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Surface damage effects caused by debris in rolling bearing lubricants, with an emphasis on friable materials

R S DWYER-JOYCE, J C HAMER, and R S SAYLES
Imperial College Tribology Section, London, UK
E IOANNIDES
SKF ERC BV (Visiting Professor at Imperial College)

SUMMARY

The influence of debris in concentrated surface contacts is reviewed in terms of the fundamental mechanisms of 3-body contact, and how subsequent surface damage effects relate to rolling contact fatigue life. Particular emphasis is placed on how friable debris causes surface damage; experimental evidence is presented to show how various forms and sizes of friable debris fragment in the inlet to EHD contacts. Although this can lead to significant wear and surface roughening of the rolling elements, the effects on fatigue life are not always seen to be as severe as with ductile debris. The reasons for these differences are examined and discussed in detail.

1. INTRODUCTION

Advances in the materials science aspects of bearing manufacture over recent years have resulted in considerable increases in rolling element fatigue life. Emphasis has shifted, away from the Lundberg and Palmgren (1, 2) sub-surface life model, to predictions based on surface initiation fatigue mechanisms.

Many of these surface defects are the result of the overolling of lubricant bourne debris. The effects of the presence of debris and lubricant filtration on fatigue life have been investigated (3-8). In parallel, the work of Ioannides and Harris (9) has provided a model which has been used to demonstrate how these local stress effects can result in bearing fatigue failure.

Research work must now concentrate on the definition of the mechanisms of deformation of ductile and ceramic debris particles in rolling contacts. This deformation and surface damage can then be related to sub-surface residual stresses and the effects on fatigue life studied.

A route for debris initiated fatigue life prediction is now clear; determine the mechanism of particle deformation or fracture, quantify the resulting surface damage and residual stress field, finally use this information in a overolling model to determine fatigue life. It is the aim of this paper to review the progress made so far along this route.

2. CONTAMINANTS IN LUBRICANT SYSTEMS

Analysis of oils from lubricant systems has shown that a variety of debris contaminants may be present; metallic materials such as steels and bronzes; and friable ceramic materials such as silicates and carbides. A comprehensive study of the contamination of rolling element lubricants must therefore encompass two types of particulates; ductile materials, which may plastically deform, and brittle materials, which may fracture in the overolling process.

3. THIRD-BODY CONTACTS

There is a high probability that debris in a lubricant will enter the rolling element contact (provided it is not greater than about 200 micrometres diameter where the friction forces may not be high enough to draw the particle in). Particles in the contact are submitted to very high loads, such that some form of deformation must occur. This deformation process can take one of three forms depending on the material properties of the debris and rolling elements;

(a) Particle plastically deforms into a platelet, with or without rolling element plastic deformation.

(b) Particle fractures, with or without rolling element plastic deformation. The fragments can then embed into the element surfaces.

(c) Particles undergo little or no deformation and can embed into the element surface.

The deformation process occurring in the contact has a direct effect on the nature of the damage to the rolling element surfaces. It is this damage that can have a major influence on the fatigue life of the bearing.

4. DUCTILE DEBRIS

4.1. THE OVEROLLING OF DUCTILE DEBRIS

A ductile debris particle is extruded in the overolling process until the surfaces of the rolling elements enclose around the particle (see figure 1)

In a friction-less situation, a relatively soft particle will be rolled out by plastic deformation resulting in an approximately uniform pressure distribution at the level of the particle material's hardness (i.e. the particle undergoes fully plastic deformation). Depending on the hardness and aspect ratio of the particle the closure of the rolling element surfaces around the particle may occur elastically. It can be shown (10) that closure will occur when;

$$D/t > E/(2H_p(1-n^2))$$

where D is the effective diameter of the flattened particle, t is its thickness, E is the surface modulus, n the Poisson ratio, and H_p is the particle hardness.

In the presence of surface friction the continued extrusion of ductile debris, as the rolling element surfaces approach each other, means that the interfacial pressures must increase towards the centre of the contact. These contact pressures can easily exceed the bearing yield point causing surface defects. This method can therefore be used to predict the critical particle aspect ratios to cause rolling element yield.

4.2. SURFACE DAMAGE CAUSED BY DUCTILE DEBRIS

To examine the damage caused by the flattening of ductile debris particles, experiments were carried out using two Cobalt steel anvils. Metals of various hardness were squashed between the anvils; the dents and final particle sizes were measured. Figure 2 shows surface profiles of the indentation resulting from the pressing of low carbon steel, mild steel, copper, and aluminium cylindrical particles of diameter 1.5mm.

The critical particle aspect ratios to cause indentation of the anvils compared well with the analytical models.

4.3. EFFECT OF RESIDUAL STRESSES CAUSED BY DUCTILE DEBRIS INDENTATION

Hamer et al (11) used a slip line field technique to calculate the residual stress distribution after the rigid plastic indentation of a half space. These residual stresses were then superimposed on the overolling stresses in the bearing life model of Ioannides and Harris (9). This analysis showed that these residual stress effects are important in defining bearing fatigue life.

5. FRIABLE DEBRIS

5.1. THE OVEROLLING OF FRIABLE DEBRIS

An optical EHD rig has been used to study the nature of the deformation of friable type debris particles in a rolling element contact. A steel ball is loaded against a rotating glass disk (see figure 3) and lubricated with an oil mixed with debris. The disk has a thin chromium coating on the contact side; the supply of incident light to the contact area results in an interference pattern (Newton's rings) related directly to the contact size and oil film thickness.

Ceramic debris materials with a range of hardness were used; glass micro-spheres, air cleaner fine test dust (ACTFD), boron carbide, alumina, silicon carbide, and quartz. These particles were fed into the contact; using short duration flash photography and high speed video photography, it was possible to study the breakdown of these particles in the contact and entry zone.

It was found that the very brittle materials fracture early in the entry zone, almost as soon as they are compressed (see figure 4). The fragments then enter the contact and can be embedded in the ball surface. The photograph included, as figure 5, shows the breakdown of 30 micrometre glass micro-spheres, in the entry zone and the fragments entering the contact.

The harder ceramic particles breakdown further into the entry zone or in the contact itself (see figure 6). The particle fragments then tend to enter the contact in a mass and damage the ball surface.

5.2. SURFACE DAMAGE CAUSED BY FRIABLE DEBRIS

Again, the experiments using hard steel anvils to compress particles were carried out to study the nature of the surface damage caused by brittle particles. 1.5mm diameter cylindrical quartz, silica, and alumina particles were crushed between the anvils and the surface damage measured. Figure 7 shows surface maps of the resulting damage. In addition the specimens from the optical EHD studies were examined for surface damage.

The damage to a rolling element surface can be caused at two stages of the particle fracture process. If the debris material is tough the ball surface will yield before fracture of the particle occurs. When particle fracture has occurred, it is the surviving fragments which embed in the rolling element surface causing the second stage of surface damage. The silica particles appear to have caused this first yield before fracture. The quartz particles, however, have caused little or no yield before fracture; the surface damage is a result of the fragment indentation process.

From these results it is possible to speculate that, for very brittle materials the initial size of debris particle is largely unimportant; it is the final fragment size which can survive the contact loads that controls the rolling element surface damage. For hard ceramic materials the initial particle size will control the first stage of element damage before particle fracture. After fracture the surviving fragments will be larger (since the fracture toughness is higher). These larger fragments can then embed whole into the ball surface. In addition, since the particles fracture further down the entry zone, the fragments tend to enter the contact in a cluster thus compounding any surface damage.

5.3. THE STRENGTH OF FRIABLE DEBRIS PARTICLES

The strength of the friable particles is dependent on the material fracture toughness, KIC, and the defect or critical crack size of the material. Since brittle materials are usually about 10-15 times stronger in compression, failure will occur at the maximum tensile stress when;

$$\sigma_{uts} = K_{IC}/(\pi a_{cc})^{1/2}$$

where acc is the critical defect or crack size which must be present, at the location of the ultimate tensile stress, to cause fracture (12). In the contact stress field, therefore, there is a certain critical crack size which is required for a particle to fracture. Any particles smaller than this size will be undamaged and embed into the ball surface.

For low fracture toughness materials the critical crack size will be lower, hence the surviving fragment size is small. In the optical EHD rig, glass fragments of one micrometre are typical, whilst silicon carbide fragments of 5 micrometres appear to survive (see figure 8).

It should be noted that the strength of the friable particles need not be entirely dependent to the material hardness. The test results for figure 7 show that silica causes more surface damage than quartz; however its hardness is approximately half that of quartz. Other factors such as the shape and crystal structure have an effect on the particle strength and resulting surface damage.

5.4. THE EFFECTS OF RESIDUAL STRESSES CAUSED BY CERAMIC DEBRIS INDENTATION

A brittle debris particle will fracture without causing serious damage to the rolling element surfaces. The bulk of the damage will be caused by the embedment of the fragments. Since these particles are small and sharp they will cause indentations which have steep slopes, but are relatively shallow. It is unlikely that the residual stresses from these indentations will compound with the overolling stresses in a bearing. The effects on fatigue life are therefore minimal, other than for very small bearings.

High fracture toughness ceramic debris will cause the bearing surfaces to yield before it fractures; the residual stresses from this deformation may then be sufficient, when compounded with the overolling stresses, to seriously reduce bearing life. In addition the relatively large final fragments will embed into the rolling elements leaving a deeper residual stress field, which again may combine with the overolling stresses.

Fatigue tests, carried out at SKF ERC on bearings lubricated with oils contaminated with silicon carbide and ACTFD, have demonstrated these concepts. The tests using silicon carbide contaminants decreased the fatigue life by a factor of about ten; the ACFTD debris had no noticeable effect on life. Figures 9a & b show Talysurf traces taken perpendicular to the rolling direction of the tested raceways.

The nature of the surface damage is clear; the silicon carbide particles have left deep sharp dents with embedded material projecting out; the ACFTD particles have left very fine shallow surface dents. Figures 10a & b show photographs of the surface damage on these tested raceways.

5.5. ABRASIVE WEAR BY FRIABLE DEBRIS PARTICLES

In the above fatigue tests the ACFTD particles have caused considerable wear of the rolling track. The wear has been greatest within the regions of micro-slip or Heathcote slip in the Hertzian contact, leading to three deep troughs (see figure 9b).

These results demonstrate that, despite the mechanisms of particle fracture, the abrasive wear is largely controlled by the slide/roll ratio. The wear rate will thus depend on the size of the surviving fragments which become interposed between the sliding surfaces.

6. DISCUSSION AND CONCLUSION

A review of the surface damage effects of lubricant particulate contaminants is presented, with an emphasis of on-going research dealing with friable debris.

Friable debris behaves quite differently, to ductile materials, in causing surface damage; it tends to fracture and fragment relatively early in the convergence to rolling element contacts, and certainly well before EHD pressures are generated. Thus, in this relatively low-pressure regime, and as would be intuitively expected, the degree of fragmentation and the extent of damage appears to be directly related to the fracture toughness of the particulates. It is conceivable that small size high fracture toughness particles which fracture further into the contact, where EHD pressures are generated, may undergo some ductile flow rather than the usual brittle fracture.

The overall effects in fatigue from fragmentation of friable debris seem relatively small for low fracture toughness particulates such as ACFTD and glass. This suggests that, although the subsequent damage appears severe in terms of localised dent shapes, the residual stress fields formed by these indentations do not extend deep enough into the surface to increase the potential for fatigue initiation by compounding with overolling Hertzian stresses. This hypothesis is in keeping with the experimental evidence; that ACFTD does not appear to reduce fatigue life in medium sized bearings but can in small bearings, Whereas the plastic extrusion processes associated with dent formation from ductile debris can produce high residual tensile stresses much deeper into the surface, and the subsequent fatigue lives of similar medium sized bearings are reduced substantially. It is also worthy of note that very large bearings do not appear to suffer reductions in life from sometimes quite excessive surface denting caused by ductile debris, which again is in accord with the arguments presented.

7. ACKNOWLEDGEMENTS

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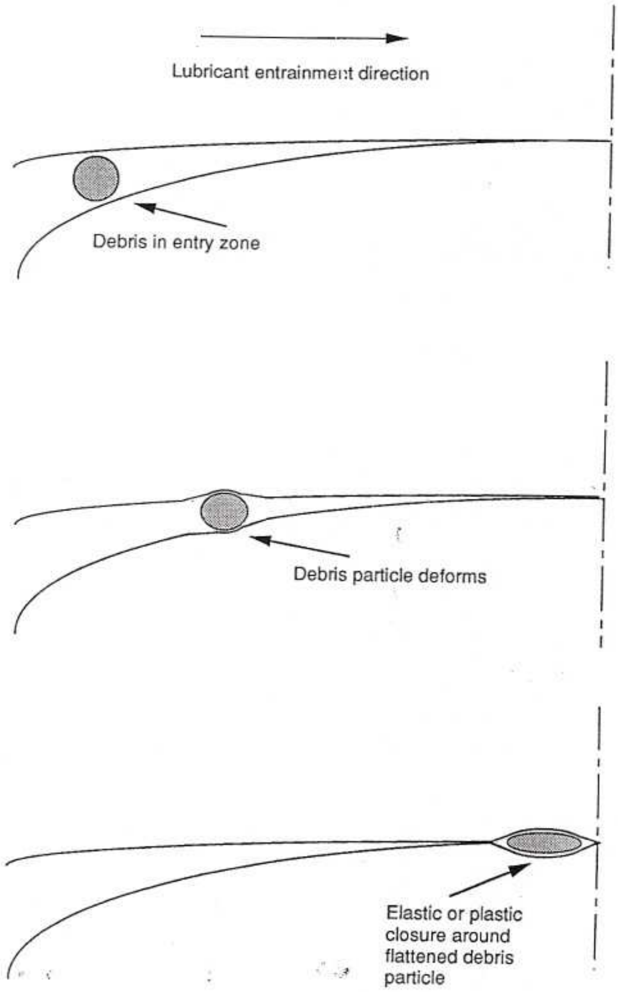

Fig 1 Deformation mechanism of ductile debris particles in a rolling element contact

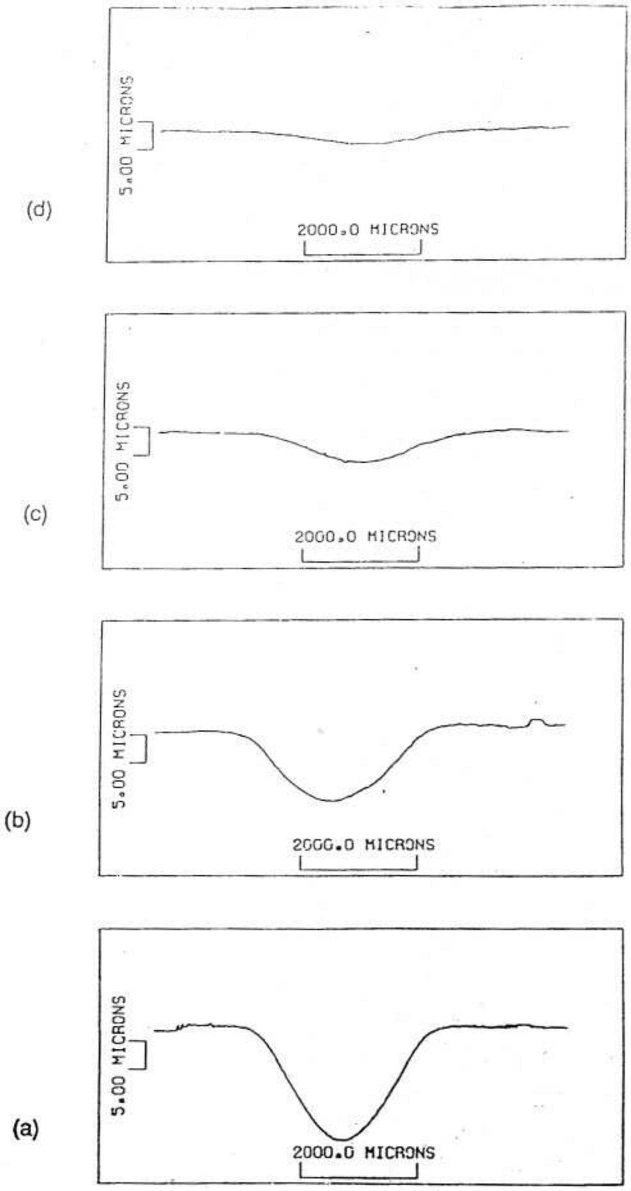

Fig 2 Dents caused by squashing 1.5mm cylindrical particles between hard steel anvils:
(a) low carbon steel, (b) mild steel, (c) copper, (d) aluminium

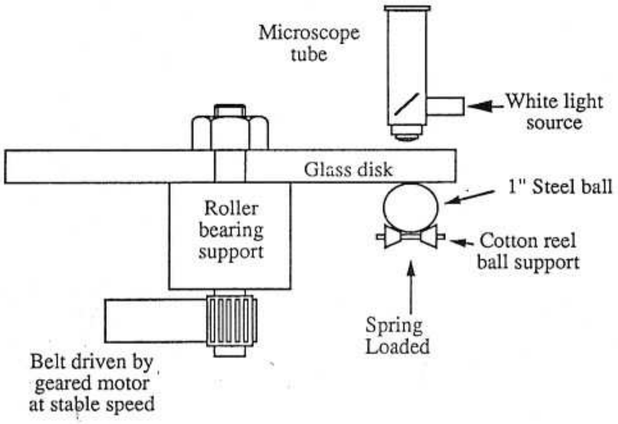

Fig 3 A schematic diagram of the optical EHD rig

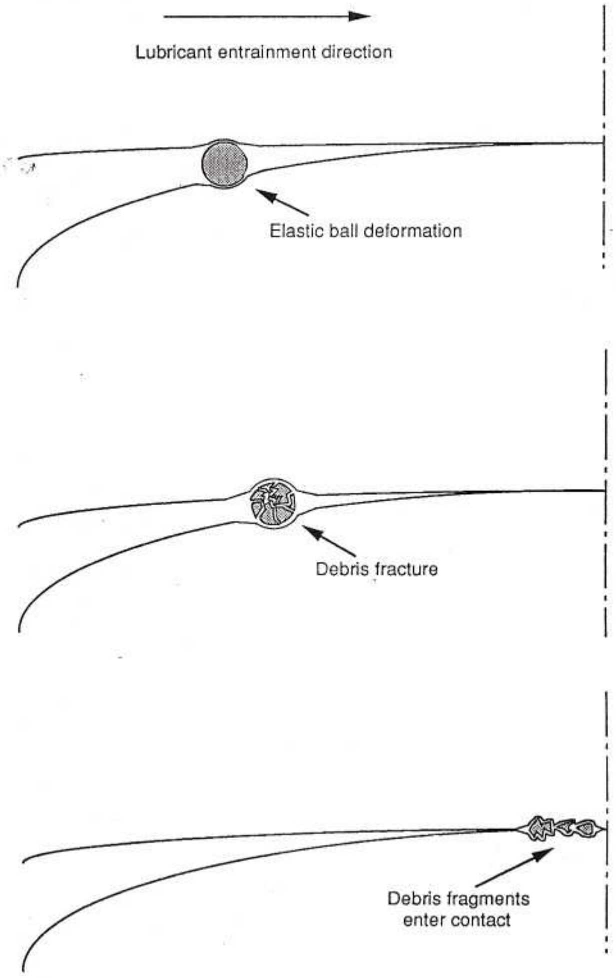

Fig 4 Fracture mechanism of brittle debris particles in a rolling element contact

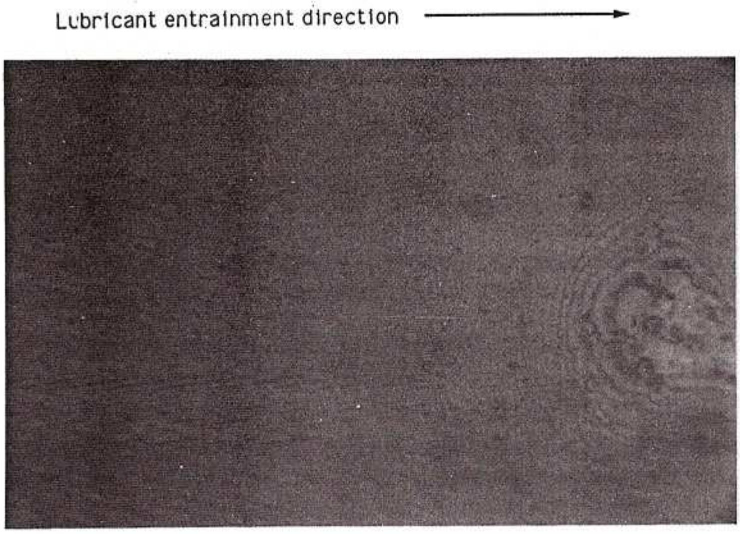

Fig 5 Optical EHD photo of 30 micron glass microspheres entering the contact (photograph magnification ×60, photographically reduced to 55 percent)

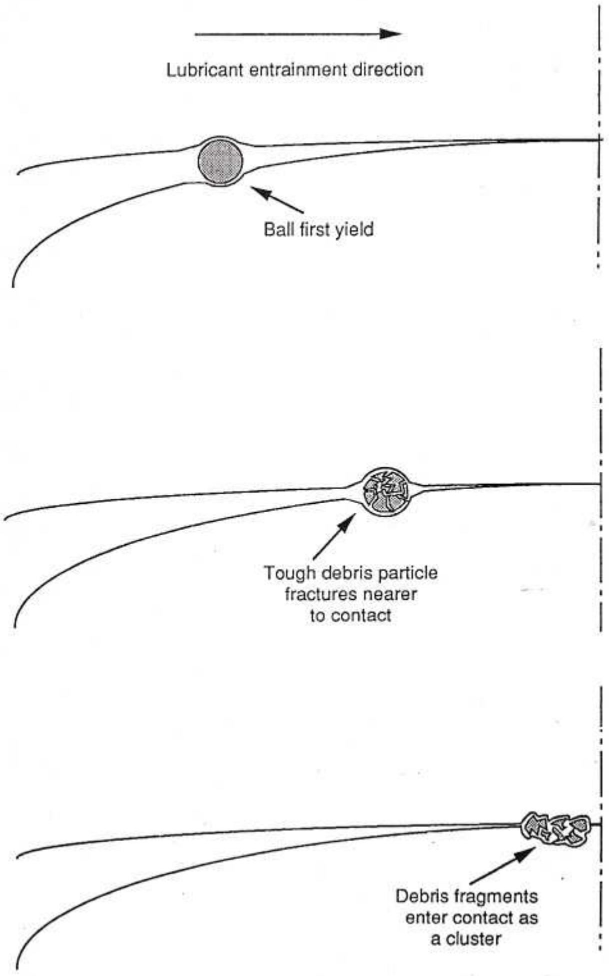

Fig 6 Deformation mechanism of high toughness ceramic debris in a rolling element contact

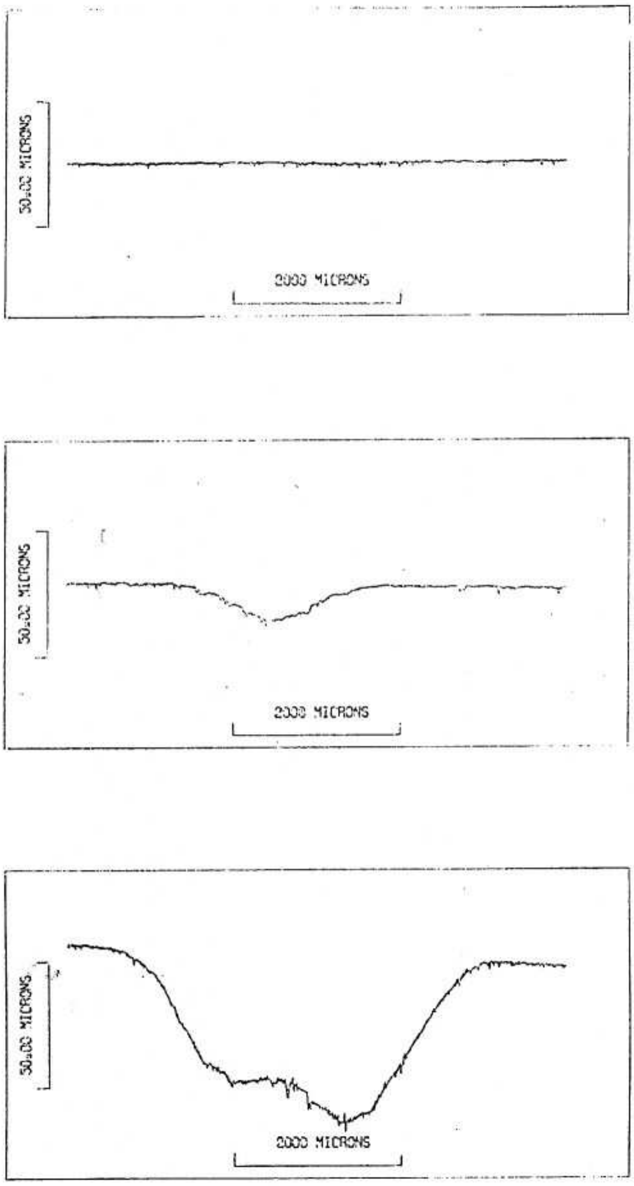

Fig 7 Dents caused by squashing 1.5mm cylindrical particles between hard steel anvils: (a) quartz, (b) silica, (c) alumina

Lubricant entrainment direction →

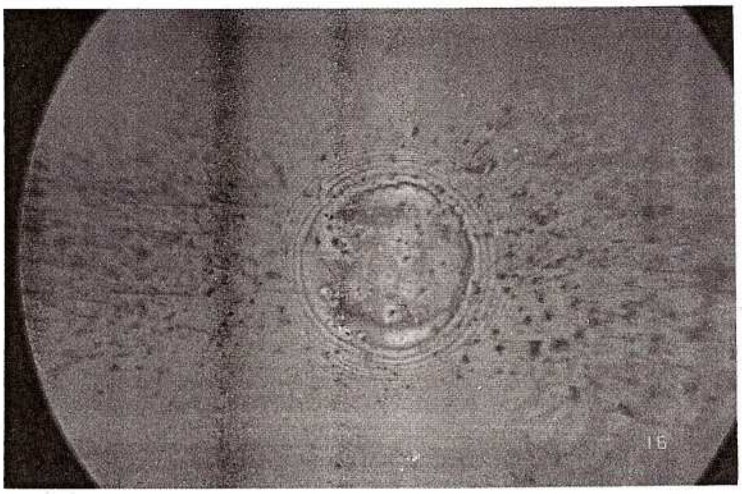

Fig 8 Optical EHD photo of 5 micron silicon carbide particles entering the contact (photograph magnification × 60, photographically reduced to 55 percent)

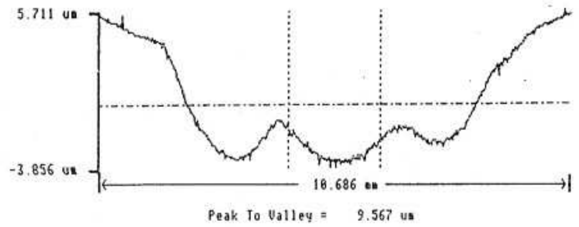

Fig 9(a) Surface profiles of raceways tested with ACTFD lubricant contaminants

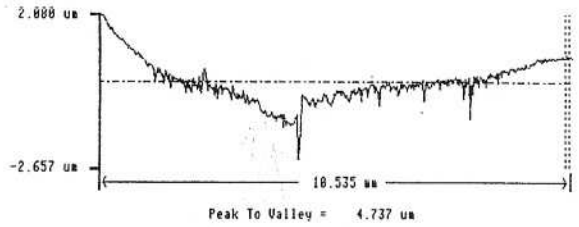

Fig 9(b) Surface profile of raceways tested with SiC contaminated lubricants

Fig 10(a) Photomicrograph of raceways tested with ACTFD lubricant contaminants (photograph magnification × 300, photographically reduced to 55 percent)

Fig 10(b) Photomicrograph of raceways tested with SiC contaminated lubricants (photograph magnification × 300, photographically reduced to 55 percent)