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Subsurface deformation and the role of surface texture—A study with Cu pins and steel plates

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Abstract. The extent of subsurface deformation below the worn surface influences friction and transfer layer formation during sliding. Thus, in this study, the extent of plastic deformation and strain localization events that occur at various depths beneath the worn surface in the subsurface zones of Cu pins slid against steel plate with various surface textures have been determined using simple metallographic techniques. Results showed that the magnitude of plastic strain gradient and the depth of highly deformed zone depend on both coefficient of friction and transfer layer formation, which in-turn depends on the surface texture of harder counterface, under both dry and lubricated conditions. In addition, it was seen that the gradient of equivalent strain, as it approached the worn surface, was higher under dry conditions when compared to that under lubricated conditions.

Keywords. Friction; subsurface deformation; surface textures; strain gradient.

1. Introduction

Sliding contact between the surfaces of ductile materials is often accompanied by severe plastic deformation localized within a small volume of material adjacent to contact surfaces. The process of transfer layer formation or wear is closely related to the magnitude and distribution of local strains and strain gradients as well as to the variation of stress state within the deformed subsurface zones (Moore & Douthwaite 1976; Solecki 1988). Extensive research has been done by Suh and his co-workers (Suh 1986, 1973; Suh & Saka 1977; Jahanmir & Suh 1977a,b; Saka *et al* 1977; Fleming & Suh 1977) to study the mechanics of deformation and crack nucleation beneath the worn surface.

Using simple metallographic techniques, the subsurface deformation could be revealed as follows. Following a sliding test, specimens to be examined were sectioned perpendicular to a worn surface and parallel to the sliding direction and then polished, etched and examined using optical or scanning electron microscope. The important features observed in section

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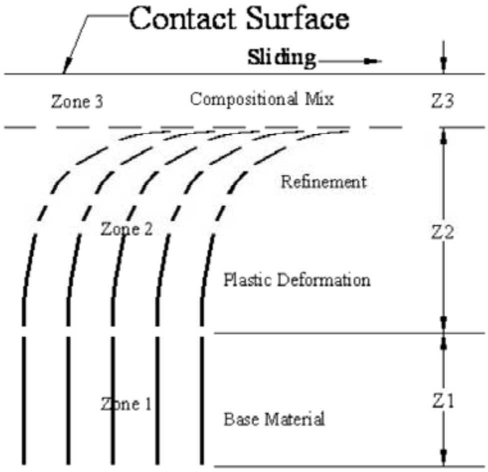

Figure 1. A schematic diagram of subsurface zones observed beneath worn surfaces.

of the specimen after the sliding test is schematically shown in figure 1 (Rice *et al* 1989). These are features of subsurface zones which depend (morphologically and compositionally) on specimen/counterface materials and geometry, the environment and the mechanical conditions of contact. Generally, there are three zones beneath the worn surface as shown in figure 1. Zone 1 represents original specimen material in an undisturbed state. This zone experiences elastic deformation and thermal cycling when loaded during tribo-contact. The structure and properties of zone 1 following a sliding test are similar to those prior to the test. However, material in zone 2 has acquired new structure and properties due to cyclic tribo-contact and considerable plastic deformation occurs in ductile materials. Depending on the materials, contact conditions and environment, zone 2 may become softer or harder than the original material. Voids may develop within zone 2, and cracks may nucleate within this region (Rice *et al* 1989). In most of the cases, due to severe plastic deformation, the reorientation and disintegration of crystallites are observed in zone 2, with attendant refinement in microstructure that increases as the contact interface is approached. However, in zone 2, no constituents from the interface or from the environment are present. The severity of deformation in zone 2 ranges from zero at zones 1 to 2 interface and maximum at the zones 2–3 interface. Zone 3 is a tribo-layer which forms *in situ*. It is the region containing the surface of contact, and it differs compositionally as well as morphologically from the base material (zones 1 and 2). Frequently, zone 3 appears to be homogeneous and finely structured consisting of the specimen and counterface material, as well as the constituents from the operating environment.

Considerable amount of work has been done to study the role of subsurface zones on wear of materials. Rice *et al* (1982, 1989) summed up the research on the progress of subsurface zones that arise in tribo-contact during sliding. Rice *et al* (1982, 1989) reported that the morphological and compositional characteristics of subsurface zones depend on the test materials, environment, nominal level of contact stress, specific nature of contact and relative sliding velocity. Jasim (1984) accounted that increasing sliding speed decreases subsurface damage and increasing normal load increases subsurface damage. Richardson (1967) related the abrasive wear resistance to the hardness of the worn surface, and Moore *et al* (1972) showed that this surface hardness depends on the bulk hardness and the strain hardening properties of the material. Because of strain hardening a large part of the energy expended in abrasive wear may be expected to be absorbed in this way. Rosenfield (1937) examined the influence of frictional force on the depth of the subsurface zone, in which shear stress exceeds resistance to flow, and showed that the zone moves closer to the surface as the coefficient of friction increases. Jahanmir (1985) studied the relationship of tangential stress to wear particle formation mechanisms and concluded that wear occurs by surface deformation and material transfer to the harder component when the tangential stress is low and it occurs by delamination and material transfer when the stress is high. Rigney and coworkers (Rigney & Hirth 1979; Heilmann & Rigney 1981) emphasized the importance of the energy expended during the near-surface deformation on friction and wear. Rigney and co-workers (Rigney & Glaeser 1978; Rigney *et al* 1984; Heilmann *et al* 1983) examined the subsurface region of worn materials and observed cellular microstructure or dislocation tangles, which present a suitable pathway for separation of wear debris from the surface. The authors (Rigney & Glaeser 1978; Rigney *et al* 1984; Heilmann *et al* 1983) viewed that the plastic deformation changes the near-surface microstructure in ways which make the material unstable to local shear. Heilmann *et al* (1983) pointed out that the microstructure below the surfaces involves a dislocation cell structure and suggested that subsurface cracks would be parallel to the cell boundaries, which develop at large plastic strains. Alpas & Embury (1991) noticed that under large strain conditions that prevail below the contact surfaces, strain localization occurs in ductile materials leading to crack initiation and propagation through the shear bands. Moore & Douthwaite (1976) tried to explain the size effect in terms of the plastic deformation below the worn surface. Moore & Douthwaite (1976) estimated the equivalent plastic strain and the flow stress as a function of depth below the worn surface and calculated the work done in deforming the material below the groove and the energy absorbed in plowing the surface since the plastic properties of the material affect the contact conditions and thus the rate of removal of material from the surface.

Attempts have also been made using FEM to study the stresses generated at the subsurface region during sliding contact. Tian & Saka (1991) studied the two-dimensional stress and strain analysis during sliding and concluded that normal stresses and strains along the interfaces are not greatly affected by friction while horizontal shear stresses and strains are strongly influenced by the friction coefficient. It has been found that the effect of tangential force is to bring the point of maximum shear stress closer to the surface. Johnson & Jefferis (1963) determined the location of initial yield in a sliding contact using both the Mises and Tresca yield criteria. Johnson & Jefferis (1963) found that yielding initiates in the subsurface region when the friction coefficient, μ, is small ($\mu < 0.25$ for the Tresca criterion and $\mu < 0.3$ for the Mises criterion), and on the contact surface when it is larger than 0.25 for Tresca and 0.3 for Mises criteria. Tian & Saka (1991), using FE method, made a similar observation.

In the literature, several authors also reported on the subsurface studies of Cu and its alloys under different operating conditions (Teixeira *et al* 1977; Tjong & Lau 2000; Wert & Cook 1988). Teixeira *et al* (1977) studied the effect of solute atoms on friction, wear and subsurface deformation by alloying OFHC copper with chromium, silicon and tin. The authors reported that the effect of solute addition reduces the friction coefficient which reduces the deformation rate, the depth of crack nucleation and crack propagation rate and thus wear rate. Tjong & Lau (2000) reported that reinforcing copper with SiC particles reduces the extent of subsurface deformation and wear during sliding.

The present study focuses on the effect of surface texture of harder materials on subsurface deformation of pure Cu during sliding. Attempts have been made earlier to study the effect of surface texture on coefficient of friction and transfer layer formation during sliding using Al-4Mg alloy, Al-8Mg alloy, pure Cu, pure Al and pure Pb under both dry and lubri-

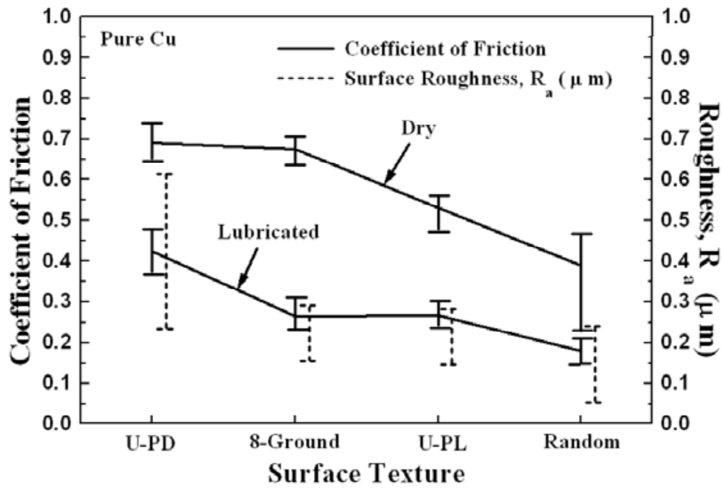

Figure 2. Variation of average coefficient of friction and surface roughness (R_a) with surface texture.

cated conditions (Menezes *et al* 2005, 2006a–c). Various kinds of surface textures, namely, unidirectional grinding marks, 8-ground, and random were prepared on steel plates using emery papers or polishing powders. Roughness, represented by R_a, of steel surfaces was varied over a range and these were prepared using different grit emery papers or polishing powders. Figure 2 shows the variation of coefficient of friction with surface textures when pure Cu pin slid on steel plate of different surface roughness (Menezes *et al* 2005). Here U-PD and U-PL represents sliding direction perpendicular and parallel to the unidirectional grinding marks generated on the steel plates, respectively. It can be observed from figure 2 that the coefficient of friction primarily depends on surface texture of harder counter surface. It can be observed that the coefficient of friction is highest for the U-PD plates and reduces for the 8-ground plates, U-PL plates, and randomly polished steel plates in the order. It was reported that the sliding perpendicular to unidirectional grinding marks (U-PD surfaces) gives maximum friction force, contributed by higher plowing component, and at the other extreme, the random texture resulted in lower friction values. For 8-ground and U-PL surface textures, the coefficient of friction lies in between these two extremes.

In this study, metallographic techniques have been used to determine the extent of plastic deformation and strain localization events that occurs at various depths beneath the worn surface in the subsurface zones of the Cu pins slid on various surface textures. When a ductile pin slides against hard steel plates, the pin experiences severe plastic deformation, localized within a small volume of material, adjacent to the contact surface. The process of transfer layer formation is closely related to the magnitude and distribution of local strains and strain gradients as well as to the variation of stress state within the deformed subsurface zones.

2. Experimental procedure

In this study, pure Cu pins that were slid on steel plates of various surface textures (Menezes *et al* 2005) were considered. To examine the microstructure of the deformed subsurface, the pins were sectioned perpendicular to the worn surface and parallel to the sliding direction. Before sectioning, the worn surfaces were nickel plated to improve edge retention during sectioning and to prevent rounding of edges during specimen preparation. One of the sectioned halves was metallographically mounted, ground and polished before optical and scanning electron microscopy (SEM) studies were carried out. Prior to SEM examination, the specimen was etched and then gold coated to reveal the subsurface microstructure.

3. Results and discussion

Scanning electron micrographs of a section parallel to the sliding direction of the Cu pins slid against U-PD, 8-ground, U-PL and random surfaces under dry conditions are shown in figures 3(a–d), respectively. In all these micrographs, the sliding direction of the plate is indicated by an arrow and the worn pin surface is towards the top of the micrographs. It can be clearly observed from the micrographs that a severely deformed zone forms beneath the worn surface of the pin appears as a result of sliding. It can also be seen that the grains of Cu adjacent to the contact surfaces are severely deformed during the sliding process and show the change in the grain morphology near the contact surface. The SEM examination also shows a region where the flow lines curve towards the sliding direction of the plate due to plastic deformation, and squeeze towards each other resulting in multiple flow patterns as they approached the worn surface. The extent of deformation, very close to the surface is severe, clearly indicating to the existence of a strong shear gradient beneath the worn surfaces. It is seen at higher magnifications that this feature extended to a greater depth for the sliding tests conducted perpendicular to the grinding marks (figure 3a) than for the case of random surfaces (figure 3d). For the 8-ground and U-PL surfaces, these features, namely, the degree and depth of deformation lie in between these two extremes. The extent of subsurface features are less

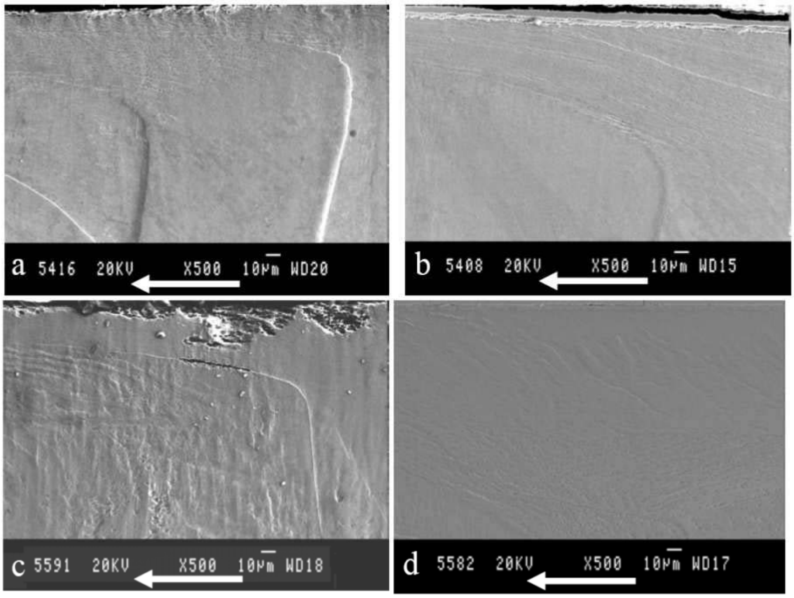

Figure 3. Scanning electron micrographs of subsurface of Cu pins that are slid on **(a)** U-PD, **(b)** 8-ground, **(c)** U-PL and **(d)** random textures under dry conditions.

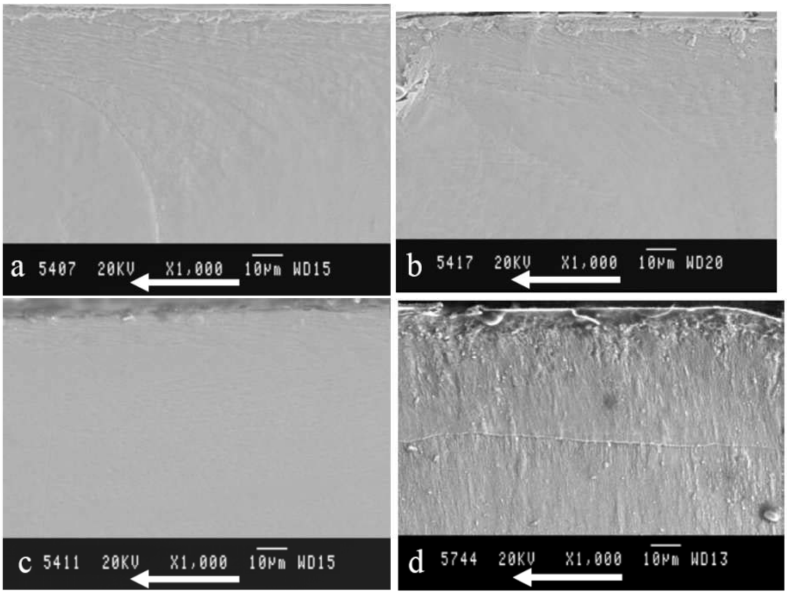

Figure 4. Scanning electron micrographs of subsurface of Cu pins that are slid on **(a)** U-PD, **(b)** 8-ground, **(c)** U-PL and **(d)** random textures under lubricated conditions.

under lubricated conditions, as shown in figures 4(a–d) for U-PD, 8-ground, U-PL and random surfaces, respectively, when compared to that observed under dry conditions (figures3(a–d)).

By identifying the location at which the flow lines start deviating from being normal to the worn surface an estimate of the depth up to which shear strain gradient exists beneath the worn surface can be easily obtained. The variation of shear strain as a function of depth from the worn surface was calculated using the curvature of the flow lines, in a manner described by Moore & Douthwaite (1976), Alpas *et al* (1993), and Venkataraman & Sundararajan (1996). The flow lines, initially normal to the worn surface, progressively curve towards the sliding direction and nearly become parallel to it as the worn surface is approached. These flow lines are traced separately and the shear angle (θ) was determined at various depths (Z) from the worn surface as illustrated in figure 5. The equivalent strain at a depth $Z(\epsilon(Z))$ can be calculated from the shear angle of the interface, θ (Dautzenberg & Zaat 1973), as follows:

$$\epsilon(Z) = \frac{\sqrt{3}}{3}\tan[\theta(Z)]. \tag{1}$$

The variation of the strain gradients with depth below the surface for various surface textures under both dry and lubricated conditions is shown in figures 6a and b, respectively. The results, expressed in terms of equivalent plastic strain, are presented for U-PD, 8-ground, U-PL and random tests. It was observed that both the magnitude of plastic strain gradients and the depth of highly deformed layers depend on the surface texture and these are observed to be highest for the U-PD case, followed by 8-ground, U-PL case and randomly polished textures under both dry and lubricated conditions. The extent of these subsurface features, namely degree of plastic strain and the depth of subsurface plastic zone, are less under lubricated conditions (figure 6b) when compared to that under dry conditions (figure 6a). It must be mentioned

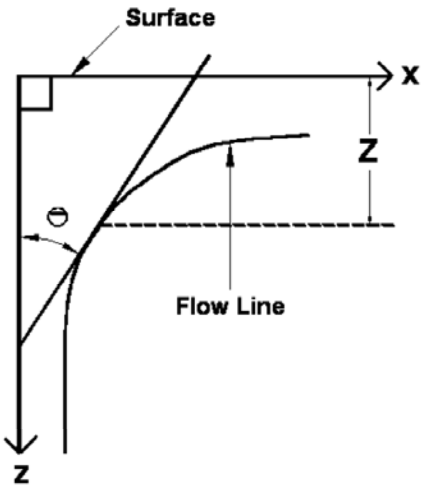

Figure 5. A schematic diagram illustrating the method for estimating the shear strain beneath the worn surface utilizing the flow lines.

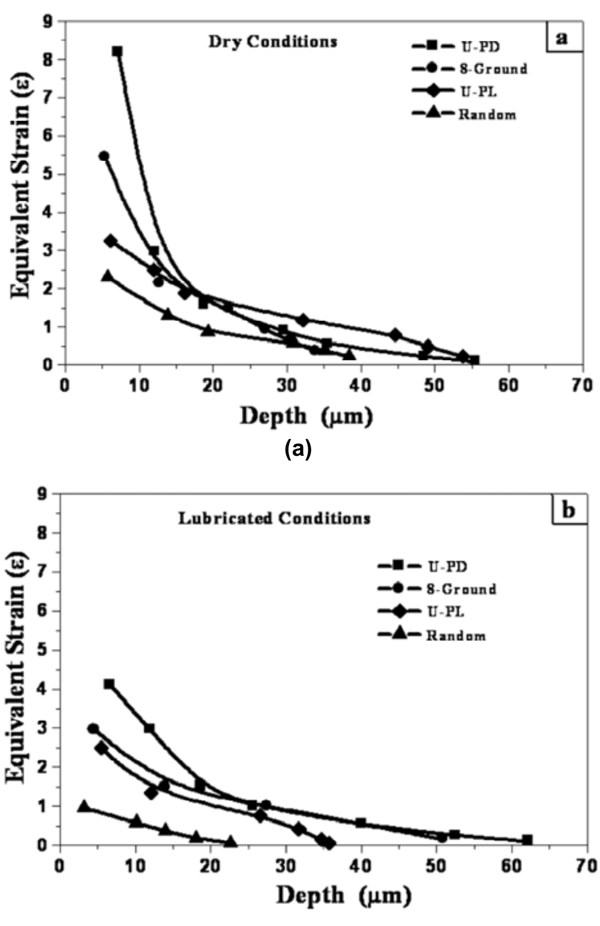

Figure 6. Variation of the estimated equivalent strain as a function of the depth beneath the worn surface of Cu pin under **(a)** dry and **(b)** lubricated conditions.

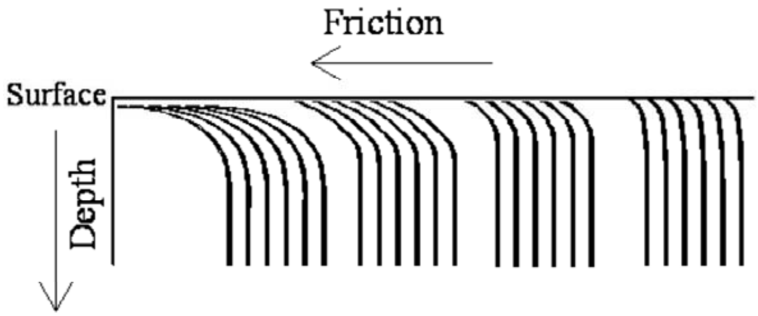

Figure 7. Schematic diagram of the variations of flow lines as a function of coefficient of friction.

here that the variations of strain in the sliding direction (x-direction) at a particular depth was very low. A feature that can be observed in figure 6 is that the gradient in equivalent strain, as it approaches the worn surface, is higher under dry conditions (figure 6a) when compared to that under lubricated condition (figure 6b).

By comparing coefficient of friction against surface texture plot presented in figure 2 with equivalent strain against depth plots (figure 6), it can be noted that the degree of plastic strain depends on coefficient of friction under both dry and lubricated conditions. Figure 7 shows a schematic diagram of the variations of flow lines as a function of coefficient of friction. Thus, based on the experimental results, it can be inferred that higher the coefficient of friction, which is controlled by the surface texture, more would be the depth of deformation and extent of plastic strain.

Using slip line field theory, Petryk (1987) and Challen & Oxley (1979) had shown that the overall friction coefficient increases when the asperity angle or the interfacial friction increases. The contact shear stress, τ, is given by $\tau = mk$, where m is the interfacial friction and k is the yield shear stress. In the present set of experiments, the average slope of the surface profile, Δ_a (Gadelmawla *et al* 2002), of the steel plates for various surface textures was found to be less than 10° and at these values of surface slopes only models in which rubbing takes place are active (Petryk 1987). This type of situation lies mostly in 'Type I' solution in Petryk's model (Petryk 1987) and the flow pattern for this solution is shown schematically in figure 8. The plastic zone, h_p is inversely related to m and thus, h_p increases as m reduces. The interfacial friction, m can be reduced by introducing lubricant at the interface. Thus, it can be understood that under dry conditions the value of m is more and thus h_p (i.e. h_d in figure 8) moves towards the surface and hence the gradient is more as shown in figure 6a. Under lubricated conditions, the value of m is less and hence the h_p (i.e. h_l in figure 8) is more and hence the gradient is less in figure 6b.

It was also stated that under both dry and lubricated conditions the formation of transfer layer on the steel plate depends on the coefficient of friction which inturn depend on surface texture of steel plates (Menezes *et al* 2005). It was reported that under both dry and lubricated conditions the amount of transfer layer formed on a steel plate surface was highest for the U-PD plates, followed by the 8-ground plates, U-PL plates, and then the randomly polished steel plates. The amount of transfer layer formed on steel plate surface was higher under dry conditions when compared to that under lubricated conditions (Menezes *et al* 2006a). Under dry conditions, the value of m is more and hence the h_p is less. This situation lies mostly in 'Type II' solution in Petryk's model (Petryk 1987) and the flow pattern for this solution is

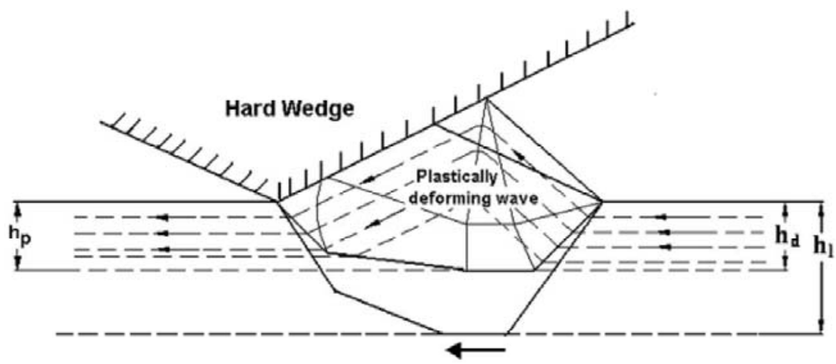

Figure 8. Flow pattern for 'Type I' Solution (Petryk 1987). The characteristic feature of the solution is the standing wave of deforming material in front of the wedge. The volume of material above the horizontal free surface is regarded as pushed out of the half-space in a non-stationary deforming process. The material crossing the deforming zone forms a plastically deformed subsurface layer of thickness 'h'. Here h_d and h_l are the depth of deformed zones formed for high and low interfacial friction values, respectively.

shown schematically in figure 9 wherein the plastically deformed zone adheres to the wedge. Thus, it can be inferred that the coefficient of friction, subsurface deformation in the softer material and the formation of transfer layer on the steel plate could be interrelated. It was believed that the hard asperities of the counter body caused the deformation in the soft pin and induced nucleation of cracks and micro voids in the deformed region of the worn sample and these cracks and voids extend to the surface and run parallel to the surface. This eventually led to delamination of material and formation of transfer layer on the steel plate. Thus, the differences in subsurface zone morphology are directly responsible for the variations in the formation of transfer layer observed on the different textured surfaces.

It was reported (Menezes *et al* 2005, 2006a,c) that the unidirectionally ground surface will have a 'wave' like texture and a 'hill-and-valley' texture if randomly polished. Surface profiles of the unidirectionally ground and randomly polished steel plates and the schematic view of the possible flow pattern when a soft pin over (a) a cylindrical asperity (unidirectionally ground with sliding perpendicular to the unidirectional texture) and (b) spherical asperity (randomly ground) were presented elsewhere (Menezes *et al* 2006c). The level of stresses were computed

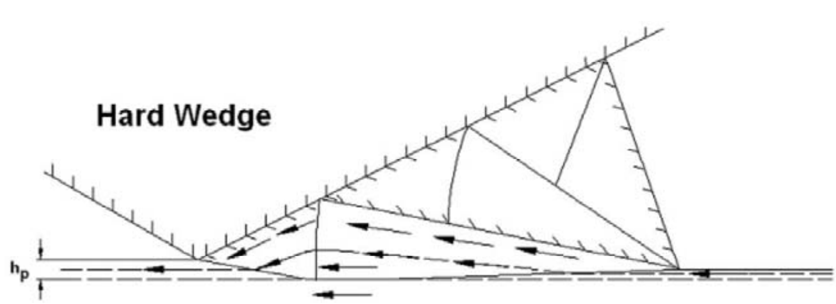

Figure 9. Flow pattern for 'Type II' Solution (Petryk 1987). In this solution, the plastically deforming zone is not bounded by a free surface but is covered by a rigid region adhering to the wedge.

when a soft pin slid on U-PD texture (i.e. flowing over a cylindrical asperity) and random texture (i.e. flowing around a spherical asperity) using finite element code, DEFORM 3D (Kailas & Menezes 2003). It was seen that the levels of stresses were higher for the cylindrical asperities (U-PD texture) when compared to the spherical asperities (random texture). It was also seen from the computational work that the coefficient of friction (measuring the ratio of tangential force to the normal force from the plots obtained during sliding in the simulations) was higher for the cylindrical asperity when compared to the spherical asperity (Kailas & Menezes 2003).

4. Conclusions

In this study, subsurface studies of pure Cu pins slid against steel plates of different surface textures were carried out using simple metallographic techniques. The conclusions based on the experimental results are as follows:

- The gradient in equivalent strain, as it approaches the worn surface, was higher under dry conditions when compared to that under lubricated condition.
- The magnitude of plastic strain gradient and the depth of highly deformed zone depend on coefficient of friction which inturn depends on the surface texture of harder counterface under both dry and lubricated conditions. Both the magnitude of plastic strain gradient and the depth of highly deformed zone in the Cu pin were highest for the U-PD case, followed by the 8-ground, U-PL case and least for randomly polished textures.
- The levels of shear stresses are more for U-PD texture when compared to random texture.

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