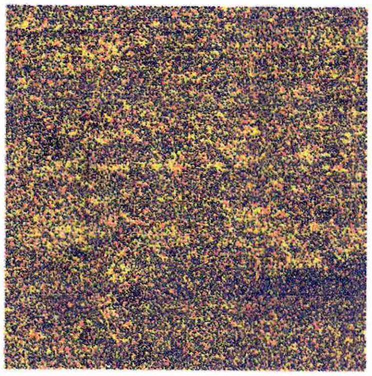
10 KV MAP x150 PHOTO 310

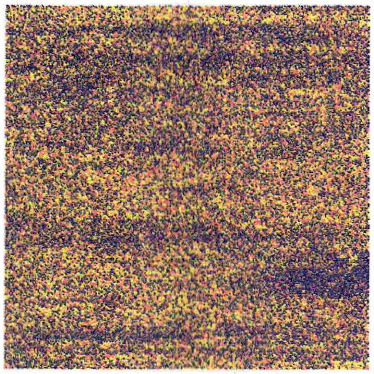

OXYGEN

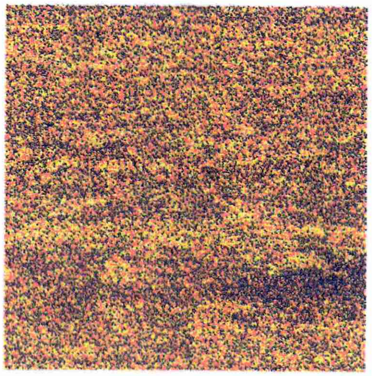

IRON

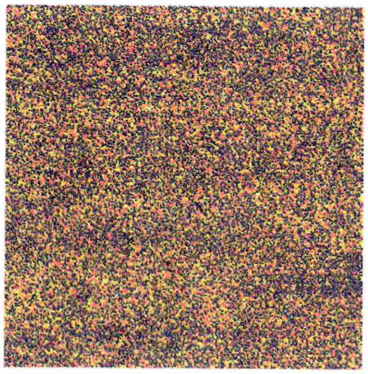

COPPER

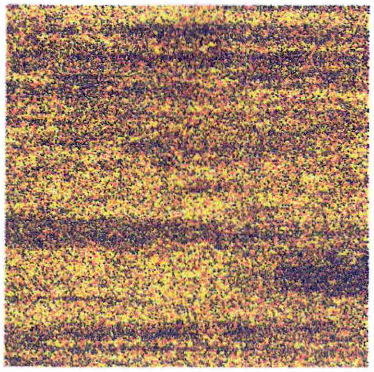

MAGNESIUM


ZIRCONIUM


BARIUM


SILICON


CALCIUM

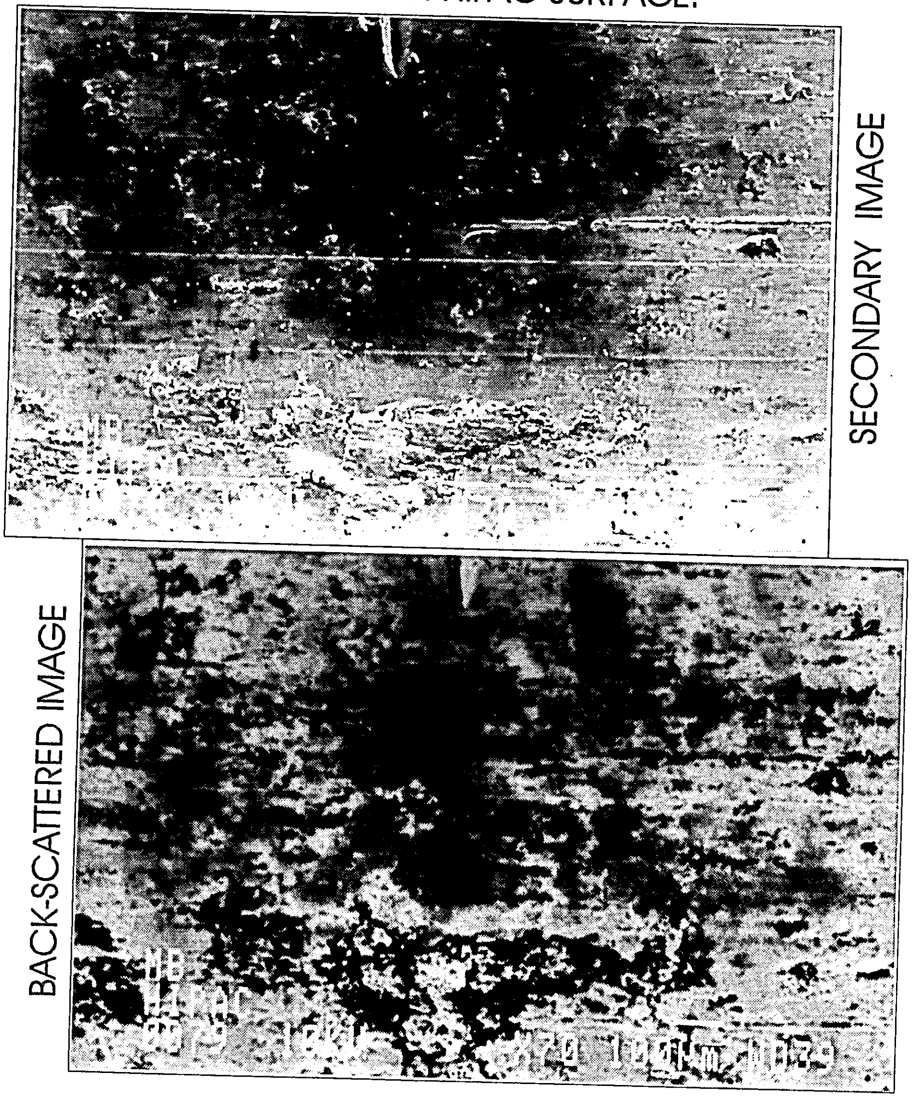

SULPHUR

Appendix 4

HIPAC COATED MOTOR BIKE DISC.

TRAPPED DEBRIS ON SURFACE OF MOTORBIKE DISC.

PATCHES OF FILM ON HIPAC SURFACE.

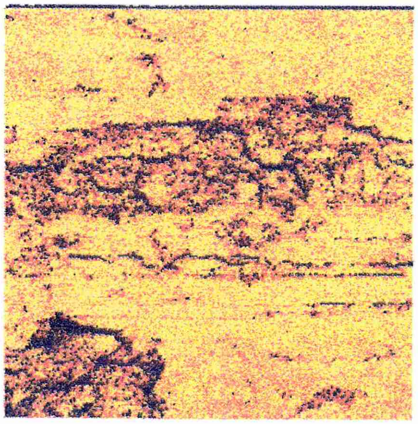


SECONDARY IMAGE

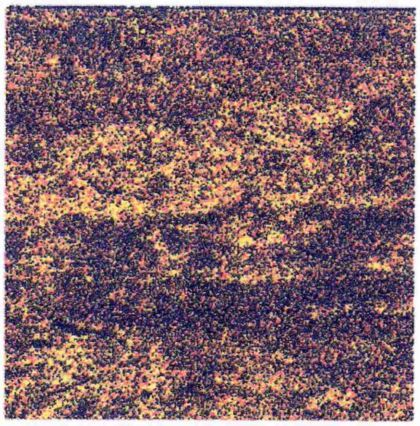
BACK-SCATTERED IMAGE

HIPAC MOTOR BIKE DISC

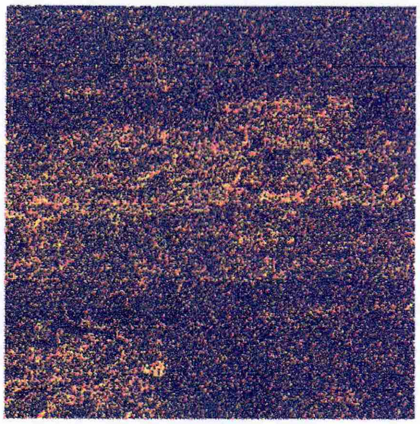
MAPPED AREA x100   10KV   PHOTO NUMBER 0032



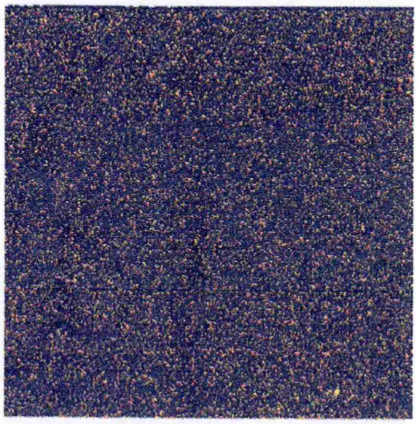
COPPER



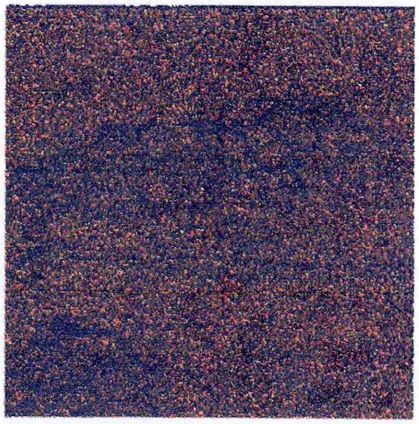
OXYGEN



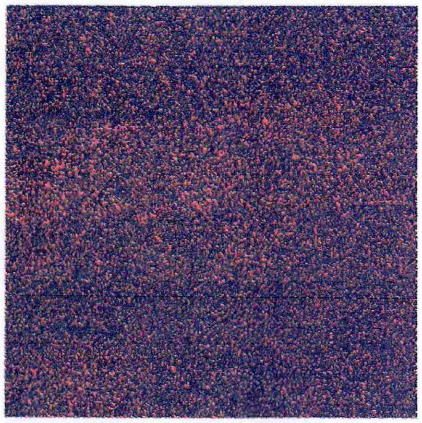
CARBON



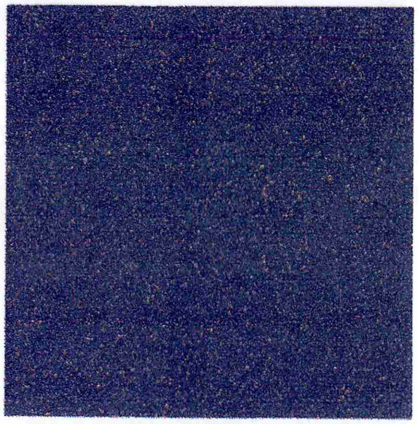
BARIUM



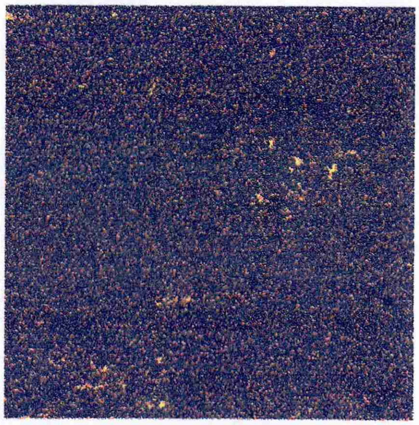
IRON



POTASSIUM



ALUMINIUM



SILICON

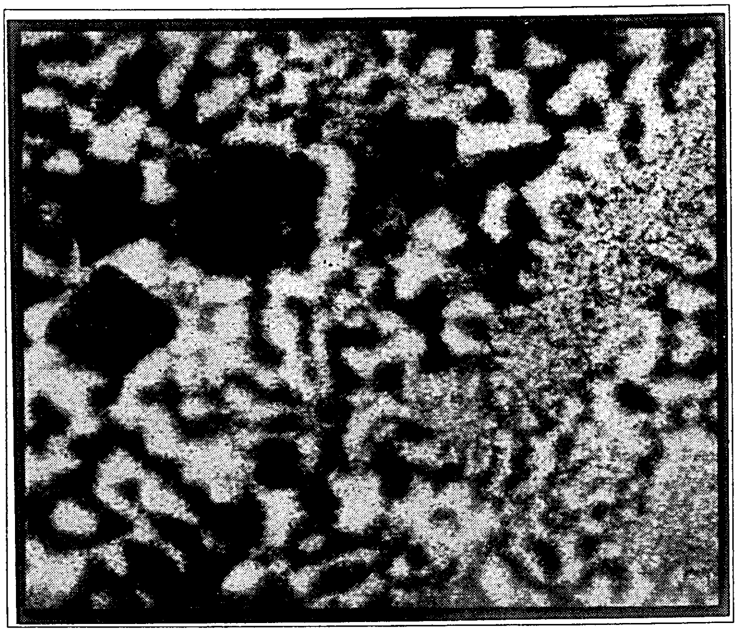
SULPHUR

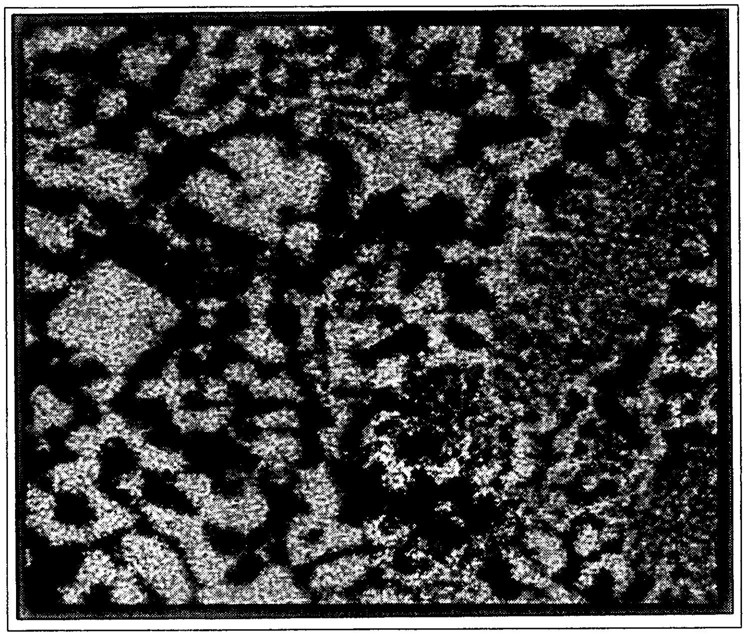
MAP AREA

x750 21 KV

DE-LAMINATION SAMPLE

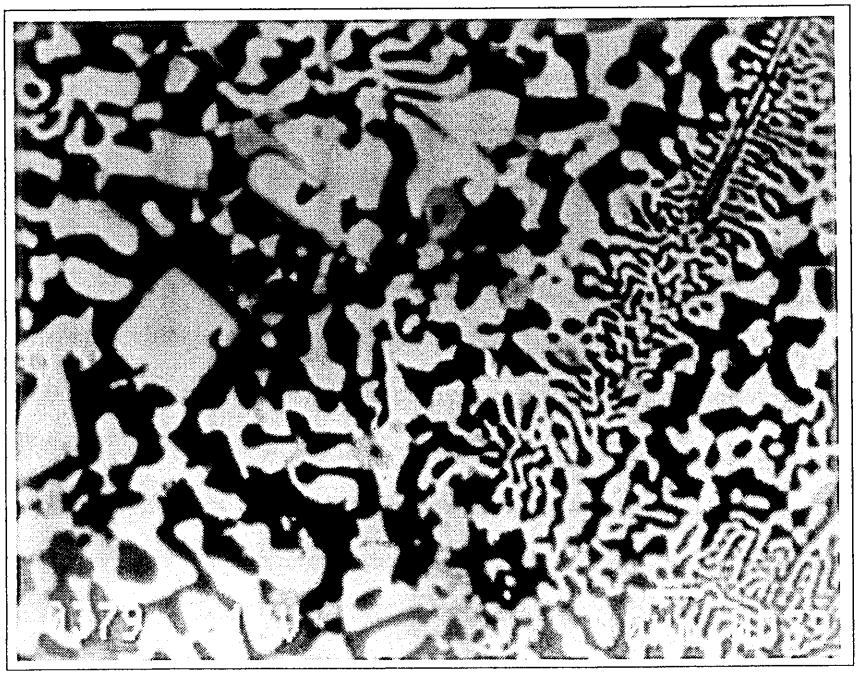
ALUMINIUM





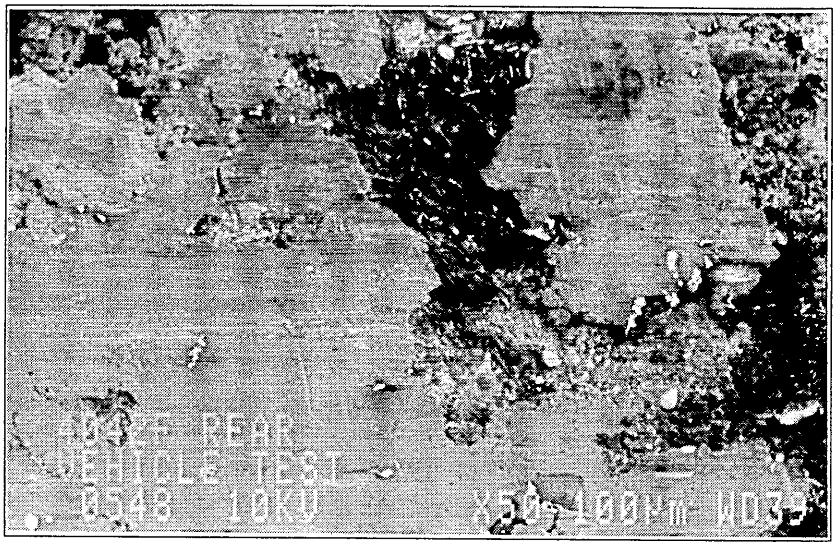
COPPER

S.E.M. MICRO- GRAPH OF MAP AREA

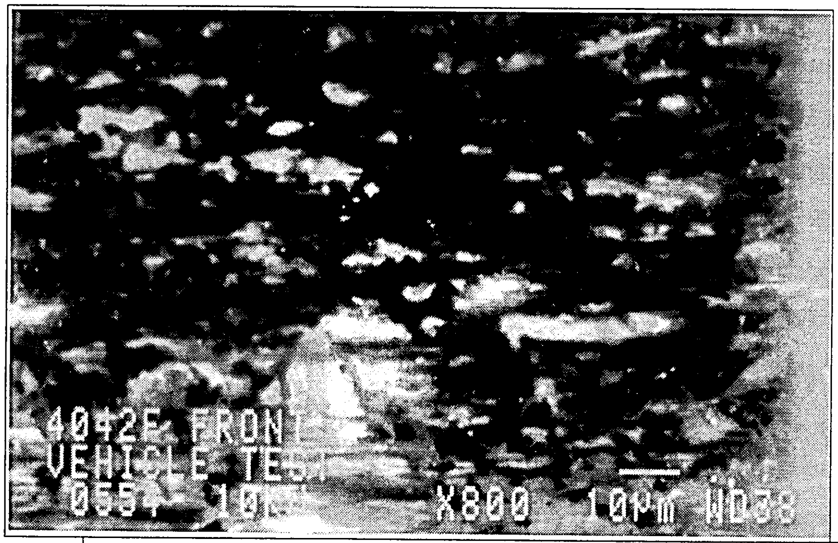


WORN LINING SURFACES FROM VEHICLE TEST

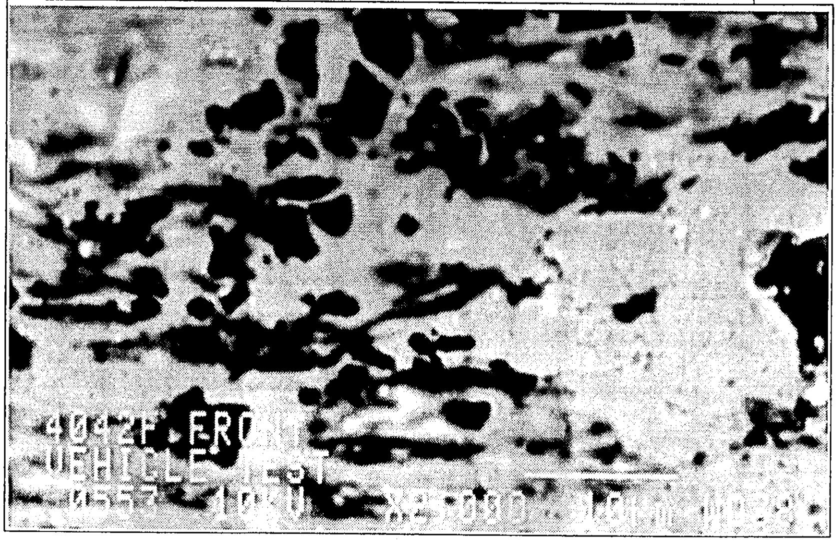
FLAKES OF COPPER METAL ON REAR PAD



GLAZED SURFACE OF FRONT PADS

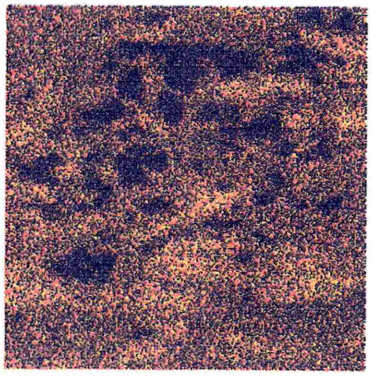


SECONDARY IMAGE

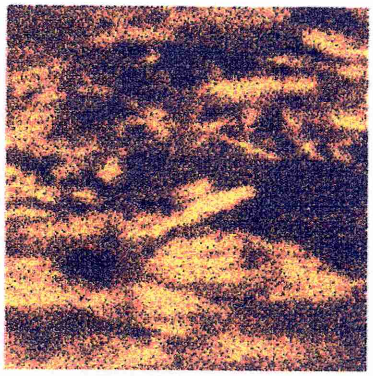


BACK-SCATTERED IMAGE

FRICTION MATERIAL 4042F
VEHICLE TEST FRONT PAD
GENERAL GLAZE ON PAD SURFACE
10 KV x2000 PHOTO 553



OXYGEN



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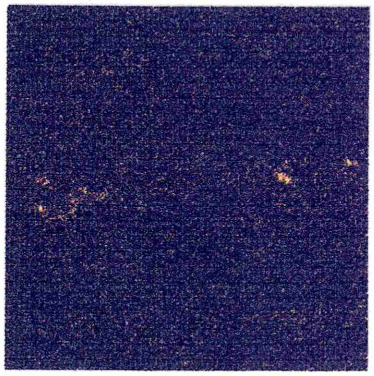
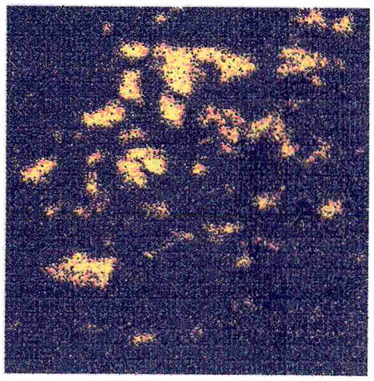
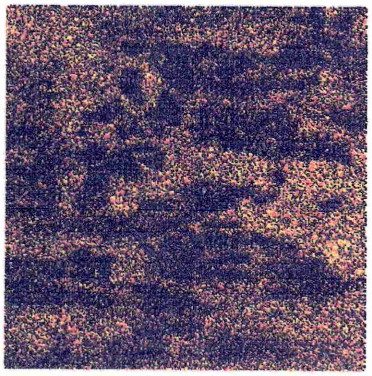


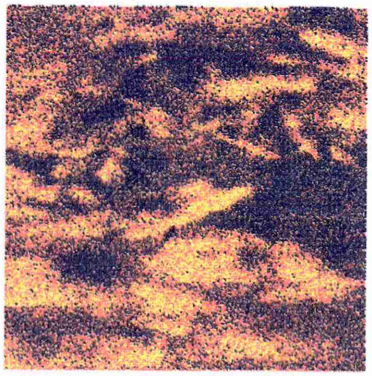
COPPER



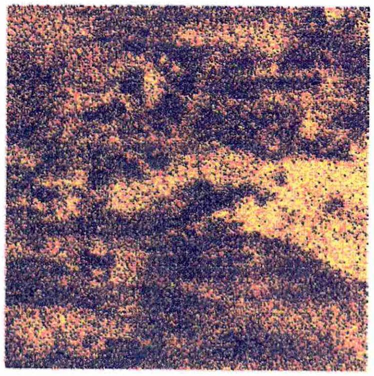
CARBON



BARIUM



SILICON



SULPHUR