ABRASIVE WEAR
WITH PARTICULAR REFERENCE
TO DIGGER TEETH

A thesis submitted for the degree of
Doctor of Philosophy.

by

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January 1987

To my wife Ekbal

my sons

Muhanad and Haidar

my daughter

Esra

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ABSTRACT

Abrasive wear occurs when a contact associated with stress between a metal surface and a hard particle (frequently of mineral origin) leads to friction between the two.

In a very wide range of industrial applications, abrasive wear is the main reason for component and equipment repair or replacement. In most of these applications, especially those of earth moving, construction and mining equipment, digger teeth are used to improve equipment performance. Digger teeth can be produced in different shapes and sizes (mainly by casting) and a wide range of materials are used.

This project is concerned with both a field trial of the wear of digger teeth fixed to the front of a bucket used in a gravel pit, and also a laboratory investigation of abrasive wear mechanisms.

It was found that the wear of digger teeth increased with increasing working hours, but the wear rate eventually decreased. The dimensions and shape of the front of the tooth changed and gravel removal became more inefficient. Plastic deformation and phase transformation were observed in the worn surfaces of the teeth.

In the laboratory study, many parameters were investigated utilising a pin-on disc technique. Wear rate increases linearly with load and decreases with sliding distance. The effect of attack angle on abrasive wear showed that wear volume increases with increasing attack angle up to a certain value (90°) and then decreases.

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Corrosion increases the initial wear rate, and the amount of material removed in the wet corrosive test was higher than the corresponding dry test.

It was difficult to reproduce the same results from the field trial in the laboratory because of the difference in the conditions in the two cases. Optical and scanning electron microscopy were used to study the worn surfaces, abrasive papers and wear debris. Different abrasive wear mechanisms were observed throughout this investigation. A cutting mechanism associated with spiral debris was observed during short pin-on disc tests and with higher attack angles. A ploughing action associated with plate-like debris was observed during longer tests and at lower attack angles. Fragmentation was observed in brittle materials.

CHAPTER ONE

INTRODUCTION

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1. INTRODUCTION

Wear is one of the most commonly encountered industrial problems leading to the replacement of components and assemblies in engineering. It can be defined according to different investigators as follows [1] :-

(i) The destruction of material produced as a result of repeated disturbances of the frictional bonds (Kragelskii).

(ii) The progressive loss of substance from the operating surfaces of a body, occurring as a result of relative motion of the surface (OECD).

(iii) The removal of material from surfaces in relative motion by mechanical and/or chemical processes (Tabor).

(iv) The removal of materials from solid surfaces as a result of mechanical action (Robinowicz).

Since chemical processes, as well as mechanical action, have a significant influence on industrial problems, the third definition is considered to be the preferable one.

In some cases there is no metal removal from the surfaces, hence wear can also be defined as the unintentional or undesired flow of metal.

Wear encountered in industrial situations can be broken down into the following categories [2] :-

Abrasive	50%
Adhesive	15%
Erosive	8%
Fretting	8%
Chemical	5%
Others	14%

There are situations in practical applications where one type of wear changes to another, or two or more mechanisms operate together. It is possible, for example, for debris produced by adhesive wear to cause abrasive wear. Wear is rarely catastrophic but it reduces the operating efficiency by increasing the power losses, oil consumption and the rate of component replacement.

Wear can be the reason for the following problems in industry:-

(1) The part becomes worn out and does not continue to support the load.

(2) Geometry of a cutting edge increases which increases friction and thus energy consumption.

(3) Change in surface topography causes a reduction in sealing and loss of fluid and/or power consumption.

(4) Increase in tolerance between the parts causes vibration and an unacceptable noise level.

(5) Generation of wear debris may cause secondary damage to the other surface (bearing, shaft, etc.).

(6) Wear debris may block up filters or cause seizure between two closely fitting parts.

(7) Economical loss due to replacements (parts, equipment, labour and the production breakdown).

(8) Equipment out of service leading to plant closedown.

Because of the wide variety of conditions causing wear, with many mechanisms contributing to the damage caused, the solution of many particular problems requires precise identification of the nature of the problem and care must be exercised in applying general solutions to individual problems. In some cases increasing hardness will reduce wear, while in others the opposite may be true. Changing the operating conditions may give greater improvements than changing the material or its condition. Increasing emphasis is being given to tailoring surfaces to match operating conditions; expensive bulk materials can sometimes be replaced by a cheaper substrate with a suitably treated surface. Solutions to wear problems encountered will only arise from an understanding of the role of operating variables and the behaviour of materials under service conditions. It has been suggested that the major growth area for the future lies in the role of coatings and surface treatments in improving tribological characteristics. New surface techniques are becoming available faster than our rate of understanding of their precise tribological characterisation and it is often difficult to make a rational choice.

It must be remembered that modifying a surface will result in change in:-

1. Topography
2. Chemical composition
3. Microstructure
4. Hardness

We must ask how these parameters control wear behaviour. In addition, there are two main questions about processing; which substrate metal to use and how thick should the surface treatment be.

Wear may be controlled in a number of ways, the choice depending on the application; the more common approaches are [3].

1. Change in the operating regime to reduce its severity.
2. Change in the geometry of the component.
3. Use of a more wear resistant material for the component.
4. Application of a surface coating (or treatment).

The benefits obtained from a better tribological knowledge are shown in Fig.1. Lower maintenance and replacement account for 50%, reduced breakdown for 25% and increased life for 20%. (4)

1.1. Characterisation of Wear.

Unlike other physical and mechanical properties, wear resistance is not an intrinsic property of a material. Wear resistance is a complex

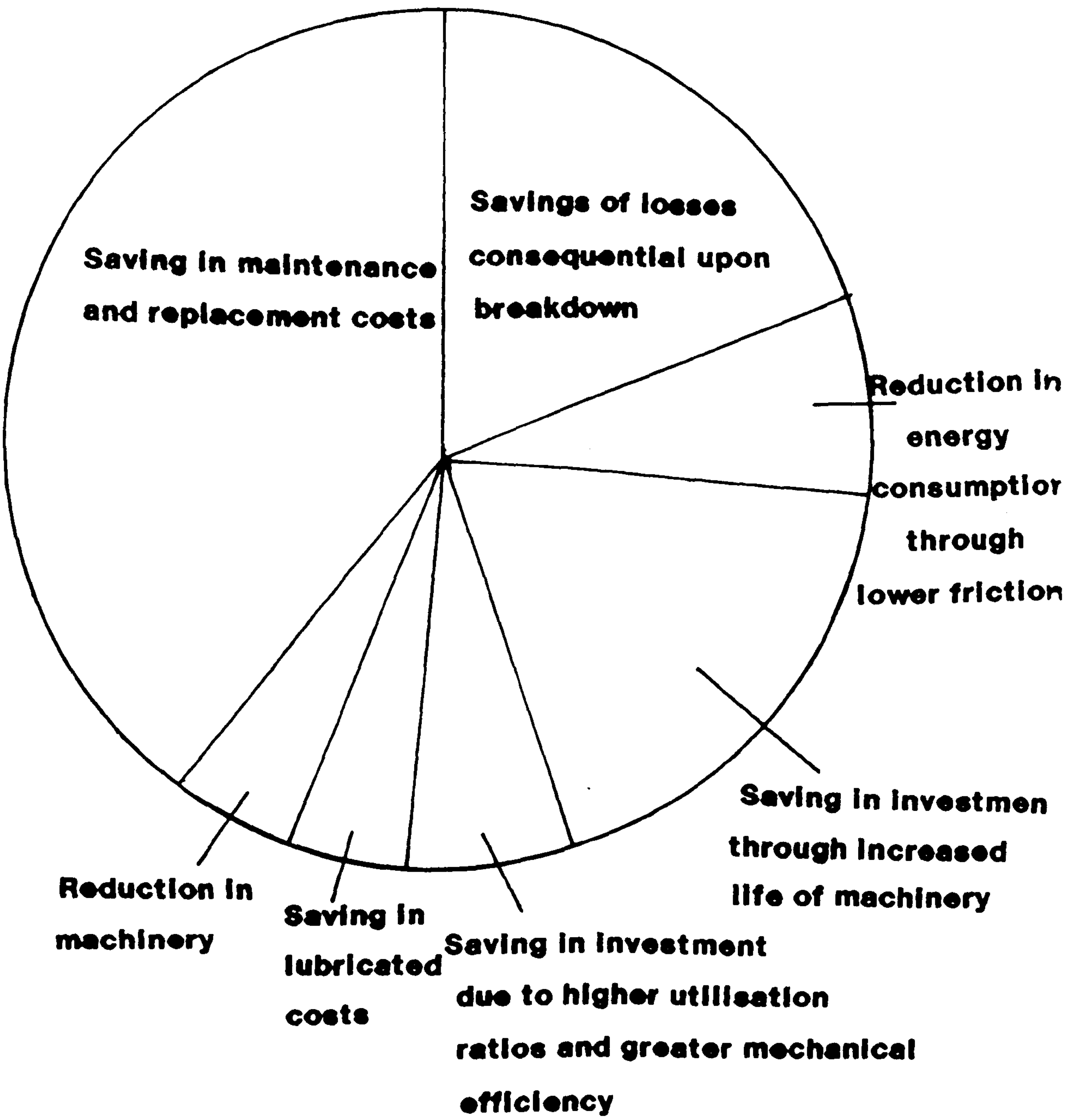

Fig. 1 Potential savings from improved tribology design (4).

characteristic that is determined by the environmental conditions giving rise to removal of material from a solid surface under the influence of a mechanical action.

To define wear resistance, it is necessary to define the nature of the mechanical action and the environmental conditions, i.e. to define the system in which wear occurs.

Fig. 2 show different types of wear. It clearly indicates that wear is not a simple, single property and that different categories of wear can be identified in which the conditions giving rise to wear are quite different [5].

Under conditions of metal to metal contact, the mechanism of wear is one of adhesive (welding) followed by fracture along a path other than that of the original interface. The wear debris is the small fragment torn away by relative movement the interface.

Under conditions of abrasion, a hard asperity penetrates and ploughs a groove in the metal over which it passes, as shown in Fig. 3. Here the mechanism is one of micromachining and the debris takes the form of a small machining chip.

These mechanistic differences are not obvious to the unaided eye but the use of both optical and electron optical techniques allows them to be dramatically demonstrated.

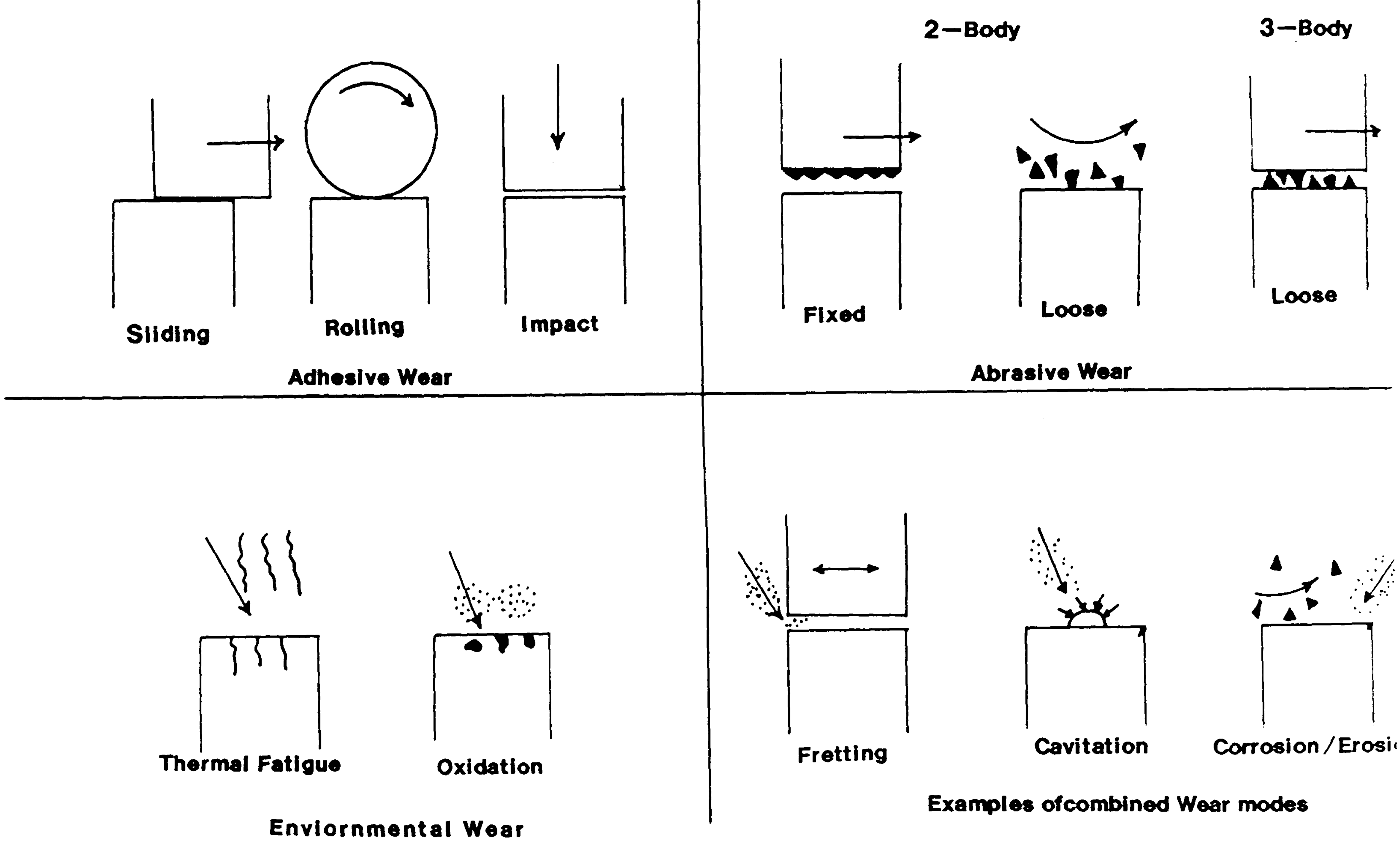

Fig.2 Schematic representation of various wear modes (5)

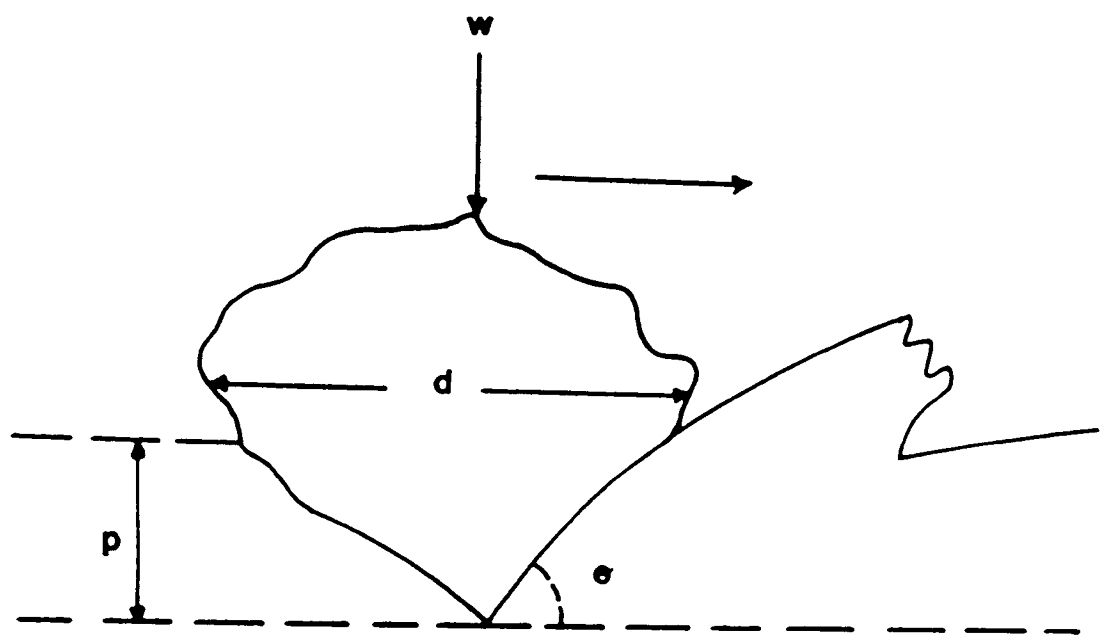

Fig. 3 Abrasive Particle Contact

w-Load

p-Depth of indentation

d-Particle diameter

σ-Attack angle

CHAPTER TWO

ABRASIVE WEAR

CHAPTER TWO

2. ABRASIVE WEAR.

It has been mentioned in the previous section that abrasive wear can be found in more than 50% of all the cases in which wear occurs in industrial situations. It therefore has great economic significance.

There are several definitions of abrasive wearing, differing only in detail. The Research Group on Wear of Engineering Materials of the Organisation for Economic Co-operation and Development (RGWEMOECD) has defined abrasive wear as "Wear caused by displacement of material from one of two surfaces in relative motion caused by the presence of hard protuberances on the second contact surface, or by the presence of hard particles either between the surfaces or embedded in them".(6)

Abrasive wear occurs when there is friction between one metal under stress and a harder body or grain, frequently of mineral origin such as pieces of ore crushed during transportation, a rock monolith subjected to boring, for example during prospecting for oil, or extraneous grains of sand dust between lubricated rubbing surfaces of metallic parts, or hard grains in the stream of liquid or gas flowing over metallic surfaces.

Abrasive wear causes an enormous expenditure by industry and consumers. Most of this is in replacing or repairing equipment that has worn to the extent that it no longer performs a useful function. In some cases, this occurs after only a very small percentage of a component total volume is worn away. For some industries, such as agriculture, as many as 40% of the components replaced on equipment have failed due to abrasive wear. Friction and wear can cause a national economic waste of $100 billion per annum in the U.S.A., DM10 billion per annum in West Germany and more than £500 million in the U.K.[(7)]

The most severe problems occur due to abrasive wear in equipment which is in contact with natural abrasives such as silica, alumina and iron oxides which, as a total, represent about 81% of the earth's crust.

Abrasive wear can be found in the following applications:-

1. Metallurgical extraction industries.
2. Mining and subsequent processing.
3. Construction industries.
4. Agricultural industries.
5. Quarrying and gravel pits.

In some of the above applications improvements have been brought about by design changes where these reduce the frequency of abrasive particle contact, contact loads or sliding distance. But the most significant improvements have been achieved by the application of existing knowledge to the selection of material for abrasive wear applications However, the most wear resistant material does not always provide the most cost-effective solution, nor is it always the correct material to use if the working environment includes high impact loads, since impact resistance and wear resistance are not highly compatible properties. The economics of materials used vary considerably from one operation to another and depend on such factors as relative cost of the replaceable components as a whole, the cost of having equipment idle whilst components are repaired or replaced, the effect of stoppages in the time scale of a larger operation, and the basic cost effectiveness of different materials. Thus, if the loss of production when equipment is idle is high, the overall cost may be reduced by using wear resistant materials which are not in themselves cost effective. On the other hand, if the loss of production and labour costs in replacing worn components are low, materials selection is controlled largely by the basic material cost effectiveness.

2.1. Types of Abrasive Wear.

Depending on the mode of the sliding abrasive particles derived from the definition mentioned above, abrasive wear occurs in one of two ways:-

1. Two-body wear. This type of wear generally operates under low stress conditions with particles being transported across the surface with little breakdown in particle size of the abrasive.

2. Three-body wear. Where the abrasive is a free grit between two surfaces, either derived externally or from particles abraded from rubbing components. As a result, the abrasive embeds into the surface causing deformation, fracture and wear. This is wear under high stress conditions.

Some investigators classify abrasive wear as follows[9]:-

Gouging Abrasion:- Is associated with large abrasive particles, extremely high stress, impact, abrasive fracture, the metal flows with a high degree of metal work hardening. This type of wear can be found in Jaw and Gyratory crushers.

High Stress Grinding:- It is associated with smaller particles, sliding rather than impact, the abrasive fractures with some work hardening. This occurs in smaller ball and rod mills.

Low Stress Abrasion:- In this type of wear small particles with a low stress slide over metal surfaces. The abrasive does not fracture and very little work hardening occurs and this occurs in screens, chutes and trays, etc.

Laboratory test methods which have been developed to simulate these three classifications are the laboratory jaw crusher test[10,11] for gouging abrasion, the pin test[12] for high stress abrasion and the rubber wheel test[13] for low stress abrasion. In all cases only a small fraction of the particles causes wear due to a variation in the angle of attack and those particles which roll or slide contribute little to wear.

Two body wear accounts for the great majority of applications met in industry and is considerably easier to duplicate under controlled laboratory conditions The relative amounts of material removed in a 3-body situation is much greater than that removed in a 2-body case.

In abrasive wear, smooth surfaces become roughened with fairly regular grooves. This type of damage is usually described as scratching, scouring or gouging, the difference being mainly in the degree of severity.

The wide range of terminology mentioned above can be considered as a useful way of describing abrasive wear because each one refers to a specific case of abrasive wear and at the same time it shows very clearly how complex the abrasive wear process is. On the other hand, this terminology might mislead the reader and cause confusion unless he is aware of it.

It is very important to use terminology which can be precisely defined in order to help in the development of scientific understanding rather than causing further confusion. It would be better to characterise abrasive wear with a description of the system in which it is produced.

2.2. Models of Abrasive Wear.

2.2.1. A Simple Model.

Most simple analytical models of the abrasive wear process agree that the following parameters should be included in order to quantify the volume of material removed (W_V).

1. Load between the abrasive and the abraded material (L).
2. Hardness of the abraded material (H).
3. Relative sliding distance (S), such that:

$$W_V = \frac{K.L.S.}{H} \qquad (1)$$

where K is a constant.

The hardness of the material determines the depth of penetration of an abrasive particle for a given load; a higher hardness results in a shallower indentation. Thus, when the abrasive particle moves across the surface it is assumed that the volume of material removed is equal to the sliding distance multiplied by the cross-section area of the static indentation.

In formulating this model, however, the following assumptions are made:

(a) The abrasives are of the same type.

(b) The abrasive particles are not deformed and are of the same geometry.

(c) Material removal is by a cutting action only.

(d) There is no build-up of material ahead of the cutting particle.

(e) The abraded material is homogeneous.

The limitations of the simple model are illustrated by Eyre[2] reporting on Krushchov's work[14] and presenting his results as shown in Fig. 4. It is seen that relative wear resistance E is:

$$E = \frac{\text{Linear Wear of Standard}}{\text{Linear Wear of Material under Test}}$$

This wear resistance, which is equivalent in concept to the inverse of wear volume, is directly proportional to hardness, but the constant of proportionality is different for pure metals and in homogeneous alloys. However, the results also show that materials of similar hardness have different wear resistance under the same conditions. Thus, the linear relationship between hardness and wear resistance predicted by the simple model is not consistant with experimental results. This was found by many investigators and it suggests that other properties such as yield strength, rate of work hardening and brittleness should be taken into consideration to obtain the real wear resistance.

However, it is important to consider a more sophisticated model which considers the other parameters avoided in a simple model, such as attack angle, fracture toughness, microstructure characteristics, abrasive particle properties and geometry and material work hardening effect.

2.2.2. A More Sophisticated Model.

Mulhearn and Samuels developed a detailed theoretical analysis for the wear of non-work hardening metals on silicon carbide paper which was found to be consistent with their experimental results[15]. However, the restriction to non-work hardening materials is unrealistic given that most wear resistant materials work harden in service. Their analysis was useful in that it tried to account for variations in abrasive geometry, the number of contacting abrasive points and the deterioration of the abrasive paper. In reviewing the mechanisms of abrasive wear, Khruschov has identified relationships for both homogeneous and inhomogeneous materials[16].

Thus, for pure metals:

$$\epsilon = C_1 \, X E^{1.3}$$

where ϵ = relative wear resistance.

C_1 = 0.47 x 10E-4; a constant of proportionality.

E = Young's modulus

However, heat treated steels show significant changes in wear resistance whilst E remains constant:

$$\epsilon = \sum_{1}^{n} ai X \epsilon_i \;, \text{ where } ai = 1$$

and

ϵ_i = relative wear reistance of an individual constituent

ai = relative volume of an individual constituent.

n = number of constituents.

That is, the wear resistance of constituents are seen to be additive. Khruschov does not explain how the Young's Modulus could be determined for constituents such as carbides. Further, this relationship does not hold for conditions where the hardness values approach those of all but the hardest abrasives.

More recently, Zum Gahr(17) has approached the problem of second phases by considering the effect of their size and distribution. For carbides in a soft matrix:-

$$f^{1/2} = C \frac{d}{\lambda}$$

where f = volume fraction

d = particle diameter

C = statistical constant

λ = mean free path between particles.

It is found that wear resistance increases according to a $\lambda^{-1/2}$ relationship for steels, white cast irons and cemented carbides when λ and d are simultaneously decreased.

Zum Gahr[17] also presented his idea of 'wear strength'. This concept combines both wear and fracture toughness considerations resulting in the following expression:

$$\dot{W} = \frac{P}{\beta H \tan \alpha} + \left[12.13 \frac{hd}{\lambda^2} \frac{P^{3/2} D \mu^2 H^{1/2}}{K_{1C}^2 \sin 2\sigma} \log \sqrt{\frac{P}{P_C}} \right]$$

where W = specific wear rate

P = applied surface pressure

P_C = critical applied surface pressure

β = abrasive shape constant

H = hardness of the worn surface

K_{1C} = fracture toughness

2α = aperture angle of wear grooves

μ = coefficient of friction

D = distance between abrasive particles

h = depth of wear grooves

and where

$$P_C \approx 0.12 \lambda \frac{KiC^2 \sin^2 \alpha}{D^2 \mu^2 H}$$

P_C is the load applied by an abrasive particle above which cracks will propagate from the plastic zone. A fracture mechanics approach is important therefore because the method of material removal is not

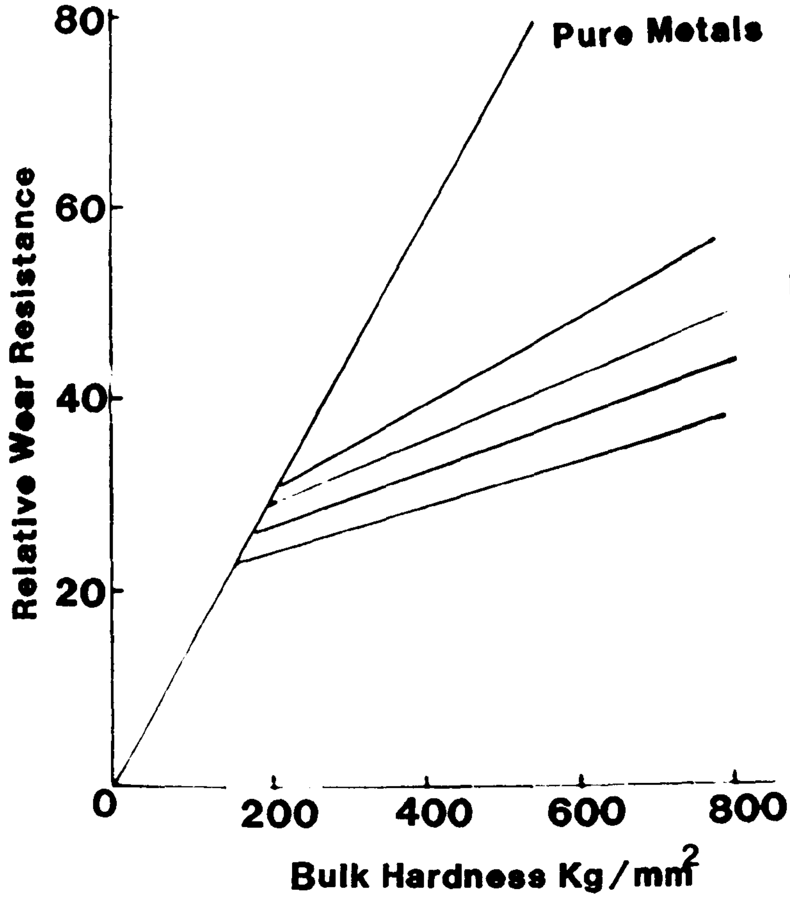

Fig. 4 Relation between hardness and wear resistance for pure metals and heat treated steels. (Khruschov)

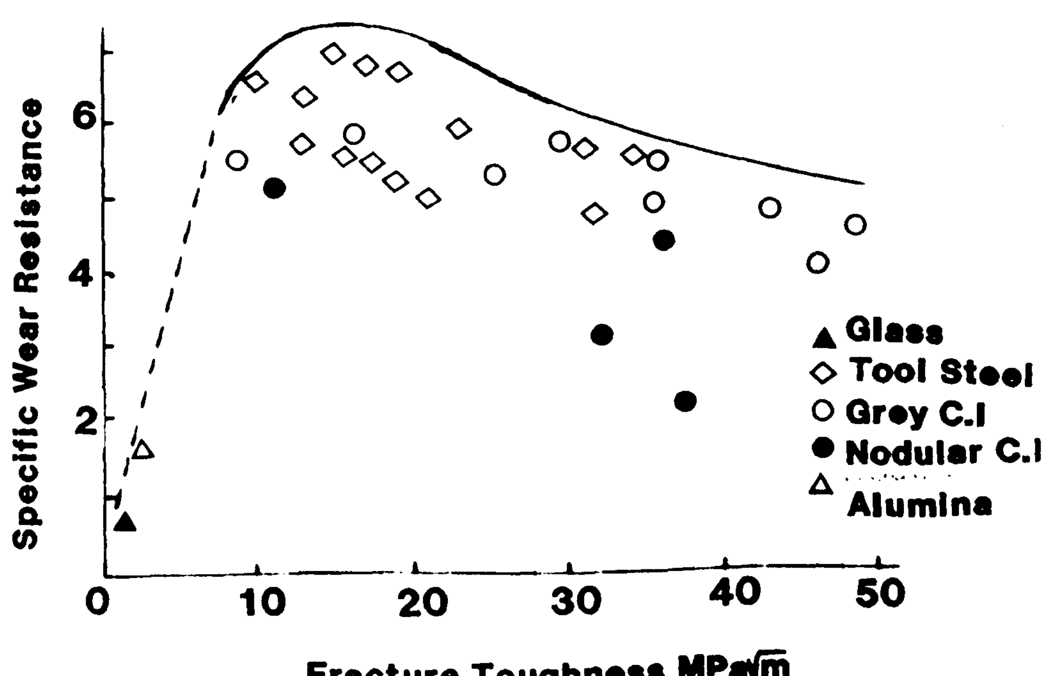

Fig. 5 The effect of fracture toughness on the wear resistance of several materials. (Zum Gahr)

simply cutting, but may also occur by 'spalling' of material similar to that found in the reciprocating abrasive wear technique used in this investigation.

When the material is subjected to high stresses beyond its fracture toughness, cracks will develop, leading to material removal during subsequent abrasion. Therefore, a less tough material might be expected to have a higher wear rate; the results of Zum Gahr are shown in Fig. 5 and from his work it is apparent that optimum wear resistance requires a trade-off between toughness and hardness.

Zum Gahr then develops the idea of wear strength, the product of wear resistance and plain fracture toughness (see Fig. 5). However, wear strength is not a material property and a structure with high fracture toughness and low wear resistance can have the same wear strength as a structure with low fracture toughness and high wear resistance. A further drawback to this method is the amount of information necessary to use it. The purpose of a model is to be predictive and avoid costly experimental testing. An easier model to use has been developed by Torrance using the results of other workers[18]. The novelty here is the incorporation of elastic, as well as the usual plastic deformation behaviour to explain the shape of wear grooves. Elastic constraints imposed on the abrasive particles by the abraded metal will affect the shape of the wear grooves. That is, some of the deformation will be accommodated elastically as well as by plastic flow. The size of the elastic distortion is dependent upon the ratio of hardness to Young's modulus.

Thus the relative wear resistance is given by:-

$$\beta_i = \frac{Hwi}{Hwr} \cdot \frac{1 + KHwr/Er}{1 + KHwi/Ei}$$

where i = refers to the test metal

r = refers to the reference metal

Hw = hardness of heavily worked metal

E = Young's modulus

K = a constant with a value of approximately 10.

The value of K was derived from Richardson's results[19]. Using this value, the model was applied to the results of other investigators by converting the reported hardness values into values that could be expected after cold working, thus:-

$$Hw = H + 300 + 130C$$

where C = carbon content for low alloy and carbon steels

H = hardness of unworked metal

A good correlation between predicted and experimental values is obtained for pure metals, annealed and heat treated alloys.

2.3. Mechanisms of Material Removal.

Because of the problems of examining wear components in-situ, and the difficulty in collecting wear debris, most studies relating to material removal mechanisms are laboratory based. Many terminologies have been used by different investigators to describe different wear mechanisms, such as cutting, microchipping, ploughing, rubbing, spalling fragmentation, plastic deformation, delamination, etc. Defining the abrasive wear mechanism according to the terminology mentioned above depends to a large extent on many variables which will be discussed in detail later.

For an abrasive particle contact at very low loads, the contact will be predominantly elastic. Such contacts may result in material removal by surface molecular mechanisms[(20)] or of surface films[(21)] or by Hertzian fracture of brittle materials[(22)]. As the load on an angular abrasive particle increases, contact on both ductile and brittle materials will involve plastic deformation to a greater extent[(23)]. Ultimately material will be removed from the surface by fracture but the rate controlling process will be determined by how much plastic strain the wearing material can sustain before fracture occurs.

Three main mechanisms of material removal have been identified by many investigators, i.e. :

1. Chip formation (cutting) - see Fig. 6a.
2. Plastic deformation (ploughing or rubbing) - see Fig. 6b.
3. Brittle fracture (spalling) - see Fig. 6c.

Khruschov and Babichev(23) identified two major processes taking place when abrasive particles made contact with the surface of a ductile material, i.e.

(a) The formation of plastically impressed grooves which did not involve direct material removal.

(b) The separation of particles in the form of primary microchips.

In both cases material is also deformed to the sides of the grooves and can become detached to form secondary microchips[(21)]. Primary microchips dominate in terms of material loss. When distinct primary microchips are not formed material may pile up in front of an abrasive particle until fracture occurs[(24)]. With fine abrasive particles some material loss can also occur by adhesive wear processes[(25,26)]. The debris produced can be extremely small and become smeared over the abrasive particle surface.

Material removal involving plastic deformation occurs for a wide range of material properties and abrasive environments. Even for materials that have predominantly brittle properties, microchip formation and ploughing occurs during abrasive wear[(27)]. This may be because of the rise in temperature at the surface and the hydrostatic

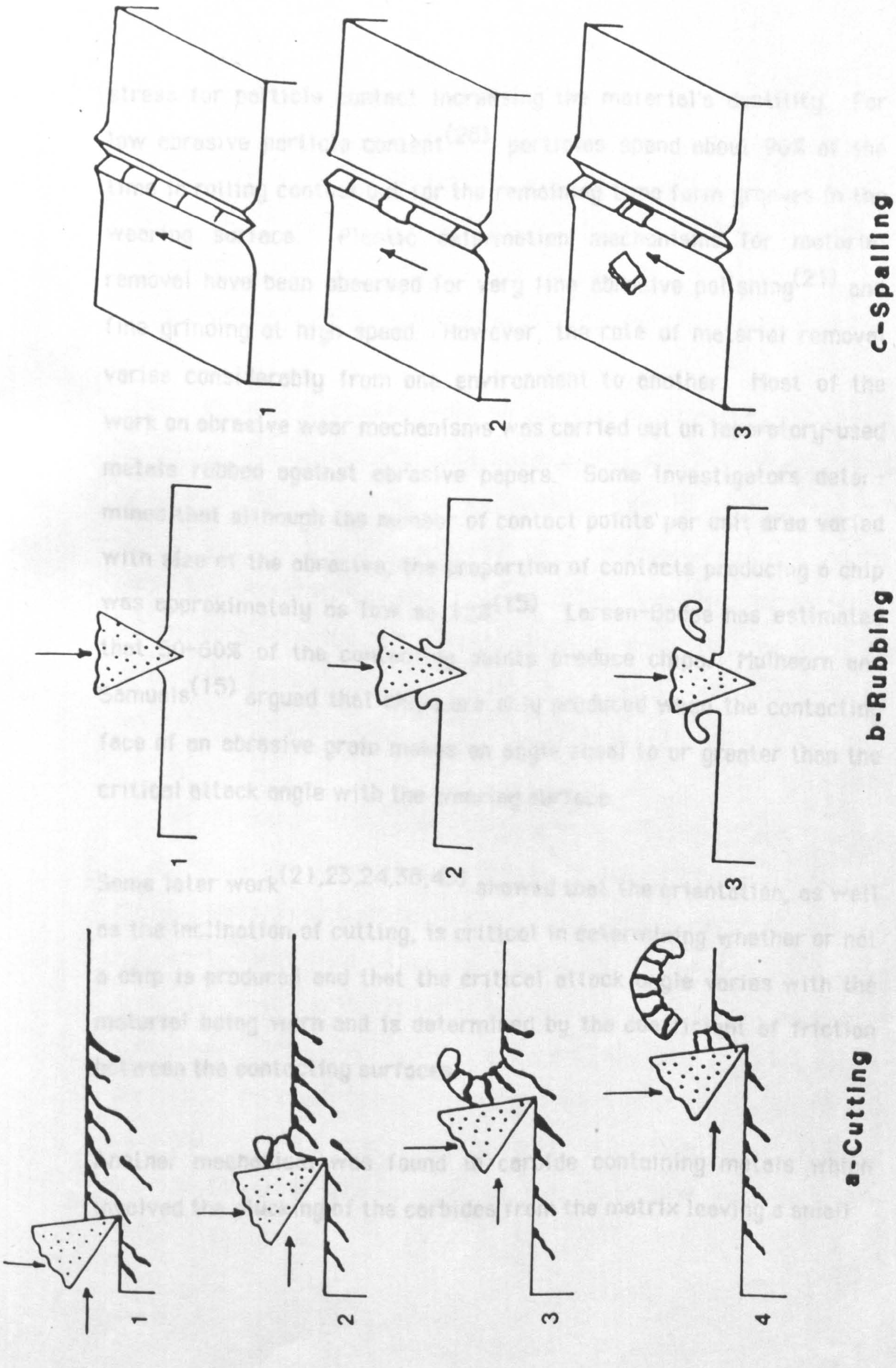

Fig.6 Mechanisms of material removal.

stress for particle contact increasing the material's ductility. For low abrasive particle content[28], particles spend about 90% of the time in rolling contact but for the remaining time form grooves in the wearing surface. Plastic deformation mechanisms for material removal have been observed for very fine abrasive polishing[21] and fine grinding at high speed. However, the rate of material removal varies considerably from one environment to another. Most of the work on abrasive wear mechanisms was carried out on laboratory-used metals rubbed against abrasive papers. Some investigators determined that although the number of contact points per unit area varied with size of the abrasive, the proportion of contacts producing a chip was approximately as low as 12%[15]. Larsen-Badse has estimated that 50-60% of the contacting points produce chips. Mulhearn and Samuels[15] argued that chips are only produced when the contacting face of an abrasive grain makes an angle equal to or greater than the critical attack angle with the wearing surface.

Some later work[21,23,24,38,43] showed that the orientation, as well as the inclination of cutting, is critical in determining whether or not a chip is produced and that the critical attack angle varies with the material being worn and is determined by the coefficient of friction between the contacting surfaces.

Another mechanism was found in carbide containing metals which involved the plucking of the carbides from the matrix leaving a small crater. Using a fracture mechanics approach, Zum Gahr[17] explains the importance of crack propagation leading to material removal (spalling). Such a mechanism operates above a critical load for a single abrasive point and gives rise to large plate-like debris.

There is little published work on the role of corrosion in removing material from wear surfaces. Peters reviews some of the synergistic effects of aqueous corrosion and abrasive wear in a mining environment showing that the contribution of corrosion can be significant[29]. Another consideration may be the oxidation characteristics of the abraded metal in a particular environment. Most of the metal oxides are brittle and would be expected to spall under conditions of abrasive wear thus increasing the rate of metal removal.

The most usual environments causing corrosion are moisture, elevated temperature and lubrication. In dry air, at elevated temperatures, the metal corrosion product will be the oxide. The presence of elevated temperatures may not be suspected since this can be caused solely by frictional heat. In moist air it will be a hydrate of the oxide or a hydroxide. With some metals it may be a carbonate from the carbon dioxide in the atmosphere. When these reaction products are formed by exposure to the atmosphere, with few exceptions, the compounds are relatively loosely adherent to the metal base and are easily removed by rubbing

In industrial environments fumes and gases may produce the corresponding chemical compounds. Chlorides, nitrates and sulphides are common examples. The occurrence of corrosive wear requires the presence of both corrosion and wear, hence static components may not appear badly corroded in cases where wear is greatly accelerated by the corrosive atmosphere because the corrosion products may protect the surface from further corrosion, unless they are removed by sliding[30].

It can be said that corrosive wear is not a specific form of wear and should more accurately be known as wear affected by corrosion.

In the following sections factors affecting those wear mechanisms will be discussed.

2.4. Influence of Abrasive Properties.

2.4.1. Size of Abrasive Particles.

Early workers established that increasing grit size on commercial abrasive papers gave an increase in wear rate up to a critical size [15,19,31]. Above this particle size wear rates remained constant or decreased. As Moore[3] notes, this increase in wear rate is due to the increased load on each abrasive particle and the increased proportion of particles contacting the metal surface.

More recently the deterioration mechanism of abrasive papers has been found to be dependent on grit size. Sugishita et al[32] found that the deterioration mechanism is grit detachment from the resin base by fatigue failure for the 600 grade abrasive paper, and chipping fracture of a cutting grit for the 100 grade paper.

In a study of the size distribution of stones in soil, Moore[31] cites Richardson who calculated that stones of size 19-38 mm in diameter caused over 50% of the total wear volume, even though their proportion by volume in the soil was less than 1.4%.

Larsen-Badse[33] has suggested that the proportion of the load carried by elastic contacts varies with grit size and more recently[34] that specimen size may account for the critical size effect since the length of contact of an abrasive particle has a different effect on the deterioration of different grit sizes. Richardson (31) has also accounted for his result by the different modes of deterioration of the different grit sizes. Rabinowicz and Mutis[35] concluded that the critical size effect is due to the interference between adhesive and abrasive particles which increases as the grit size decreases. Avient, Goddard and Wilman[36] have suggested that abrasive particles which become emebedded in the wearing surface might cause an increase in wear resistance on the smaller grit sizes, and Johnson[37] has confirmed that the pick up of abrasive increases rapidly as the grit size decreases.

2.4.2. Geometry of Abrasive Particles

Kragelskii[38], Khruschov and Babichev[23], Aghan and Samuels[21] and Graham and Baul[24] have found that chip cutting and rubbing depend upon the shape of the indenting particle. In particular, spherical indenters have been observed to show a changeover from rubbing to at least partial chip formation when the indentation strain (defined as the depth of indentation divided by the diameter of the indenter) exceeds a certain value. Goddard and Wilman[35] have calculated that the coefficient of friction depends upon the particle shape which, in the light of Sedriks and Mulhearn's findings[39] might account for the observed particle shape dependence.

Burwell[40] cites the results of R.D. Haworth who found that angular soft particles produced more wear than rounded hard particles. Hata and Muro[41] found experimentally, using a quadrahedral diamond tool, that resistance to abrasion increases as the cone angle decreases and if a facet leads as opposed to an edge. It was found that the rate of abrasion increases as the particles become less plate-like and suggest that this is because plates are more likely to lie flat at the sliding interface[42]. Swanson and Klann[88] have also suggested that the shape of the abrasive is a significant factor. They found that the use of an angular abrasive produced a significant increase (by as much as a factor of ten) in volume loss of steels compared to round abrasives.

2.4.3. The Effect of Attack Angle

The work of Mulhearn and Samuels[15] showed, not surprisingly, that angular particles contributed more than rounded ones to the total material removal. There is considerable evidence that orientation, as well as the shape of a contacting abrasive particle, determines whether or not material is removed[21,22,24,38,43].

Most investigators have studied the effect of attack angle on abrasive wear characteristics and agree the definition of the critical attack angle to be the angle between the front face of the abrasive particle and the abraded surface under which no cutting ocurrs.

In a series of experiments with pyramidal tools, Sedriks and Mulhearn [39,44] found that the critical angle varies according to the abraded metal. The values of critical angle for some metals are listed below.

Material	Critical Attack Angle
Pb	55°
Al	85°
Cu	45°
Ni	65°

As can be seen from the table there is no direct relationship between the critical attack angle and the type of material.

Sedriks and Mulhearn predicted that the critical attack angle should decrease as the coefficient of friction between the leading face of the abrasive particle and the material increases.

The observation[43] that a smooth diamond tool produces ploughing wear debris but no microchips for an attack angle of 22°, whereas for an attack angle of 30° a damaged diamond tool produces equal quantities of microchips and ploughing debris, confirms this friction effect.

It is difficult to find one value of a critical attack angle to describe the ploughing/cutting transition in materials, especially in the case of alloy steels. In the case of soft (fully annealed) steels, Mulhearn and Samuels[15] quote $\alpha_c = 90°$ (see Fig. 7), while Doyle and Samuels[45] obtained $\alpha_c = 80°$. In their work Murray et al[46] found that machining appeared to be the dominant mode at $\alpha_c = 60°$, and an even lower value was suggested by the work of Mann and Broese Van Groenou[47] who observed some chip formation in non-hardened high carbon steel at $\alpha = 40°$. These variations in the critical angle of attack happen to span a range similar to that found for pure metals, as shown in the previous table. Murray et al[46] found also that as the attack angle increases, the abrasive mechanism varies from ploughing to cutting. In the case of steels they concluded that as the hardness of the steel increase, the critical attack angle decreases.

Stepina, Sidorova and Tolstenko investigated the effect of hardness, and microstructure of different materials at two attack angles (i.e. 20° and 90°) on the wear resistance. They found that wear resistance

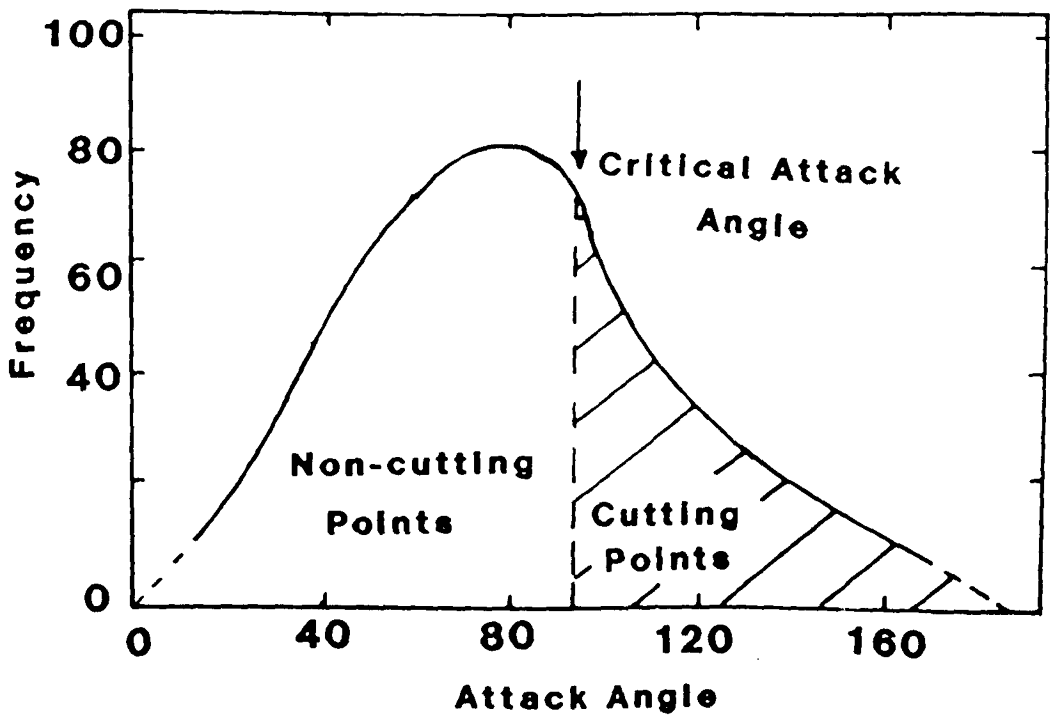

Fig.7 Frequency distribution of abrasive particle attack angles. (Mulhearn and Samuels)

was increasing with an increase in hardness at 20° attack angle and a decreasing wear resistance with increasing hardness at 90° attack angle[48].

2.4.4. Physical Properties of the Abrasive.

Perhaps the most important property of an abrasive is its hardness. Richardson investigated different abrasives classified as hard and soft[19,31]. He concluded that an abrasive can be considered hard when:-

$$Hm/Ha \leq 0.85$$

where Hm = metal hardness

Ha = abrasive hardness

If this ratio is exceeded (see Fig. 8), then wear rates decrease rapidly, but the flow stresses of the two materials must be equal before scratching of the metal by the abrasive stops.

Materials of different microstructures used in producing parts which can be used in abrasive wear applications will produce different hardness values.

These materials, as well as those used in the laboratory to study the abrasive wear characteristics when abraded against abrasive papers of certain types, will be affected by the type of abrasive. Gundlack and Parks[89] studied the influence of abrasive hardness on the wear

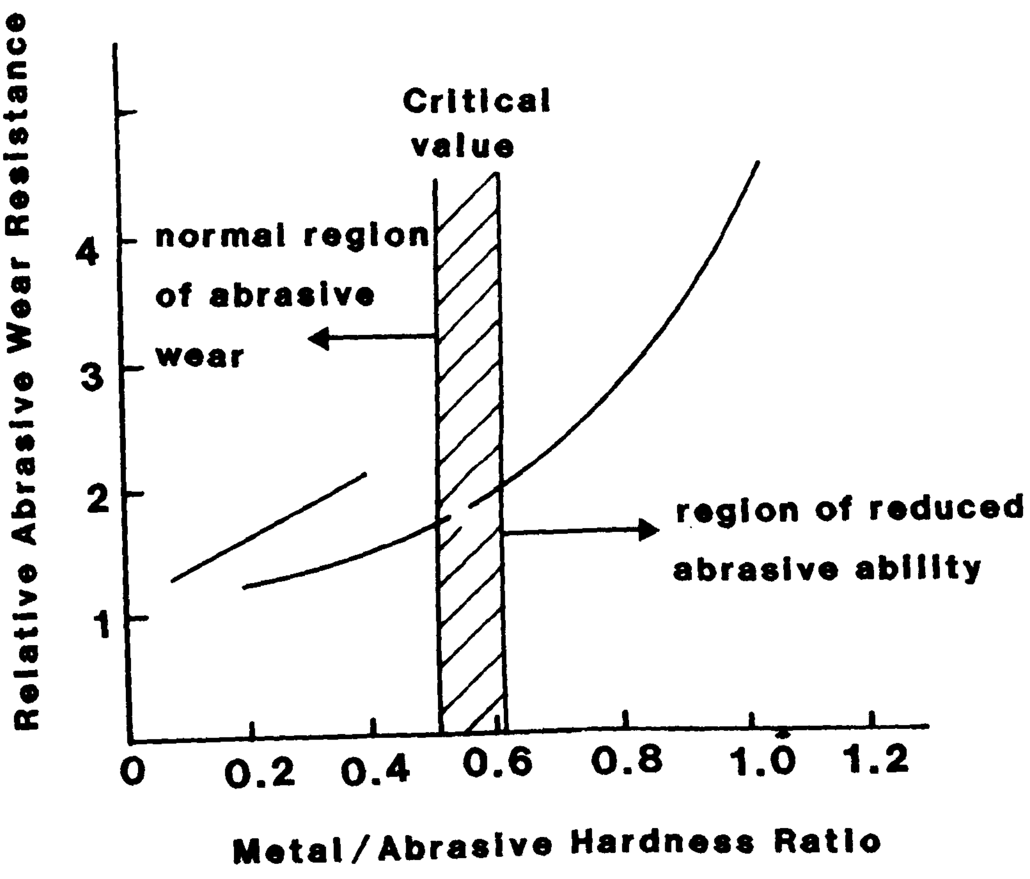

Fig. 8 Effect of metal to abrasive hardness ratio on abrasion resistance.

resistance of high chromium irons and steels. They found that variations in type and hardness of the abrasive media greatly influenced the resistance to abrasive wear in austenitic and martensitic white irons, while they had less influence on steels. As the hardness of the abrasive increased (from garnet to alumina to silicon carbide) the amount of wear in white irons increased.

The following table lists the hardness of different materials and microstructures.

Abrasive	Hardness H_v	Material	Hardness H_v
Coal	32	Ferrite	70 - 200
Gypsum	36	Pearlite	250 - 460
Lime	110	Austenite	170 - 350
Calcite	140	Martensite	500 - 1000
Fluorspar	140	Cementite	800 - 1000
Coke	200	Chromium Carbide	1200+
Iron Ore	470	Alumina	2000
Glass	500	Tungsten Carbide	2400
Sinter	750	Vanadium Carbide	2800
Quartz	900-1300		
Corondum	1800		

Fig. 9 shows the wear rate of materials versus mineral hardness[49].

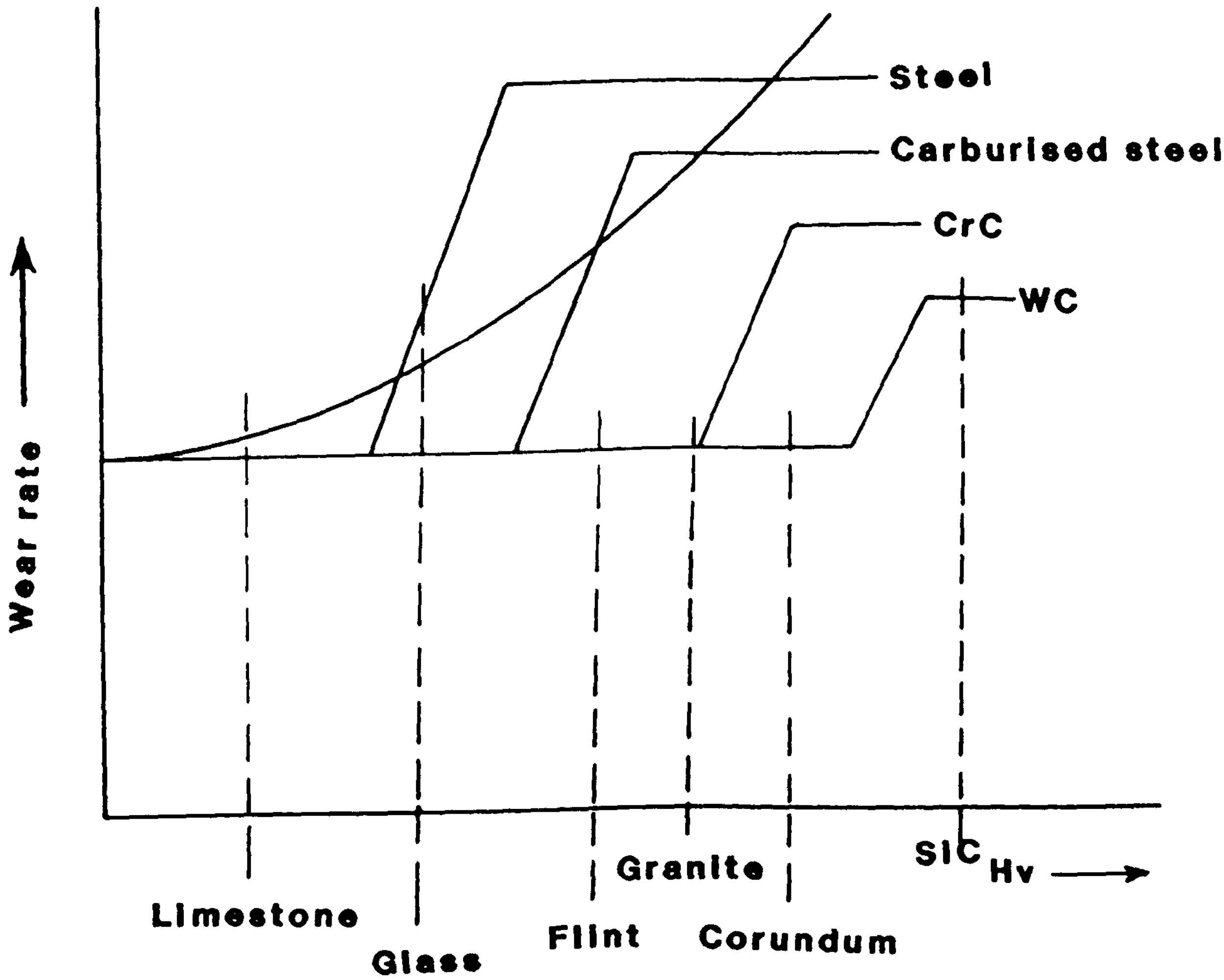

Fig.9 Effect of mineral hardness on wear rate for different materials (49).

Toughness of the abrasive particle is another important property which determines the manner of the particle deterioration. This property is not directly related to hardness or strength but generally decreases with increasing strength. It was found that the toughness of the abrasives vary significantly. The harder abrasives happen to have better toughness; this is probably coincidental, but this is not always so[50].

The coefficient of friction relative to metals could have a major influence on the fundamental processes by which a machining chip separates from the workpiece surface.

During abrasive wear, high temperatures may be generated. The strength of abrasives deteriorates at high temperatures, hence thermal conductivity is important in circumstances where significant amounts of heat are generated at the interface between the abrasive grit and the workpiece.

2.5. Influence of Properties of the Abraded Material.

Many of the material parameters affecting abrasive wear are implicit in the models discussed above. Several workers have tried to correlate wear resistance with physical properties of materials, such as solid state cohesion and Young's Modulus, with some success [16,18,51]. However, apart from Torrance's analysis, these relationships tend to be restricted to pure or homogeneous materials. Wear resistant materials are rarely either. For this reason the abraded material will be reviewed in terms of mechanical properties. Such properties are often easier to measure and can then be related to the wear behaviour of the material.

2.5.1. Hardness.

It is well established that wear rate is inversely proportional to hardness. The effect of hardness is shown most clearly in the work of Khruschov(14) who has shown that wear resistance (inverse of abrasive wear rate) is proportional to the bulk hardness for a large number of pure metals. He also found that prior work-hardening of pure metals had no effect on wear rate. This has been confirmed by other investigators(19). Khruschov also found a linear relationship between wear resistance and hardness for heat treated steel. The data fitted an equation of the type:-

$$E = E_0 + C_1 (H + H_0)$$

where E is the relative wear resistance of steel, E_0 is the relative wear resistance in the annealed condition, C_1 is a constant, H is the Vickers bulk hardness of the steel and H_0 is the hardness of the steel in the annealed condition. The constant C_1 is varied systematically with carbon content of the steel.

Despite evidence of straight line relationships between hardness and wear resistance, it now seems that this is a simplification and in some cases wear resistance may even decrease when hardness increases[17,52].

Mutton and Watson investigated the relationship between wear resistance and both bulk hardness and surface microhardness for two heat treated steels[52]. The correlation for each was almost identical, appearing as an 's' shaped curve, not a straight line. Another investigation by Murray, Mutton and Watson[45] showed the same 's' type relationship between the bulk hardness of three steels and wear resistance. Their data were as a series of sigmoidal curves which depart from normal (pure metal) behaviour at a point corresponding approximately to pure iron. The curves were displaced to higher wear resistance as the carbon concentration was increased (Fig.10).

Hardness affects abrasive wear by determining, to a certain extent, how deep abrasive particles may penetrate the surface being worn. Other properties which have not been investigated as thoroughly, such as flow stress, may be important in a dynamic situation. The energy balance between the work done in forming a groove and the energy expended in plastically deforming the material is considered by Moore(53). This approach may be more useful in the future if the ambiguity of hardness data is to be avoided.

Rubenstein[54], in a simplified analysis, has shown that relative wear resistance, when plotted against the ratio hardness of the test

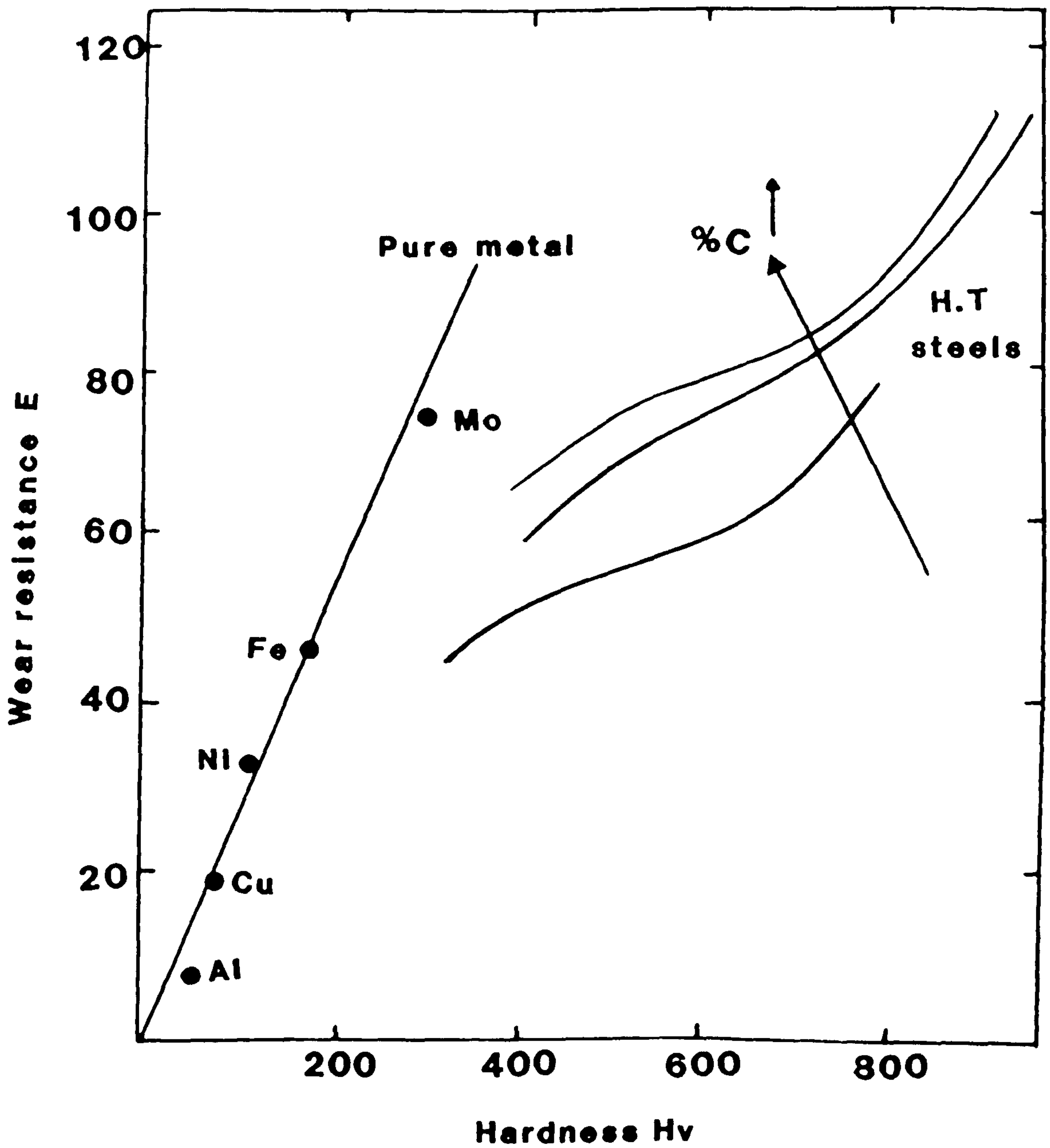

Fig. 10 Wear resistance as a function of hardness for the pure metals and heat treated steels (46)

material/hardness of the standard material will give a better representation of the data. The wear behaviour of heat treated steels however does not confirm to this rule but obeys Khruschov's equation.

2.5.2. Toughness.

Zum Gahr has presented a theoretical and experimental analysis for the influence of fracture toughness upon wear resistance(17). In theory, wear rate is only indirectly related to fracture toughness since hardness usually decreases with an increase in toughness. Zum Gahr's work shows that the interaction between hardness and toughness is complex; but it may be concluded that for a given hardness, increasing toughness increases wear resistance. This can be explained by a reduction in the spalling mechanism of material removal described above. Khruschov and Babichev(87) found that isothermally transformed steels exhibit higher wear resistance than their corresponding quenched and tempered variants. They suggested that this may be related to the presence of high internal stresses in the quenched microstructures, thereby contributing to their poor fracture toughness and consequently low wear resistance.

The optimum in achieving a good correlation between hardness and toughness may result from a suitable casting process and controlling the carbon content, followed by adequate heat treatment in the case of steel castings used in abrasive wear applications.

2.5.3. Influence of Microstructure.

For steels it is well established that, in order of increasing wear resistance, the microstructure changes as follows:-

Ferrite, Pearlite, Bainite and then Martensite

The changes in wear resistance cannot be accounted for by hardness difference only. This is illustrated in the case of bainitic steels having better wear resistance than tempered martensitic steels and that of pearlitic structures having better wear resistance than martensitic and spheroidal cementite structures of the same hardness[19,55]. Zum Gahr[17] identified the following microstructural features as being important in determining wear rates.

a - Inclusions

b - Second Phases

c - Grain boundaries

d - Matrix structure

e - Internal notches

f - Anisotropy

In general, the highest wear resistance is obtained in microstructures with fine, well dispersed, semicoherent particles (see Fig.11). It is important to realise that microstructural features may act as stress concentrators depending upon their size, mechanical properties and distribution.

The interface between second phases, inclusions and the matrix can be a site of crack initiation and propagation under the high localised stresses of abrasive wear.

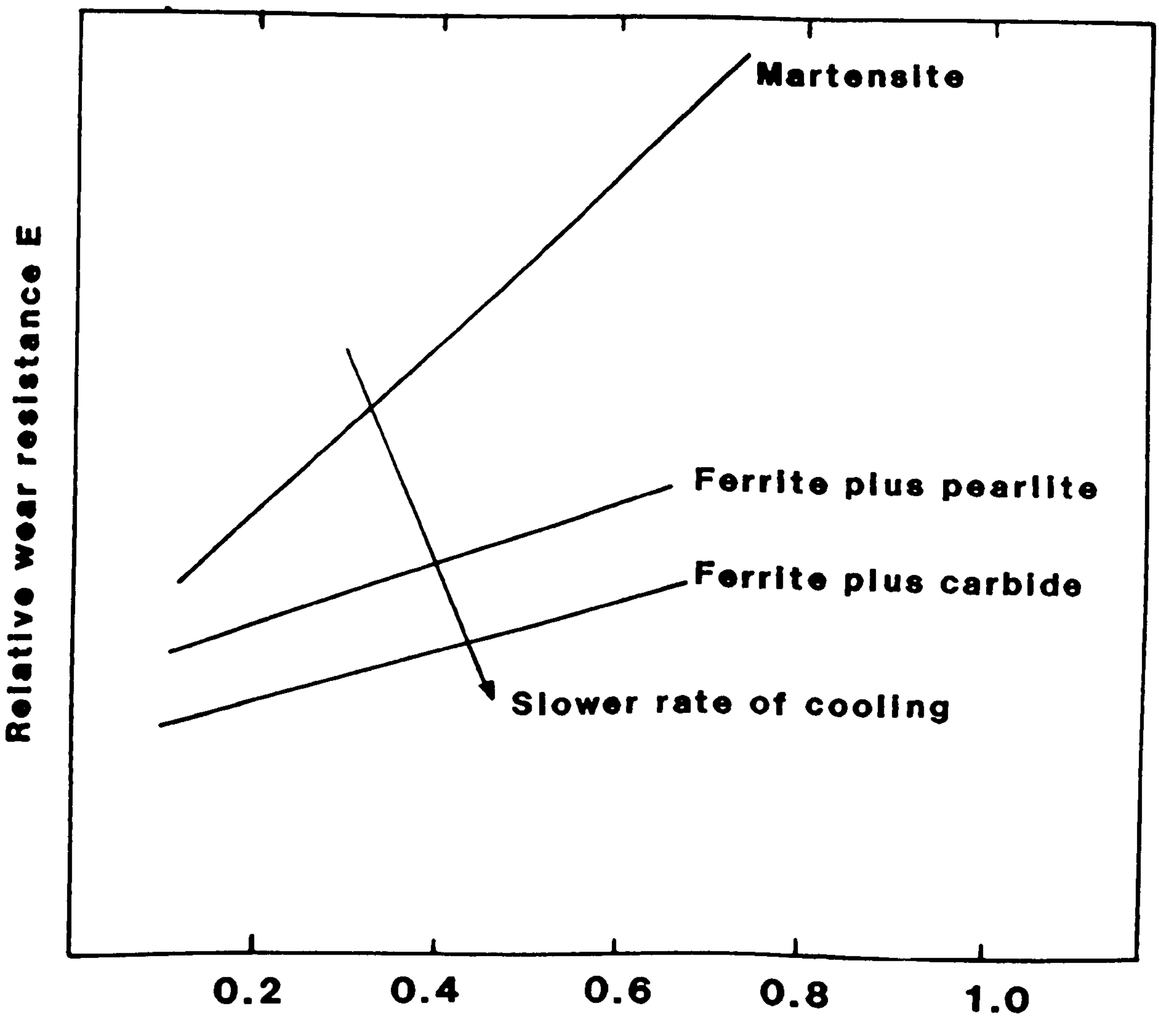

Fig. 11 Abrasive wear versus carbon content (2).

The relative sizes of the abrading particle and the second phase are also significant. Crack propagation can lead to enhanced wear rates by spalling.

The correlation between microstructure and the material removal mechanism has been frequently investigated. Mutton and Watson[52] found the mechanism of groove formation to be fundamentally different for two phase alloys, with hard brittle particles, and for single phase alloys of higher ductility. Chip formation was reported to be easier as hardness increased, but more importance was attached to the effect of fracture propensity flow behaviour and, in two phase materials, the morphology of the constituent phases.

Larsen-Badse and Mathew[56] investigated the wear of plain carbon steel with both spheroidized and pearlitic structures. They reported that the wear resistance of spheroidized steels was inversely proportional to the square root of the carbide spacing and that of pearlitic steels was proportional to the volume percentage of pearlite.

In his investigation, Kar[79] concluded that in complex steels microstructual variants affect the two-body abrasive wear process. He found that retained austenite appeared to enhance the wear resistance of these steels and secondary alloy carbides also appeared to alter the two-body abrasive wear properties of the secondary hardening steels.

Hurricks[80] has suggested that the degree of cohesion between the austenite phase and carbides is greater than the cohesion between martensite and carbide, thereby enhancing wear resistance.

Zum Gahr(17,81) attributes the presence of retained austenite enhancing wear resistance to:-

(i) The presence of these ductile austenite films around ferritic laths tending to impede microcrack formation and growth associated with abrasion.

(ii) The increase in workhardening rate with strain because of the austenite to martensite transformation.

(iii) Residual austenite undergoing transformation locally during abrasive wear, producing surface compressive stresses, thereby tending to retard microcrack formation.

Hornbogen[82] has also suggested that wear may be related to the fracture properties of steels. The presence of retained austenite films enhancing the fracture toughness of several heat-treated steels has been well documented[53,83,84-86].

Prasad and Kulkarni[57] studied three-body abrasion resistance of plain carbon steel in relation to the matrix and second phase features. Studies of the wear track showed that the ferrite underwent ductile fracture and the groove depth was large compared with its width. They also concluded that the carbides not only offered resistance to the free movement of the abrasive, but also reinforced the matrix to resist penetration of the pearlitic structure. Grooves were sharply defined and shallower than the grooves in ferrite.

Recently Rac[58], in his work on the effect of laboratory variables on the wear characteristics of grey cast iron, found that the shape of graphite has an effect on the wear characteristics. He concluded that nodular graphite cast iron showed greater resistance to wear than that of flake graphite under a wide range of loads and sliding distances. In other cases, when the sliding speed exceeded a certain value with low load, the situation was different and the flake graphite iron showed higher wear resistance. This suggests that there are certain sets of test conditions under which the material can produce its optimum wear resistance.

Norman[59] has studied the effect of different microstructures on steel abrasion resistance. He found that martensitic structures tend to improve in abrasion resistance as their austenitizing temperature is increased and their carbon content is increased; the high carbon martensitic steels compare favourably with the martensitic white iron in abrasion resistance. In pearlitic structures he found that the abrasion resistance tends to improve as the carbon content is increased up to 1%. Adding certain amounts of Cr, Mo to the steel showed little, if any, loss in abrasion resistance when tempered to 500°C. When tempered at 600°C or higher, their resistance is lowered to some extent. Norman also found that pearlitic Cr, Mo steels, with a hardness value of 38-40 Rc, were more abrasion resistant than bainitic structures having the same composition.

In laboratory investigations, as well as the composition, structure and preparation procedure, the test conditions might affect the wear characteristics of the metals tested. It can be said that there are certain values of load, sliding distance, sliding speed and specimen size to be recommended for each metal to achieve its optimum wear resistance.

Stepina, Sidorova and Tolstenko[48] found that, under a certain set of test conditions, the wear resistance of austenitic, pearlitic, sorbitic, troostitic, martensitic and austenitic with carbide eutectic alloys increased linearly with an increase in hardness. They also observed that with the same hardness the wear resistance of austentic alloys is higher than that of alloys of other groups. By changing the attack angle of the abrasive particle the situation was quite different. The wear resistance decreased with increasing hardness and with the same hardness the wear resistance of pearlitic and martensitic alloys was higher than both ferritic and austentic alloys. It can be concluded therefore that the wear resistance of ferrous castings used in wear applications is a complex matter with the wear resistance determined as much by the wear situation as by the material itself. The various factors controlling abrasive wear can be understood in terms of a model of wear in which the most important feature is the size of individual wear scar in relation to the scale of the microstructure of the material.

For applications involving heavy impact, the choice of one of the 12% manganese steel grades is clear. For those where impact is completely absent, the alloyed white cast iron provides the best wear resistance. In between these two extremes, the choice of wear material is more complex and the many factors involved ensure that there is no universal solution. This complexity is reflected in the large number of steels and irons commercially available. Recently developed materials, which combine alloyed white irons with a tougher material, foreshadow the way in which future developments are likely.

CHAPTER THREE

DIGGER TEETH AND THEIR USES

CHAPTER THREE

3. DIGGER TEETH AND THEIR USES.

It has been mentioned that there is a very wide range of applications where abrasive wear is the main reason for component and equipment repair or replacement. In most of these applications, especially those of earthmoving, construction and mining equipment, digger teeth can be used to facilitate their performances (see Fig.12). They can be used in various kinds of earthmoving equipment, such as the dragline, bucket, shovel dipper, hoe dipper, clamshell bucket and dredge cutter. Digger teeth are mainly used to protect the front of buckets which remove, handle and transfer minerals of different origins. They also affect the efficiency with which material is separated and removed.

A wide range of materials have been used from time to time to make digger teeth which can be produced in different shapes and sizes. The selection of material, shape and size of digger tooth depends to a great extent upon location conditions. The following materials and techniques can be used in making digger teeth:-

1. Low alloy steel
2. Hadfield (Manganese) steel
3. White cast irons
4. Tungsten carbides

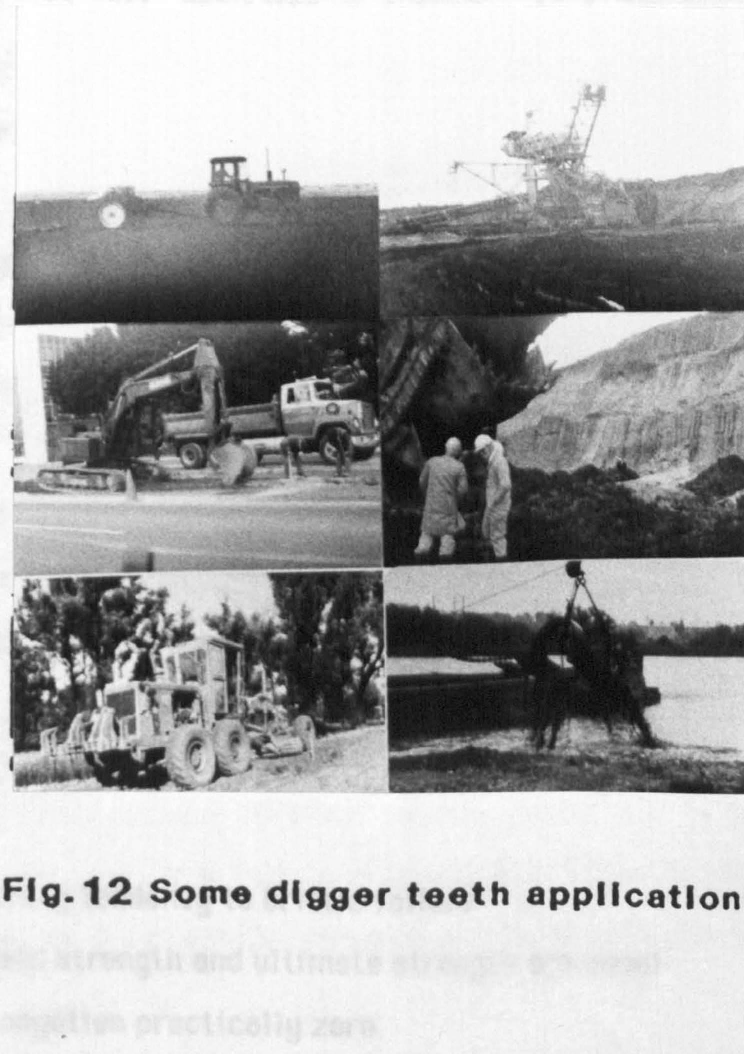

Fig. 12 Some digger teeth applications.

5. Composite materials
6. Hard facing

Manufacturing cost, replacing or repairing cost, service life and the working conditions should be taken into consideration when deciding which material will be used.

Low alloy steel is used when wear resistance is required with good impact resistance; it is however, difficult to attain a hardness above 500 HV with high toughness.

White cast iron has excellent wear resistance because of its complex microstructure and high hardness. When alloyed with chromium it also has good corrosion resistance.

However, white irons have definite shortcomings as an engineering material:-

- Strong tendency to brittle failure
- Yield strength and ultimate strength are equal
- Elongation practically zero
- Plastic flow in areas of high local stress does not occur.

White iron castings provide premium abrasion resistance in the application where no high impact resistance is required and hence the only physical property which controls abrasion resistance is hardness.

It is necessary to overcome the inherent weakness of this material in order to broaden the areas of application of the white iron. This can be achieved by laminating the white iron to a mild steel plate, the result being a composite consisting of a hard martensitic white iron wear surface combined with a tough, ductile plate to handle mechanical loading[68].

In ferrous alloys, carbon is the main controlling factor, but unfortunately it leads to a reduction in toughness. To optimise both abrasion resistance (which is related to hardness) and toughness, the carbon content must therefore be taken into consideration and this depends upon particular applications.

The alloy content must also be suitably adjusted to obtain sufficient hardenability for the section thickness required. By applying precautions with respect to steel making conditions to obtain a low impurity content, low inclusion levels and a fine microstructure, a component with suitably balanced properties may be obtained.

Special work hardening or transformation type manganese steels have been widely used for general abrasive wear applications, in particular for grinding and crushing applications. The reasons for this are to be found in their high resistance to gouging (high stress) wear, coupled with probably the highest toughness of any of the wear resistance steels. Manganese steel with an austenitic structure is not completely stable and the as-cast structure, particularly in thick sections, may have extensive carbide precipitation at grain boundaries. Although this has little direct influence on wear resistance, it can drastically reduce the toughness[5].

Transformation hardening steels are only successful if sufficient strain is applied to generate the high hardness required for abrasion resistance. If this level of strain is not applied to generate a high hardness, the teeth will wear out quickly. In other applications, for example in milling, where the strain is high, they provide excellent wear resistance. Hence, manganese teeth have two drawbacks; they have a low yield of about 3.4×10^7 N/M^2, so sections have to be heavy, and they have poor resistance to sliding abrasion, causing excessive wear if the material does not have an opportunity to work-harden.

Tungsten carbide is very expensive and rather brittle so it is used under non-impact conditions and where a high mineral hardness demands it. This type of material may be bonded onto the working surfaces of a digger tooth or used as tips welded or brazed to the teeth. In an attempt to study the service life of both types of tungsten carbide protected teeth, a test was carried out in one of the Australian coal mines. It was found that the tungsten carbide chip impregnated teeth showed superior wear life compared to the standard tungsten carbide tipped teeth already being used. There was little change in the geometry of the front face of the chip impregnated teeth due to the protection given by the carbide chips and so they retained their full cutting width, while the tipped teeth suffered from impact damage and corner wear.

Hardfacing is widely used to facilitate on-site repair work and it is used for large digger teeth, but the improvement in life is proportional to the cost involved and would only be used where replacement teeth are not available. It is also used in the situation where the replacement of the parts or the equipment is costly or impractical, such as in undergound mining equipments. General repair of bucket bodies, fixtures for teeth, plate supports, etc., are carried out by hardfacing.

Hardfacing provides a way to deposit the selected alloy on a specific portion of the equipment experiencing severe wear. Alloys designed to resist wear are generally produced as welding consumables to be used to produce overlays on critical wear surfaces. Hardfacing alloys are normally in the range of 40 to 60 HRC. In general, they contain high levels of carbon and/or boron to promote carbide and/or boride formation during solidification. These hard phases play the dominant role in controlling abrasion.

Hardfacing alloys are generally categorized by the alloy base and subcategorized by alloy element content and the quantity and type of hard phases present. Iron base, nickel base, cobalt base and tungsten composite systems are most frequently used to overcome nearly all of the wear modes encountered in agricultural and off-road equipment.

Four basic weld overlay techniques are typically used for agricultural and off-road equipment. They include gas welding, using either rod or powder consumables; shielded metal arc welding (SMAW), using coated (stick) electrodes; gas tungsten arc welding (GTAW), using rod consumables; and metal arc techniques, using continuous wire products (metal cored tube wires). The first three methods are manual welding techniques and are readily employed by general maintenance shops or even right at the work site. The fourth process uses continuous consumable wires with a granular flux covering the surface to be overlaid (submerged arc welding) or wires with a flux core that are used without additional granular flux or shielding gas (open arc welding).

In agricultural and off-road equipment, the wear resistant alloys used are often steels or chromium white irons with hard carbide phases. Extremely severe wear environments may call for the use of tungsten carbide composite materials.

Additional complications such as corrosive chemicals or elevated temperature metal-to-metal contact often require nickel or cobalt base alloys.

In the case of digger teeth, the recommended hardfacing alloys are the low alloy steel and the hypereutectic chromium white irons because of their excellent high and low stress abrasion resistance and moderate impact resistance. They are used primarily to build up worn teeth(60).

Many reviews on the subject of hardfacing for wear resistance have been published[61,62]. Besides the many advantages the hardfacing process can provide, there are several problems associated with it[63,64]:-

1. Wear varies from one place to another on the same part.
2. The cost of some hardfacing materials is prohibitive.
3. Welding problems, when some parts have to be replaced, may arise due to thermal or cracking problems and lead to a loss of efficiency.
4. Change in physical properties of the part.
5. Spalling of the hardfaced part due to a tensile stress which often results in tip deflection which may cause it to crack and then to spall off the tooth surface.
6. Compressive stresses on the very brittle hardfacing material may cause spalling away from the tooth material.
7. The application of hardfacing softens the base material which increases abrasion of the base metal. It invariably results in a thin, unsupported layer of hardfacing at the tooth tip which fractures. Weld dilution may also change the composition, structure and hardness of the hardfacing and should be considered at the design stage.

Digger teeth in use today are generally medium carbon quenched and tempered low alloy steels with relatively low alloy content to ensure through-hardening in the largest tooth used. Until recently these materials generally were about 475 HV with a toughness as measured by charpy 'V' of about 15 ft/lb at -40°[65].

More recently, ESCO Corporation have been successful in increasing the hardness of their tooth alloys to 555 HV nominal hardness with no loss in toughness. This has been accomplished by the use of AOD process to refine the steel used in the manufacturing of points. The AOD is a Union Carbide patented steel finishing method. It is an Argon Oxygen Decarburization method and by the nature of the process is a natural desulfurizer[65].

In trying to predict what future needs might be, it is thought that good materials can be developed for abrasion resistance in the application of digger teeth to a hardness of about 600 HV. Beyond this point, lacking some unforeseen breakthrough in metallurgy, some design of a duplex alloy system will need to be developed to meet the needs of the every increasing power of the digging system.

In digger teeth applications, and the dragline (present field study) in particular, a very wide range of parameters are involved in material selection for mineral processing and digging, etc. They are summarised below:-

Digger Teeth

Design	Mineral	Material Selection
- Shape and angle of tooth	- Type of abrasive	- Composition - Fabrication route
- Depth of digging	- Shape and size of abrasive	- Hardness
- Ease of removal of teeth for replacement	- Hardness - Water ph.	- Toughness - Corrosion resistance

If materials development for these, and other applications, is to proceed on the basis of laboratory tests for wear resistance, it is imperative that the wear mechanism in the field is observed and understood. If this is not carried out, it is likely that 'ranking orders' produced in the laboratory will be useless or even misleading.

CHAPTER FOUR

EXPERIMENTAL PROCEDURE

CHAPTER FOUR

4. EXPERIMENTAL PROCEDURE

This work is concerned with both a field trial of the wear of digger teeth fixed to the front of a bucket used in a dragline, and also a laboratory investigation of abrasive wear mechanisms. The study of both field trial and laboratory work was carried out to clarify the features associated with the abrasive wear process and provide a fundamental understanding of the system in which those factors operate and their performance.

The field trials will provide:-

1. Close observation of the teeth service life by monitoring their performance. This will supply statistical evidence with respect to the effect of abrasive wear on the teeth life. In this respect very few studies can be found in the literature.
2. The knowledge of the different factors playing a role in the tooth performance. This will enable a network of all the factors affecting the abrasive wear process and the relations between them to be produced. Many practical suggestions can then be made to improve the performance to extend the component's life.
3. An understanding of how the worn component will affect the performance of the whole equipment, and what kind of side effects they might produce. In this investigation the effect of worn teeth

on fuel consumption and the number of buckets required to fill a barge were observed.

4. An appreciation of some other factors which are thought to be insignificant in abrasive wear, such as corrosion and rubbing action. The field trial showed their importance.
5. The information required to establish a suitable experimental procedure in the laboratory.

On the other hand, the laboratory work was carried out to:-

1. Establish an experimental procedure which recreates the same sort of damage produced on the teeth surfaces in the field trial.
2. Study the wear characteristics of different materials under various test conditions.
3. Rank materials of different compositions, structures and physical properties according to their wear resistance.
4. Study the different wear mechanisms and theories supporting them.
5. Study the effect of such factors which cannot be controlled and investigated in the field trials, such as the effect of corrosion and the attack angle.
6. Investigate in more detail the wear characteristics of the digger teeth using different technqiues.

In the following sections, both field trial and laboratory work will be discussed in detail.

4.1. Field Study.

Field trials have been carried out at a long established mineral extraction site, close to the University laboratory, so that adequate observation has been possible on a regular basis. This particular study involved the removal of loose gravel from a flooded gravel pit using a dragline bucket attached to a crane (Fig. 13). The gravel is loaded into a barge to facilitate transport to the treatment plant, about 2 km away. The bucket has four teeth, each of which was numbered, one to four. These were fastened to the bucket with a steel peg and a rubber pad. This enabled easy removal in service examination.

After reviewing the site working situation, it was decided that the following would be monitored to provide a full case study:-

1. Wear of all four teeth by removal and weighing.
2. Photographs each time against a standard unworn tooth.
3. Dimensions of the teeth.
4. Amount of material removed from the gravel pit.
5. Fuel consumption.
6. Examination of the teeth after removal from service and comparison with a standard tooth.
7. Collection and examination of gravel and water.

4.2. Laboratory Work.

It has been mentioned in the literature review that abrasive wear is a very complex process due to the fact that so many variables are involved. It has been decided that the following features should be considered in the laboratory investigations to study the factors affecting the wear characteristics:-

1. The effect of composition.
2. The effect of microstructure.
3. The effect of hardness.
4. The effect of abrasive type.
5. The effect of abrasive size.
6. The effect of test variables (load, sliding distance).
7. Workhardening effect.
8. Abrasive degradation.
9. The effect of attack angle.
10. Extent of deformation.
11. Debris analysis.
12. The effect of corrosion.

4.2.1. <u>Materials</u>.

Steels of different compositions, shown in Table 3, were cast as keel blocks by the Steel CastingS Research and Trades Association (SCRATA) and analysed by a spectrographic technique. A commercial digger tooth was also supplied for examination. The wide range of steel compositions will provide different structures, hardness values and other material property variations which are important to investigate different possible wear mechanisms and their resistance. For example, carbon content varies from 0.17% to 0.6% among different steel compositions; this will lead to the possibility of studying the effect of carbon content on the wear characteristics. Chromium content varies from zero to 10%; three steels of 2, 5 and 10%

chromium were used to study the effect of corrosion on wear rate in wet testing conditions.

Pure metals (Al, Cu and Fe) with three other steels of different hardness values were also used in the investigation of the effect of attack angle on the wear characteristics. A specimen of grey cast iron was used to study the wear mechanism of a brittle material.

4.2.2. Specimen Preparation.

Cylindrical test pins were machined from each steel block to the dimensions 30 mm long x 10 mm diameter. Specimens of the same dimensions were cut from a commercial digger tooth used in the field trial. The ends of the pins were all ground on a high-speed grinding wheel to produce a smooth, uniform surface finish of 0.1 to 0.3 μm. These pins were prepared to be fitted in a specially designed holder and used in a pin-on disc abrasive testing machine (Fig. 23). Flat specimens of 50 mm x 30 mm x 7 mm dimensions were prepared from blocks of pure metals, grey cast iron and three steels. These specimens were used on a unidirectional single point abrasive testing machine (Fig. 48).

The density of each metal and alloy was determined by accurately weighting (using a balance of ± 0.0001 gm accuracy) and measuring several specimens of each tested metal.

4.2.3. Laboratory Wear Evaluation.

Two-body abrasive tests were carried out utilising the pin-on disc machine (Fig.23) on which pins are rubbed against rotating abrasive papers supported by a steel disc. This technique was adopted because it has been proved by many investigators to be one of the most practical tools of studying the abrasive wear of many ferrous materials. It can be used with different abrasive types and grit sizes and enables the invesigator to study the wear characteristics of various materials and their ranking wear resistance.

This technique is useful in the sense that it shows the damage produced during the test on the abrasive particles as well as the worn surfaces. It can also be used to study the effect of corrosion on the wear rate.

In this technique, a 3.7 KW electric motor drives the disc via a hydraulic variable speed unit, vee-belt and shaft. The sample was placed in a holder which is mounted on a 2.2:1 lever arm, the weight of which is counterbalanced by a counterweight attached to the opposite end. The counterweight is adjusted until the lever is just horizontal by means of using a spirit level. The load is applied to the end of the lever arm and applied to the sample under test. A pin was inserted into a close fitting holder and held in place by two grub screws. Abrasive papers of different types and grit sizes were used.

One of the major drawbacks of the pin-on disc wear test, used in this investigation, which also applied to the well-known rubber wheel test, is lack of control of the contact or attack angle between the abrasive particle and the surface being abraded. Because of this lack of control any systematic approach with regard to attack angle must utilise another technique. Hence, a new technique was developed to study the effect of the attack angle on the wear mechanisms involved and the extent of deformation produced for different metals. The new technique was developed using the unidirectional single point abrasive wear testing machine. In this technique (Fig.48) the same setting up procedure, described in the pin-on disc technqiue, was followed except that flat specimens were moved along the x-axis in a unidirectional movement and the abrader was held stationary in a specially designed holder.

4.2.3.1. Wear Measurement (Pin-on Disc).

A number of techniques are available for measuring the amount of wear which has occurred in any test. These include gauging, weighing, radiotracer technique, indentor depth changes, microscopy, etc. A simple and direct comparison of the wear resistance of a series of samples can be obtained by weighing the samples before and after the test and comparing them.

Providing care is taken to ensure that the specimens are clean and dry prior to weighing, and the method of mounting the specimens does not cause material transfer, this method is sufficiently accurate.

In order to obtain more detailed information from a wear test, it is normal to measure continuously. This can be achieved by removing the wear specimen periodically during a test to weigh it. The information can then be used to plot a weight loss versus time curve which will indicate any change in wear rate. However, the removal of the specimen during a test can present problems due to the change of the environment, surface state changes (e.g. surface temperature) and exact realignment of the speicmen. The linear voltage displacement transducer (LVDT) technique can also be used to measure wear and friction continuously. Wear volume calculated by this method is very close to that obtained by the direct weighing method.

Silicon carbide abrasive papers of 60, 100, 120, 220, 320, 400 and 600 grit sizes and aluminium oxide abrasive papers of 60, 80, 120, 220 and 320 grit sizes were used in this investigation. The silicon carbide papers were self-adhesive, so they could stick to the surfaces of the steel disc. Aluminium oxide papers were cloth-backed abrasives; double sided adhesive tape was used to stick the paper on the disc. In both cases the paper was held firmly in place by a washer and bolt which formed the axis of the disc.

To start a test, the pin was lowered gradually on to the paper over a period of approximately 10 seconds. A sliding speed of 0.25 MS^{-1} was used for each test; the sliding distance over a period of time could then be calculated.

Two types of test were carried out:-

(i) Wear volume versus load for 45 minutes duration, at loads of 44, 66, 110, 154 and 198 Newtons. The upper load was limited by damage to the abrasive paper in the form of tearing of the paper backing.

(ii) Wear volume versus sliding distance at a load of 66 N for times of 15, 30, 45, 60 and 75 minutes (corresponding to 225, 450, 675, 900 and 1125 meters respectively).

Each pin was weighed before and after testing; any loosely attached material was removed before re-weighing. The pin was washed with acetone and dried by hot air before weighing.

The wear volume was calculated by weight loss divided by density.

The abrasive paper grade number refers to the number of divisions per inch of a sieve used to grade the SiC or Al_2O_3 particles. These numbers correspond to a maximum particle size shown in Table 1; the higher the grade number, the smaller the particle size and vice versa.

4.2.3.2. Wear Measurement (Unidirectional Single Point).

Unidirectional single point wear tests were carried out utilising the rig shown in Fig. 48. In this technique a flat specimen, of dimensions mentioned in Section 4.2.2., is fixed on a flat plate connected to a lever driven by a motor. Different stroke lengths could be achieved by connecting the lever with a disc containing drilled holes at different radius lengths from the centre of the disc.

Single point diamond (60° appex) and tool steel (20° appex) conical abraders were used. The abrader was mounted in a specially designed holder. The holder is mounted on a 2:1 lever arm, the weight of which is counterbalanced by a counterweight attached to the opposite end. The counterweight is adjusted until the lever is just horizontal using a spirit level. The load was applied to the end of the lever so it was applied to the sample under test in the ratio given above. The tests were unidirectional and the abrader was sliding over the specimen in one direction at each attack angle.

The load range was between 1 and 10 Newton. The tests were carried out for pure metals, some of the steels shown in Table 3 and white cast iron. Different attack angles were used by using the specially designed holders at different loads and numbers of passes (Fig.49). The wear volume was calculated from the groove profile produced by a talysurf technique (See Fig.50). This technique shows the cross-section of each groove from which the area was determined, then the area was multiplied by the groove length to find the groove volume. Wear volume was plotted against attack angle, applied load and number of passes for different metals.

4.3. Optical Metallography.

Optical microscopy was used to investigate the nature and distribution of phases in the specimens to show the effect of composition on the microstructure of steel. Features such as cracks, plastic flow, inclusions and other casting defects were observed. It was also used to study the replica taken from a worn tooth, in service, which clearly shows the topography of different surfaces of the worn tooth.

Optical microscopy was used to reveal any changes in the structure of worn teeth due to wear. Phase changes were observed by studying different transverse sections cut from several places of the worn tooth. The same procedure was followed to examine worn pins in the laboratory work. In unidirectional single point wear testing the extent of deformation, due to the use of different attack angles at different loads and numbers of passes, was also examined by optical microscopy.

The sections cut from the tested specimens were prepared for optical metallography examination by the usual process of grit and diamond polishing. A Vickers M55 microscope was used for the optical metallography and photography throughout this investigation.

All the ferrous sections were etched in 2% Nital.

4.4. Scanning Electron Microscopy (SEM).

The SEM is an invaluable tool for the identification of surface characteristics of the worn parts, in service and laboratory, due to its high resolution and depth of focus. Unlike the optical microscope, the SEM enables a three dimensional viewing of worn surfaces as related to the metallography of the substrate. However, the main advantages in the use of the SEM in wear studies can be listed as follows:-[67]

1. This technique bridges the gap between optical and transmission electron microscopy by enabling us to examine surfaces at magnifications as low as 20 times so as to isolate specific areas for further examination. Then the magnification can be increased without loosing picture clarity and without changing over from one technique to another. However, only rarely will magnifications greater than two to five thousand be required in wear studies.
2. Direct observation of both smooth and relatively rough wear surfaces is preferable to taking replicas from such surfaces, particularly if there is any danger of removal of loosely adherent wear debris.
3. Direct observation of the worn surfaces is possible with a minimum of preparation and, in some cases, with no preparation at all.
4. It is often of considerable value to examine wear surfaces for transferred material which may be adhering to or embedded on its surface and then to obtain positive identification of its sources by in-situ chemical analysis.
5. In comparison with the transmission electron microscope (TEM), quite large surfaces can be examined and it may even be possible to place small engineering components in the SEM chamber.
6. In cases where it is difficult, on a single photograph, to differentiate between height differences on the wear surfaces.
7. Because of the great depth of focus available, it is possible to combine an optical taper microsection technique with direct SEM viewing so that the wear surface and the substrate structure may be viewed simultaneously.

In this investigation a Cambridge Stearscan 600 SEM was used and a magnification range of 100 - 5000 times was used to study the worn surfaces of selected specimens. All information was recorded on 35mm film.

To prevent charging in the electron beam, some of the specimens (i.e. the abrasive paper and the debris) were mounted on aluminium stubs using double sided adhesive tape. They were then placed in a sputter coater. The debris and abrasive papers (as new and worn) were coated with gold before examination.

After giving attention to the preparation of samples for examination the following features were studied:-

1. Worn surfaces of digger teeth after being removed from service.
2. Replicas taken for the worn teeth during their service.
3. Sample of the gravel (sand particles) to study the size and geometry of abrasive particles.
4. New and worn abrasive papers of different types and grit sizes, used at different loads and sliding distances, to show different types of particle deterioration.
5. Worn pins at different loads and sliding distances rubbed against abrasive papers of different types and grit sizes.
6. Grooves formed by diamond and tool steel abraders on flat specimens of tested metals at different attack angles.

7. Debris collected from both pin-on disc and unidirectional single point abrasive wear testings, from short and long duration tests, under different test conditions.
8. Transverse and taper sections of the tested specimens.

CHAPTER FIVE

RESULTS

CHAPTER FIVE

5. RESULTS.

5.1. Results of Field Study.

As was mentioned in section 3, teeth were removed for weighing approximately every two weeks, although the bucket was only used for fifteen hours each week. Weight loss was plotted against working hours, as recorded by the driver of the dragline, after providing him with a timetable (see Fig. 14). Working hours were easily related to actual weight of mineral removed; the bucket load was 3 tonnes, the barge load was 120 tonnes and 62,000 tonnes of gravel were removed in 250 working hours. Although a record of all four teeth is available, (Table 2) only 1 and 2 are plotted for clarity, the others giving almost identical results.

Whilst the teeth were off the bucket they were cleaned and photographed for comparison with an unused standard (Fig. 15). It will be observed that the teeth are relatively smooth and metallic in appearance. It is also observed that teeth number 1 and 4 have worn more than 2 and 3.

The bucket and the material being removed is shown in Fig. 17 and it will be observed that the larger pieces are relatively smooth. The size distribution of the gravel is shown in Fig. 18, which is representative in size and weight of the gravel shown in Fig. 17. This shows sand particles up to 150 µm and stones between 8 and 120 mm in size.

Both small and large abrasive particles are silica based and have a hardness in the range of 1100 to 1200 HV which was determined by both Knoop and Vickers hardness testing.

In view of the rather intermittent use of the bucket in and out of the gravel pit, it remained wet for a significant part of its life. It was therefore felt important to establish the possible effect of corrosion. Observations on site showed that very little change in appearance occurred by rusting between working hours and the teeth remained largely metallic in appearance (Fig.15). It is appreciated that this is a somewhat superficial observation and this will be further examined in the metallurgical study.

5.1.1. Metallurgical Examination of Worn Teeth.

It was possible to observe the surface of the teeth whilst in service by using a plastic replica technique and Fig. 19a shows that ploughing, with the production of grooves in the sliding direction, occurred. When the teeth were examined after final wear-out, the scanning electron microscope showed considerably more detail and further evidence of ploughing and deformation could be seen (Fig. 19b).

A microsection obtained from below the surface showed the structure to be tempered martensite with no second phase (Fig.20) and this is consistent with the hardness of 510 HV. These teeth were produced by CO_2 sand casting, followed by oil quenching from 900°C, and then tempered at 200°C.

Extensive micro-examination of the worn surface was undertaken and it varied locally from place to place from the front nose along the working faces of the teeth. However, the most significant observations are as follows:-

1. Local deformation of the martensite.
2. Development of small cracks running in from the working face.
3. A plate-like debris breaking away from the surface, although it was not possible to actually collect wear debris in this field trial.
4. Evidence of a cutting abrasive wear mechanism associated with sharp grooves and also a ploughing mechanism associated with large plate-like debris detached from the surface.
5. Evidence of significantly different structures being produced, best exemplified by the presence of tempered martensite, spheroidised areas and white layers.

Because of the problems associated with optical microscopy, namely the limitations of magnification and depth of focus, not all of these features were produced photographically, but some of the more important ones are shown in Fig. 21. Fig. 21a shows a spheroidised or tempered martensite and Fig. 21b shows a white layer area, below which is tempered martensite and below this the normal martensite structures. These are consistent with the hardness survey shown in Fig. 22 and suggest a significant magnitude of rubbing between the teeth and mineral particles producing high contact temperatures.

5.2. Experimental Results (Pin-on Disc).

Numerical results from all the wear tests are shown in Tables 4 to 10. Some tests were repeated three times under the same set of testing conditions and the variation in results was within ± 15%. This variation is within acceptable limits and the pin-on disc machine used in this investigation can be considered as a reliable method of investigating the wear behaviour of materials.

5.2.1. Effect of Load on Wear Volume.

All the steels tested showed a linear relationship between wear volume and load (Figs. 25,26). In general, a higher hardness conferred a greater wear resistance, although materials of the same hardness did not show the same wear resistance.

However, it was observed that wear resistance of tested steels was different according to the abrasive paper being used, i.e. one steel had a higher wear resistance than another when tested on SiC and a lower wear resistance when tested on Al_2O_3.

During the tests it was observed that, at higher loads, grit fracture occurred at the leading edge of the pin when it was lowered on to the abrasive paper. The tests were carried out on 4 steels for 45 minutes at a range of loads between 44 and 198 Newtons, and two abrasives (SiC and Al_2O_3) were used.

5.2.2. Effect of Sliding Distance on Wear Volume.

A clear division in behaviour was observed between the hard and soft steel (Figs. 27,28). The softer steels showed a more rapid increase in wear volume with sliding distance. That is, the effective wear resistance of the harder materials increased more rapidly with sliding distance.

Fig. 27 shows the relationship between wear volume and sliding distance for 4 steels tested on aluminium oxide paper of 120 grit, and Fig. 28 shows the same relationship with silicon carbide paper of 100 grit.

The results for one steel (steel A) have been plotted to show the effect of different abrasives on the wear rate and Fig. 29 shows that the wear volume produced by Al_2O_3 abrasive is about 3 to 4 times that of SiC. Fig. 30 shows the same relationship with different grit sizes.

It was observed that in all the tests there was a reduced wear rate with increasing sliding distance. In an attempt to determine the effect of paper degradation on the wear rate, a test was carried out by using a new abrasive paper every 15 minutes. Fig. 31 shows the relationship between wear volume and sliding distance for steel B by using one paper throughout the 75 minutes test and a new paper every 15 minutes. It shows clearly that the wear rate is increasing linearly when a new paper is used every 15 minutes.

5.2.3. Examination of Worn Surfaces and Debris.

Most of the worn pins were examined in the SEM to study the wear topography. For example, Fig 32a of steel C is representative of the features observed which show sharp wear grooves and partly detached debris. On other wear pins, particularly steel D which is more ductile, plastic deformation on both sides of the wear grooves was observed (Fig. 33). On most of the worn pins examined there was evidence of both plastic deformation and cutting to produce wear grooves. Fig. 32b shows transverse cracks at the edge of a worn pin indicating evidence of stresses in excess of the yield point of the steel. Fig. 34a shows spiral shaped debris collected from a short duration test which confirms the cutting nature of the wear process. Fig. 34b shows plate-like debris collected from a long duration test, which confirms the rubbing nature of abrasive wear, indicating damage to the abrasive particles during the wear test. Shallower, less angular grooves were found in the harder material in comparison to the deep angular grooves and sub-grooves in the softer material. That the grooves had different sizes seemed to indicate either a variation in abrasive particle size or a variation in the depth of penetration of the different particles.

Wear debris from the tests was examined in some detail because information concerning the way in which material is removed can be deduced from the form of the debris particles.

As mentioned above, the two main types of debris of one type of steel were the spiral and the plate-like debris of short and long duration tests. The size and shape of debris, as well as mechanism of material removal, varied considerably with material, abrasive type and test conditions. However, two main types of debris could be distinguished:-

1. Long, swarf-like debris subsequently referred to as spiral debris.
2. Short, thick debris referred to as plate-like debris.

5.2.4. Effect of Abrasive Particles (Size and Type).

Tests were carried out using SiC and Al_2O_3 abrasive papers of grit sizes from 60 to 320 (250 to 46 μm particle size). It was observed that the wear volume of any steel tested on both abrasive papers under the same testing conditions, was greater with Al_2O_3 than that with SiC. With the same abrasive paper it was found that wear volume increased with increasing abrasive particle size (Fig. 40).

Fig. 40 shows the relationship between wear volume and particle size for the steel of digger teeth in as-cast condition using both SiC and Al_2O_3 abrasive papers. It can be seen that wear volume increases slightly with increasing particle size until a particle size of 125 μm and then it increases sharply. The increase in wear volume is more clearly notable with Al_2O_3 paper

It was found that groove depth and surface roughness vary with different abrasive particle sizes and vary slightly with load (Figs. 41, 42). It was also observed that the worn surface roughness (measured as Ra value) increased with increasing abrasive particle size and the relationship was in the shape of "S" curve (Fig. 43), and generally it decreased with increasing load (Fig. 42)

5.2.5. Effect of Corrosion

Three steels of different chromium content (2%, 5% and 10%) were tested, in both dry and wet conditions, to establish the effect of corrosion on the abrasive wear rate. The dry test was carried out to produce a relationship between wear volume and sliding distance, utilising the pin-on disc technique with a new SiC paper of 100 grade used after every 15 minutes (225 M).

Two wet testing procedures were adopted to study the effect of corrosion using the same pin-on disc technique, with the addition of a current of water at ph6 flowing over the abrasive disc at a very slow flow rate. In the first wet testing procedure, pins of three steels were rubbed against the SiC paper for 15 minutes (225 M), with the stream of water flowing, and then the paper was changed and a new paper was used, and so on. The wear volume after each 15 minutes test was calculated and Fig. 44 shows the relationship between sliding distance and wear volume for the three steels in both the dry and wet testing conditions.

In the second wet testing procedure, the pin was left for 24 hours in a wet condition until a rust layer was formed on the tested surface, then the same testing procedure was followed as described above. Fig.45 shows the relationship between sliding distance and wear volume for the three steels, in the dry and wet condition, using the second testing procedure.

In all three procedures the test were carried out at 66N load. The results show that wear volume increases in sequence - dry test, continuous wet testing and wet testing with pin left for 24 hours in a wet condition.

In an attempt to study the effect of corrosion on wear rate in a single test, a 15 minute (225 M) test was interrupted and the wear volume was calculated every 2 minutes. Fig. 46 shows the relationship between wear volume and time for one test. It shows very clearly that wear rate is higher in the first minutes of the test when a rust layer covers the tested surface and then the wear rate decreases.

It was observed that as the chromium content increases, the depth of the rust layer decreases and with a 10% Cr there was no rust at all (Fig. 47).

5.3. Experimental Results (Unidirectional Single Point Wear Tests).

A unidirectional single point abrasive wear test machine (Fig. 48) was utilised mainly to establish a procedure to examine the effect of the attack angle of the abrasive on wear. Several wear mechanisms were observed during the investigation. The effect of load, number of passes, as well as the attack angle, were studied.

5.3.1. Effect of Load.

Fig. 51 shows the relationship between wear volume and load, for steel H, at three different attack angles. It can be seen that wear volume is linearly related to the applied load and, at any load, the wear volume increases with increasing attack angle.

5.3.2. Effect of Number of Passes.

Fig. 52 shows the relationship between wear volume and number of passes, for steel F at 3N load, using diamond as the abrader. The tests were carried out at attack angles of 30°, 60° and 90°. It can be seen that wear volume increases with an increasing number of passes and the wear rate decreases with increasing number of passes. At any stage the wear volume increases with increasing attack angle. The decrease in wear rate at higher attack angles was observed to be less than that at lower attack angles.

5.3.3. Effect of Attack Angle.

A range of attack angles (Fig. 49) was used at different loads and number of passes to investigate how the abrasive wear mechanism is influenced. Fig 53 shows the relationship between wear volume and attack angle for three steels under the same test conditions. The same relationship was plotted for the commercial digger tooth at a different number of passes (Fig. 54). The results indicate that the wear volume increases with an increase in attack angle until an optimum value is reach at 90°. At attack angles greater than 90° the wear volume decreases. The results also show that the wear resistance increases with an increase in hardness of the steels.

5.3.4 Metallographical Examination (SEM and Optical).

The SEM was used to study the effect of attack angle on the wear mechanism at the worn surfaces. Figs. 55 and 56 show the different effects produced by different attack angles on specimens of pure metals and steels. Both ploughing and cutting mechanisms can be distinguished. Transverse sections were cut from worn specimens, metallographically prepared and examined with an optical microscope. Fig. 57 shows the extent of plastic deformation caused by different attack angles on pure metals at 50 passes. Microhardness measurements were taken to determine the depth of deformation from the base or the wear groove at three different attack angles. Fig. 58 shows the relationship between the depth of deformation and its hardness value. Fig. 59 shows examples of debris produced after different tests carried out using both diamond and tool steel abraders and it will be observed that it varies from plates to spirals

It was decided to investigate a brittle metal and a grey cast iron was investigated under very specific conditions. The results shown in Fig.60 indicate the fragmentation into small plates of wear debris. The test was carried out using diamond at a 60° attack angle.

CHAPTER SIX

DISCUSSION

CHAPTER SIX

6. DISCUSSION.

6.1. Field Trial.

It is appreciated that the field trial hardly supplied strong statistical evidence and another identical trial has already commenced. On this site, only one bucket is in operation and, although Fig. 14 shows that wear-out with a loss of approximately 35% by weight of the teeth has occurred in 200 hours, this trial was completed in a considerably longer period of four months. Other, different sites are also being investigated and the author[75] is in touch with a dry quarry site where teeth of the same steel technology wear out in less than twenty working hours (Fig. 16).

In this field trial it was observed that teeth number 1 and 4 wear at a faster rate than 2 and 3 which is consistent with more mineral flowing over and around the outside teeth. It would therefore be advisable, in production, to periodically change the position of the teeth to even out wear and to extend their life. Wear is directly proportional to hours worked over the main period of use. There is, however, a decrease in wear rate towards the end of the working period (Fig. 14). This could be affected by two factors. Firstly, the change in geometry of the tooth. It becomes more blunted with time and the included angle of the front of the tooth is increased. It is also possible that a reduction in wear rate would be favoured by an increase in hardness due to contact with the abrasive particles. There is evidence in Fig. 21 which shows a white layer with a hardness value as high as 800 HV (Fig. 22).

Unfortunately, the crude method of determining fuel consumption, which was based on a dial reading of the diesel engine fuel tank capacity, was unsatisfactory and clearly an improved fuel monitoring device is required for subsequent trials. However, it was noted that more buckets were required to fill the barge at the end of the working life of the teeth than when new. The teeth were therefore becoming less efficient in penetrating and picking up mineral. As more buckets were required this clearly indicates increased consumption of fuel.

In abrasive wear both the hardness of the abrasive and the angularity of the particles control the proportion of cutting to rubbing. The effect of rubbing is greater than previously appreciated and there is considerable evidence in this study for surface deformation and frictional heating effects only previously reported in dry metal-to-metal sliding conditions or nominally lubricated contacts(69). Under these circumstance the formation of white layers and tempered layers has been widely reported(70). In the following section the theories of white layer formation will be discussed.

6.1.1. White Layer

The term "white layer" refers to hard surface layers, formed in a variety of ferrous materials under a variety of conditions, which appear white under the microscope. They have two common factors; firstly, a high hardness in comparison to the bulk hardness and secondly, an apparently featureless structure when viewed in a low powered microscope. Although "white layer" seems to have become the usual way of referring to such layers, other terms are used, such as "phase transformed material" , "white phase", "non-etching layers", "white etching", etc[71].

Many different types and forms of white layer have been observed and, with respect to worn surfaces alone, seven different types have been identified depending upon the precise operating conditions and the materials used[74].

Three main, or general, mechanisms can be identified which are associated with white layer formation. They are:-

1. The mechanism of plastic flow which produces a homogeneous structure or one with a very fine strain structure[70].
2. The mechanism of rapid heating and quenching which results in transformation productions[72].
3. The mechanism of surface reaction with the environment, e.g. nitriding, carburising and oxide ploughing[73].

It is most likely that these three mechanisms cannot be separated and that they act in combination, to a greater or lesser degree, to produce a range of white layer types. The term "white layer" is thus a generic term describing layers created under conditions of great diversity, whose common feature is their etch resistance.

In this particular application of the wear of digger teeth, the similarity with abrasive wear therefore becomes clear if the sliding and rolling of mineral particles over the digger tooth surface is accomplished with little cutting taking place and it is these rubbing contacts that contribute to flash temperature rises which, on the evidence contained in this investigation, must have been high enough to cause tempering (600°C), and also the production of martensite or other transformation products (800°). This confirms previous work which explains the theory of white layer formation mentioned in 2 above.

6.1.2. <u>Wear Topography of Worn Digger Teeth</u>.

It has been mentioned earlier in the field study that the evidence of cutting, as well as a rubbing action, were observed on the surface of the worn tooth.

There is no evidence, either from service observations or from the surface examination of worn teeth, that corrosion plays a significant part in wear at the site investigated. A ph of 7 shows that the water is fairly benign. It would, therefore, appear that abrasion dominates the superficial corrosion that occurs. However, this is an over-simplified picture of the effect of corrosion. There was a very thin orange rust layer on the surface of the tooth in service when it was left idle for a reasonable period of time. Hence, it was decided to study the effect of corrosion on abrasive wear rate in the laboratory because it was not possible to investigate that effect in-service. This will be discussed in detail later.

Fig. 19a, which is a replica of the worn surface of the digger tooth taken during the field trial, shows quite clearly the domination of abrasive wear as indicated by wear grooves, together with some detached debris, which is similar to the damage produced in the laboratory by the abrasive paper (Fig. 28). Plastic deformation was observed in both the field trial of the digger teeth and also the pins worn in the laboratory.

The main challenge in the development of improved steel digger teeth should involve:-

1. Increasing the hardness significantly above the 500 HV presently produced. However, it must be borne in mind that a steel with greater work-hardenening propensity may also be desirable. The hardness of the silica based minerals being processed is approximately 1000 HV and it would therfore be necessary to set a target of 700 HV for an improved steel.

2. By producing a second hard carbide phase in the martensite it may be possible to limit the extent of abrasion grooving and also plastic deformation of the surface layers. This would reduce the possibility of fracture and consequently reduce the particle size of wear debris produced which would be expected to reduce the wear rate. The volume, size and distribution of the carbide phase must itself be related to the size of the grooves produced by the abrasive. If the second phase is, for example, much smaller in size, its only contribution is likely to be a general strengthening of the matrix of the steel. Larger particles could provide a physical barrier, limiting the scale of the damage to the softer martensite.

6.2. Comparison Between Field Trial and Laboratory Work.

It has been mentioned in the literature review that digger teeth are used in many applications and industries. In all of these applications the teeth are subjected to various kinds of variables which cannot easily be separated and controlled to investigate their effect. It is expected, therefore, that the results obtained in the field trial and laboratory will be different. The differences can be summarised as follows:-

1. The presence of moisture which affects the service life of the teeth by producing a corrosion effect.

2. The abrasive in service is to some extent unbonded so that particles may roll, as well as slide. In the laboratory, the abrasive is bonded and slides over the tested surface without rolling, unless particles of abrasive are detached.
3. Friction heating may occur under some conditions in the field trial.
4. The tangential velocity may vary widely in the field trial, while it is constant in the laboratory test.
5. The local wear intensity and contact pressure may vary very widely and are generally very variable with respect to time.
6. The particle size is variable and covers a very wide range in the field trial but it is constant for a given test condition in the laboratory.
7. Different abrasives are encountered and each has its own distinctive hardness.
8. The loading and motion of the gravel particles may depend on the friction of the wear surface.
9. The worn surface area is larger in the case of digger teeth compared to that of the tested pin and that is why the wear volume in the field trial cannot be compared to that obtained in the laboratory.

It is very difficult to reproduce the same results obtained from the field study and compare these with those obtained in the laboratory, since the conditions are quite different in both cases. In order to correlate the results of the field and those in the laboratory, it is important that a new procedure should be developed in the laboratory.

The same loading and motion of the gravel particles applied in the field must be reproduced in the laboratory test.

Examination of the worn digger tooth showed that grooves of different widths and lengths run in different directions and they are very short (300 µm to 2 mm) compared with those found on the laborarory wear pins (up to 10 mm).

In the field, the gravel particles spend most of their motion time rolling on the surface and only for a very short time sliding over the surface. In the laboratory, the abrasive particles are fixed and well supported and they form wear grooves across the entire length of the worn surface, unless they are subjected to fracture, The grooves on the worn pins are uniform and run in one direction only.

6.3. **Laboratory Results**

The major part of this investigation was carried out utilising the pin-on disc technique. In this technique abrasive papers of different types and grit sizes were used. It was found that wear by abrasive paper is a process of complex interactions that do not lend themselves easily to numerical treatment. In this investigation a 'systems' approach has been adopted and Fig. 24 shows the relationships that have been examined For clarity, most relationships have been discussed in separate sections.

6.3.1. Experimental Accuracy.

Scatter in the experimental results can be traced to two sources:-

(i) Hardness variations of ± 10 HV were noted in the batches of heat treated specimens.

(ii) The abrasive papers of the same batch gave different results due to manufacturing variations. Pins of one steel tested on abrasive papers of same grit size from one batch gave about 10% variation.

Variations in accuracy due to weighing and density measurements would have been small and insignificant with respect to the above.

A quantitative assessment using the simple model described in section 2.3.1. is possible. The maximum variation in experimental results was 20% and part of this can be attributed to hardness variations. Porosity and changes in the properties of abrasive papers would then account for the remaining cause of variation in this extreme example. The effect of abrasive paper manufacturing defects was minimised by repeating some tests three times and taking the average measurement.

6.3.2. Influence of Hardness.

It is clear from the experimental results that bulk hardness does not give an accurate assessment of the relative wear resistance of these steels. Steels with the same bulk hardness have different wear resistance. The role of bulk and surface hardness values will be discussed extensively in the following sections.

6.3.3. Effect of Load on Wear Volume.

In theory, as the load on abrasive particles increases, the depth of penetration increases and so does the wear volume. The results show a linear form of relationship suggesting that the wear volume is directly proportional to load (Figs. 25 and 26). It is interesting that all the tested steels show an approximately similar slope when tested on the same abrasive paper grade. The slope varies with different abrasive types and grit sizes. It was observed that the wear rate of harder steels decreased with increasing load This could be due to:-

(a) As the load increases, the hard steel causes more rapid degredation of the paper than the softer steel.

(b) As the load increases, the hard steel workhardens at the surface to a higher value than the other steels.

Evidence for (a) is provided by the large amount of abrasive particles found amongst the debris collected after the test (see Fig.36). However, the degredation of paper in the case of tests with hard steel seemed to proceed largely by grit shearing (Fig. 37b), and to a lesser extent by grit removal (Fig.37a). Grit shearing usually gives rise to similarly sharp cutting facets, although of lower height, and so would not be expected to reduce wear volume significantly.

Another possible explanation for the abrasive action of the paper being reduced is clogging by debris. With higher grit size (smaller particle size) the clogging effect was more significant than the lower grit size papers.

The effect of the load in this case can be described as follows:-
By increasing the load, the amount of debris produced will be large

enough to fill the spaces between the abrasive particles. This will lead to the clogging of the paper and the reduction in wear rate. This effect will be more significant as the test duration increases.

Surface hardness measurement, although of limited accuracy, supports the suggestion that the harder steel attains a higher surface hardness than the softer steel, so that the wear rate decreases with increasing load in the case of the harder steel.

Moore found that increasing the volume fraction of pearlite and carbon content increased wear resistance, but these factors were not isolated from hardness which also increased[17].

6.3.4. Effect of Sliding Distance on Wear Volume.

The majority of tests in the literature use an apparatus that brings the wearing pin into contact with fresh abrasive continuously. In this investigation the pin was abraded against the same abrasive paper and a single track was formed, i.e. the pin surface is subjected to the same abrasive particles during the test. The relationship between sliding distance and wear volume, shown in Figs. 27 and 28, will be determined primarily by the factors that were discussed for load versus wear volume, namely:-

(a) Paper degradation.

(b) Surface workhardening.

If results for wear volume versus sliding distance were available for pins contacting fresh abrasive, then the effect of paper degradation could be obtained by a comparison with the present work.

The single track pin-on disc abrasive testing technique is the only one available and to show the effect of paper degradation the following procedure was followed:-

For a test duration of 75 minutes, the abrasive paper was removed and replaced every fifteen minutes. Fig. 31 shows the relationship between sliding distance and wear volume for steel tested on SiC paper, using one paper for the 75 minute test and a new paper every 15 minutes. The figure clearly shows that wear rate increases linearly with the use of a new paper every 15 minutes, whilst it decreases if only one paper is used throughout the test. This confirms that the decrease in wear rate due to the paper degradation occurs as described above.

The results from field tests show a similar relationship between abrading time and wear volume. The large difference in time scale should be noted; at times comparable with the pin-on disc test the field tests would show an almost linear relationsip. Factors such as tooth geometry, which changes during service, may also complicate the comparison as well as the other factors mentioned in section 6.2. Thus, in the current test, it is likely that both paper degradation and surface workhardening contribute to the fall-off in wear rate with time. It is not possible to draw definite conclusions from the results since the effects of paper degradation and workhardening are likely to be synergistic. However, it is clear that the harder materials show a greater effective increase in wear resistance with sliding distance than the softer materials.

Workhardening and paper degradation effects will be discussed in relation to their influence on material removal mechanisms later.

6.3.5. Workhardening Mechanism.

It has been mentioned that a higher carbon content would be expected to result in more rapid strain hardening under given conditions. The lower wear resistance of steel D in these tests seems to contradict the expected effect of surface hardening. In the pin-on disc tests the local strains experienced by the metal will be very high. The plastic deformation, caused by the abrasive, is necessary for strain hardening. If rapid strain hardening occurs at the surface of the harder steel, the depth of hardening may be very small. The results in this investigation show a greater depth of deformation for the softer steels than that for the harder steels in support of this argument.

Because of the nature of the abrasive process, the superficial hardening of the hard steel may have little effect on the material removal mechanism. Another more acceptable explanation can be surmised from the work of Moore who found the amount of strain hardening to be dependent on the metallurgical structure[53].

The size and type of debris produced can give an indication as to the extent of workhardening. Mutton and Watson[52] found that small microchips were formed from hard (HV = 858) materials, whereas softer materials were subject to ploughing with a larger abrasive particle size. Deeper penetration, especially of softer materials, is expected for a given load and, therefore, a greater tendency for chip formation.

All the materials used in these tests can be considered to be relatively soft and ductile in comparison to a steel of 800 HV. There are distinct differences in the mechanism of material removal, even so, these can be related to the hardness of the wear surface.

Examination of the debris from all the steels tested has shown that the size of the debris decreases with increasing hardness. In this respect the debris shows a transition from large, swarf debris to smaller, thinner debris with a few long, thin swarf particles and more plate-like debris, as the hardness increases.

It is likely that increasing load would cause deeper strain hardening, leading to the formation of smaller debris. It is not possible to deduce whether this is due to the initial production of smaller debris or to the degradation of the debris produced.

Thus, as the wearing surface becomes harder, the mechanism of removal changes from deep cutting and ploughing to shallower cutting, reduced ploughing and some spalling.

6.3.6. Paper Degradation Mechanisms and the Effect of Grit Size.

The effect of grit size in soft abrasive wear may be explained if "fine" grit abrasive deteriorates predominantly through wear and plastic flow at the contacting points, whilst in "coarse" grit this effect is reduced and modified by extensive fracture of the grit on both hard and soft metals and alloys. In fine grit, extensive fracture is inhibited due to low particle loading, the confinement of the well-supported grit and a general hydrostatic pressure. In the absence of fracture, the grit may strengthen through plastic flow and scratch very hard materials. The dimensions of the engaged facets are small and the track length per particle is relative very large. The resulting wear and plastic flow at the cutting facets has a profound effect on their shape.

Many investigators found that the deterioration mechanism of the abrasive grit depends on the grit size. Sugishita et al[32] found that for SiC paper grade 100, the principle mechanism is chipping fracture.

There are other factors affecting the deterioration mechanism during the test which can be summarised as follows:-

1. Abrasive type.
2. Material of abrasive backing (paper, cloth, etc.)
3. Applied load.
4. Test duration.
5. Mode of the test (dry or wet).
6. Abraded surface properties.

In this investigation SiC and Al_2O_3 abrasive papers were used. SiC abrasive particles were paper backed and Al_2O_3 particles were cloth backed. Three mechanisms of grit deterioration were observed:-

(a) Grit removal from the resin base (Figs. 37a and 38a).

(b) Shearing or chipping fracture of the grit (Figs. 37b and 38b).

(c) More gradual blunting of the grit (Fig. 38a).

In addition, clogging of the paper by wear debris was observed and could have reduced the abrasive effectiveness (see Figs. 37c and 38c). Considering the effect of these mechanisms on material removal mechanisms:-

(a) Grit removed will have an obvious effect; material will not be removed by any method that is proposed for attached grits. However, the loose grits may contribute to the abrasion process by three-body wear. Using the SEM, short ploughing grooves were found, indicating the presence of loose particles causing abrasive wear.

(b) Shearing or chipping fracture of the grit will produce facets as sharp, or sharper, than the original particles (Fig. 37b). Thus, the effect on material removal would be similar to that caused by a reduction in grit size. The regeneration of sharp facets will promote the cutting method of material removal, but for a very short time, because the sharp weak edge will wear out very quickly. The fractured pieces of abrasive particles may cause three-body wear.

(c) Gradual blunting of the abrasive particles occurs by incremental chipping of the particles as the local stresses exceed the fracture limit. Because of the localised nature of the chipping, lower stresses would be necesssary than for shearing of the whole particle. With the removal of sharp cutting facets a particle is more likely to cause wear by the the ploughing method and so will not be as efficient at removing materials as a cutting particle.

6.3.7. Material Removal Mechanism.

Microstructure can affect material removal by influencing paper degradation and surface workhardening. However, it is the mechanism of material removal itself which directly affects the wear volume, and the microstructure can directly affect this.

Zum Gahr(17) has established, for other materials, that a small mean free path, a small ratio of abrasive groove to carbide size, a high volume fraction of carbides and a low interfacial energy between carbide and matrix all favour high wear resistance in microstructures consisting of carbides in a softer matrix.

6.3.7.1. Effect of Number of Contacting Abrasive Points.

High abrasion rates are obviously favoured by the presence of a high proportion of contacting points which have an attack angle greater than the critical angle necessary for the cutting of a chip. Since the critical angle is about 90° for steel, it follows that no cutting would occur if all the abrasive particles had the axis of their contacting points aligned strictly perpendicular to the mean surface of the abrasive paper. In other words, the cutting points are all ones which have tilted sufficiently to give one side a favourable attack angle; only 10% of the abrasive particles are favourably arranged in an unused paper. An increase in abrasion rate would result if this proportion could be increased by imposing a small additional tilt on some of the abrasive particles.

The abrasive papers deteriorate in use. This is due to a decrease in the fraction of cutting points (see Fig. 39). Inferior mechanical strength of the cutting points would, therefore, contribute to rapid deterioration. This could result, firstly, from an unsatisfactory shape of cutting point. In this respect acicular particles are inferior to equiaxed ones and this factor appears to far outweigh the beneficial effect of acicular particles on the initial abrasion rate.

The presence of defects, such as cracks, in the abrasive particles would also have a major influence on the strength of the cutting point. Indeed this may be a critical factor because the stress applied to a cutting point cannot be much greater than the yield stress of the material abraded.

Wear volume versus sliding distance, shown in Figs. 27 and 28, indicate that the highest wear rate occurs in the first 15 minutes of the test. It is expected that the metal removal was by a cutting action, in which each abrasive particle of the favourably arranged particles on the paper, acts as a cutting tool producing metal chips and hence sharp grooves.

Additional tests were carried out to show the effect of test duration on the wear mechanism. Debris from a 15 minute test was collected and evaluated using the SEM. It was observed that the chips had a spiral shape (Fig. 34a) unlike the plate-like debris resulting from the one hour test discussed in section 6.3. It is believed that the metal removal of most of tested steels in the first few minutes of the test was by pure cutting since the abrasive particles have not deteriorated; they are efficient enough to act as hard cutting particles.

Debris from a one hour test was investigated and found to be plate-like, which indicates that the metal removal is by rubbing action because of the particle deterioration from one side and the absence of new unused particles replacing the deteriorated ones, either due to their unfavourable orientation, or the fact that they are too small to be effective after the first particles are damaged (Fig. 34b).

Clogging of the abrasive paper by abrasive dust and also by metal transfer may be a conributory factor in this case. At some intermediate period, both types of debris could be observed caused by the cutting and rubbing action (Fig. 38c). It can be seen from Fig. 39 that only 10 to 15% of the abrasive particles of the unused paper participated in the metal removal process which confirms the observations of many other investigators.

6.4. Effect of Corrosion

In many practical situations, abrasion and corrosion are jointly responsible for the wear of metal components. In one of these situations, i.e. the transportation of quartzite rock from the face of gold mines

[76], it was found that the replacement costs for conventional materials was very high. The hard quartzite rock slides over metal surfaces and copious amounts of acidic water, together with the temperature and humidity levels, give rise to an extreme condition of corrosive-abrasive wear. In such extreme corrosive situations, it was found that the wear resistance of the stainless steel was seen to improve dramatically with respect to mild steel or other grades of proprietary abrasion resistant materials.

Although the wear resistant alloys are generally better in dry abrasion, they become markedly worse than all the stainless steel grades when significant corrosion is present[77].

In their investigation on the synergistic effect of abrasion and corrosion during wear, Noel and Ball[78] found that the initial wear of a corroded mild steel pin increases with increasing corrosion time before the abrasion test. They also found that the ridges on both sides of the wear track were plastically deformed regions containing a high density of dislocations which presented a high internal energy.

The corrosion action is not always apparent because the abrasive actions continuously remove the corrosion products and consequently rusting is not observed.

In this investigation it was found that corrosion increases wear volume, especially at the initial stage of the abrasive wear test. It was also found that as the chromium content of the steel increases, the effect of corrosion on abrasive wear decreases (see Figs. 44 and 45). The variation in wear volume due to corrosion in the steels of 2%, 5% and 10% Cr was 42%, 29% and 12% respectively.

6.5. Effect of Attack Angle.

This investigation has confirmed that there are two main mechanisms in abrasive wear, i.e. ploughing and cutting. However, there is no sharp boundary which distinguishes between the two. At low angles the mechanism is totally ploughing. The literature suggests that at higher angles the mechanism is totally cutting, but the results obtained here show that even at 90° there is always some degree of ploughing involved in the wear process. Murray et al[46] have shown that the critical attack angle, below which no cutting occurs, is dependent on the hardness of the steel. They also concluded that at 30° the dominant mechanism for the softer steel is ploughing whereas cutting was the dominant mode in the wear of the harder steel.

Sedriks and Mulhearn[44] investigated a range of different materials and found that there is a critical attack angle for each material; for Al it is 85° and for Cu it is 45°. The values obtained in this investigation agree very closely with their results.

The two main wear mechanisms which have been mentioned above can be found in the abrasive wear of most of the pure metals and steels, because each has some level of ductility. Hardness and toughness are the two properties which control the two mechanisms. The domination of each of the two mechanisms depends to some extent on which property is playing the main role.

In brittle materials such as cast iron, it is believed that another mechanism may be dominant. In this investigation cast iron, worn under an attack angle of 60°, was investigated and there is no significant amount of ploughing or cutting and the dominant mechanism is by fragmentation which therefore must be related to its brittleness. It would be expected that this behaviour would occur at all attack angles.

It is observed from this investigation that the attack angle is very important and has a significant effect on the wear rate of the worn surfaces. Fig. 53 shows the optimum value of wear volume occurring across a range of angles around the 90° point with the width of the range varying with the type of steel tested. The harder steel shows a smaller range, whilst the softer steel shows a wider range. This suggests that in the case of the softer material the range in which ploughing and cutting mechanisms occur is much greater than that in harder material. The boundary between ploughing and cutting is clearer in softer materials.

The relationship between wear volume and load, at different attack angles, is shown in Fig. 51. It is observed that as the attack angle increases, the wear volume increases for a given load and number of passes. The wear volume at an attack angle of 90° was, for example, two or three times greater than that at 30°. The same relationship was found between wear volume and number of passes, i.e. the wear volume increases with increasing number of passes (Fig. 52). The figure also shows that there is a decreasing wear rate with increasing number of passes at different attack angles, i.e. there is an increase in the wear resistance of the metal with an increase in the number of passes. That can be related to the workhardening effect.

The workhardening effect leads to an increase in the hardness of the abraded surface so that the surface becomes more resistant to the penetration of the abrader. This effect was more significant in the case of a low attack angle in which a higher degree of plastic deformation occurs (Fig. 57).

The SEM was used to show the different mechanisms associated with material removal from the abraded specimens. Fig. 57 shows that in all the specimens there was evidence of ploughing when the abrader was sliding at attack angles of 15° and 30°, whilst a cutting mode dominates the process at angles of 80° and 90°. In the intermediate values of attack angle both mechanisms were observed.

Fig. 57 shows transverse sections of pure metals abraded by diamond at different attack angles. It can be seen that the cross-sectional area of the groove, as well as the depth of deformation, increases with increasing attack angle. Microhardness measurements were carried out on the deformed areas as shown in Fig. 58. The figure shows that the highest workhardening effect occurs in the case of pure copper at an attack angle of 90°. The other two pure metals, i.e. Al and Fe, exhibited the same behaviour with somewhat reduced deformation with a higher attack angle. The SEM was also used to study the debris produced throughout the tests. Fig. 59 shows that at higher attack angles the shape of the debris is spiral, whilst plate-like debris was observed with lower attack angle and both were observed at intermediate angles. The size of the debris depends on the load as well as the number of passes. It can be seen from Fig. 59a that big plate-like debris is produced from a long duration test of 100 passes at 30° attack angle and small spiral shaped debris at an attack angle of 90° and one pass experiment (Fig. 59c). 50 passes produced medium sized debris (Fig. 59b).

CHAPTER SEVEN

CONCLUSIONS

CHAPTER SEVEN

7. CONCLUSIONS.

1. Abrasive wear is a complex process and many parameters play a role in determining wear resistance. These parameters need to be isolated and studied separately to determine their influence. Some of them were studied here and the results agree with the main body of the literature.

2. The field trial offered a unique experience in the understanding and monitoring of the wear behaviour of digger teeth in-service. Some of the results derived from the field trial are:-

   2.1. The teeth showed considerable changes in shape and size. Worn teeth decreased the digging efficiency of the dragline and increased fuel consumption.

   2.2. There was evidence of some unexpected phase transformation such as a white layer and tempered martensite. It is the first time that such microstructural changes have been reported in the abrasive wear literature. These changes can be related to the rubbing action between mineral particles and teeth surfaces. Before this field trial, the rubbing action was not expected to play so significant a role, at least not in this kind of industrial application.

3. The use of a pin-on disc technique to determine wear characteristics of different steels was reliable. The results agree with those of other investigators concerning the effect of load, sliding distance, etc., on wear rate. Other important results derived from utilising this technique are:-

   3.1. Wear debris can be analysed and the wear mechanism is related to the shape of debris produced in the test. A cutting mechanism was related to spiral shaped debris and a rubbing action to plate-like debris. Debris size increased with increasing abrasive particle size.

   3.2. Degradation of abrasive papers showed a significant effect on change in the wear mechanism. New sharp abrasive particles were responsible for cutting wear, whilst worn particles caused rubbing.

   3.3. The pin surface roughness was load independent and it increased with increasing abrasive particle size.

   3.4. It was impossible to recreate the same sort of damage on the worn surface of the specimen tested in the laboratory compared to that produced in the field. In both cases this can be related to the different applied conditions.

4. The effect of attack angle on abrasive wear was studied using a new technique (unidirectional single point abrasive wear technique). It was not possible to do this in a pin-on disc

technique. Some of the most important results derived from using the new technique are:-

4.1. Wear volume increases with increasing attack angle up to 90° and then decreases. This is the first time that the effect of attack angle on wear rate has been studied and real calculated values were plotted to show this relationship. Most of the results in the literature are theoretically based.

4.2. Attack angle affects the wear mechanism. A rubbing action occurs at low attack angle, whilst a cutting action occurs at a high attack angle.

4.3. Attack angle affects the extent of deformation under the surface. Greater deformation was observed with a higher attack angle and a long sliding distance.

4.4. There is no sharp boundary between rubbing and cutting and hence there is no specific critical attack angle for any of the materials investigated. The values of critical attack angles which are theoretically predicted by previous investigators are not valid according to the evidence found in this investigation.

5. Corrosion increases the initial wear rate in a wet test, and the material removal is higher than the corresponding dry test. The difference berween dry and wet wear volume decreases as the percentage of chromium increases in the steel.

CHAPTER EIGHT

FUTURE WORK

MISSING

PRINT

CHAPTER EIGHT

8. FUTURE WORK.

The work described here was the first attempt to study abrasive wear in the "Tribology Group" at Brunel University and therefore forms a substantial foundation on which further work can be based. The following topics are put forward for future study.

1. The effect of microstructure to be studied in detail; steels of different microstructures (produced either by adding alloying elements or by heat treatment) to be investigated in the laboratory to determine their abrasive resistance.
2. The effect of casting technique on abrasive wear to be studied both in the field and the laboratory by producing parts cast by different casting routes.
3. The author is aware of a new technique being used in which a layer of tungsten carbide covers the surfaces of teeth. This technique is required to be extended so that carbide layers of different thicknesses are produced with different particle sizes. Abrasive wear resistance of a specimen containing a certain tungsten carbide layer thickness and size can then be determined.
4. The present pin-on disc abrasive testing machine to be modified so that the pin faces fresh abrasive particles during the test.
5. It is important that digger teeth produced from developed steels are mounted in the real dragline and a comprehensive field study to be carried out to determine the wear behaviour.

6. Effect of digged ... [illegible]

Note:

The following papers have been published during the course of this investigation.

1. Mashloosh, K., Akbasoglu F., Eyre, T., 'Wear of Digger Teeth, Tribology in Mineral Extraction, I.Mech.E., 1984, paper C343/84, 29-34.

2. Mashloosh, K. and Eyre, T., 'Abrasive Wear and Its Application to Digger Teeth', Trib. Int., 1985, (18) 5, 259 - 266.

3. Mashloosh, K. and Eyre, T., 'Effect of Attack Angle on Abrasive Wear', Metals and Materials, 1986, (2) 7, 426 - 430.

CHAPTER NINE

ACKNOWLEDGEMENTS

CHAPTER NINE

9. Acknowledgements

I would like to thank Dr. T.S. Eyre for his advice, encouragement and invaluable discussion during the course of the work.

I would also like to express my appreciation to the Steel Casting Research and Trade Association (SCRATA) for providing the materials used in this investigation.

I am also grateful to all my colleagues in the Tribology Group for their encouragement and valuable discussion.

I would like to thank the Iraqi Government for their financial support during this period of study in the U.K.

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REFERENCES

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10. REFERENCES

1. Vingsbo, O., Proc. Conf. "Wear of Materials", 1979, 621-635, New York, ASME.

2. Eyre, T.S., "Wear Mechanisms", Powder Metallurgy, 1981, 24(2), 57-63.

3. Smart, R.F., "Wear : Causes, Cure, Control", Surfacing J., 1984, 15(3), 37-41.

4. Wilson, R.W., ASLE Trans., 1979, 36(5), 263-269.

5. Watson, J.D. and Brown, G.G., A Symposium on Direct Reduction in Energy Conservation Pollution Control Foundry Practice and Products, Thailand, 5-9 Sept. 1977.

6. Moore, M.A. in "Treatise on Materials Technology", Academic Press, Ed. Scott, D. (1979) 217-253.

7. Moore, M.A., "Abrasive Wear", Materials in Engineering Applications, 1978, 1, 97-111.

8. Richardson, E., Jones, M. and Atwood, D., Proc. Agri. Eng. Symposium, Div. 2, Paper 26. Inst. Agr. Engrs., London 1967.

9. "Recommended Practice for the Jaw Crusher Gouging Abrasion Test", ASTM Commitee G2 on Erosion and Wear, Feb. 1978.

10. Marks, G., Mutton, P. and Watson, J., "Gouging Abrasion Tests on Several Irons and Steels", BHP Melb. Res. Lab. Report MRL/113/76/ 002, August 1976.

11. Mutton, P., "High Stress Abrasion Testing of Wear Resistant Steels and Cast Irons", BHP Melb. Res. Lab. Report MRL/PM3/78/001.

12. Muscara, T. and Sinnott, M., "Construction and Evaluation of a Versatile Abrasive Wear Testing Machine", Metals Eng. Quarterly, 12 (May 1972) p.21.

13. "Wet Sand Rubber-Wheel Abrasion Test Method", SAE. Iron and Steel Technical Committee, April 1977.

14. Khruschov, M., "Resistance of Metals to Wear by Abrasion as Related to Hardness", Proc. Conf. Lubrication and Wear, London 1957, p.655.

15. Mulhearn T. and Samuels, L., Wear, 1962, 5, 478-498.

16. Khruschov, M., Wear, 1974, 28, 69-88.

17. Zum Gahr, A., Metal Progress, 1979, Sept., 46-52.

18. Torrance, A., Wear, 1980, 63, 359-370.

19. Richardson, R., Wear, 1967, 10, 291-309.

20. Rabinowicz, E., Scient. Am., 1968, 218(6), 91-99.

21. Aghan, R. and Samuels, L., Wear, 1970, 16, 293-301.

22. Lawn, B.,and Wilshaw, T., Mater. Sci., 1975, 10, 1049-1081.

23. Khruschov, M. and Babichev, M., Research on the Wear of Metals, Chap.18, NEL Transition No. 893, National Engineering Laboratory, East Kilbride, 1960.

24. Graham, D. and Baul, R., Wear, 1972, 19, 301-314.

25. Date, S. and Malkin, S., Wear, 1976, 40, 223-235.

26. Blomberry, R.I. and Perrot, G.M., J. Aust. Inst. Met., 1974, 19, 255-258.

27. Dobson, P. and Wilman H., Br. J. Appl. Phys., 1963, 14, 132-136.

28. Rabinowicz, E., Dunn, L. and Russel, P., Wear, 1961, 4, 345-355.

29. Peters, J., M.Sc. Dissertation, University of the Witwatersrand, May, (1983).

30. Askwich, T., Surfacing J., 1980, 11(4), 2-6.

31. Richardson, R.C.D., Wear, 1968, 11, 245-274.

32. Sugishita, J., Fugiyoshi, S. and Imura, T., Wear, 1979, 52, 219-234.

33. Larsen-Badse, J., Wear, 1976, 40, 223-235.

34. Larsen-Badse, J., Wear, 1972, 19, 27-35.

35. Rabinowicz, E. and Mutis, A., Wear, 1965, 8, 381-390.

36. Avient, B., Goddard, J. and Wilman, H., Proc. Roy. Soc. (London) A258 (1960), 159-180.

37. Johnson, R., Wear, 1960, 16, 351-358.

38. Kragelskii, I., "Friction and Wear", Butterworth, London, 1965, pp. 20-26 and 88-110.

39. Sedriks, A., and Mulhearn, T., Wear, 1964, 7, 451-459.

40. Burwell, J., Wear, 1957, 1, 119-141.

41. Hata, S. and Muro, T., Mem. Fac. Engn. Kyoto Univ., 1969, 31, 456-489.

42. Giltrow, J. and Grozek, S., R.A.E. Technical Report 69024, 1969, Royal Aircraft Establishment.

43. Dean, S. and Doyle, E., Wear, 1975, 35, 123-129.

44. Sedriks, A. and Mulhearn, T., Wear, 1963, 6, 457-466.

45. Doyle, D. and Samuels, L., "Further Development of a Model of Grinding", Proc. Int. Conf. Prod. Eng., Tokyo, 1974, 45-50.

46. Murray, M., Watson, J. and Mutton, P., "Abrasive Wear Mechanisms in Steels", Wear of Materials, Conf. 1979, U.S.A.

47. Mann, N. and Broese Van Groenou, A., "Low Speed Scratch Experiments on Steels", Wear, 1977, 42, 365-390.

48. Stepina, A., Sidorova, L. and Tolstenko, E., Met. Sci. Heat Treat., USSR, 1982, 24(9-10), 607-612.

49. Wahl, W., Surfacing J., 1980, 11(1), 2-5.

50. Samuels, L., Abrasives, Phys. Tech., 1985, 16, 214-220.

51. Vijh, S., Wear, 1975, 35, 205-209.

52. Mutton, P. and Watson, J., Wear, 1978, 48, 385-398.

53. Moore, M., Trib. Int., 1975, June, 105-110.

54. Rubenstein, C., Wear, 1965, 8, 70-72.

55. Moore, M., Wear, 1974, 28, 59-68.

56. Larsen-Badse, J. and Mathew, K., Wear, 1969, 14, 199-206.

57. Prasad, N. and Kilkarni, S., Wear, 1980, 63, 329-338.

58. Rac, A., Trib. Int., Feb (1985), 18, 29-33.

59. Norman, T., "Factors Influencing the Resistance of Steel Castings to High Stress Abrasion", American Foundrymen's Society - Reprint No.58-9.

60. Price, L., Metal Progress, 1983, Aug., 21-25.

61. Riddihough, M., Hardfacing by Welding, 4th Ed., Swindon Press, Swindon, England.

62. Chavanne, R., Welding J., 1983, 62(15), 15-18.

63. Hardy, M. and Yardley, E., Surfacing J., 1985, 16(1), 11-19.

64. Hoogensen, C., Lichtenberger, P. and Hardy, R., "Abrasion Resistant Alloys for Excavation Equipment", ASM Conf. on Mat. Eng. in Arctic Canada, 1976, 78-92.

65. Vanne, L., "Abrasion Resistant Materials for Earthmoving and Coal Mining", ASM, 1981, Met. A., (8111-72-0469), 39-46.

66. Coated Abrasive Microgrit Size Standard, FEPA Standard 30GB 1971 and 31GB 1971.

67. Eyre, T. and Dutta, K., ASLE Lubrication Engineering, 1975, 31(10), 521-529.

68. Davies, B. and Wilding, D., "A Composite Approach to Reducing Abrasive Wear", International Off-Highway Meeting (Proc.Conf.), Milwaukee, Wis., U.S.A., 12-15 Sept. 1983, SEA, Tech. Paper Series No. 831375, pp.4.

69. Eyre, T., Dent, N. and Dale, P., Lub. Eng. 1983, 39(4), 216-221.

70. Eyre, T. and Baxter, A., Trib. Int. 1972, 5, 256-261.

71. Griffiths, B. and Furze, D., Proc. of the Inst. of Metals Conf. Eng., The Surfaces, Royal Lancaster Hotel, London, May 1986.

72. Scott, D., Smith, A., Tait, J. and Tremain, G., Wear, 1975, 33, 293-315.

73. Rowntree, R., "Metallurgical Phase Transformation in the Rubbing of Steels", Ph.D. Thesis, Leicester University, England, 1982.

74. Grozin, B.D. and Iankevich, V.F., "Friction and Wear in Machines", Symposium, Moscow, USSR, 1962, 15, 143.

75. Mashloosh, K.M., Abrasive Wear of Digger Teeth, M.Sc. Dissertation, Brunel University, 1984.

76. Joughin, N., Progress in the Development of Mechanised Stoping Methods, J.S. Afr. Inst. Min. Metall., 1978, May, 78, 207.

77. Allen , C. and Ball, A., The Abrasive-Corrosive Wear of Stainless Steel, Wear, 1981-1982, 74, 287-305.

78. Noel, R. and Ball, A., On the Sunergistic Effect of Abrasion and Corrosion During Wear, Wear, 1983, 87, 351-361.

79. Kar, N., Investigation of the Role of Microstructures on the Two-Body Abrasive Wear Resistance of Steels, Wear of Materials, Int. Conf., San Francisco, California, U.S.A., 1981, 415-425.

80. Hurricks, P., Wear, 1973, 26, 285-304.

81. Zum Gahr, K., Z. Metallkde., 1977, 68, 783-792.

82. Hornbogen, E., Wear, 1975, 33, 251- .

83. Lai, G., Wood, W., Clark, R., Zackay, V. and Parker, E., Metallurgical Transactions, 1974, 5, p.1663.

84. Parker, E., Inter-relations of Compositions, Transformation Kinetics, Morphology and Mechanical Properties of Alloy Steels, 1977, AIME, Atlanta, GA.

85. Gerberich, W. and Birat, J., International Journal of Fracture Mechanics, 1971, 7, p.108.

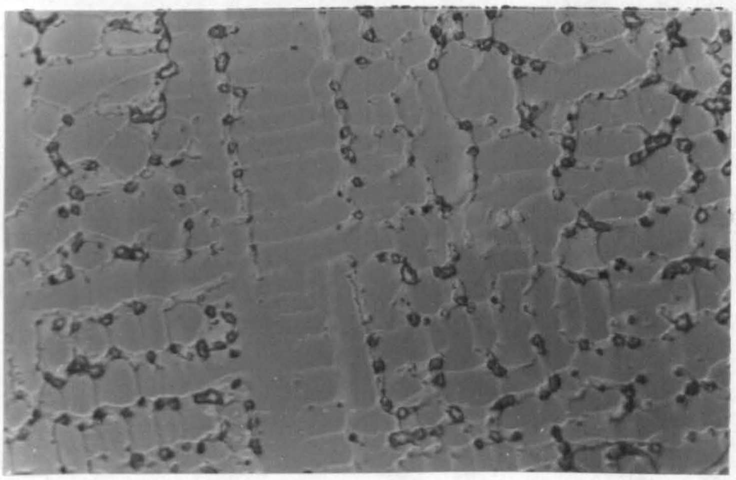
86. Webster, D., Metallurgical Transactions, 1971, 2, p.2097.

87. Kruschov, M. and Babichev, M., Friction and Wear in Machinery, 1965, 19, p.1.

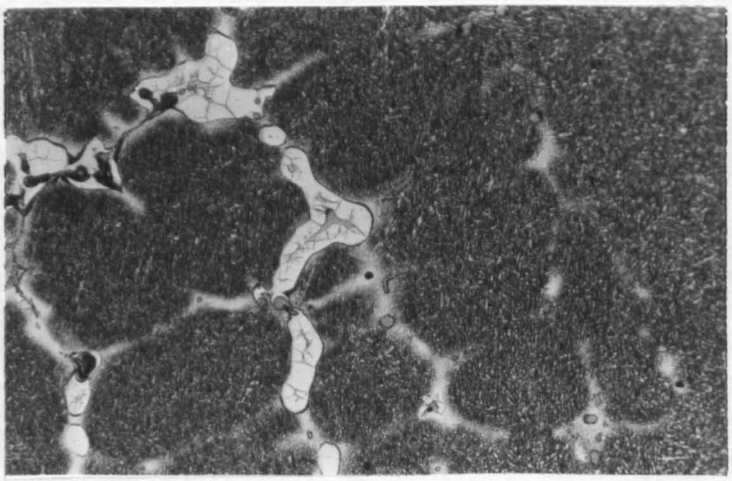
88. Swanson, P. and Klann, R., Abrasive Wear Studies Using the Wet and Dry Rubber Wheel Tests, Wear of Materials, Int. Conf., 1981, California, U.S.A., 379-389.

APPENDIX 1

MICROSTRUCTURES OF STEELS USED IN THIS INVESTIGATION

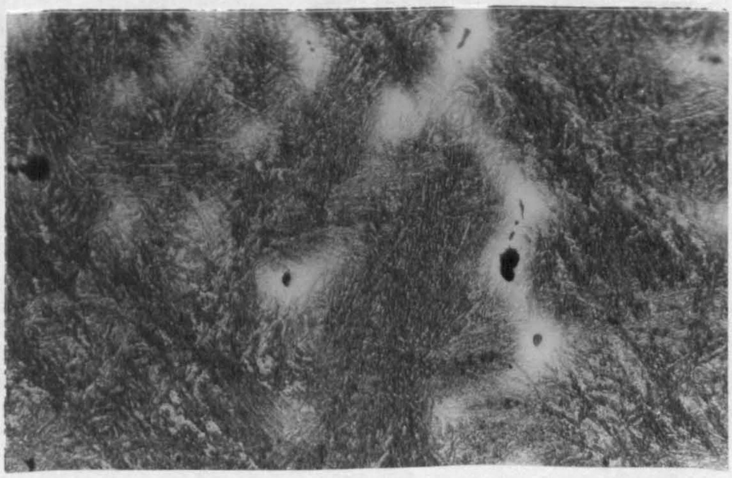


Steel A



Steel B

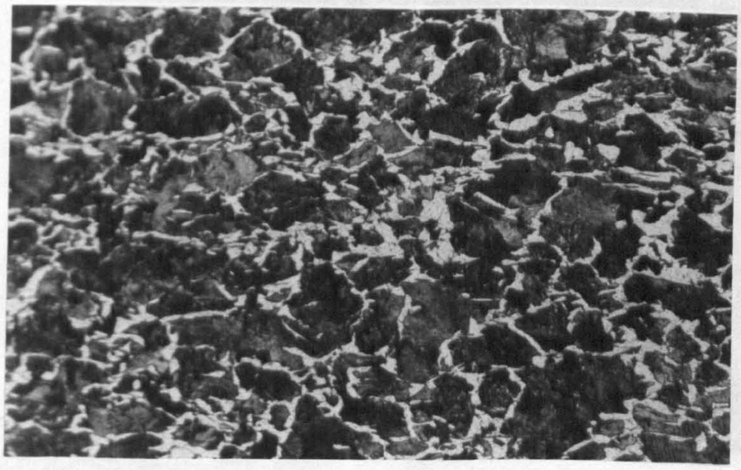
100 μm



Steel C

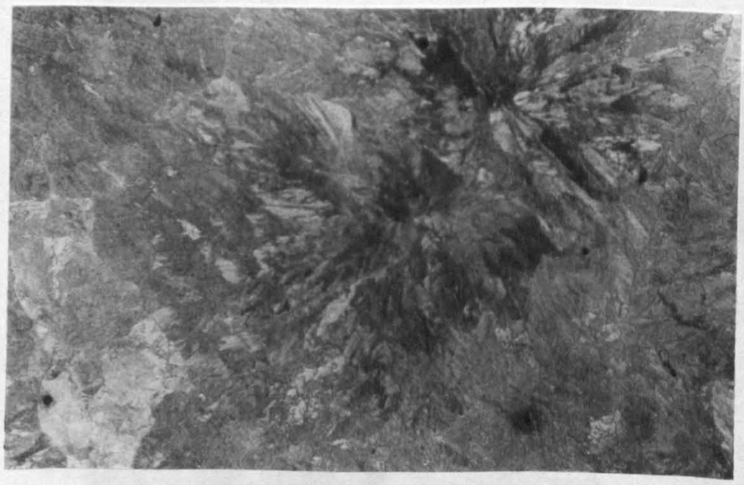
Steel D

Steel E

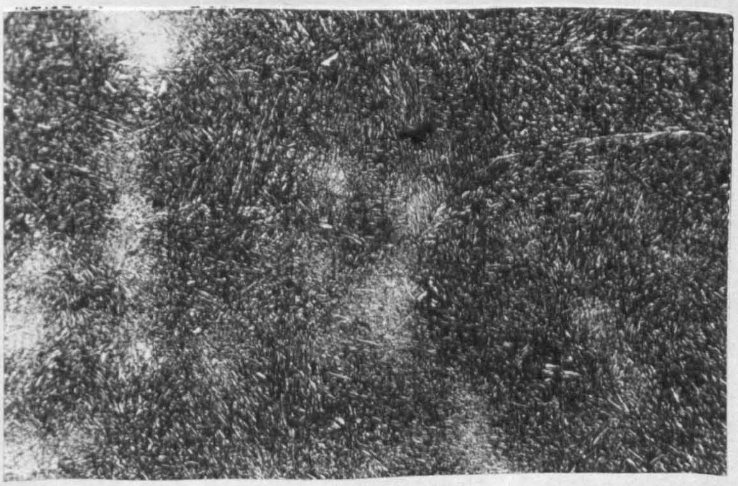


Steel F

100 μm



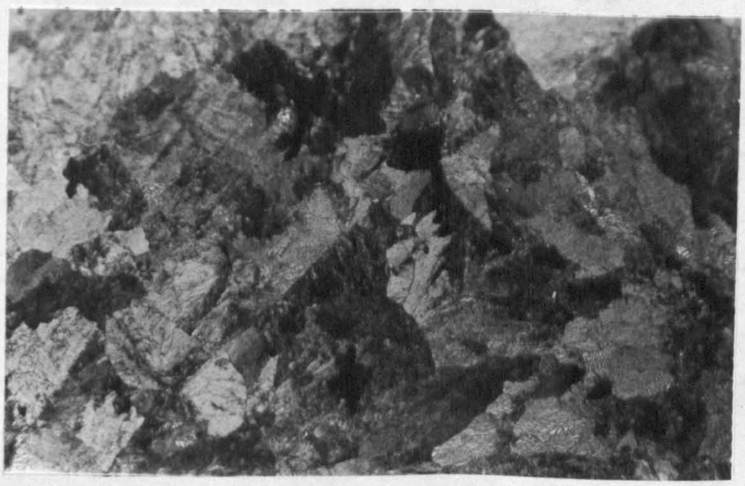
Steel G



Commercial D.T.

Steel H

100 μm



Steel I

Table 1 :— Grade number and particle size of SiC and Al-Oxide abrasive papers (66).

Grade	particle Size (μm)
60	250
80	180
100	150
120	125
220	65
240	58
320	46
400	35
600	25

Table - 2 : Weight loss (gms) Vs working hours of the digger teeth in service.

WORKING HOURS	DIGGER TEETH			
	1	2	3	4
0	0	0	0	0
1	150	200	50	150
11.5	550	500	350	500
35.5	800	700	550	750
51.5	1300	1150	850	1150
77.5	1950	1650	1350	1650
109.5	2350	2000	1700	2050
136.5	2650	2200	1950	2250
163.5	2950	2550	2300	2650
201.5	3250	3100	2750	2950
230.0	3500	3400	3250	3250
260.0	4150	4200	3750	3950
335.0	4450	4800	4250	4050

Table 3 :- Chemical compositions of steels used.

Steel	C%	Si%	Mn%	S%	P%	Cr%	Mo%	Density gm/cm^3	Hv	Microstructure
A	1.35	0.44	13.2	–	–	2.3	–	7.79	455	Austenite +Carbides
B	0.23	1.4	0.85	0.06	0.06	2.0	0.52	7.60	510	Martensite +Ret. Aust.
C	0.27	0.66	0.74	0.04	0.02	5.04	0.002	7.87	467	Martensite
D	0.36	0.43	0.44	0.02	0.015	4.94	0.003	7.89	253	Pearlite
E	0.58	0.47	0.47	0.016	0.018	10.14	0.02	7.93	605	Pearlite + Carbide
F	0.35	0.3	0.88	–	–	–	–	7.78	221	Pearlite + Ferrite
G	0.51	0.61	0.49	0.022	0.015	5.04	0.005	7.83	194	Pearlite
Commerti D.T.	0.17	1.95	0.86	0.016	0.014	1.96	0.33	7.87	490	Martensite
H	0.54	0.58	0.51	0.019	0.025	4.95	0.001	7.85	248	Pearlite
I	0.51	0.54	0.59	0.017	0.022	2.12	–	7.82	230	Pearlite

Table 4 :— Wear Volume (mm^3) Vs. Load (N) ,SIC grit 100, 675 M Sliding distance.

Steel	44 N	66 N	110 N	154 N	198 N
Commercial D.T	4.0	6.2	18.8	38.1	56.3
A	6.1	17.4	35.2	60.2	68.4
D	18.6	36.0	63.3	101.0	120.3
G	19.0	38.1	86	133.1	170.4

Table 5 :— Wear Volume (mm^3) Vs. Load (N),Al-Oxide grit 120, 675 M Sliding distance.

Steel	44 N	66 N	110 N	154 N	198 N
C	148	202	370	465	595
D	137	168	247	339	412
E	47	84	141	170	202
G	209	282	390	565	705

Table 6 :— Wear Volume (mm^3) Vs. Sliding distance (M), Al-Oxide grit 100, Load 110 N.

Steel	225 M	450 M	675 M	900 M	1125 M
Commercial D.T.	86	125	161	192	210
A	164	272	362	450	472
D	112	198	263	325	351
E	102	155	214	252	275

Table 7 :— Wear Volume (mm^3) Vs. Sliding distance (M), SiC grit 100, Load 110 N.

Steel	225 M	450 M	675 M	900 M	1125 M
Commercial D.T.	8.2	10.5	13.4	13.6	14.3
A	20.3	30.3	41.6	53.4	56.3
C	10.3	26.3	34.6	51.4	56.3
E	35.2	58.3	80.2	96.4	112.4

Table 8 :— Wear Volume (mm^3) Vs. Sliding distance (M), Steel A, SiC grit 100 & Al-Oxide grit 100, Load 110 N.

Abrasive	225 M	450 M	675 M	900 M	1125 M
SiC	20.3	30.3	41.6	53.4	56.3
Al-Oxide	164	272	362	450	472

Table 9 :— Wear Volume (mm^3) Vs. Sliding distance (M), Steel B SiC grit 100, Load 110 N.

Type of test	225 M	450 M	675 M	900 M	1125 M
New paper every 15m	13.6	26.0	36.8	44.8	58.3
One paper during 75m	13.4	16.3	21.3	24.1	26.3

Table 10 :— Wear Volume (mm^3) Vs. Sliding distance (M), Steel J Al-Oxide, Load 66N.

Grit Size	225 M	450 M	675 M	900 M	1125 M
80	220	310	465	590	730
120	173	218	304	413	550
220	151	194	225	358	390

Fig. 13 Crane and bucket dragline.

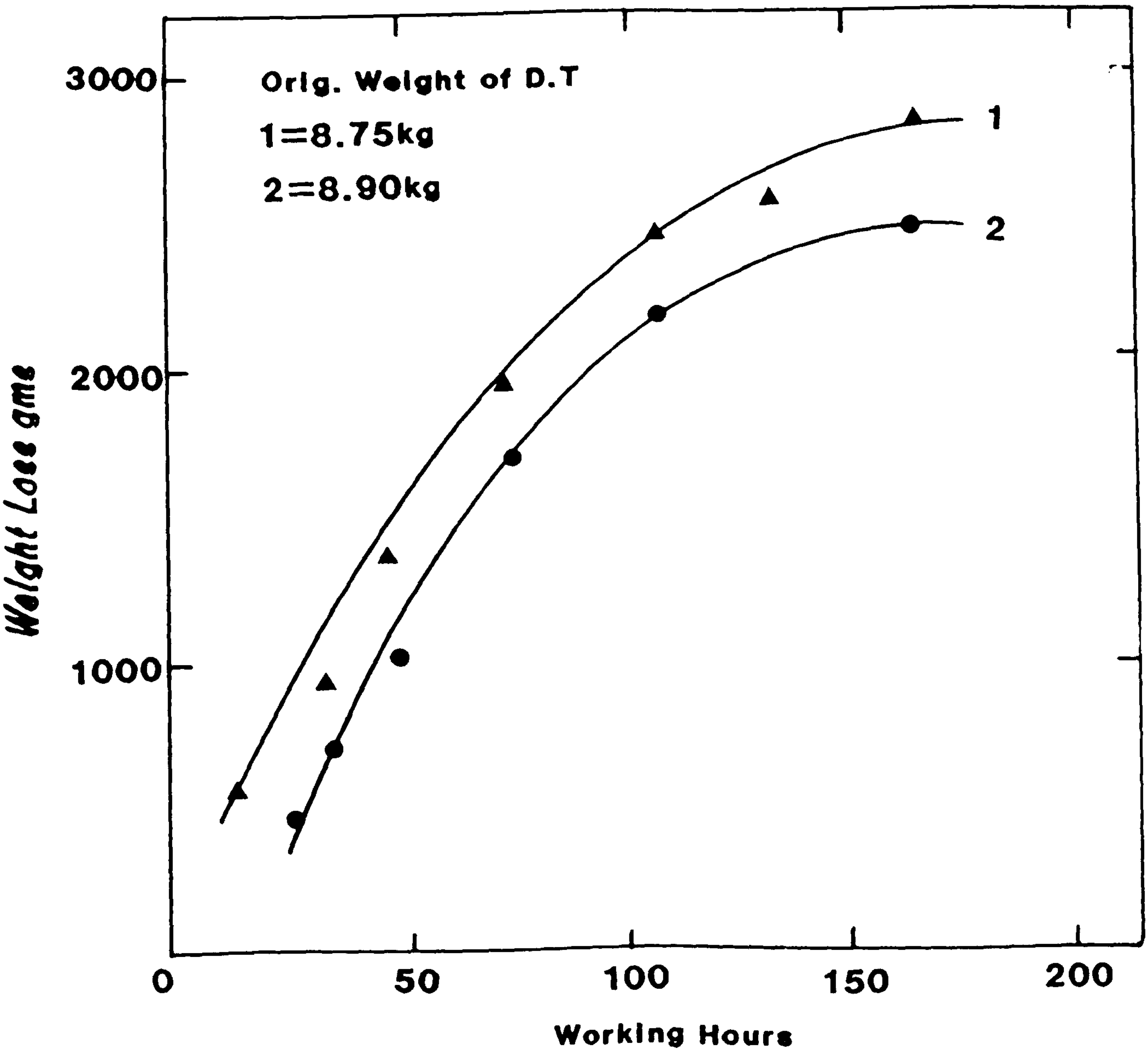


Fig. 14 Weight loss vs working hours of digger teeth in service.

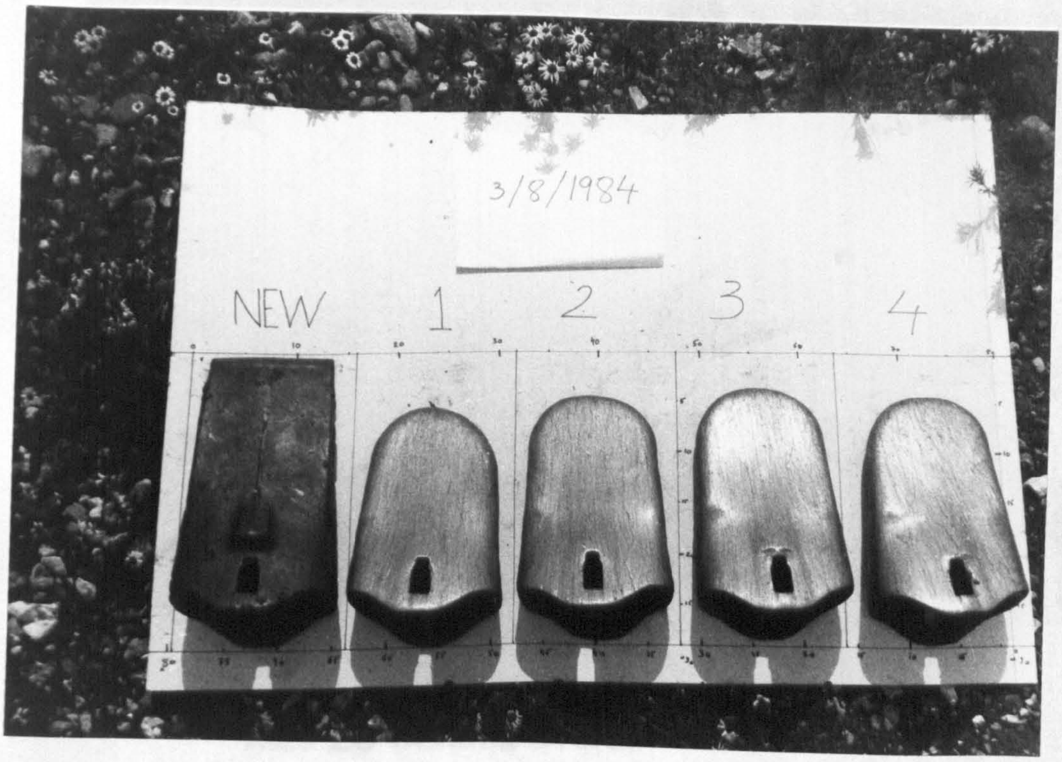


Fig. 15 New and worn digger teeth.

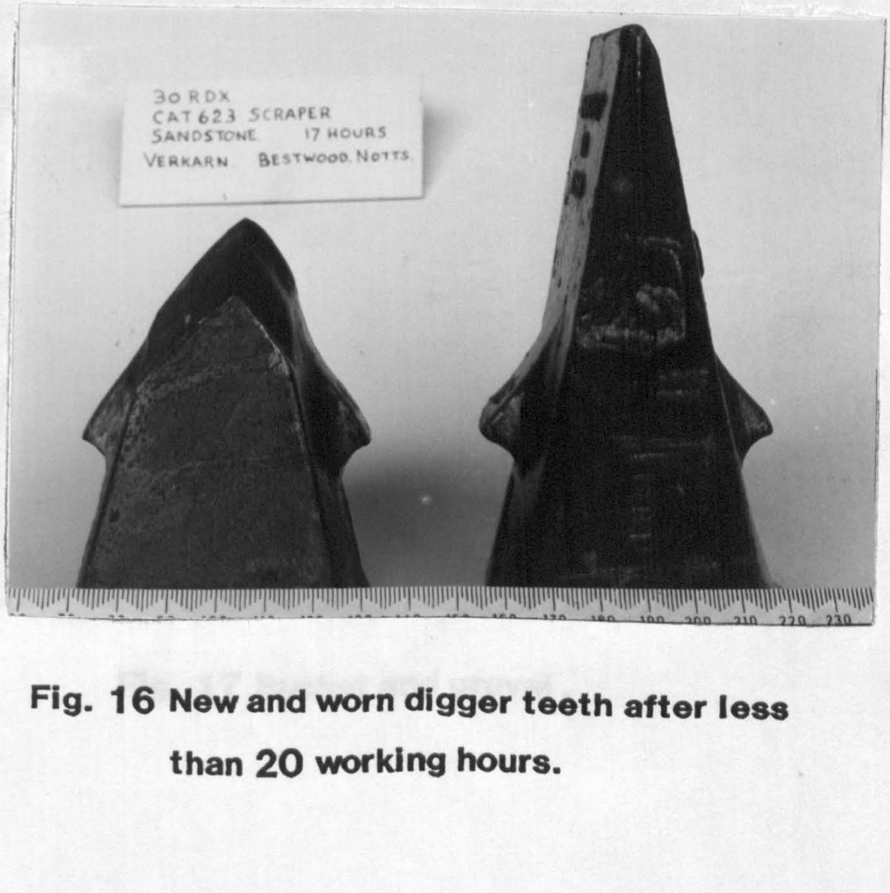


Fig. 16 New and worn digger teeth after less than 20 working hours.

Fig. 17 Bucket and gravel .

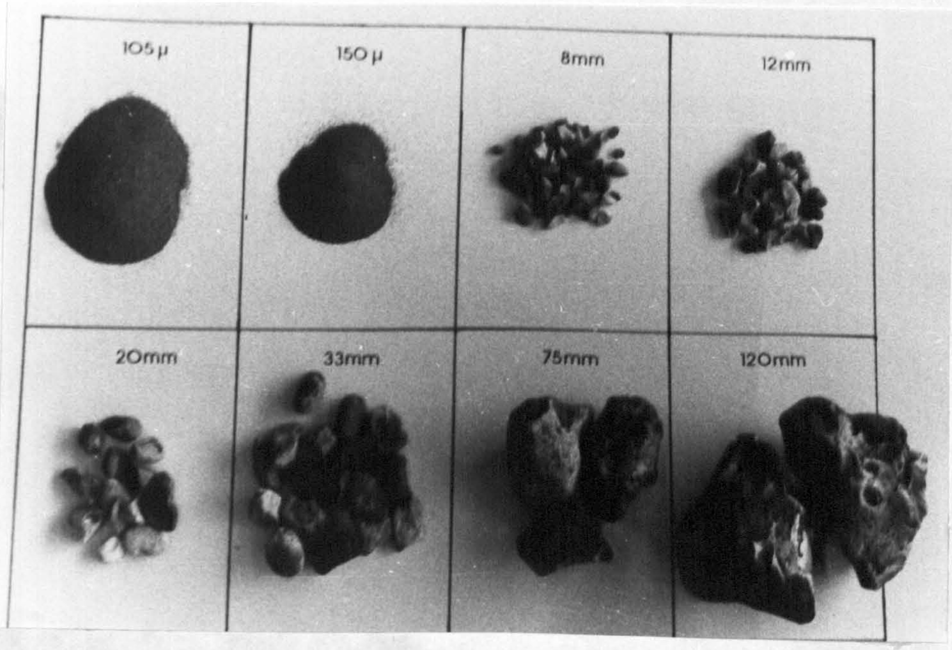
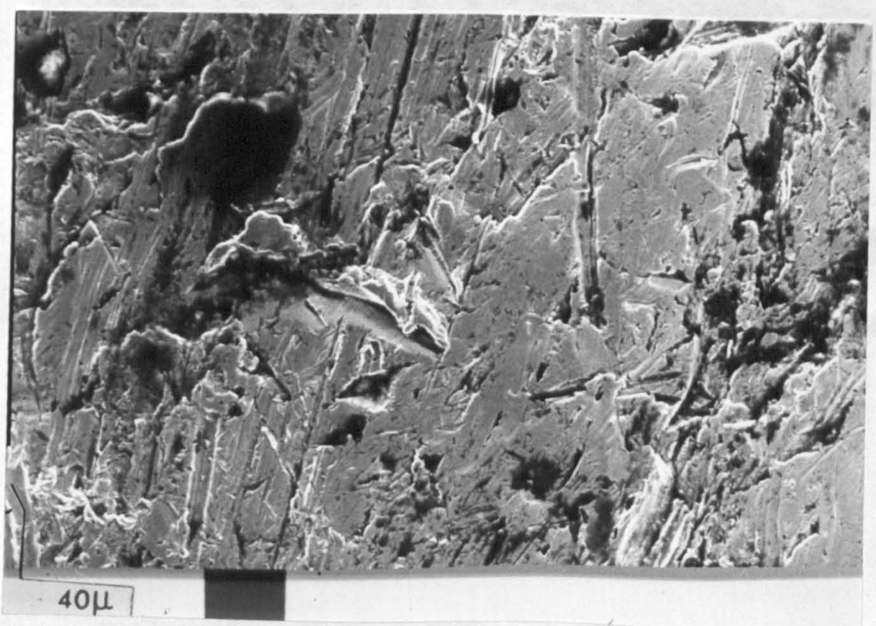


Fig. 18 Gravel size distribution.

a



b

Fig. 19 a- Replica of worn surface of digger tooth.
b- The same surface viewed in the SEM.

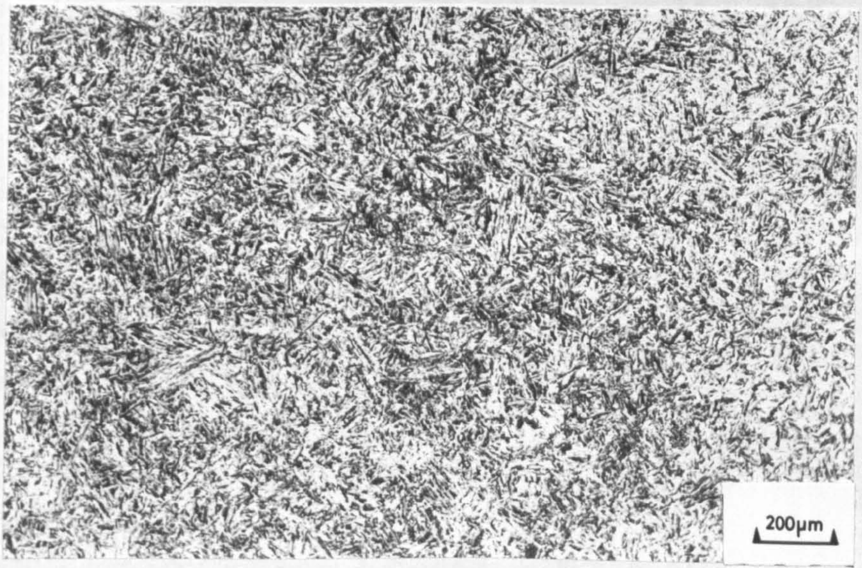
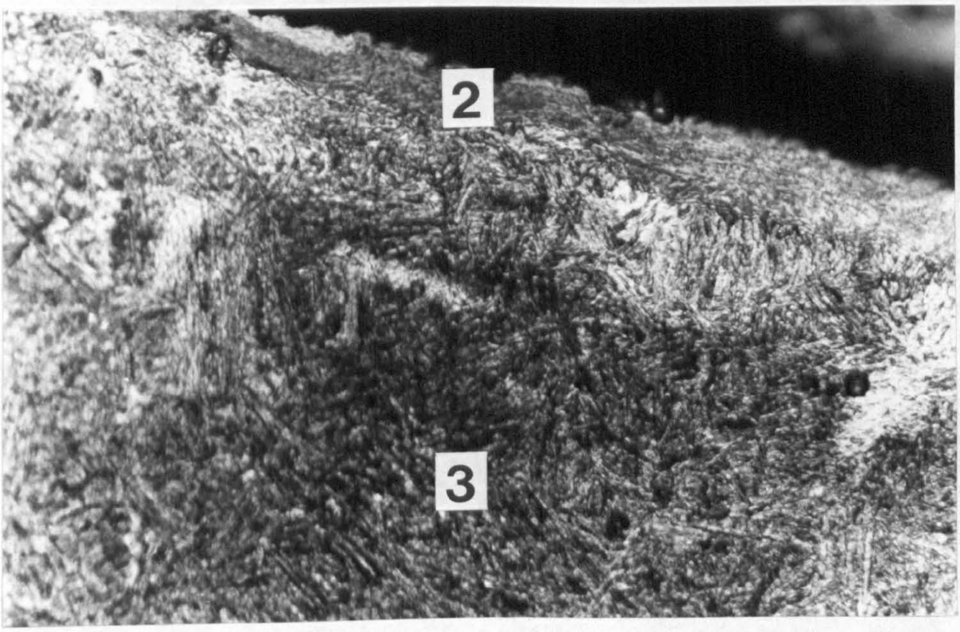
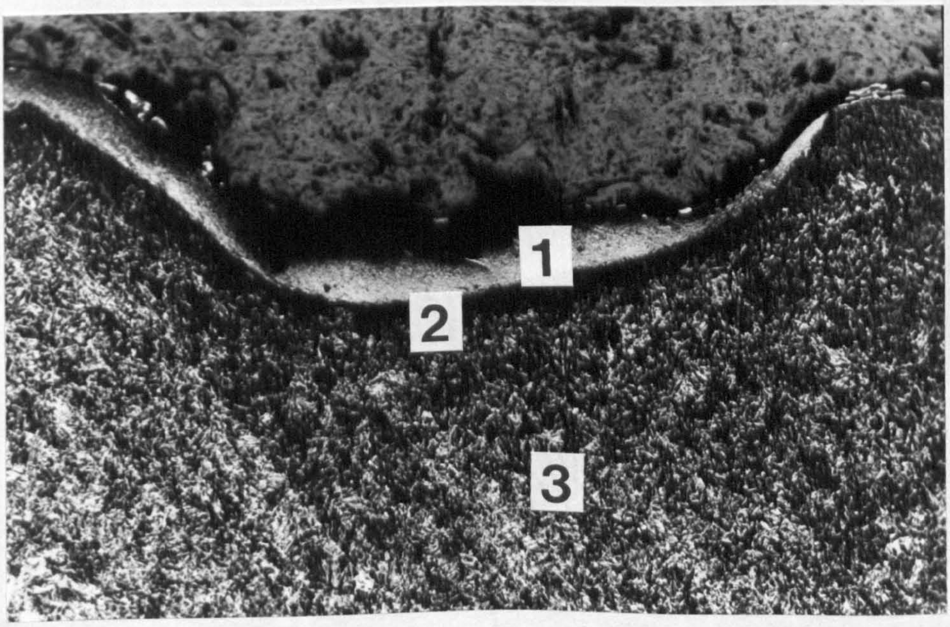


Fig. 20 Martensitic Microstructure of digger tooth.



a



b

Fig. 21 Transverse sections for digger tooth worn surfaces showing some microstructure changes.
a- Tempered martensite (2) and martensite (3)
b- White layer (1) followed by tempered martensite (2) and untempered martensite (3)

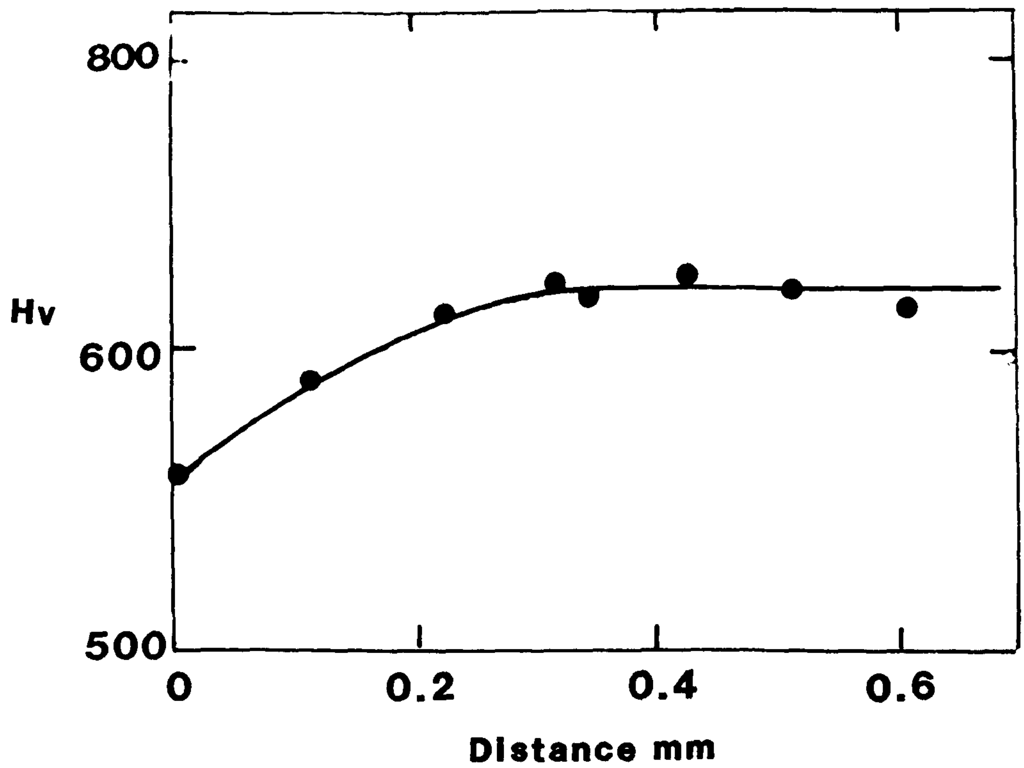


Fig. 22a Microhardness transverse through a tempered layer.

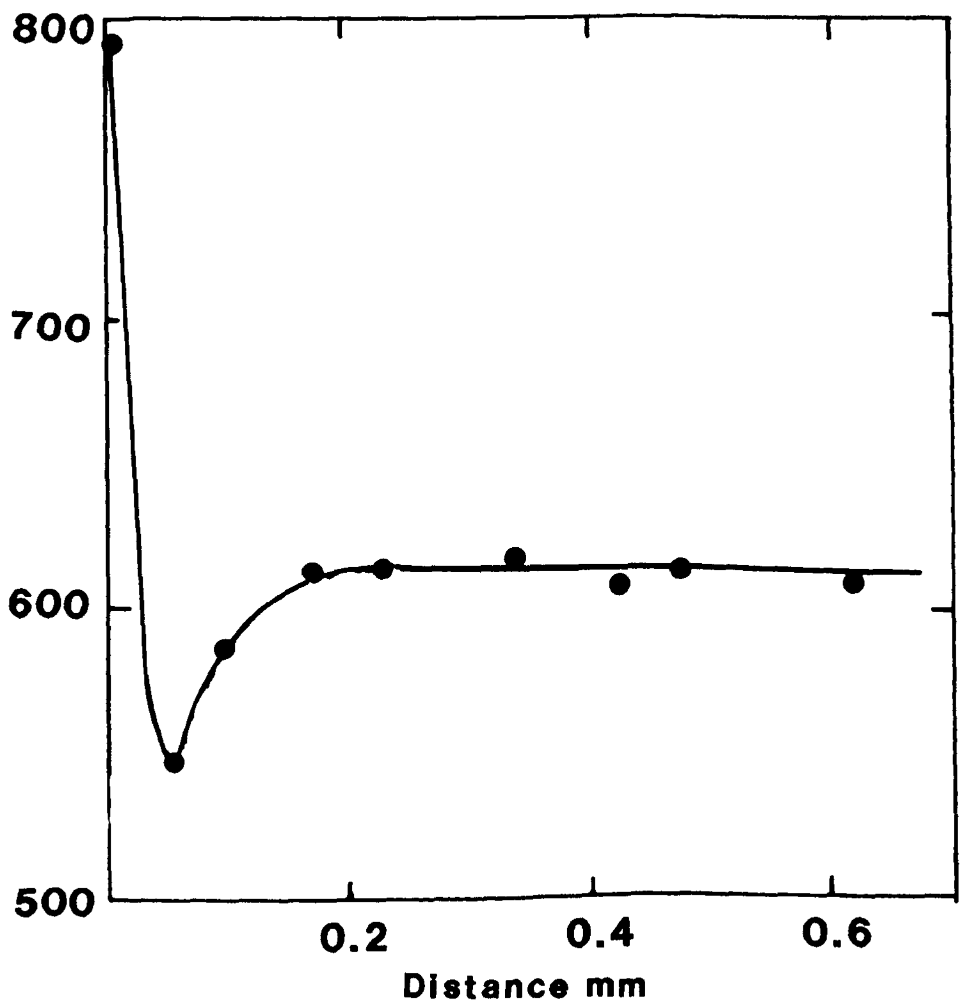


Fig. 22b Microhardness transverse through a white layer.

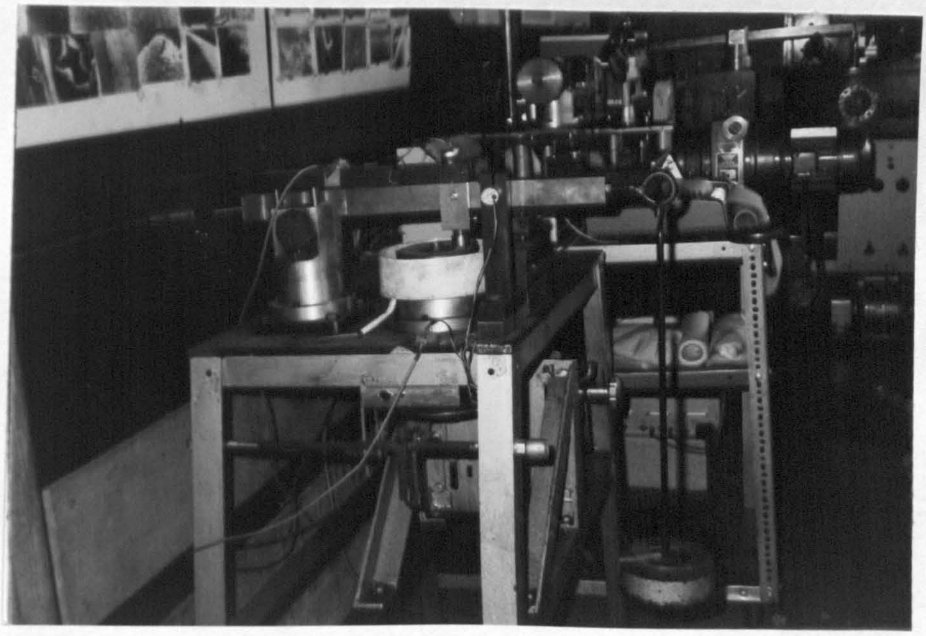


Fig. 23 Pin-on disc abrasive wear testing machine.

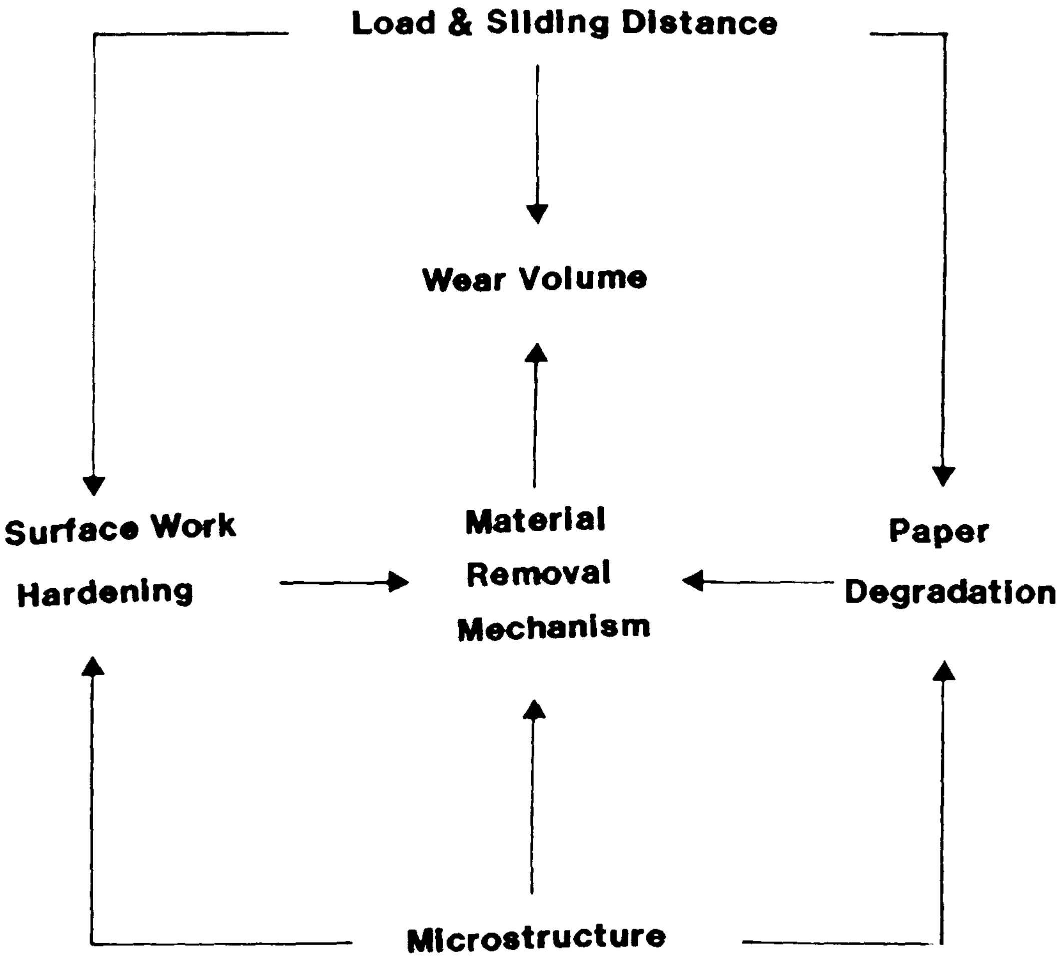


Fig. 24 A systems view of the pin on disc abrasive wear evaluation technique. The arrows represent direct relationships.

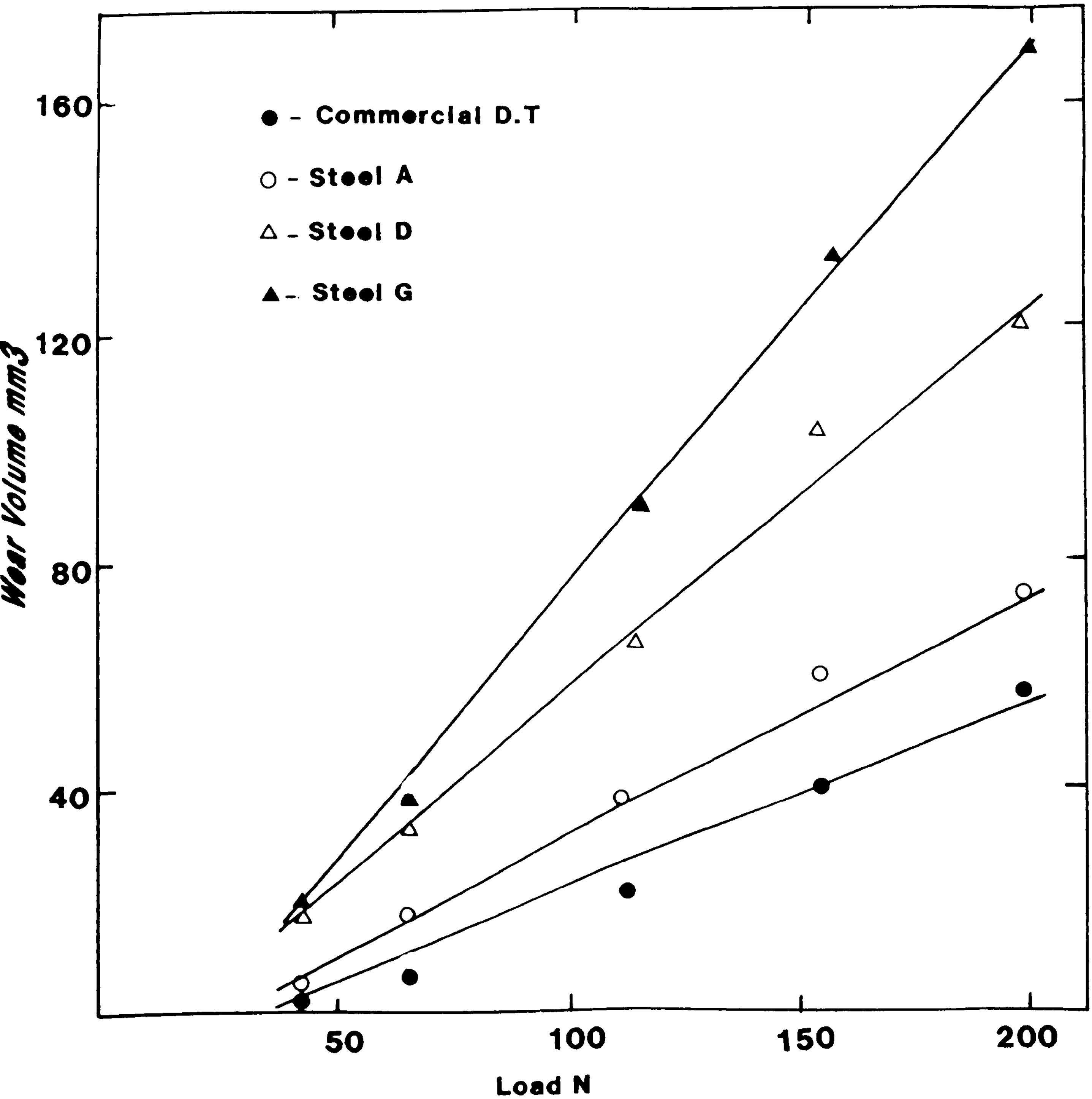


Fig.25 Wear volume Vs Load,SIC-G 100,dry test.

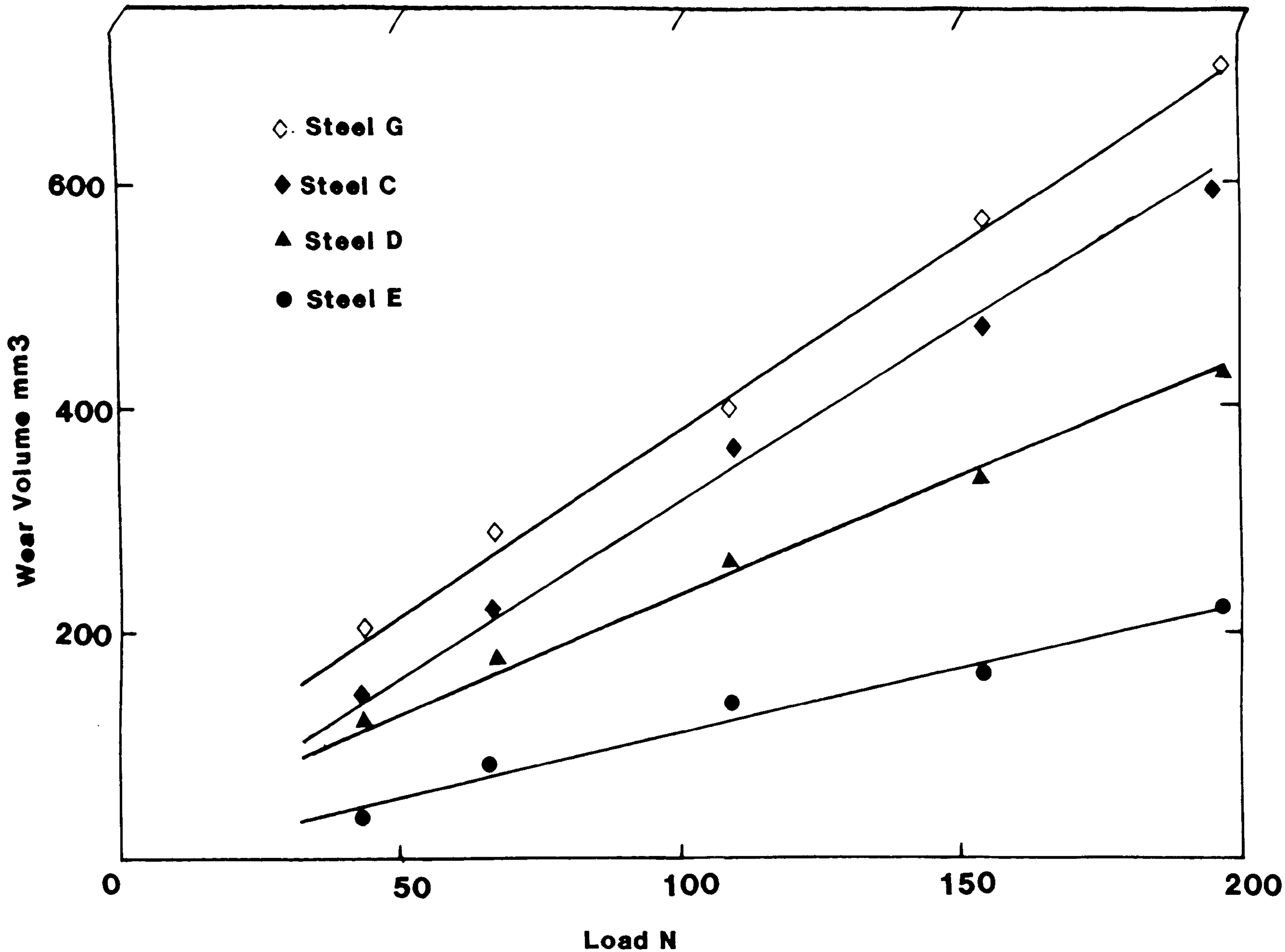


Fig.26 Wear volume Vs load ,Al-Oxide,grit 120, 675 M Sliding distance.

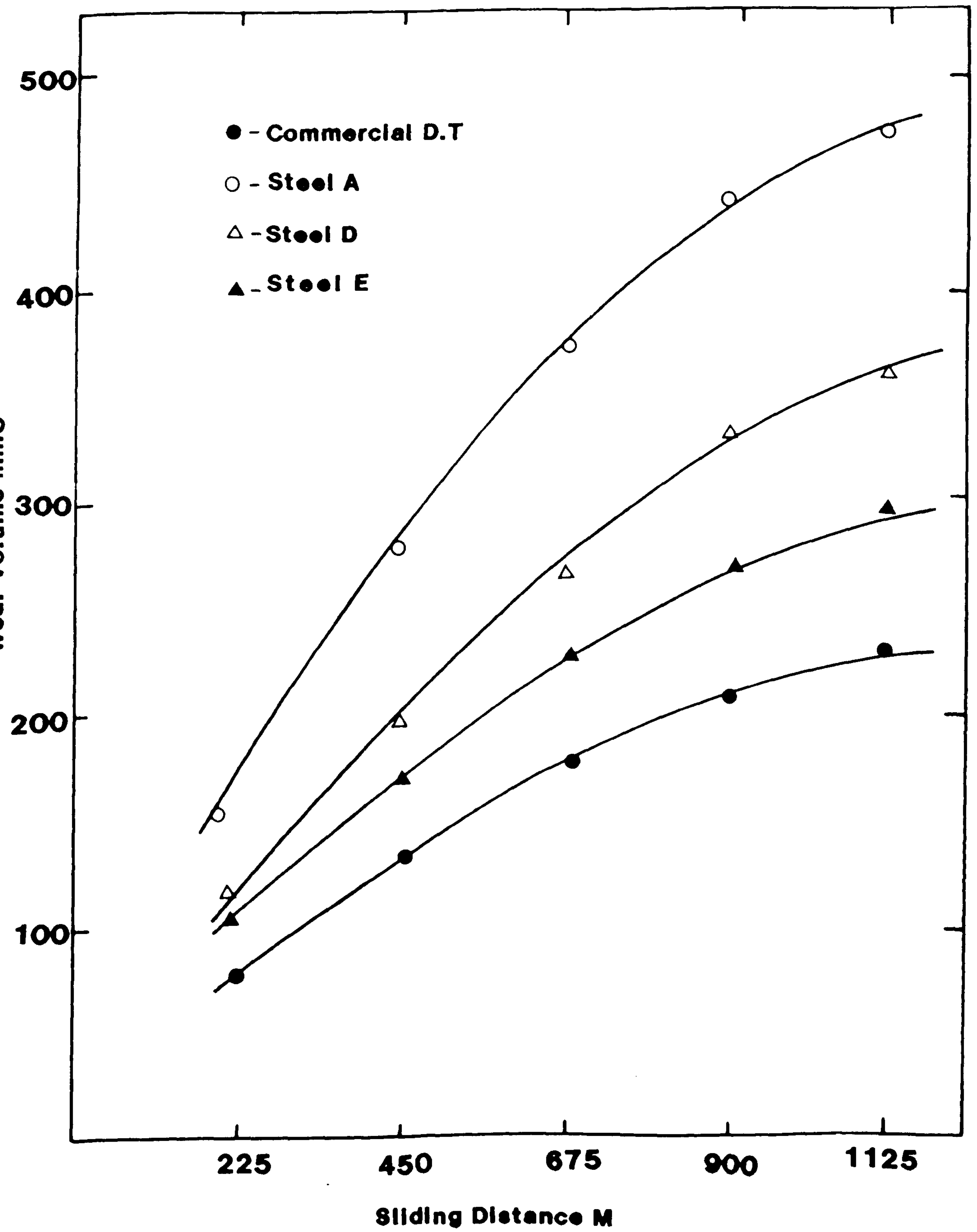


Fig.27 Wear volume Vs sliding distance,Al-Oxide, grit 100

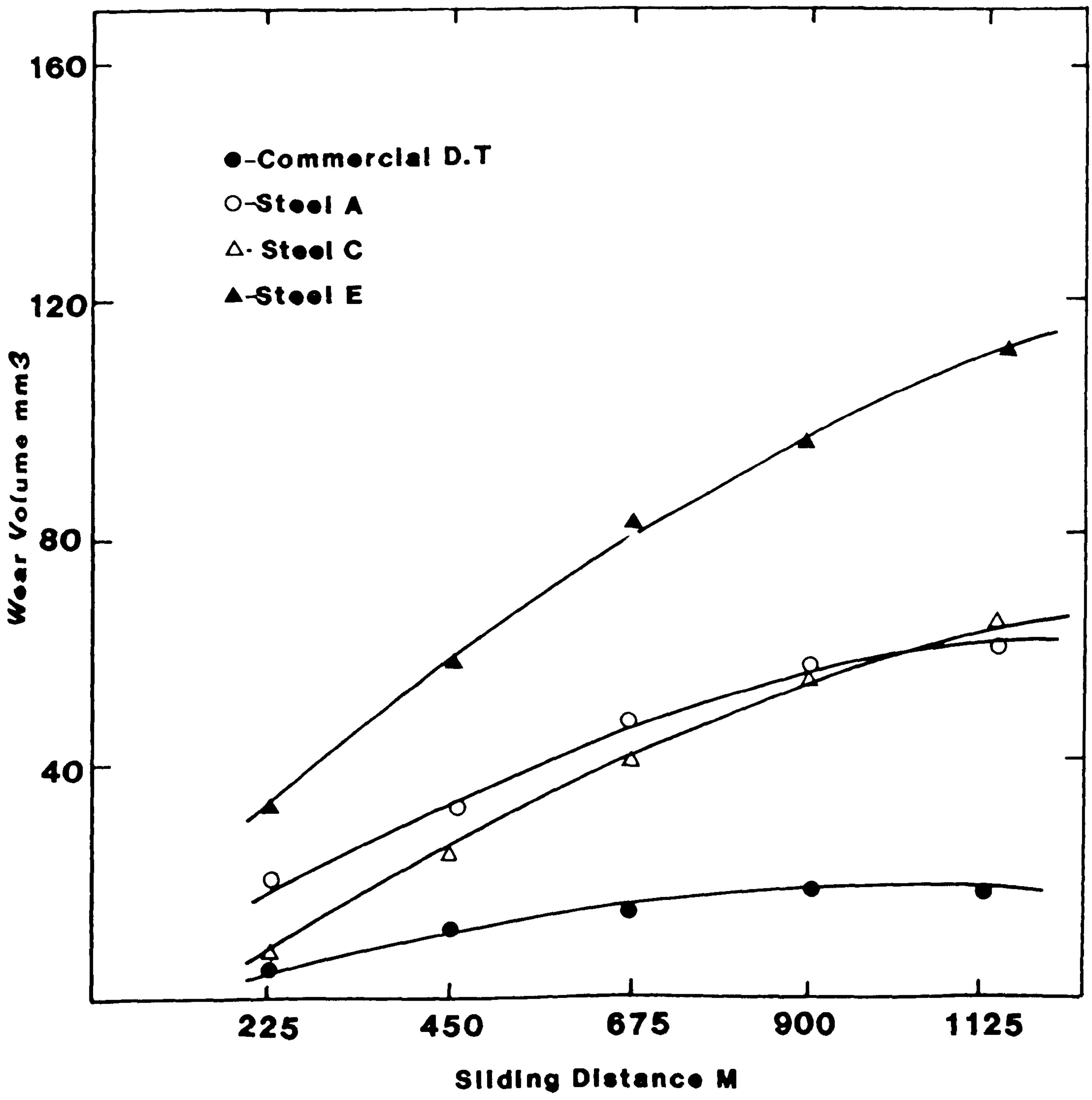


Fig.28 Wear volume Vs Sliding distance,SiC,grit 100,Load 110 N.

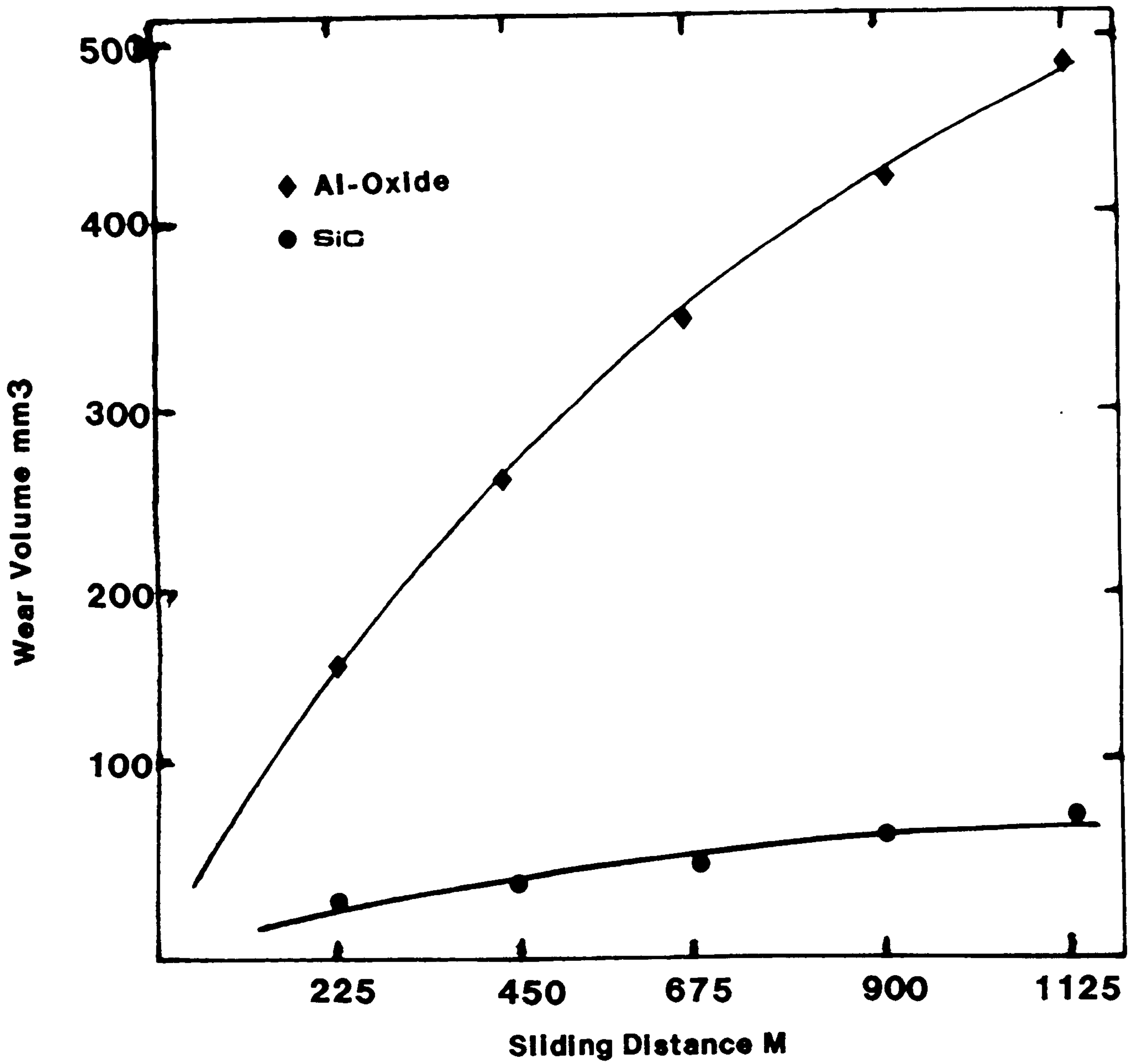


Fig.29 Wear volume Vs Sliding distance,Steel A,Load 110N.

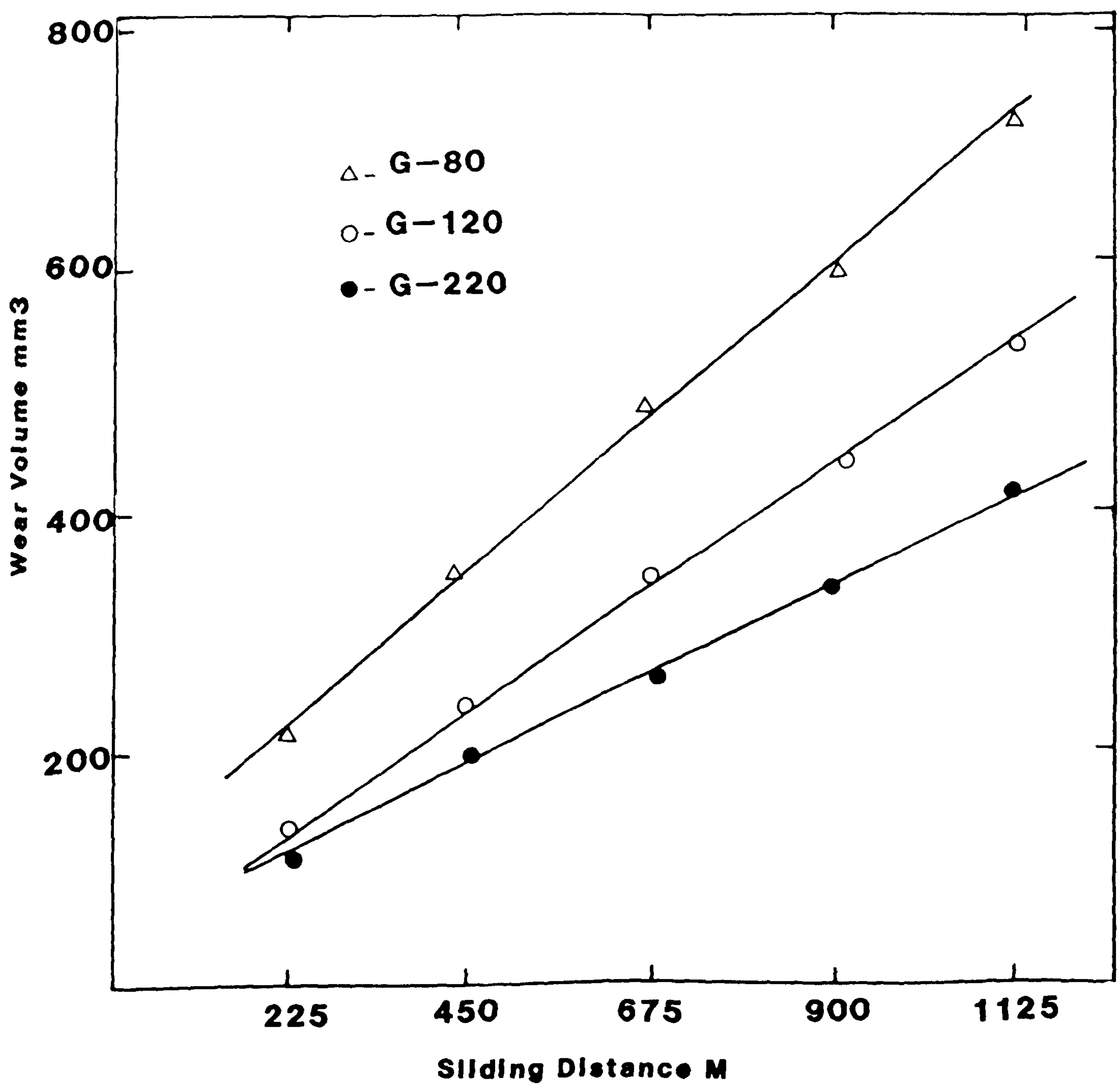


Fig.30 Wear volume Vs Sliding distance, Steel I ,Al-Oxide.
Load —110N

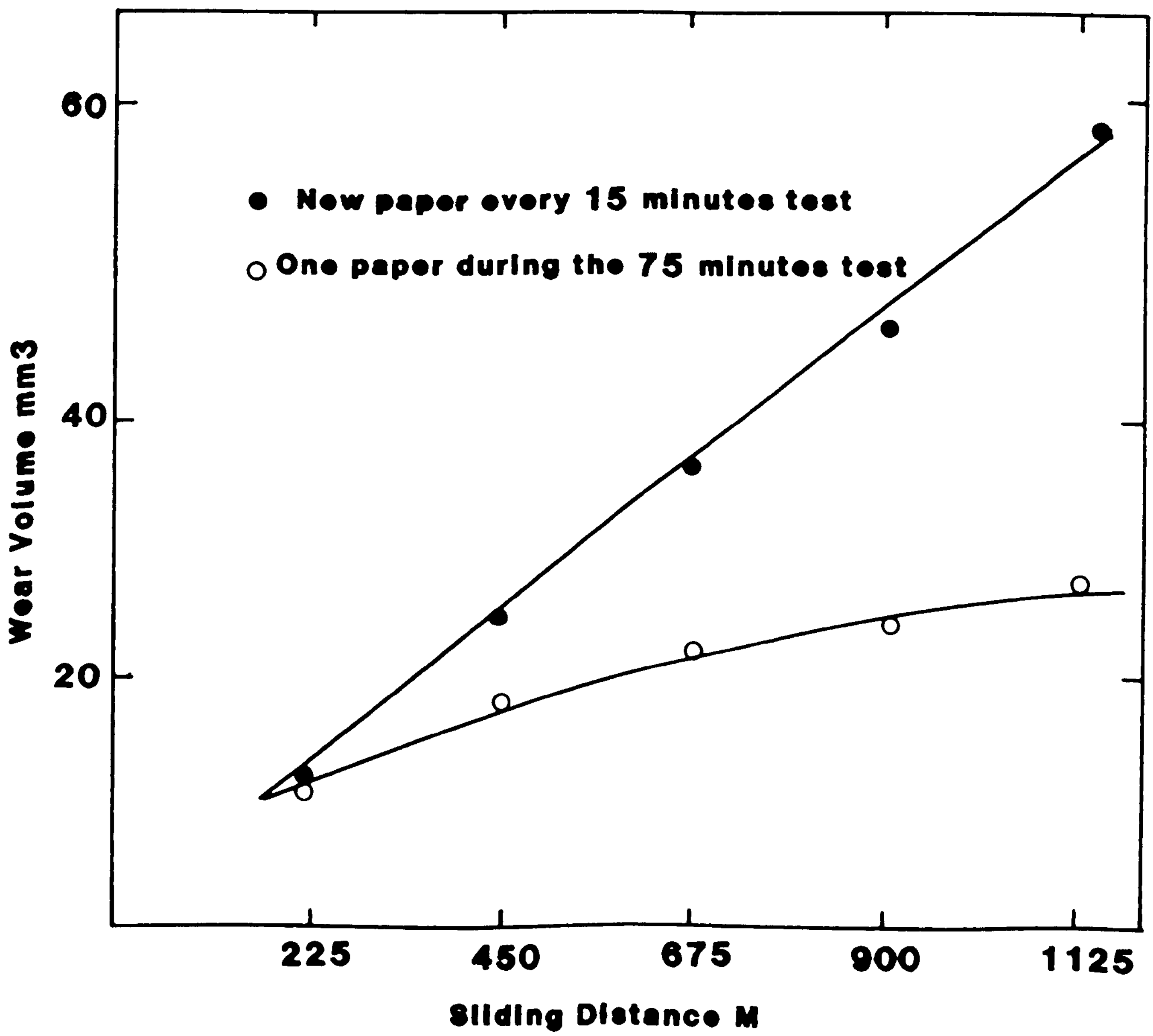
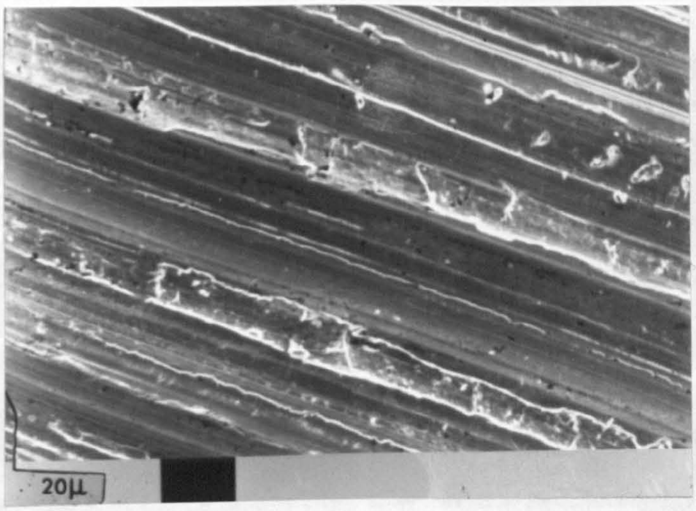
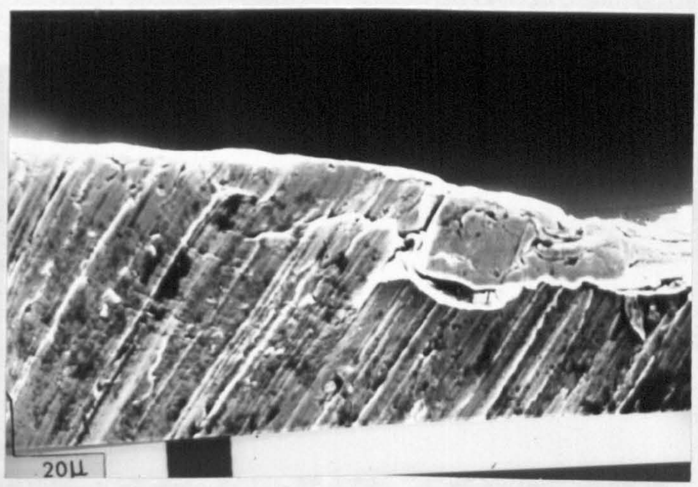


Fig.31 Wear volume Vs Sliding distance,Steel D,SIC,grit 100, Load-110N.



a



b

Fig.32 Worn pin surfaces viewed in the SEM,Steel C, Al-Oxide,Load-66N,75M sliding distance.

a. The middle of the worn surface.

b. The edge of the worn surface.

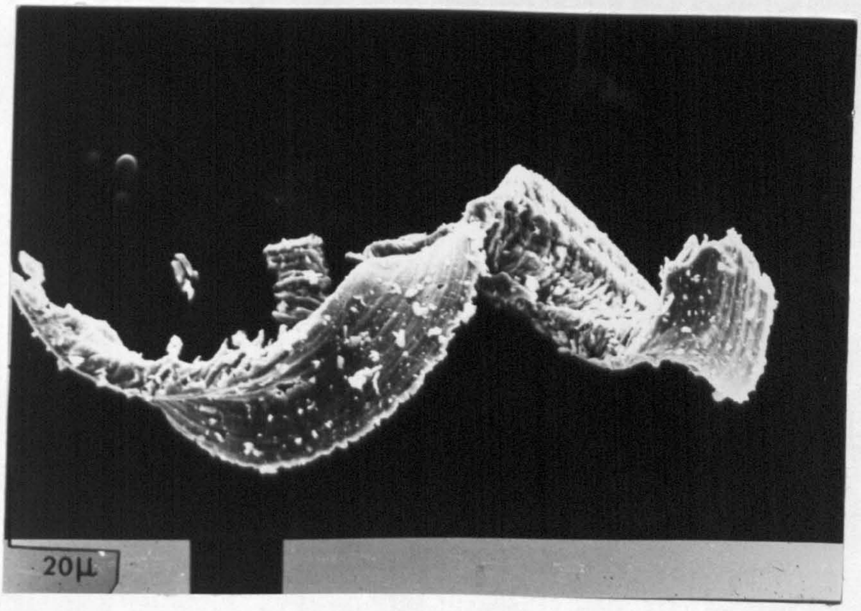
a

b

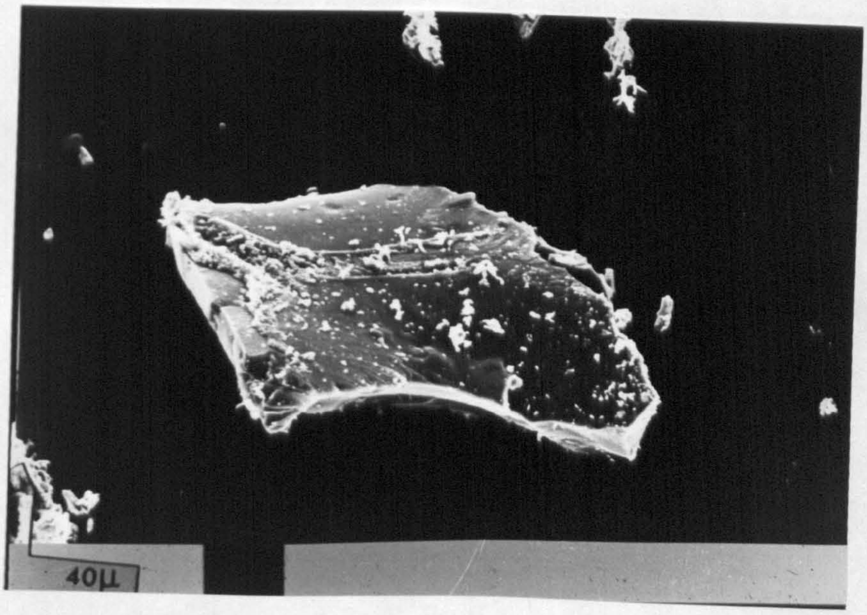
Fig. 33 Worn pin surfaces viewed in the SEM,Steel G,Al-Oxide grit 80,154 N load,75 M sliding distance.

a- middle of the worn surface

b- edge of the worn surface



a



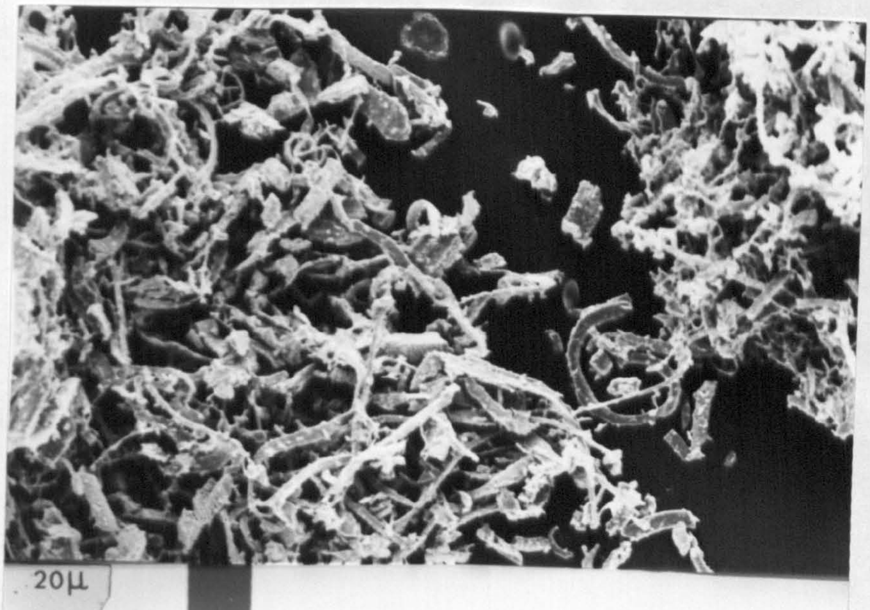
b

Fig.34 Debris collected from the wear tests

a. Cutting wear debris ,steel B,SIC,grit 100 , Load-66N,75MSliding distance

b.Rubbing wear debris,Steel B,SIC,grit 100, Load 66N,1125M Sliding distance

a



b

Fig.35 Debris collected from the wear tests,viewed in the SEM showing the effect of abrasive particle size,Steel C,Al-Oxide,Load 66N, 75M Sliding distance
a.Grit 60
b.Grit 320

Fig.36 SEM photomicrograph of SiC particles mixed with the debris

a

b

c

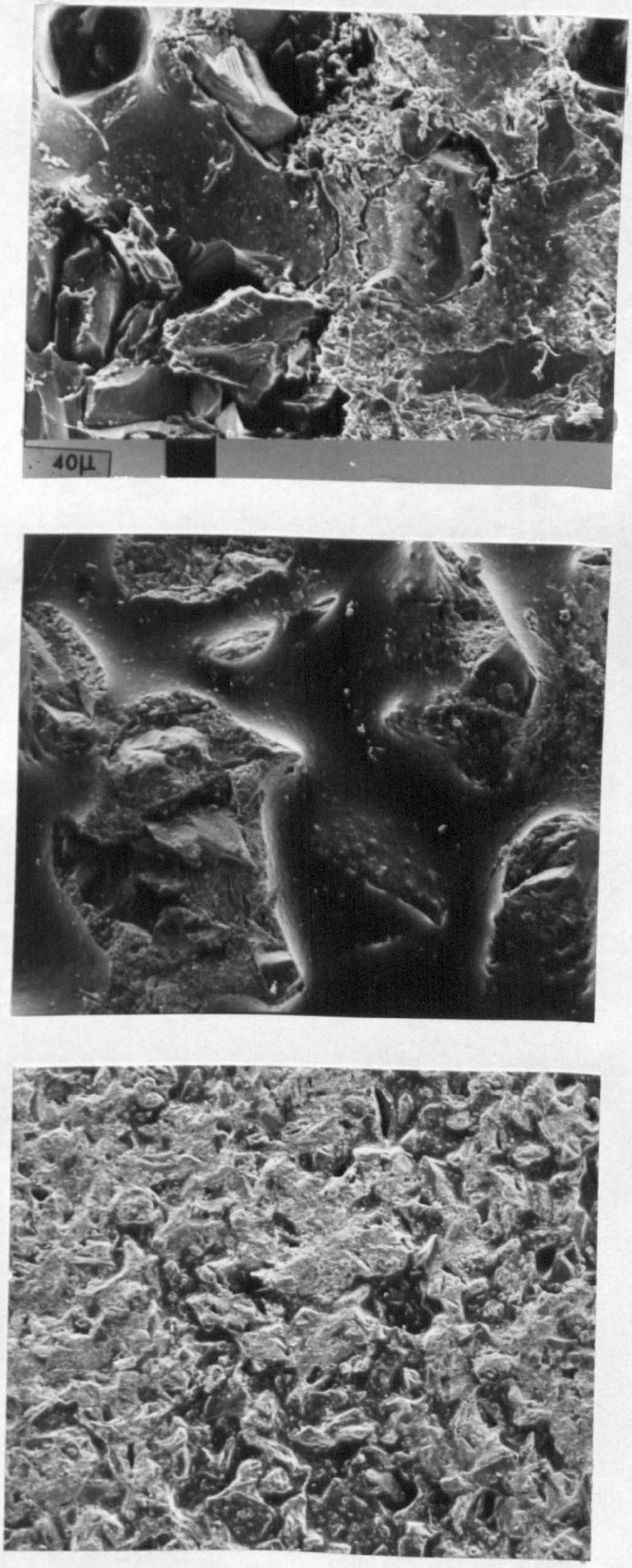


Fig. 37 SEM photomicrograph of abrasive papers showing the degredation mechanisms.

a- grit removal

b- grit shearing

c- clogging by debris

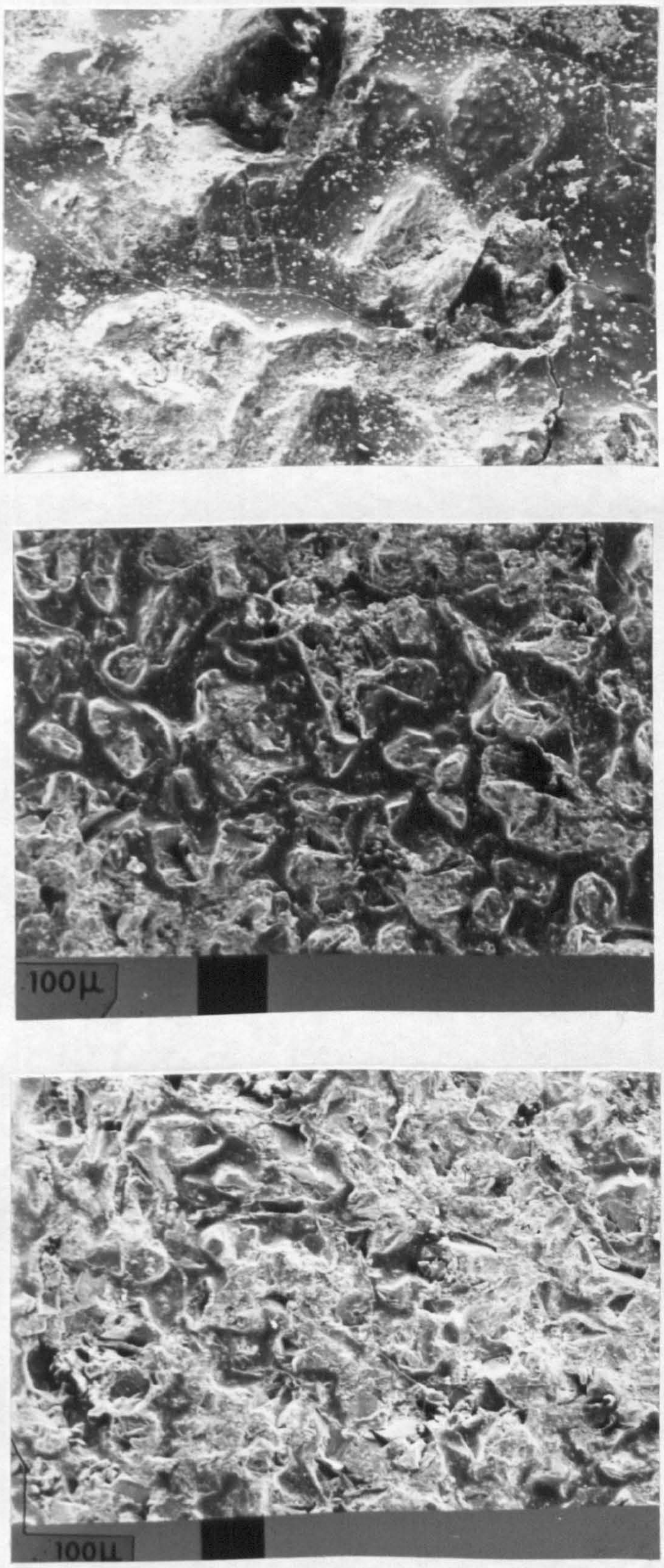
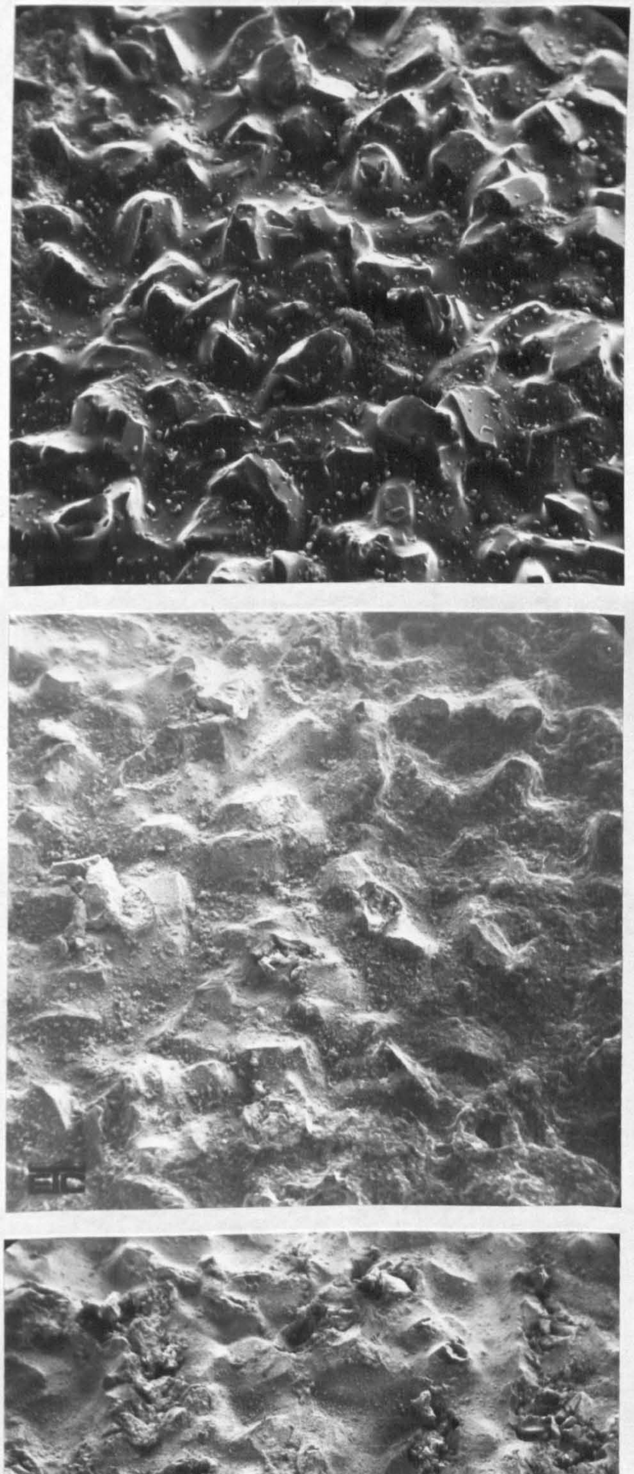


Fig. 38 SEM photomicrographs of worn Al-Oxide abrasive papers of different grit sizes.

a- grit 80, 198 N load   b- grit 120, 110 N load

c- 220, 110 N load



a

b

c

Fig. 39 SEM photomicrographs of SiC papers, grit 100, 110 N load

a- unused b- 225 M sliding distance

c- 900 M sliding distance

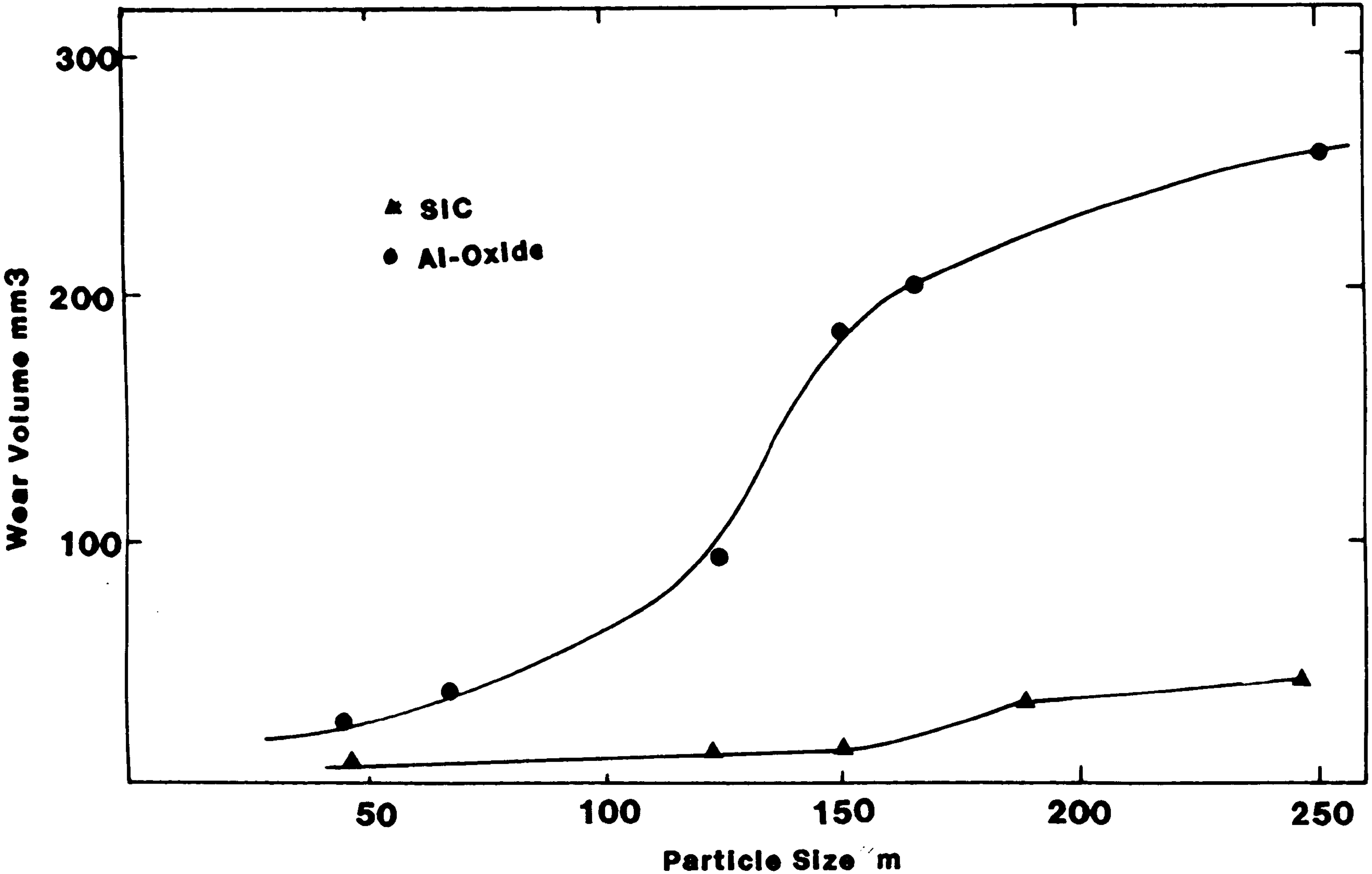


Fig.40 The effect of abrasive particle size on wear volume,Commercial digger teeth steel,Load-66N, 75M sliding distance.

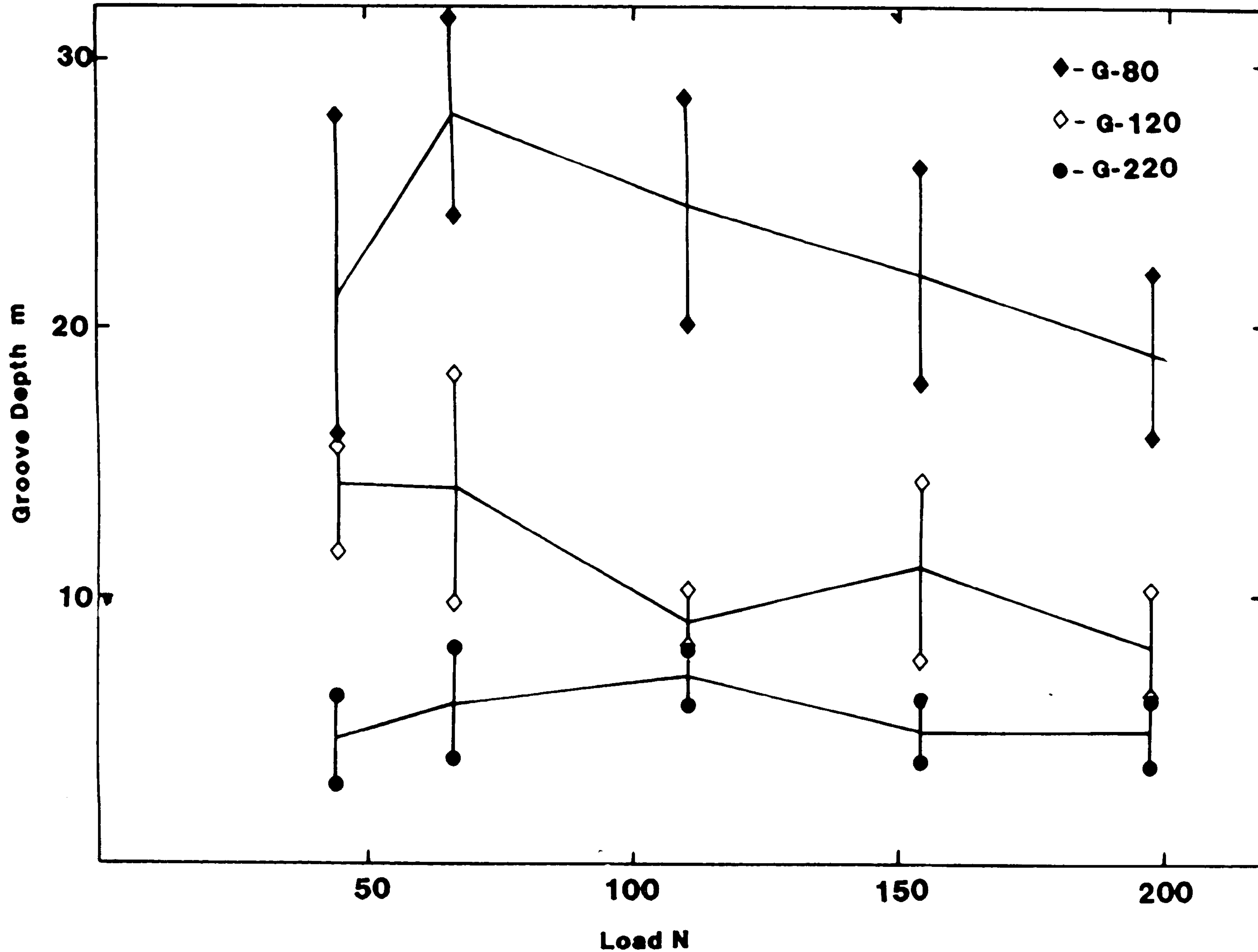


Fig.4 1 Groove depth Vs load,Steel C,Al-Oxide abrasive papers.

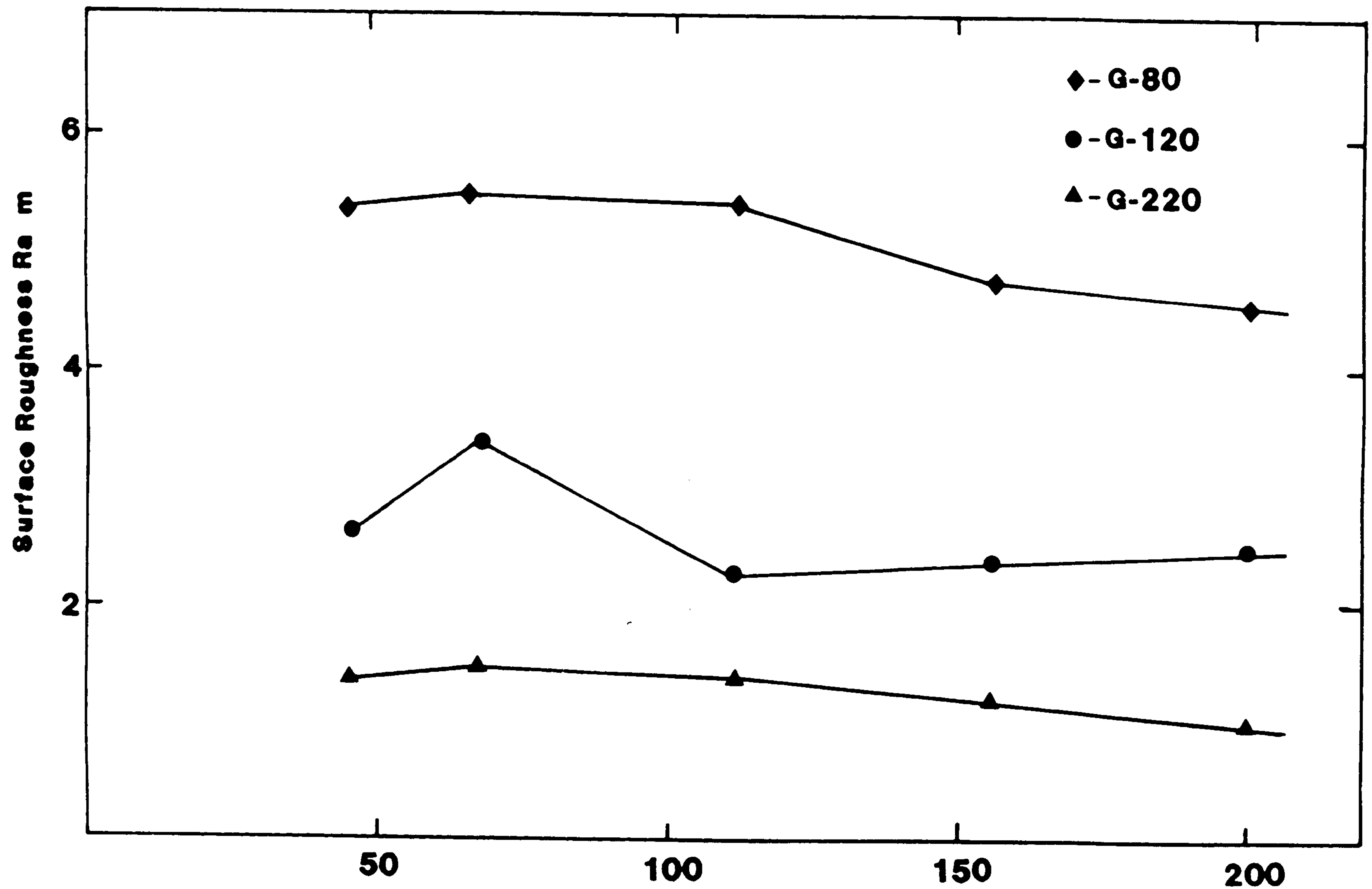


Fig.42 Surface roughness Vs load,Steel C,Al-Oxide abrasive papers.

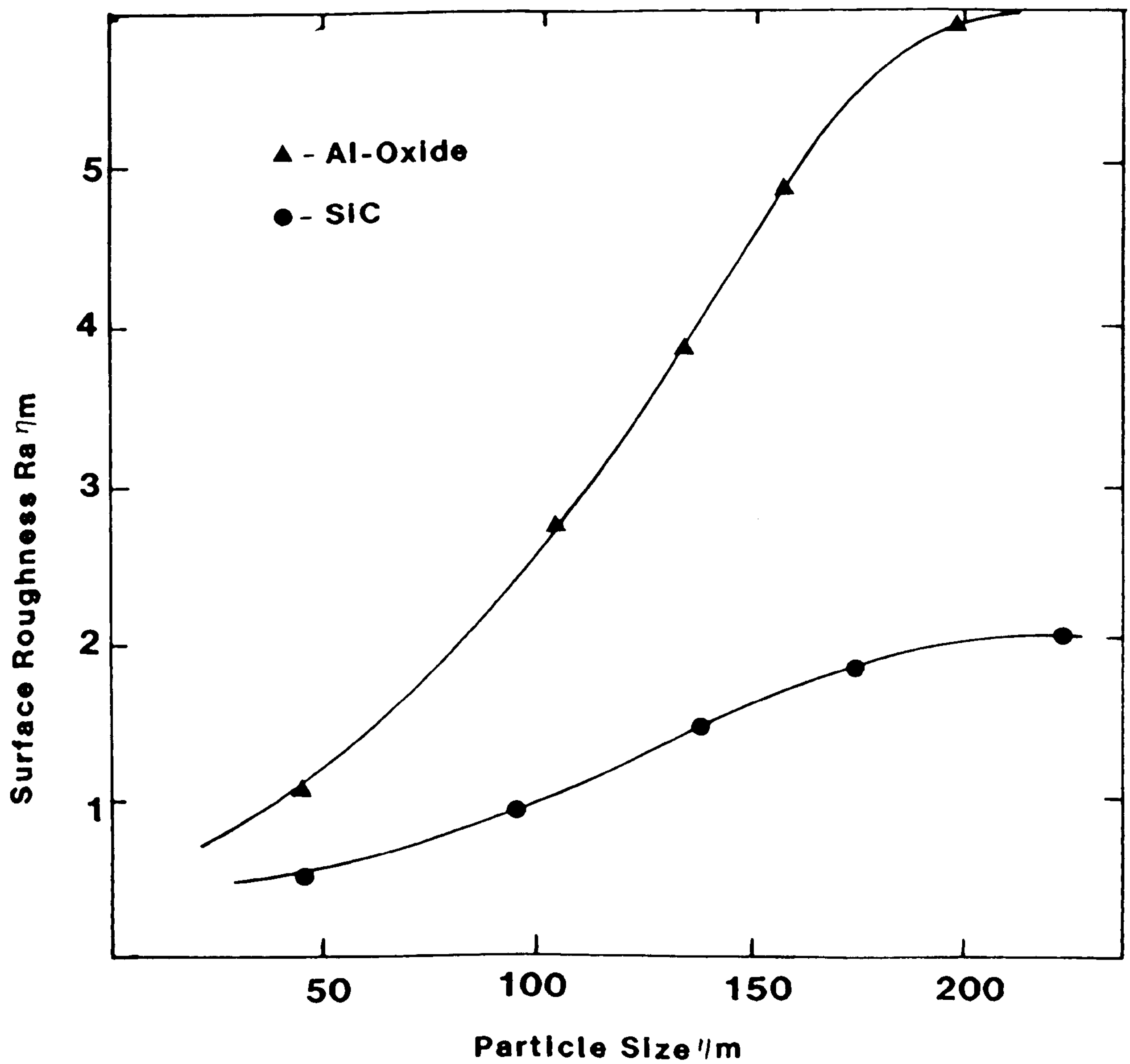


Fig.43 Surface roughness Vs abrasive particle size,Steel C, Load—66N,75M sliding distance

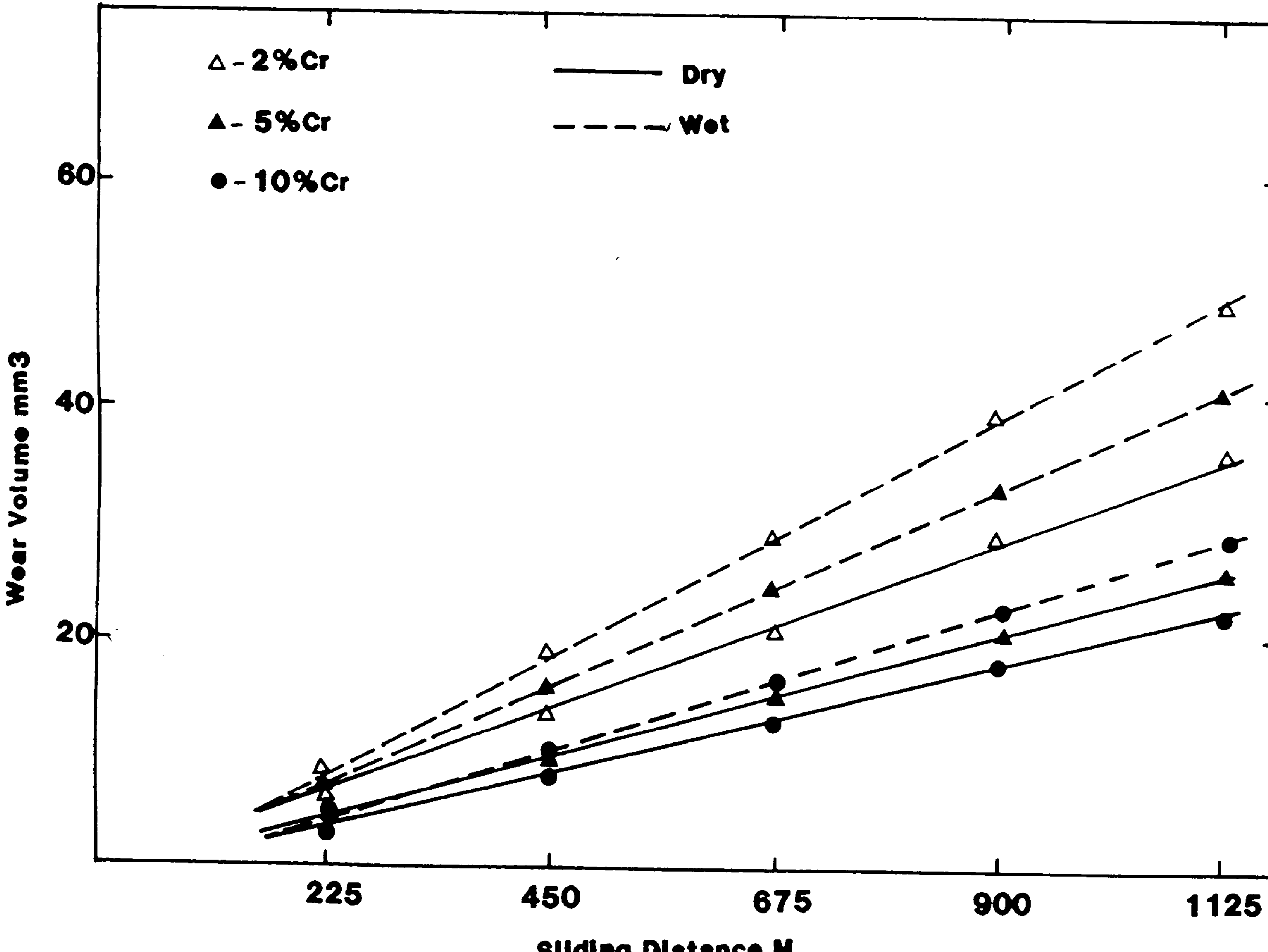


Fig.44 Wear volume Vs sliding distance,SIB SIC,grit 100,Load-66M,Dry and wet

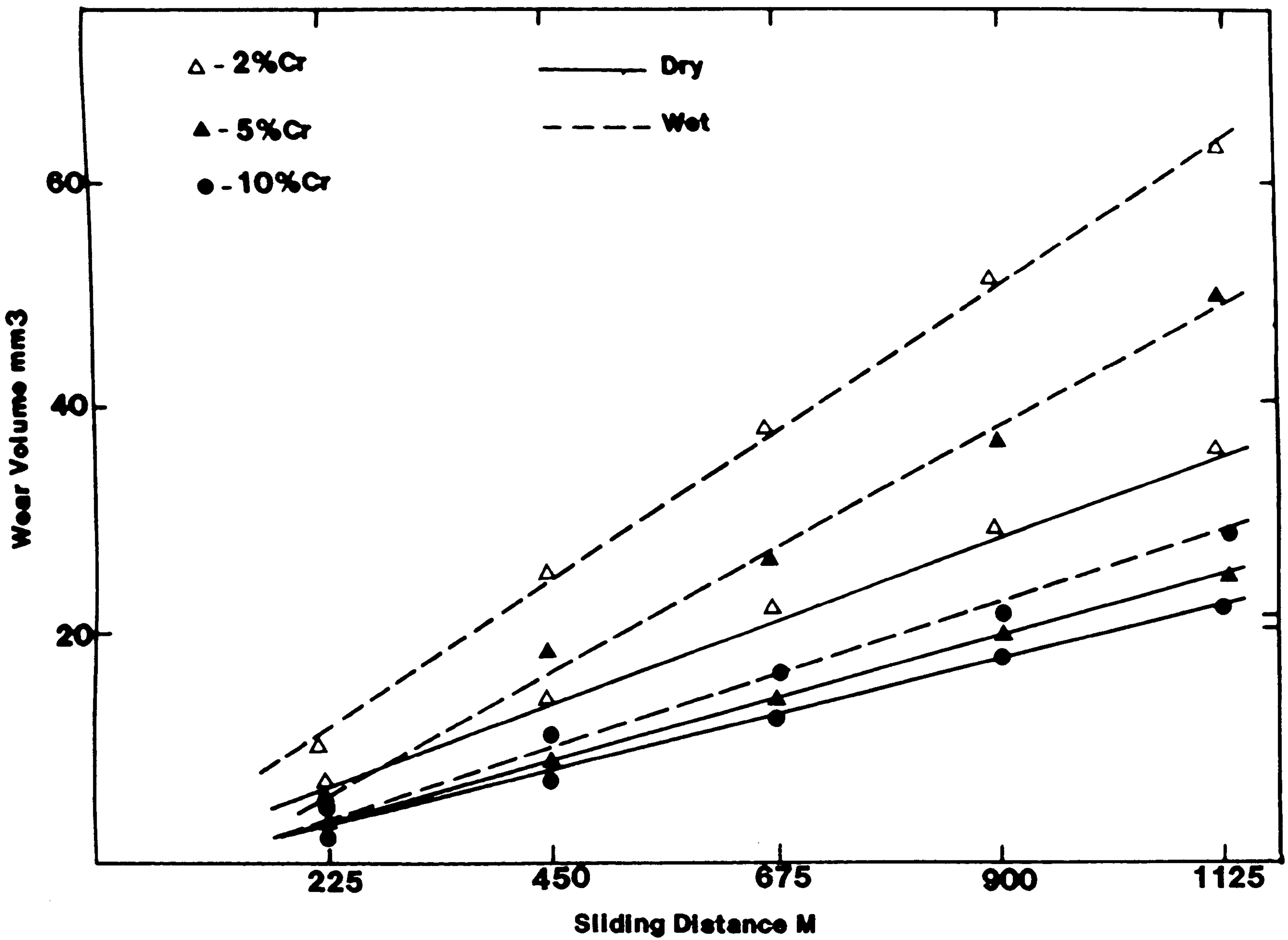


Fig.45 Wear volume Vs sliding distance,SIC grit 100,Load-66N,dry and wet with pins left 24 hours in wet condition.

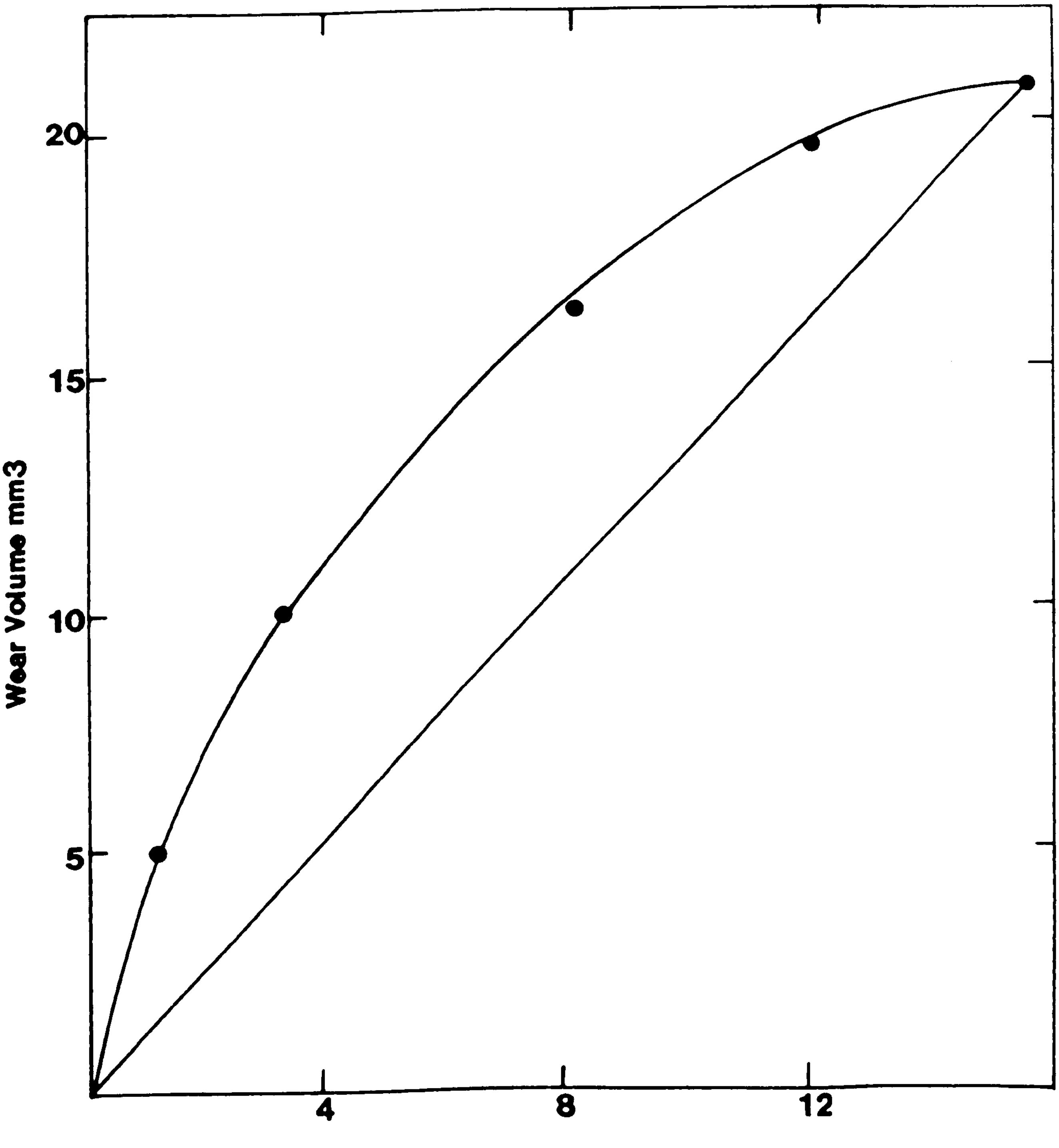


Fig.46 The effect of corrosion on the initial wear rate,Steel I,SIC grit 10
Load-66N,Wet test with pins left 24 hours in wet condition.

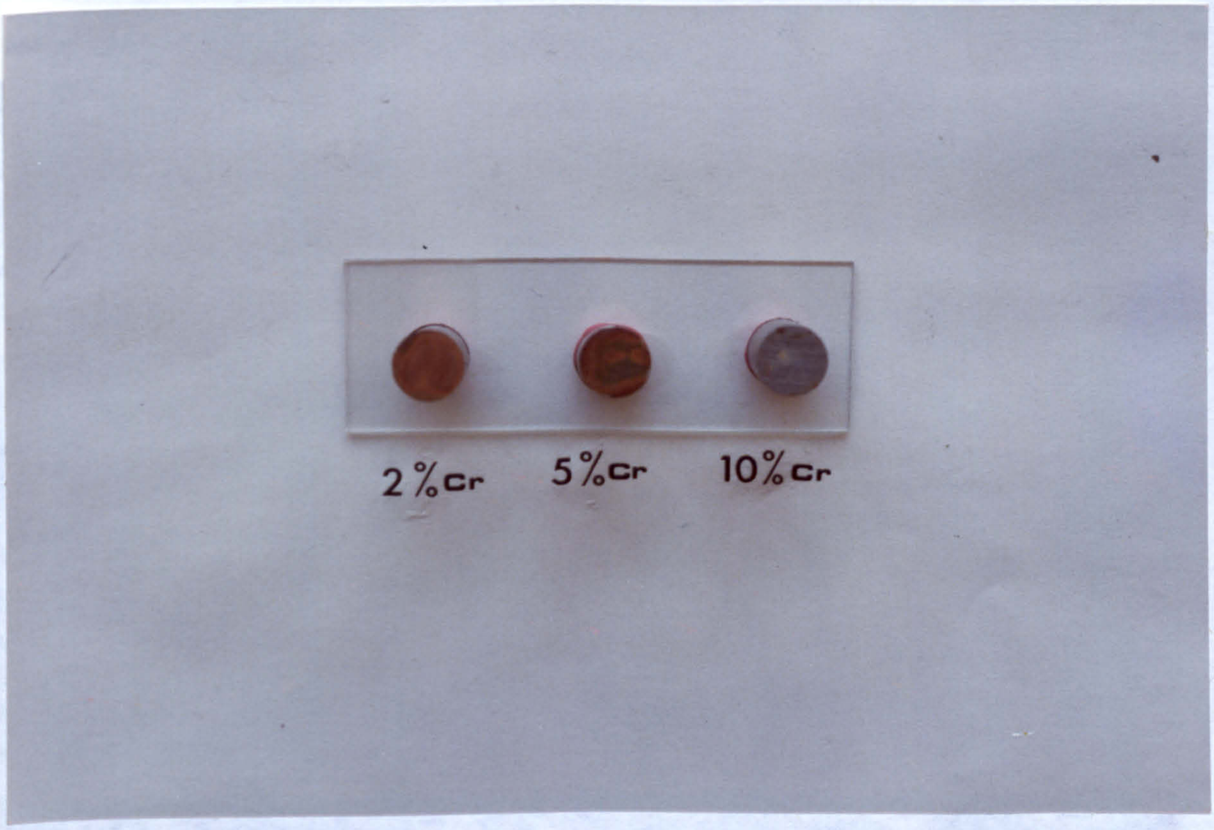


Fig.47 Three pins of different Cr content after being left in wet condition for 24 hours before test

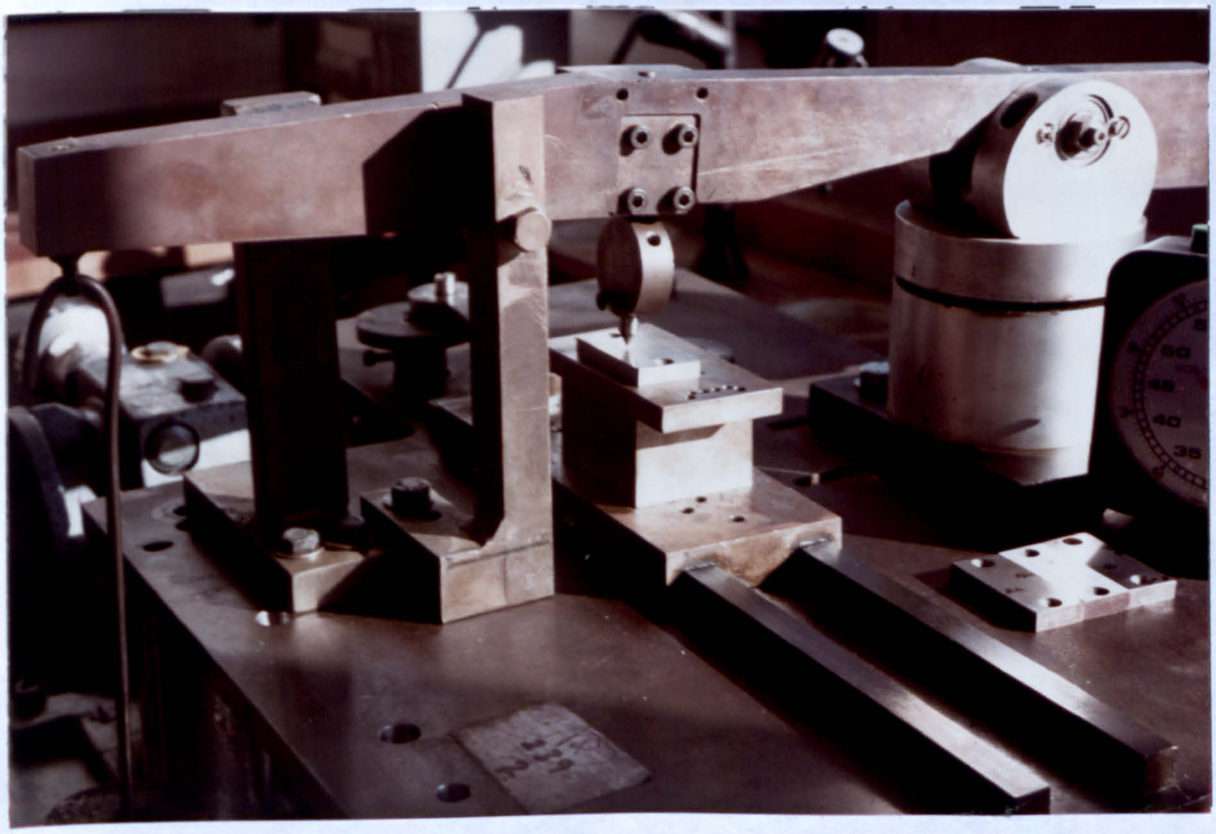


Fig. 48 Reciprocating abrasive wear testing machine.

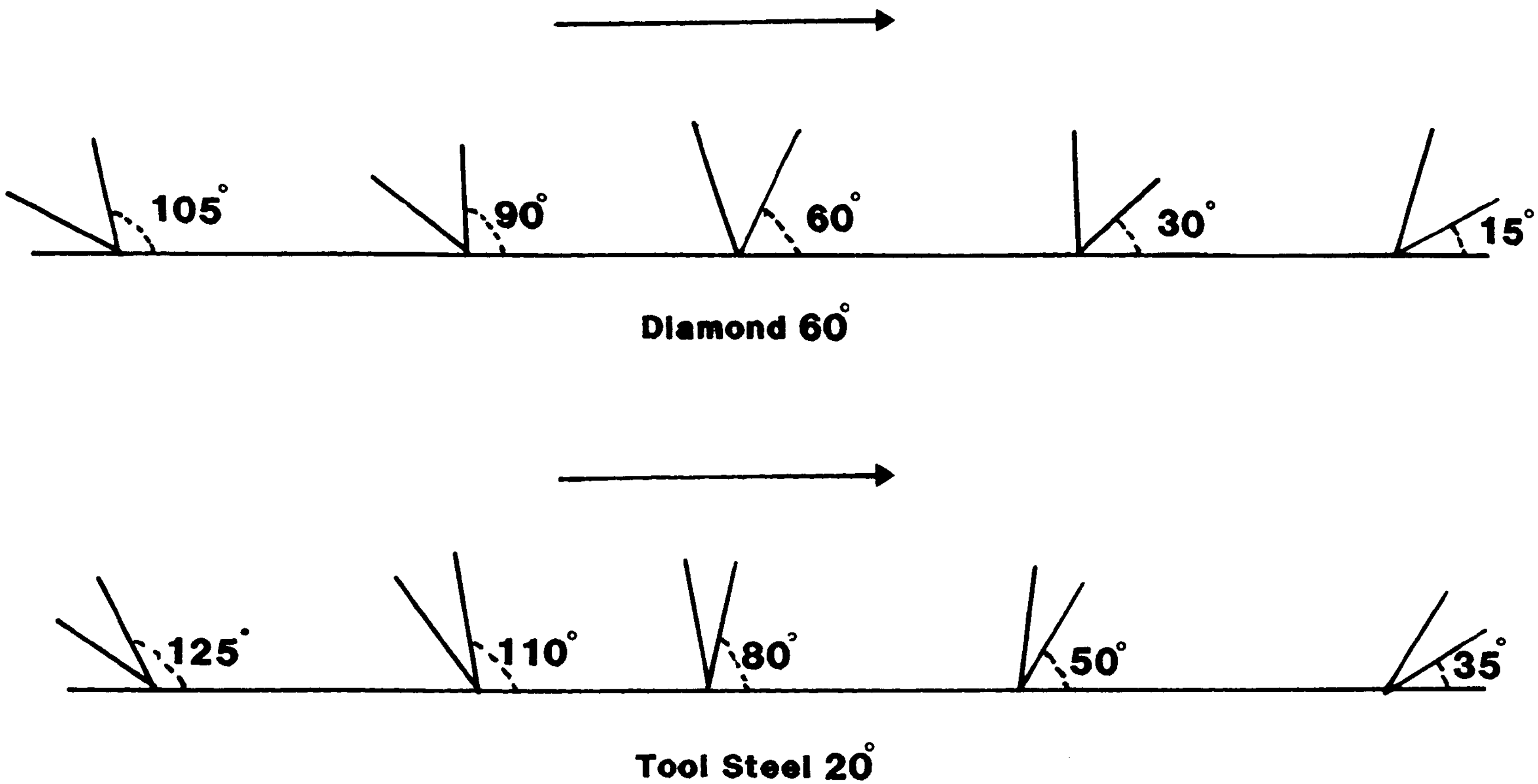


Fig. 49 Attack angles used with both diamond and tool steel indentors.

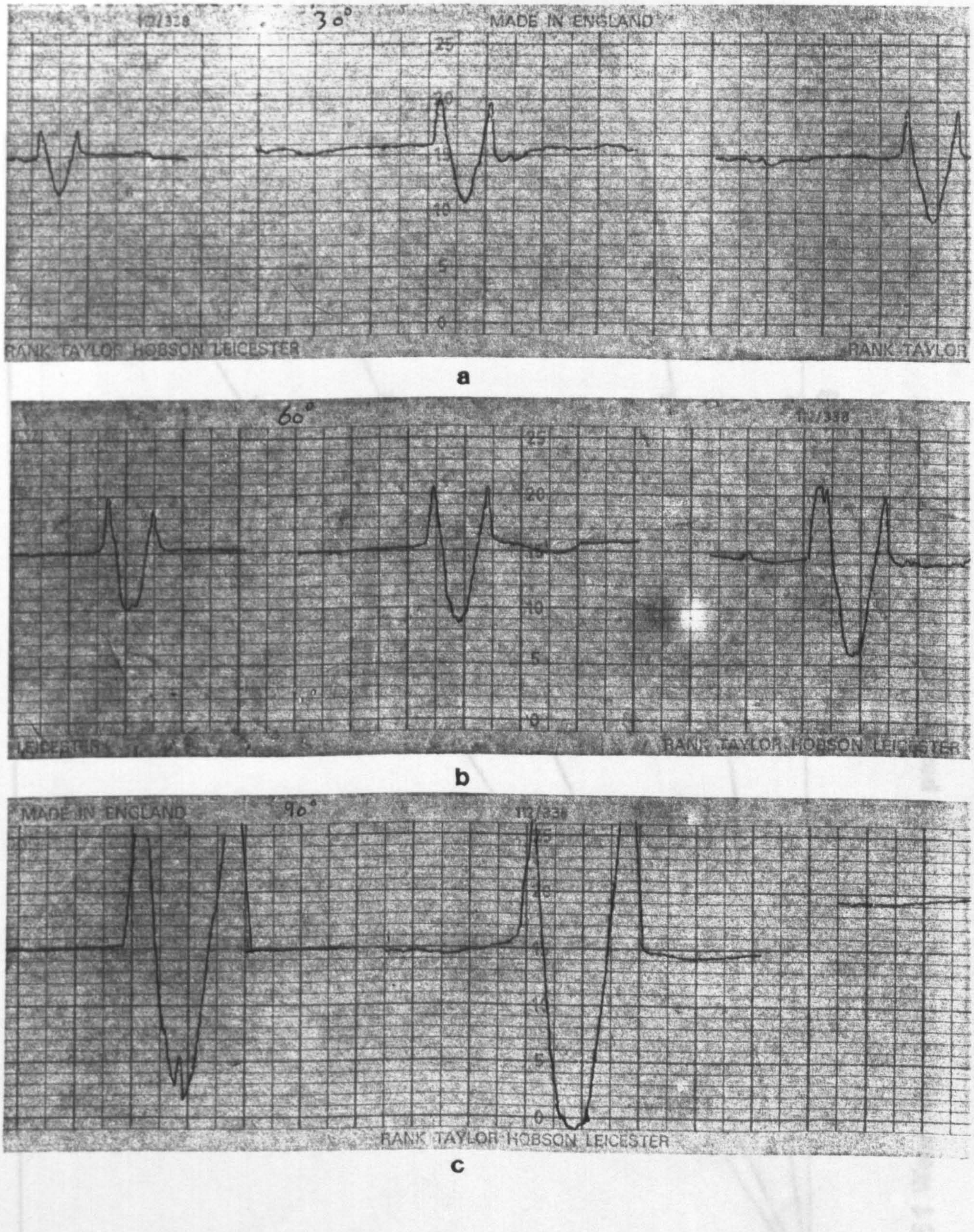


Fig. 50 Talysurf traces showing the groove profile at different attack angles, 50 passes.

a- 30° b- 60° c- 90°

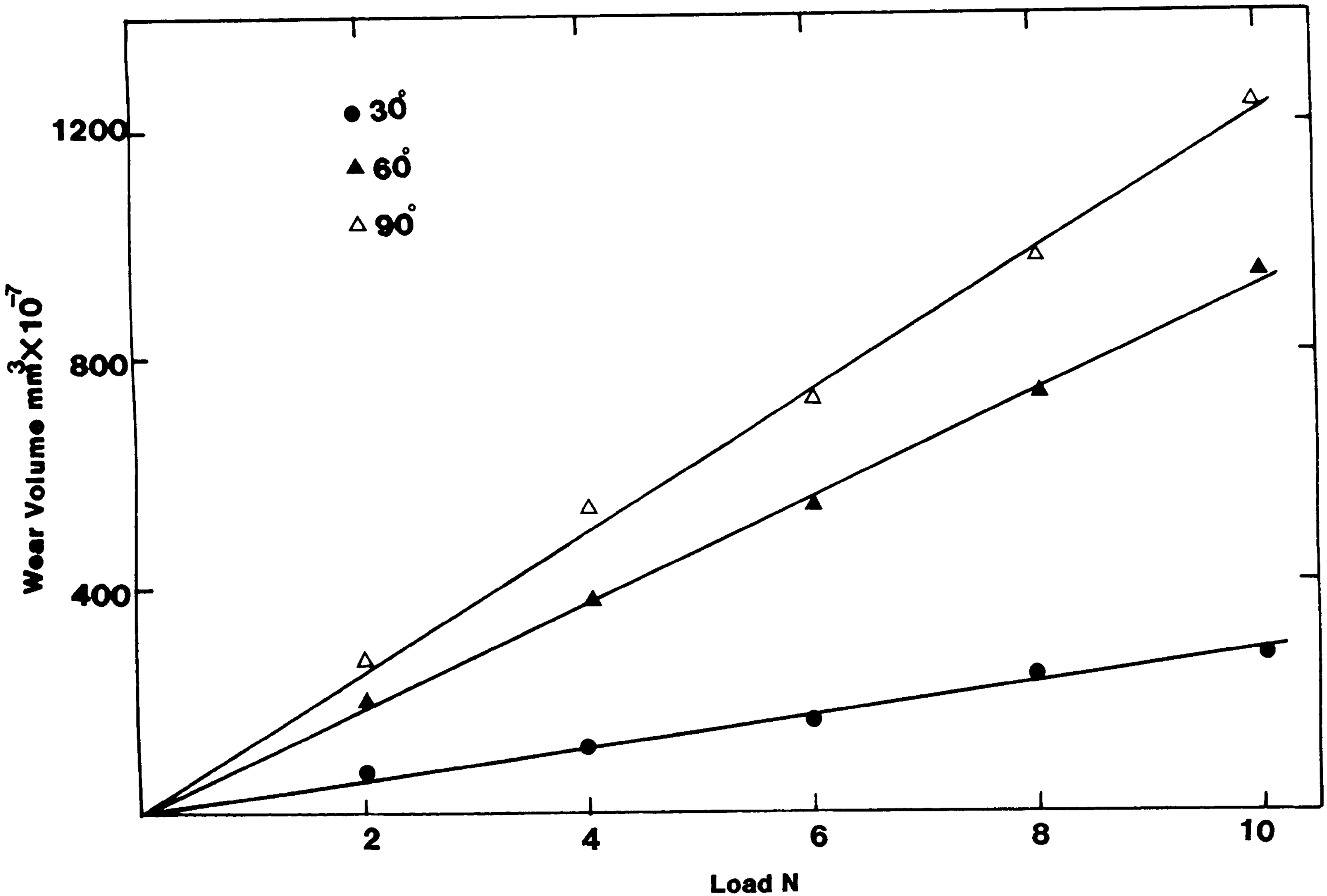


Fig. 51 Wear volume Vs load, Steel H, 10 passes, Diamond indentor.

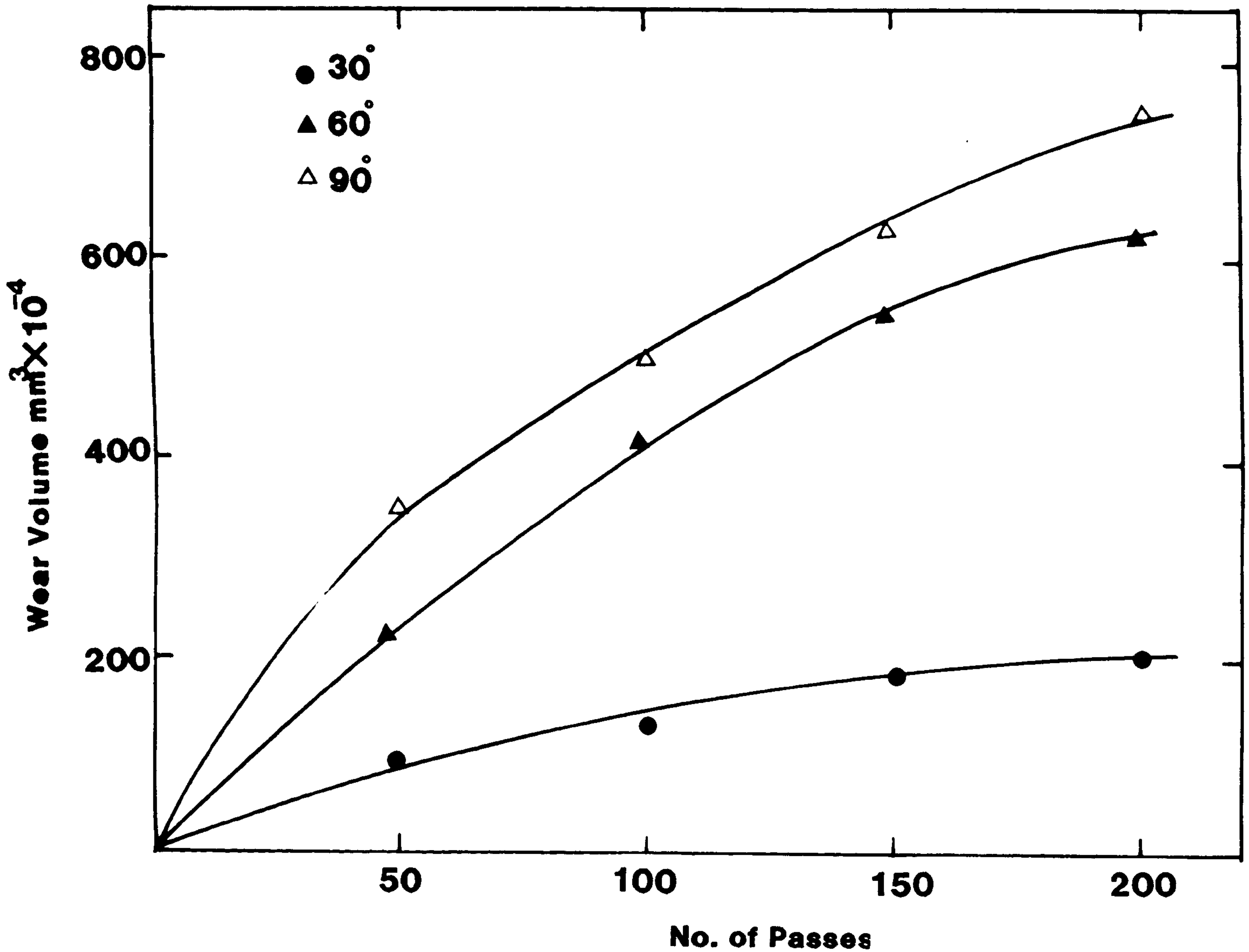


Fig. 52 Wear volume Vs number of passes, Steel I, Load-3N, Diamond indentor.

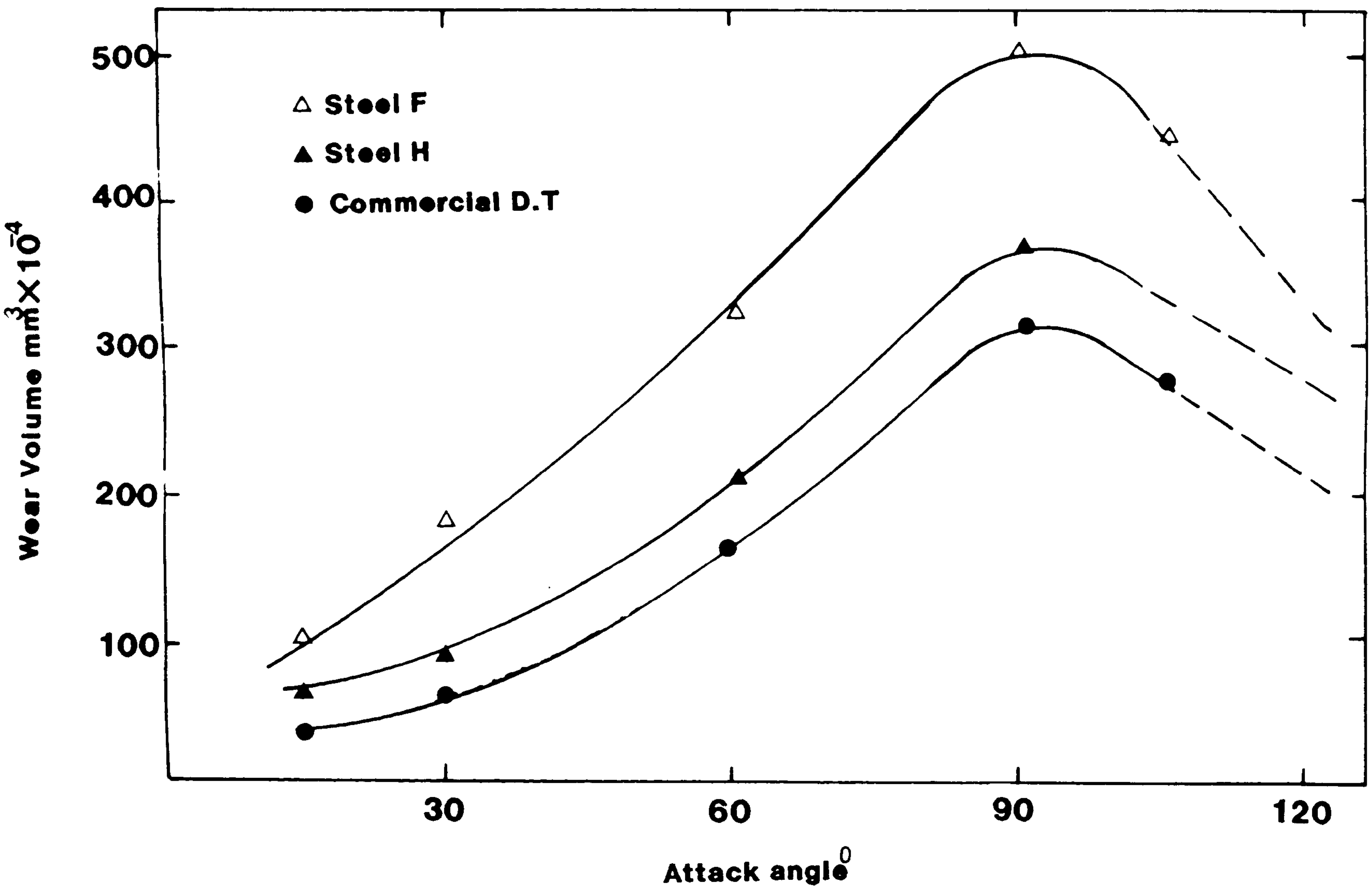


Fig. 53 Wear volume Vs attack angle, Load-3N, 50 Passes, Diamond indentor.

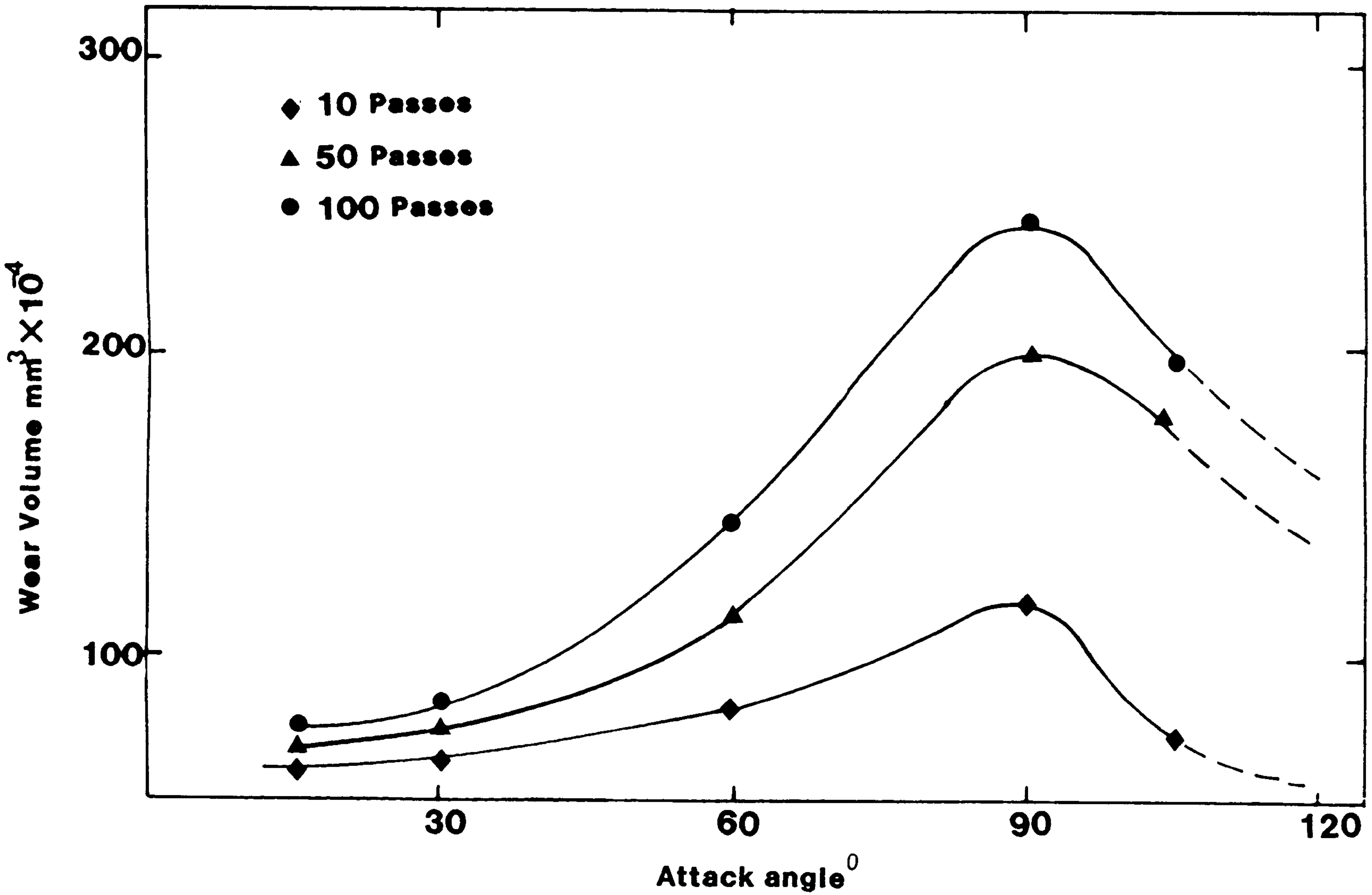
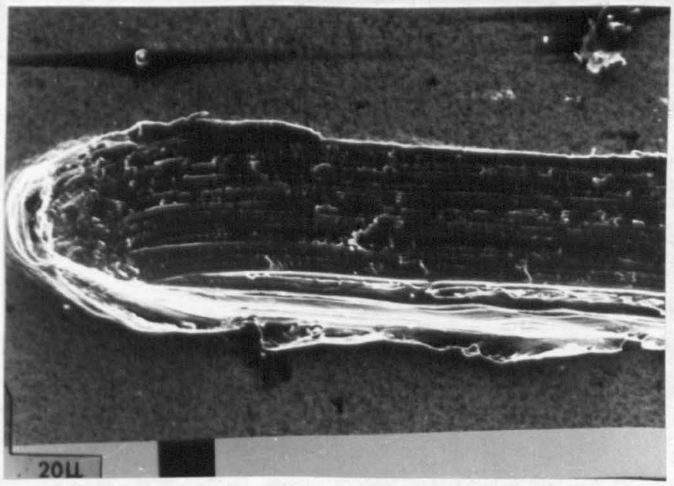
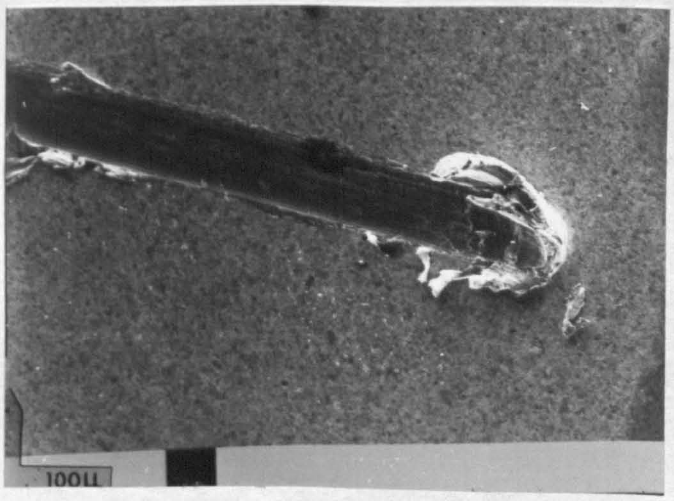


Fig.54 Wear volume Vs attack angle,Commercial D.T steel,Load-3N,Diamond indentor.

a



b



c

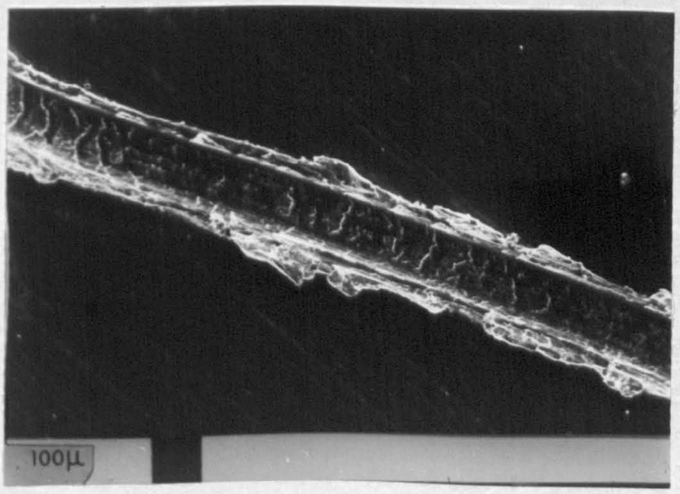


Fig. 56 SEM photomicrographs of wear grooves, 3N load, 35° attack angle, tool steel indentor.

a- pure Fe

b- pureCu

c- pure Al

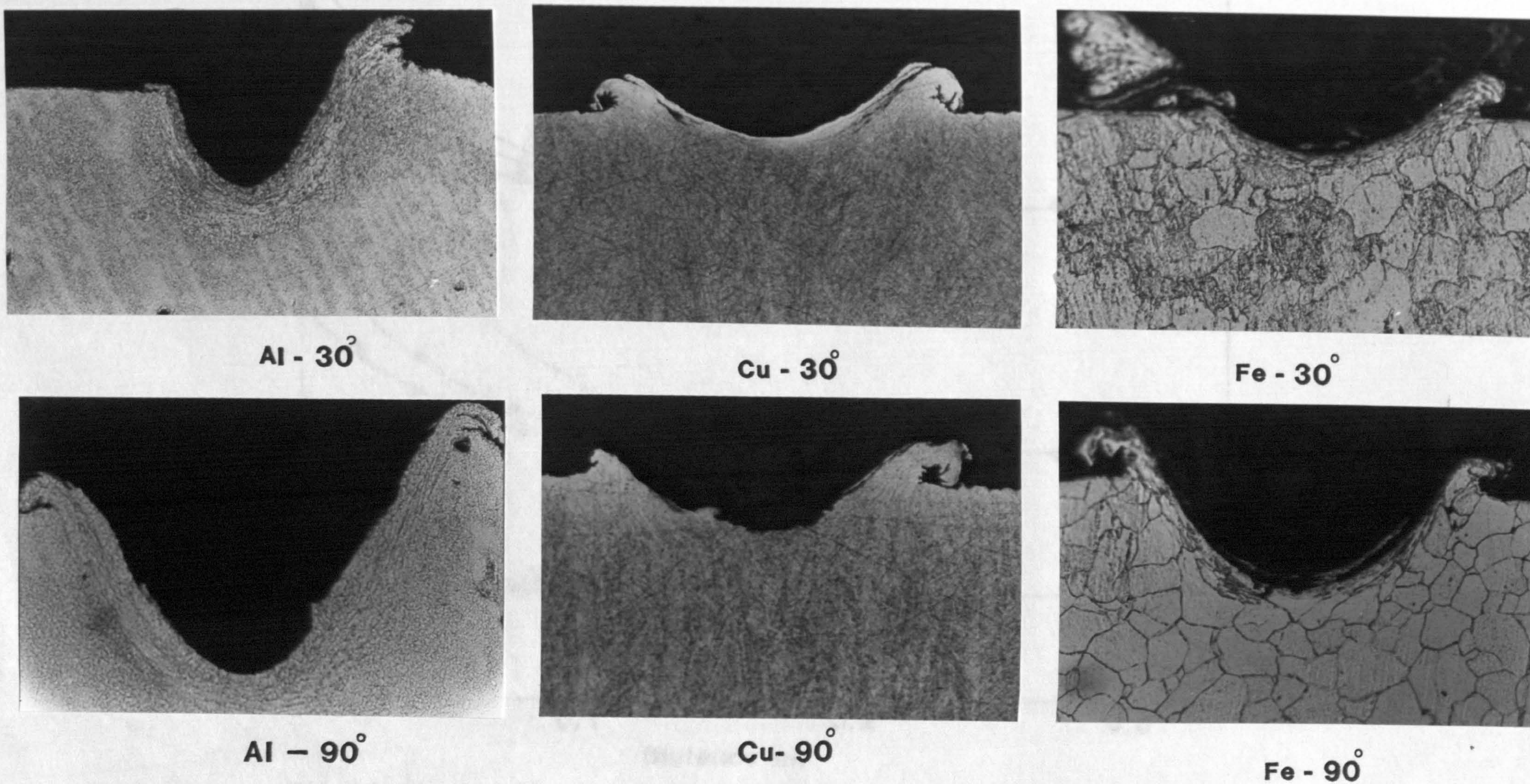


Fig. 57 Transverse sections for pure metals at different attack angles,3 N load,50 passes,diamond indentor

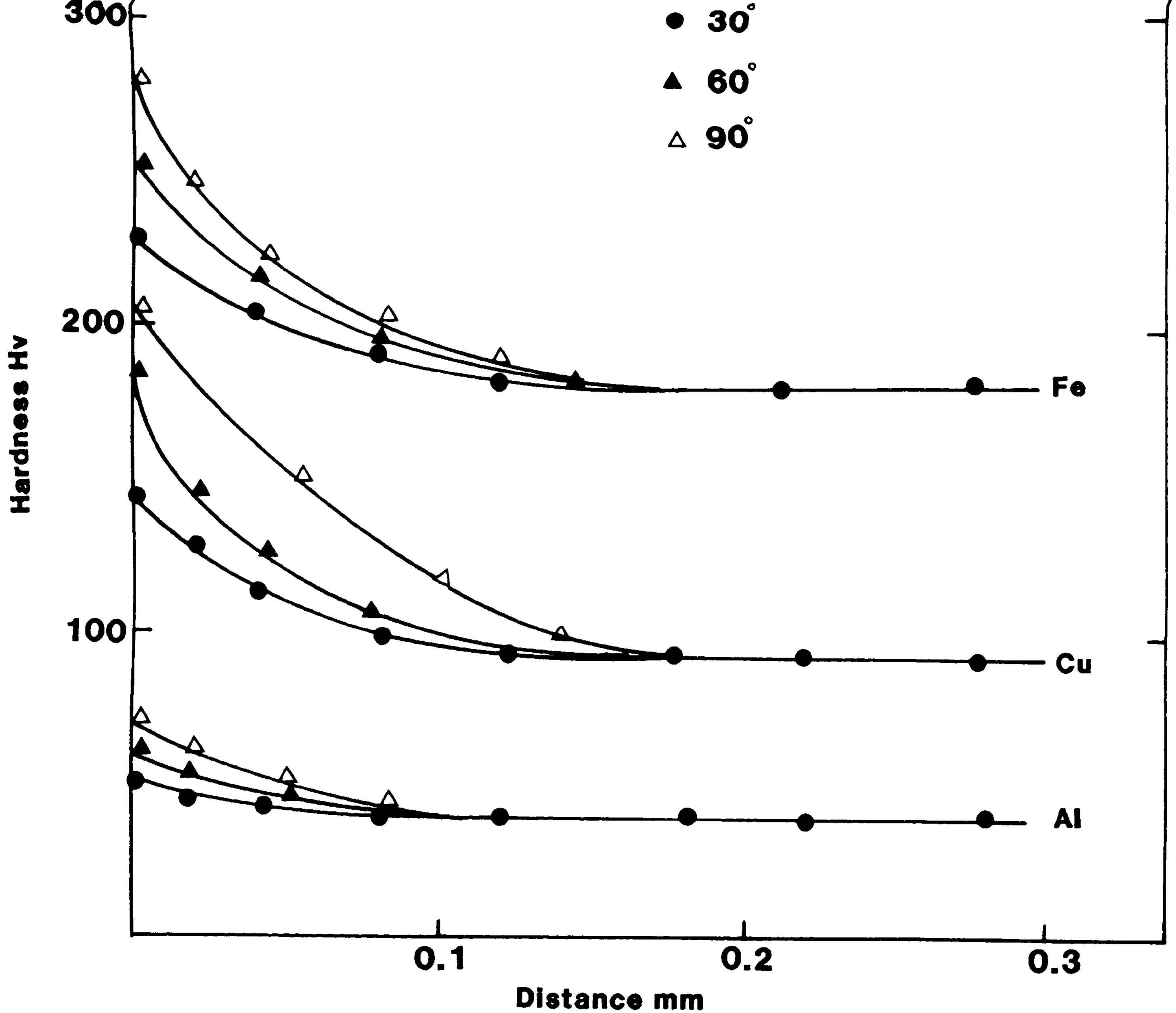
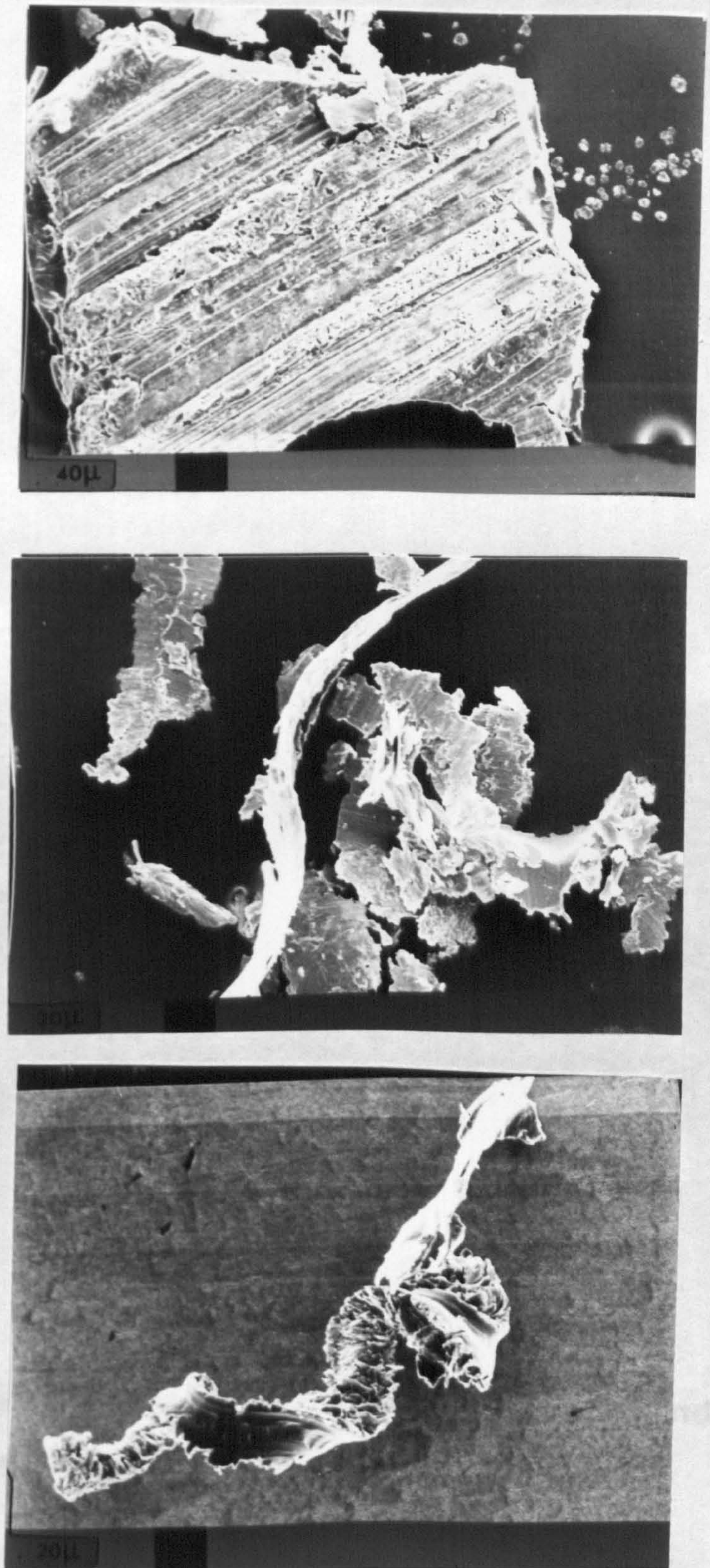


Fig. 58 Hardness Vs distance from the surface at different attack angles, Load-3N,50 Passes,Diamond Indentor.



a — 30^{o}, 100 passes, 3N

b — 60^{o}, 50 passes, 3N

c — 90^{o}, 10 passes, 1N

Fig. 59 SEM examination of collected debris.

Fig. 60 Grey cast iron fragmentation,diamond indentor at 60 attack angle.