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A Study of the Strain Rate Microstructural Response and Wear of Metals

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Titanium (Ti) and copper (Cu) pins were slid against alumina in a pin-on-disk machine at a load of 50 N and sliding speeds varying from 0.1 to 4 ms^{-1}. The evolution of the microstructure in the subsurface of the material and the wear rate was co-related to the strain rate microstructural response of the material in uniaxial compression, at different strain rates (0.1-100 s^{-1}) and temperatures (298-673 K). The strain rates and temperatures in the plastically deforming zone near the surface of the pins were determined using noniterative methods. The strain rates were found to be in the region of 100 s^{-1} near the surface and decreases as one moves into the sub-surface of the pin. The temperatures increased as the speed increased. These estimated strain rates and temperatures were superimposed on the strain rate microstructural response maps of these materials. The uniaxial compression test results of Ti showed adiabatic shear banding as a microstructural mechanism that evolves at high strain rates (≥10 s^{-1}) and lower temperatures (<575 K). Adiabatic shear bands are sites of easy crack nucleation and propagation. When Ti is slid at low speeds the near surface region of the pins deform in the adiabatic shear banding regions in the strain rate microstructural response map. At such speeds the wear rate is found to be high and reduces as the sliding speed is increased, when the material undergoes a more homogeneous deformation. The microstructural response of Cu under uniaxial compression showed that the material undergoes flow banding at intermediate strain rates (1 s^{-1}) and temperatures of up to 473 K. The subsurface microstructure of the pins slid at low speeds showed subsurface cracking and sheet like debris formation. This happen at lower speeds because the flow banding and crack nucleation is expected in the subsurface where the strain rates and temperatures are lower. The present test results show a clear relation to exist between the strain rate response of the material in uniaxial compression and its subsurface microstructural evolution and wear rate.

Keywords adiabatic shear banding, flow banding, homogeneous deformation, microstructural response, strain rate, wear

1. Introduction

The factors that influence and control the wear mechanism, wear rate, and coefficient of friction have been researched and debated since the pioneering work by Bowden and Tabor.[1,2] A large number of factors influence wear, which include the hardness, toughness, and surface characteristics of the materials being rubbed. Since the work by Bowden and Tabor[1,2] it has been shown that the plastic deformation near the surface is high and reduces as once moves into the subsurface.[3-8] Various authors have studied the parameters that control the wear mechanism and wear rate. Dorison[9] deduced four primary wear mechanisms from the behavior of moving surfaces in contact under load: (a) the adhesive mechanism, (b) the plastic deformation mechanism, (c) the spalling or pitting mechanism, and (d) the chemical or corrosive mechanism. Suh[10] proposed a new theory of wear called the "delamination theory of wear." This theory was based on the behavior of dislocations at the surface leading to subsurface crack and void formation, and subsequent joining of cracks by shear deformation of the surface. This theory could predict qualitatively that the wear particle shape is likely to be thin flake like sheets and that the surface layer could undergo large plastic deformation. Hornbogen[11] proposed a model to explain increasing relative wear rates with decreasing toughness of the metallic materials. The model was based on comparison of the strain that occurs during asperity interactions with the critical strain at which crack growth is initiated. He proposed that if the applied strain is smaller than the critical strain, the wear rate is independent of toughness and Archard's law is followed. Rigney and Hirth[12] reviewed the various explanations of friction and proposed a new model to describe the source of friction during steady state sliding of metals. The model appeared to be consistent with a number of published observations on the relation of friction to load, sliding distance, surface temperature, and microstructure. Madakson[13] also reviewed the various friction models and presented a general equation, based on dimensional analysis, which took into account the environment, material properties, surface roughness, the area of real contact, rubbing velocity, deformation, and surface energy. Madakson suggested that friction to be system dependent. Montgomery[14] studied the sliding behavior of copper (Cu) alloys and found that metal transfer, scuffing, and friction could not be related to any property. Johnson[15] reviewed research into the progressive plastic deformation of surfaces in repeated sliding and found that the surface layer beneath a wear track to have acquired severe plastic strains, which suggests that cracks are ductile fractures,

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driven by plastic strain rather than elastic stress intensity. Some of the more recent papers that review and address the phenomena of wear of metals were by Rigney,[16] Blau,[17] and Kato.[18] Some of the other papers that touch on the role of various aspects of friction and wear are by Akagaki and Kato,[19] Rigney,[20] Dautzenberg,[21] Beckman,[22] Suh and Sin,[23] Rosenfield,[24] Qui and Pesha.[25] A good summary of the various factors involved in the wear process has been given by Zum Gahr.[26] Despite all the research and modeling, an interesting observation was made by Meng and Ludema[27] in a paper that reviewed most of the published wear models and equations (till 1995) and analyzed them with respect to their origin, context, and applicability. No single predictive equation or group of limited equations was found to be general and of practical use. They observed that "the reasons include the perpetuation of erroneous and subjective expressions for the mechanisms of wear, the slow pace of translation of microscopic observation into macroscopic models of the wearing process and the paucity of good experiments to verify the proposed models."[27]

All of these models neglect one aspect during plastic deformation of metals and its role in wear—the role of "strain rate microstructural response of a material." During deformation of metals and alloys the power input into the material, at any given strain rate, is dissipated as heat and is also used for microstructural changes. The amount of power used for microstructural changes depends on the strain rate and temperature of deformation.[28,29] Depending on the ratio of this power partitioned and the change of this ratio with strain rate and temperature, the material may undergo stable or unstable microstructural evolution. An efficiency parameter of power partitioning has been developed, which controls the microstructural evolution.[28,29] During sliding, the material undergoes plastic deformation at the contacting asperities, and this plastic deformation propagates well into the subsurface at varying strain rates and temperature. The strain rates and temperatures of deformation depend on the normal load, coefficient of friction, and the sliding velocity. The coefficient of friction depends on various parameters of the system like the surface roughness of the mating surfaces and lubrication. Thus for a given surface condition, one can control the strain rate and temperature by changing the normal load applied and the velocity of sliding. This in turn would control the microstructural evolution in the surface and subsurface regions. Thus one can expect a relation to exist between the strain rate response of the material and the surface and subsurface microstructural evolution. Some work has been done by the author in this direction.[30-35]

The present work looks into the effect of strain rate and temperature in the plastically deforming zone. Two materials, Ti and Cu are taken as test materials to check out this hypothesis. Titanium (Ti) and Cu pins are slide on an alumina discs in the current study. The strain rates response map is got from uniaxial compression tests and the computed strain rate and temperature existing in the near surface and subsurface of the pin is superimposed on the map. The co-relation between the strain rate response map and the plastic deformation in the surface and subsurface of the pin is looked into for these two test materials.

2. Experiments

Uniaxial compression tests[29] were done on commercial purity Ti pins (V-0.258, Fe-0.44, C-0.014, S-0.005, H-26 ppm, O-1286 ppm, and N-48 ppm and 40 mm grain size) and oxygen free high conductivity (OFHC) (cold rolled and annealed with 10 ppm oxygen and 42 mm grain diameter) at constant true strain rates of 0.01, 0.1, 1, 10, and 100 s^{-1} and temperatures of 298, 373, 523, and 673 K. A few additional tests were done for Ti to confirm some results. The tests were done on a computer controlled servo hydraulic test machine (DARTEC, UK), which had the facility to change the speed of the ram exponentially, so that constant true strain rates were maintained. The temperature, which was controlled to ±2 K, was measured using a thermocouple inserted into the specimen. This thermocouple was also used to measure the adiabatic temperature rise in the sample during the test. The specimens were then cut axially, and the microstructure evolved was studied using conventional micrographic methods. The same material was used as the pin and slid against an alumina disk [99.5% sintered, 0.2 mm, Center Line Average, (CLA)] at speeds of 0.1, 0.4, 1.0, 1.5, 3.0, and 4.0 ms^{-1}, at a constant load of 50 N. The pin was run in at 0.1 ms^{-1} and 20 N load to ensure complete contact between the pin and the disc before the start of the experiment. The tests were carried out till constant wear rate was reached, which was around 500 m of sliding in the present set of experiments. The sample and the pins were cleaned ultrasonically in acetone before the start of the experiment. The tests were carried out in ambient conditions (300 K) and relative humidity of around 40%. The frictional force was measured using a load cell and the height loss of the pin was measured using a linear variable differential transformer (LVDT) of 1 micro meter accuracy. There was no appreciable wear of the disk during the tests. The experiments were repeated 5 times at each speed. The data was found to fall within 6% of the mean. The coefficient of friction was found to be 0.45 ± 0.05, irrespective of the sliding speed. The worn pins were plated with nickel and cut axially along the sliding direction. This section was polished and etched using conventional metallographic methods and the microstructure evolved in the subsurface studied using a scanning electron microscope.

3. Results and Discussion

Because the paper discusses the role of strain rate microstructural response of a material in wear, it is necessary to estimate the strain rate and temperature existing in the near surface and subsurface regions. When a material is slid against another material a gradient of strain builds up as the sliding progresses. The strain would be maximum near the surface and would decrease as one moves from the surface into the subsurface.[8,12,15] This gradient can be expected to be constant under steady state sliding conditions when the coefficient of friction and wear rate is expected to be constant. The gradient of strain that exists in a subsurface is shown schematically in Fig. 1 for the pin, which is softer, in the pin-on-disk experiments conducted here.

As the pin wears under steady-state conditions, the material, which was originally in the sub-surface, approaches the surface at a constant rate. In doing so, the material undergoes increasing strain. It finally reaches the surface and detaches as debris. The material also experiences deformation at increasing strain rates and temperatures (to a lesser degree) as it approaches the surface. For a given rate of height loss (wear rate) of the pin the strain rate can be given as

$$\dot{\varepsilon} = \left(\frac{d\bar{\varepsilon}}{dt}\right) = \left(\frac{\partial\bar{\varepsilon}}{\partial x}\right)\cdot\left(\frac{dx}{dt}\right) + \left(\frac{\partial\bar{\varepsilon}}{\partial y}\right)\cdot\left(\frac{dy}{dt}\right)$$

$$= \left(\frac{\partial\bar{\varepsilon}}{\partial x}\right)\cdot\left(\frac{dx}{dt}\right) \left(\text{As } \frac{\partial\bar{\varepsilon}}{\partial y} = 0 \text{ for steady state sliding}\right)$$

$$= \sqrt{3}\left(\frac{d\partial_x}{dx}\right)\cdot\left(\frac{dx}{dt}\right).$$

Here $d\varepsilon_x/dx$ is the change in strain as one moves from the surface to the subsurface, and dx/dt is the rate of height loss of the pin. The x and y directions are indicated in Fig. 1. $d\varepsilon_x/dx$ can be estimated by methods given by Dautzenberg[3,4] or Alpas et al.[8] If dx/dt is known from experiments, the strain rates can be estimated in the plastically deforming regions near the pin surface. The estimation of temperatures existing in the surface and subsurface has always been a debated point.[26] In the present work the temperature is estimated by simple 2D equations given in the book by Zum Gahr.[26] During plastic deformation of a material, part of the work done is used for the microstructural evolution and part is dissipated as heat.[28,29] This partitioning of power depends on the strain rate and temperature at which the material is deformed and also decides the microstructural evolution of the material. Some of the microstructural mechanisms that operate, depending on the strain rate and temperature, are dynamic strain aging, wedge cracking, dynamic recovery, dynamic recrystallization, adiabatic shear banding, and inter-crystalline cracking. The microstructures evolved during the compression tests of Ti are shown in Fig. 2. The strain rates and temperatures estimated in the pin are also superimposed. The strain rates are estimated at a depth of 0.1, 1, 10, and 100 μm below the surface, and the temperatures are estimated for various sliding speeds tested. The curves in the left represents 0.1 ms^{-1} and as one move towards the curves on the right, the speed increases to 0.4, 1.5, and 4.0 ms^{-1}. The surface and subsurface temperatures are expected to increase as the sliding speed is increased. From the microstructures evolved in uniaxial compression tests, it can be seen that Ti undergoes intense adiabatic shear banding when compressed at high strain rates (>10 s^{-1}) and at lower temperatures (<575 K). Adiabatic shear banding is a microstructural evolution that causes flow localization and regions of crack nucleation. This can be seen from the micrographs of the compression tests at various strain rates and temperatures shown in Fig. 3. Figure 3(a) shows the microstructure evolved when compressed at 298 K and 100 s^{-1}, where the intensity of adiabatic shear banding is high. The intensity adiabatic shear banding can be seen to

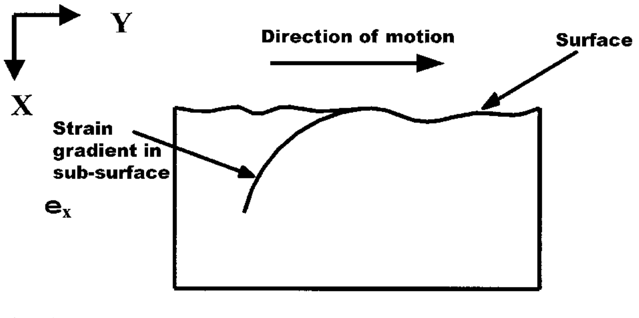

Fig. 1 Schematic of the plastic strain gradient that exists in the sub-surface of the pin

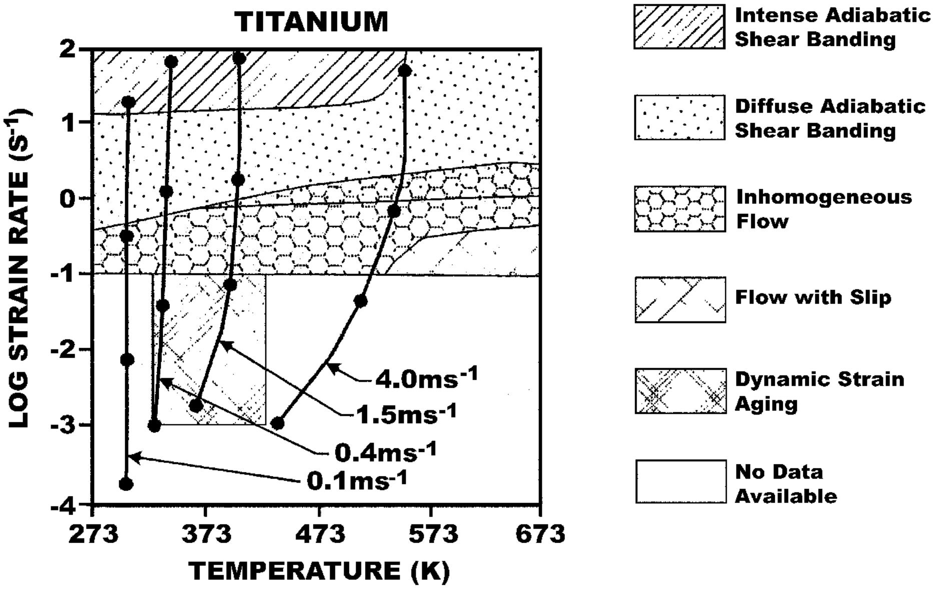

Fig. 2 Strain rate microstructural response map for Ti obtained from the uniaxial compression tests done at various constant true strain rates and temperatures. The curves represent the strain rates and temperatures estimated in the subsurface of the pin at various sliding speeds and depths. The speed increases from 0.1, 0.4, 1.5, and 4.0 ms^{-1} for the dashed lines from left to right, and the depth at which the strain rates and temperature are estimated increases from top to bottom. The solid line represents depths of 0.1, 1.0, 10.0, and 100 μm from the surface.

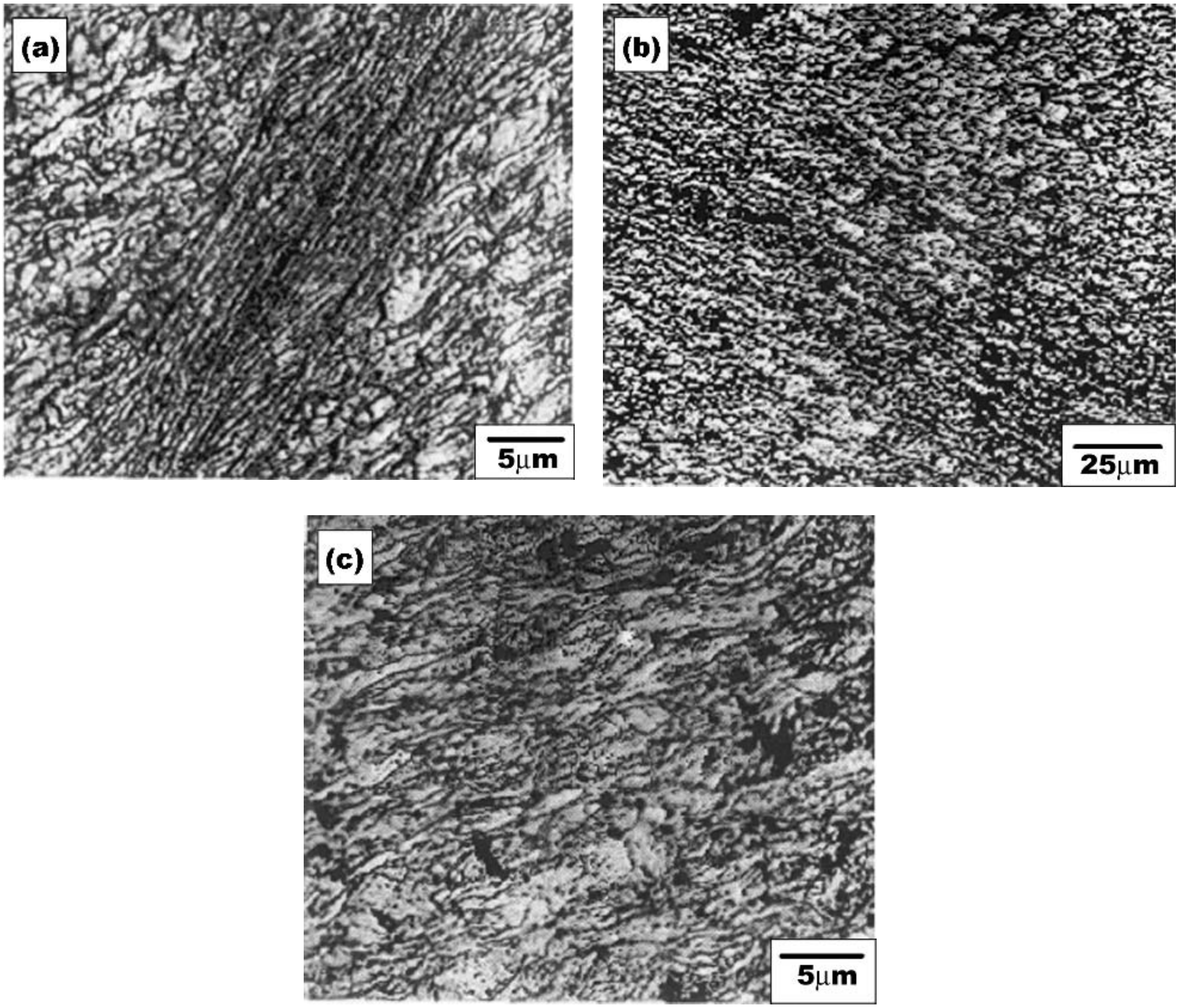

Fig. 3 Optical micrographs of Ti microstructures evolved during compression of titanium: **(a)** 298 K and 100 s^{-1}; The intensity of the adiabatic shear banding is high. **(b)** 298 K and 10 s^{-1}; The intensity of adiabatic shear banding has reduced. **(c)** 673 K and 100 s^{-1}; Adiabatic shear bands are almost absent.

reduce as the strain rate is reduced (Fig. 3b) or the temperature is increased (Fig. 3c). As wear is a process in which cracking is essential to form debris, a microstructural evolution that increases the probability of cracking could affect the wear mechanism and wear rate.

Figure 2 shows that the near surface region is expected to undergo intense adiabatic shear banding at low sliding speed. As the sliding speed increases, the intensity of this adiabatic shear banding, in the near surface region, is expected to decrease and the microstructure evolved would be more homogeneous. When the intensity of adiabatic shear banding is high in the near-surface region, it can be expected that the cracking intensity will be high in these regions. This is because adiabatic shear bands are sites for crack nucleation and propagation. This would lead to a larger number of wear debris being generated, leading to a high wear rate. The wear rate is, then, expected to reduce as the sliding speed increases, when the adiabatic shear banding intensity reduces; which in turn should reduce the intensity of cracking and debris formation. This, in fact, is what

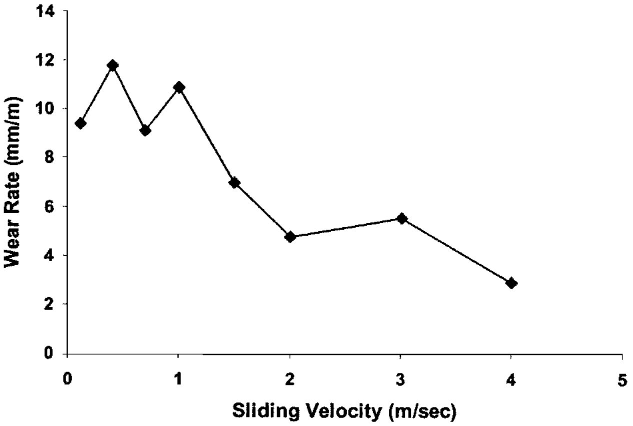

Fig. 4 Variation of wear rate with speed for titanium. The wear rate is high when the near-surface regions undergo intense adiabatic shear banding. The wear rate reduces as the as the sliding speed increases and increases the sub-surface temperature, reducing the intensity of adiabatic shear banding.

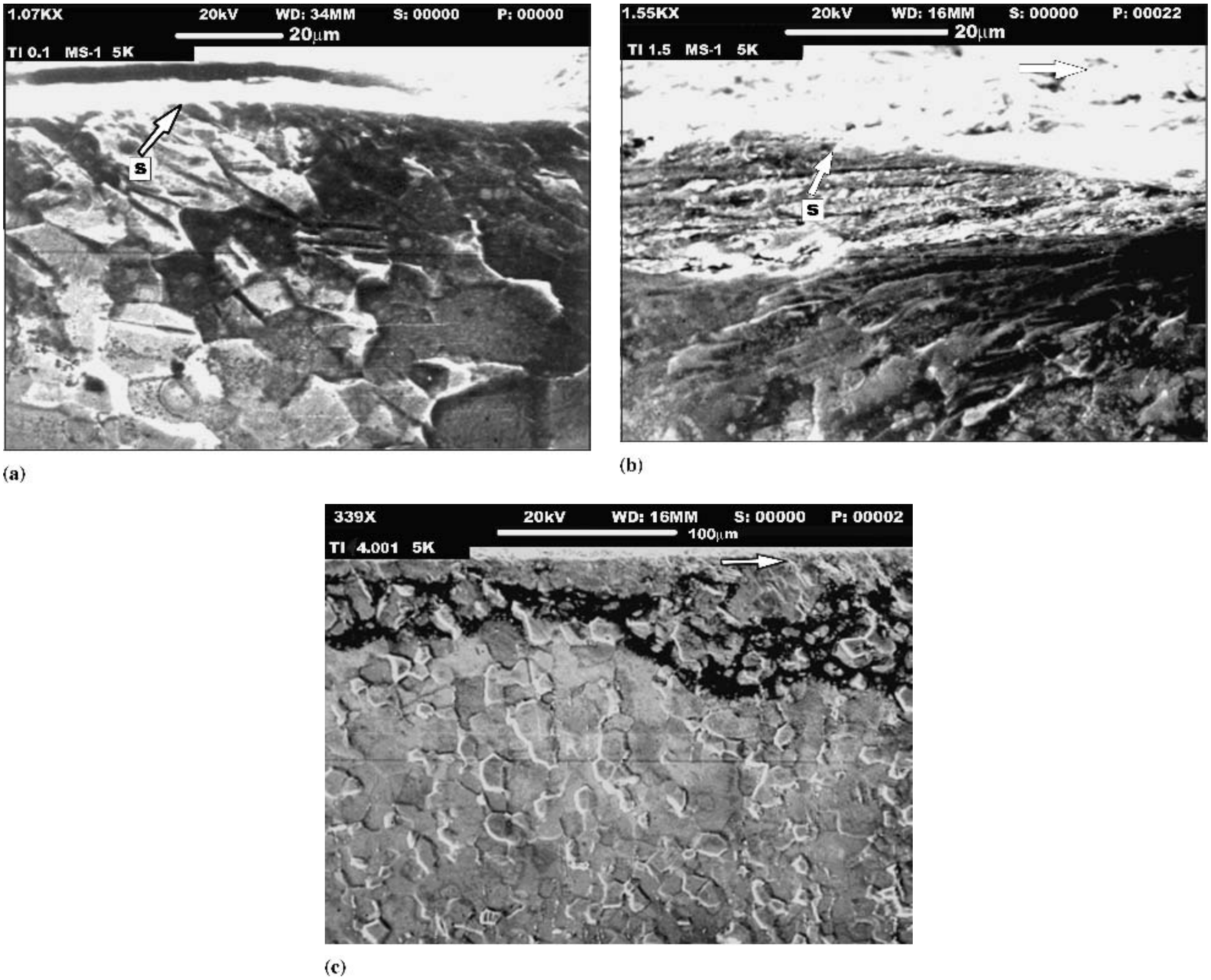

Fig. 5 Sub-surface micrographs of Ti pins at various sliding speeds: **(a)** Sliding speed of 0.1 ms^{-1}; the subsurface deformation is low due to adiabatic shear banding induced cracking near the surface that does not allow plastic deformation to propagate to the sub-surface. **(b)** Sliding speed of 1.5 ms^{-1}; the intensity of subsurface deformation increases as adiabatic shear banding intensity reduces allowing plastic deformation to propagate to the sub-surface. **(c)** Sliding speed of 4.0 ms^{-1}; large amount of inter-crystalline cracking can be seen in the subsurface. The big arrow indicates the direction of sliding.

is observed in Fig. 4 which show that the wear rate is high when the adiabatic shear banding intensity is high (low sliding speeds). The wear rate is seen to reduce as the adiabatic shear banding intensity in the near surface regions reduces (higher sliding speeds). The subsurface micrographs of the titanium pins are shown in Fig. 5. Figure 5(a) shows the micrographs at a sliding speed of 0.1 ms^{-1}. Here it can be seen that the sub-surface deformation is almost absent. This can be expected as the intense adiabatic shear band induced cracking near the surface will not allow plastic deformation to propagate to the subsurface. For a sliding speed of 1.5 ms^{-1} (Fig. 5b) the amount of subsurface deformation increases. This is due to the fact that the intensity of adiabatic shear banding and the concomitant cracking is lower, which allows plastic deformation to propagate to the subsurface. At 4 ms^{-1} (Fig. 5c) an inter-crystalline cracking can be seen. Inter-crystalline cracking occures in pockets, while the other regions have a homogeneous deformation structure similar to that seen in Fig. 5(b). The fact that the inter-crystalline cracking is observed only in pockets keeps the wear rate low. Inter-crystalline cracking is a phenomenon that is expected to occur at temperatures higher than the one that is estimated here. This indicates that the method adopted to calculate the sub-surface temperatures here has errors at higher speeds of sliding. Though the quantum of error is debatable it is felt that a more accurate calculation of the temperature is required. Despite these errors in the calculation of temperature, from the results discussed, it is clear that the strain rate response of Ti, which undergoes intense adiabatic shear banding at high strain rates and low temperatures, plays a role in its wear rate and subsurface microstructural evolution.

The micrographs of Cu got from the compression tests are shown in Fig. 6. Here the micrographs at intermediate strain rates (1 s^{-1}) and low temperatures (<500 K) show flow banding

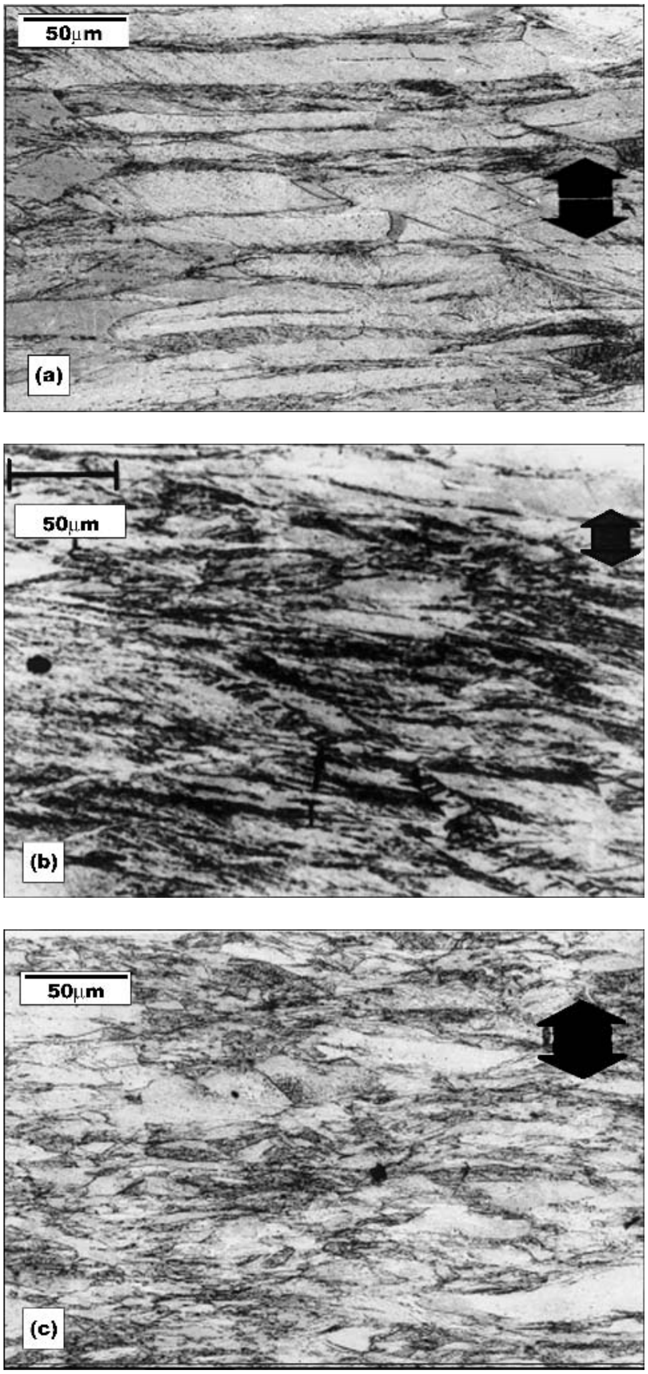

Fig. 6 Optical micrographs of microstructure evolved in Cu from compression tests: **(a)** At 298 K and 1 s^{-1}, flow bands are seen. **(b)** At 298 K and 100 s^{-1}; no flow banding is observed. **(c)** At 298 K and 0.1 s^{-1}, no flow banding is observed

Fig. 7 Scanning electron micrograph of a flow band seen at 298 K and 1 s^{-1}. Cracks at flow band boundaries (marked by arrows and "c") can be seen.

(Fig. 6a). The intensity of flow banding decrease at strain rates higher than 1 s^{-1}(Fig. 6b) and at strain rates lower than 1 s^{-1} (Fig. 6c). The flow banding intensity also reduces as the temperature is increased. These flow bands are also sites of crack nucleation (Fig. 7). The strain rates and temperatures existing in the subsurface are estimated at various speeds and superimposed on the strain rate response microstructural map (Fig. 8). The curves are drawn for the same subsurface depths as in the case of titanium and speeds of to 0.4, 0.7, 1.0, 1.5, 2.0, 3.0, and 4.0 ms^{-1}. In this case, at low speeds, the combination of strain rate and temperature at which flow banding and crack nucleation will take place is in the subsurface. The flow near the surface, where higher strain rates and temperatures exist, would be homogeneous as the strain rates are higher. Thus one can expect subsurface cracking at low speeds. Investigation of the micrographs of the subsurface of the specimens slid at lower speeds shows intense subsurface cracking (Fig. 9a) and formation of sheet like debris (Fig. 9b). This subsurface cracking disappears at higher sliding speeds (Fig. 9c). A "beard" formation is also seen at higher sliding speeds (Fig. 9d). This "beard" is due to high temperature material being extruded and squeezed out of the trailing edge of the pin. Figure 8(d) also indicates that the temperatures calculated at higher sliding speeds is underestimated. The increase in the wear rate at high speeds could be due to high temperature squeezing out of material from the trailing edge. The wear rate data for Cu is shown in Fig. 10, where it can be seen that the wear rates are high when subsurface cracking is intense (low sliding speeds) and reduces when the intensity of subsurface cracking reduces (high sliding speeds). The existence of subsurface cracking and sheet-like debris formation in Cu at lower sliding speeds also indicate that the strain rate response of a material plays an important role in deciding the wear mechanism and wear rate. The investigation also revealed that the wear rate does not depend on hardness, as Ti is a harder material than Cu with a much higher wear rate.

In the present paper the wear of Ti and Cu was related to the strain rate microstructural response of these metals in uniaxial compression. It is known that the state-of-stress could play an important role in the microstructural response of the material, a response that is termed as "geometric response."[35,36] The microstructural response of the material could also be state-of-stress independent, a response that is termed as "intrinsic response." Further, the strain rate microstructural response of the

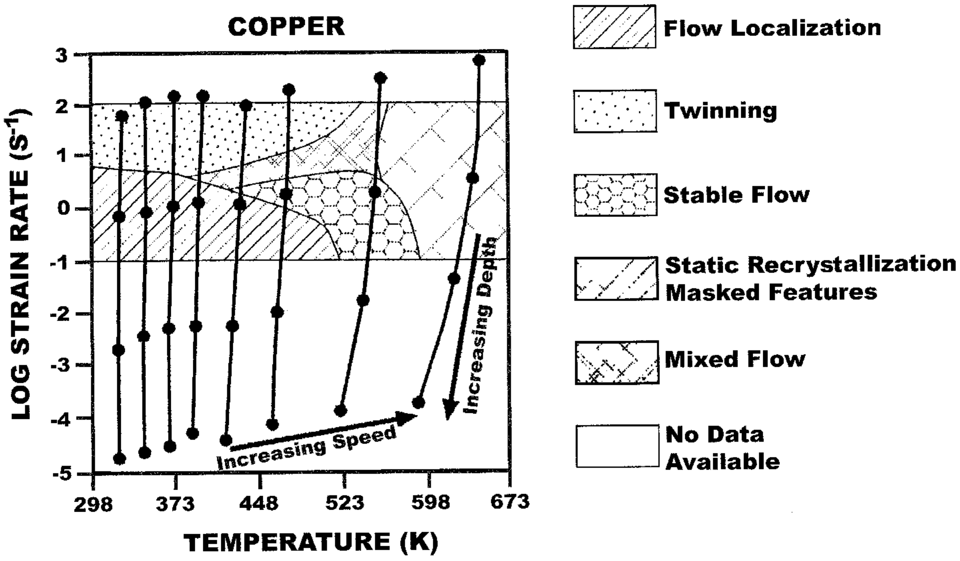

Fig. 8 Strain rate microstructural response map of Cu obtained from compression tests at various constant true strain rates and temperatures. The curves show the estimated strain rates and temperatures existing in the subsurface at various speeds of sliding. The speeds increase for curves from left to right (0.1, 0.4, 0.7, 1.0, 1.5, 2.0, 3.0, and 4.0 ms^{-1}). The points, from top to bottom, on the curve represent strain rates and temperatures estimated at 0.1, 1.0, 10.0, and 100.0 μm from the surface.

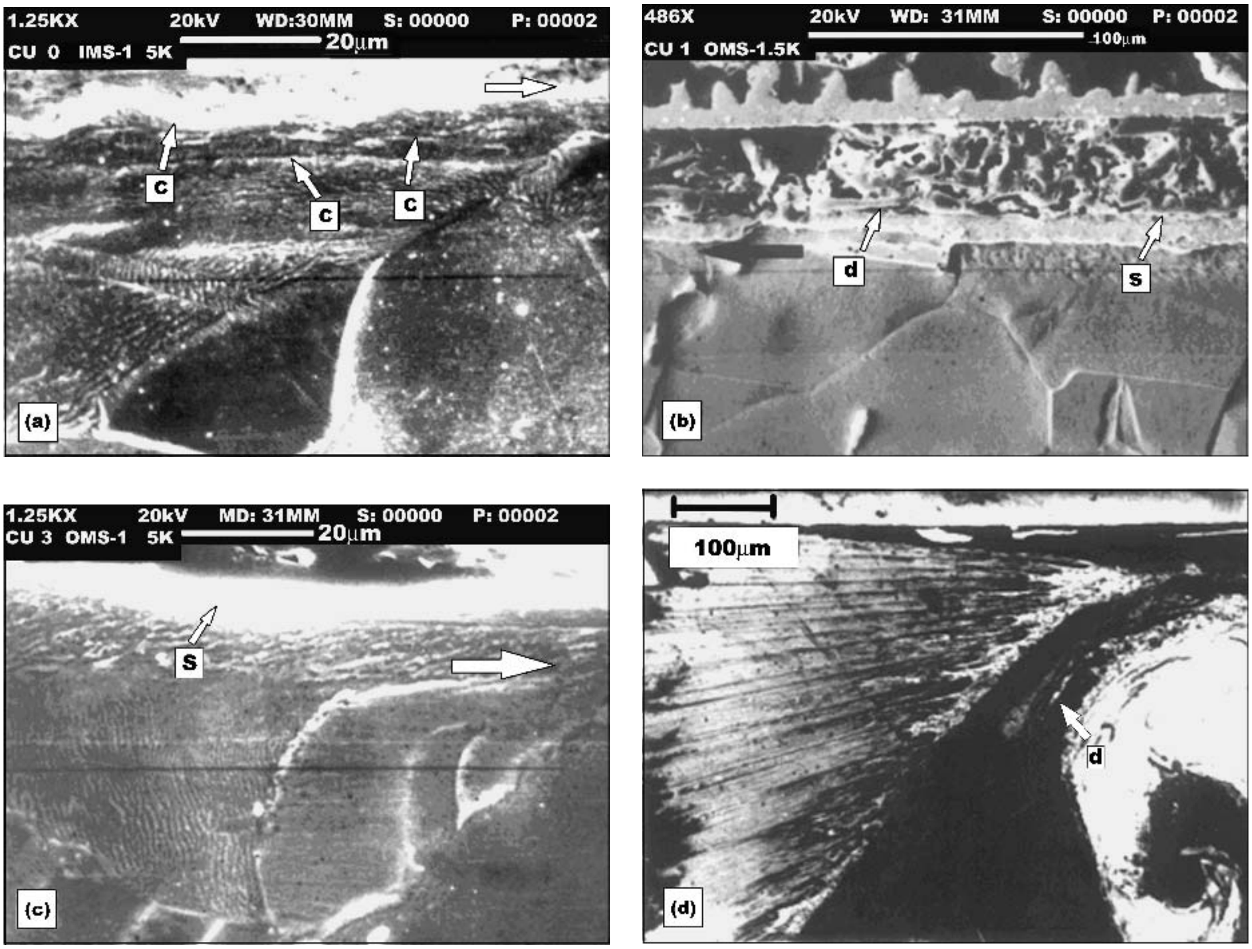

Fig. 9 Subsurface scanning electron micrographs of Cu pin at various speeds: **(a)** Sliding speed of 0.1 ms^{-1}; sub-surface cracking is observed. **(b)** Sliding speed of 0.4 ms^{-1}; sheet like debris are seen. **(c)** Sliding speed of 2.0 ms^{-1}; subsurface cracking is absent. **(d)** Sliding speed of 4.0 ms^{-1}; "beard" formation, indicating high temperature near the surface, is seen.

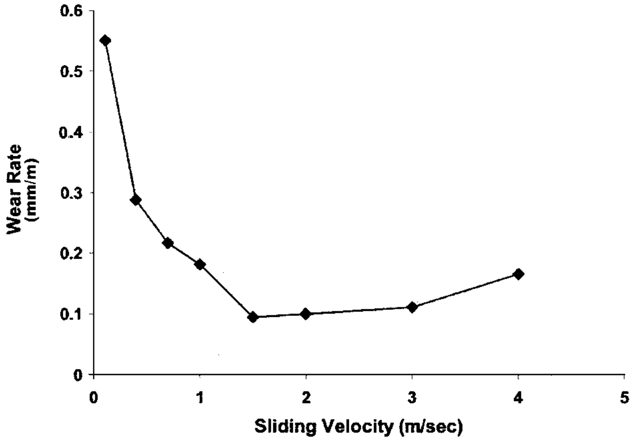

Fig. 10 Variation of wear rate as a function of speed for Cu. The wear rate of Cu is higher at low speeds of sliding, when the strain rate microstructural response induced subsurface cracking is high, and reduces as the sliding speed increases when the strain rate microstructural response induced subsurface cracking is absent.

material depends on the prior processing history of the material[37] and on the initial texture.[38] These factors have to be considered in relating the strain rate microstructural response of the material to the surface and subsurface microstructural evolution of the material during sliding. It is important to consider the prior processing history as the material during sliding undergoes deformation at increasing strain rates and temperatures as it approaches the surface. And texture could also play a role in the wear of material.[39] Apart from these factors, the factors that could change the worn surface chemistry need to be looked into. The factors that could change the near surface chemistry include mechanically mixed layers and oxidation. Despite not considering these factors there is a definite correlation between the strain rate microstructural response of the material to the surface and subsurface microstructural evolution, wear mechanism, and wear rate of materials. In the present set of experiments, it can be said that when the strain-rate-dependant microstructural response leads to an inhomogeneous microstructure prone to cracking, the wear rates would be high.

4. Conclusions

Ti, which undergoes intense adiabatic shear banding at high strain rates (≥ 10 s^{-1}) and low temperatures (<573 K) has high wear rates when slid in conditions that promote a similar strain rate and temperature in the near surface regions. When Ti is slid in regions of high adiabatic shear banding intensity the subsurface strain is low. This is because the intense cracking in the near surface regions does not allow strains to propagate to the subsurface. When the sliding speed is increased for Ti, the adiabatic shear banding intensity near the surface decreases, decreasing the cracking intensity in this region. This leads to an increase in the strain in the subsurface. At higher sliding speeds (4.0 ms^{-1}) intercrystalline cracking is observed in the subsurface of the pin. This indicates to the existence of high temperature (0.9 T_m) in the subsurface of the pin, as intercrystalline cracking is a high-temperature, high-strain-rate microstructural phenomenon for Ti.

Cu, which undergoes flow banding at intermediate strain rates (0.1 s^{-1}) and lower temperatures ($\leq$473 K) has high wear rates when slid in the conditions that promote a similar strain rate and temperature in the subsurface region. When Cu is slid in regions of high flow banding, cracks are observed in the subsurface, and sheet like debris forms. At higher sliding speeds, the subsurface cracking disappears as the microstructural response moves to a more homogeneous response. The "beard" formation, due to squeezing out of high-temperature material from the trailing edge, at high sliding speeds (4.0 ms^{-1}) indicates that the near-surface temperatures calculated is much lower than what actually exists.

The strain rate microstructural response of a material plays an important role in the near surface and subsurface microstructural evolution and wear rate of a material. If the strain rate response promotes cracking in the near surface or the subsurface, the wear rate will be higher.

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