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Research Paper

WEAR BEHAVIOR AND MICROSTRUCTURAL ANALYSIS OF COMMERCIALLY PURE TI AND ITS ALLOYS ON DRY SLIDING: A REVIEW

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Titanium and its alloys exhibit a unique combination of physical and corrosion resistance properties which make them ideal materials for space flight engine component such as disks and blades of compressor, marine applications, chemical industries and many bio medical applications. However the use of these materials is limited due to its poor tribological properties. Because of this reason, these materials are of much interest to the researchers from few decades and they were subjected to many experiments to explore the wear behavior to a maximum extent. In this paper an attempt has been made to consolidate some aspect of wear behavior of CP Ti and factors affecting the wear mechanism.

Keywords: CP Titanium, Ti-6Al-4V, Strain rate response, Tribo-oxidation, Mechanically mixed layer, Dry sliding behavior

INTRODUCTION

Titanium alloys are being increasingly used in aerospace and automobile industries owing to their enhanced properties such as high strength to weight ratio, corrosion resistivity, tensile strength at room and elevated temperatures, wear resistance combined with significant weight savings over unreinforced alloys.

These materials have gained a lot of commercial importance in places where there is a requirement of high strength and density (Collings E W, 1984)). But these materials are observed to have a low siding wear resistance owing to their low resistance to plastic shearing and the poor protection provided by the surface oxides (Budinski K G, xxxx; Yerramareddy S and Bahadur S, 1992; Eyre T S and Alsahin H, 1977). With a view to improve the wear resistance there are a number of surface modification treatments being developed (Bell *et al.*, 1986).

Wear is a process of damage that generally involves progressive loss of material due to mechanical contact of matter. Wear is

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quantified by the term wear rate which is defined as the mass or volume or height loss of material removed per unit time or sliding distance. Wear phenomena can be characterized in to two main groups depending up on the mode of interaction of the contact surfaces (Jahanmir S, 1978). In first group, wear mechanism is dominated by mechanical interaction which includes adhesion, abrasion, delamination, impact wear and surface fatigue, etc. Second group is primarily dominated by chemical interaction which includes corrosive wear, diffusive wear and oxidative wear.

The characteristics features and definitions of different wear mechanisms are given in Table 1.

Another method of classification of wear depends on the intensity of material loss. Such classification asmild wear and severe wear, is based on scale size of wear debris. In mild wear, wear occurs at the outer surface layers and worn debris contains fine oxide particles of size vary from 0.01 nm to 100 nm. In severe wear, wear occurs at deep surfaces and size of wear debris ranges from 100 nm to 100 μm.

Nagaraj and Kailas studied the effect of strain rate response approach and tribo oxidation to explain the wear and friction behavior of Ti. (Kailas S V and Biswas S K, 1995; Kailas S V and Biswas S K, 1997; Kailas S V and Biswas S K, 1999). Strain rate response approach is associated with microstructural response of metal to imposed condition of strain, strain rate and temperature. Microstructural response is mainly based on Dynamics Material Model (DMM). DMM is based up on the principle that the efficiency by which the material dissipates power

Table 1: Characteristics Features of Different Wear Mechanisims

Mechacnism	Definition	Characteristics
Adhesion	Wear due to transfer of material from one surface to another surface by shearing of solid welded junctions of asperity	Adhesion bonding, shearing and material transfer
Abrasion	Wear due to hard particles or proturburence sliding along a soft solid surface	Ploughing, wedging and cutting
Delamination	Wear caused by delamination of thin material sheets beneath the interface in the subsurface	Plastic deformation, crack nucleation and propagation
Erosion	Wear due to mechanical interaction between solid surface and a fluid, or impinging liquid or solid particle.	Angle of incidence, large scale subsurface deformation, crack initiation and nucleation.
Fretting	Wear due to small amplitude oscillatory tangential movement between two surfaces	Relative displacement, amplitude and entrapment of wear particle
Fatigue	Wear caused by fracture arising from surface fatigue	Cyclic loading and fatigue crack propagation
Oxidation	Wear takes place when sliding occurs in oxidative environment	Formation of weak, mechanically incompatible oxide layer.

decides its microstructural response. The power involved during plastic deformation is given by P=σE. According to DMM (Prasad Y V R K *et al.*, 1984; Prasad Y V R K and Seshacharyalu T, 1998), this power is consumed in heat dissipation and microstructural changes. This power partitioning is decided by strain rate sensitivity of flow stress (m) of the material. The various microstructural responses of material include Adiabatic Shear Banding (ASB), flow banding (FB), twining, dynamics recrystallization, and super plasticity. Narrow shear bands occur quite frequently in a variety of materials under dynamic loadings and are usually termed as adiabatic shear bands (ASB) (Rogers H C, 1979; Bai Y L, 1990). These bands relate closely to failure and cracking in structural materials (Xu *et al.,* 1989; Meyer L W *et al.,* 1994). For a given metal or alloy the specific microstructural evolution was found to be related to the imposed strain rate and temperature and therefore designated as strain rate response. This frame of work may be extended to a wear situation, as in the subsurface regions a large gradient of strain exists (Kailas S V and Biswas S K, 1995; Kailas S V and Biswas S K, 1997; Kailas S V and Biswas S K, 1999). Adiabatic Shear Banding (ASB) is a microstructural mechanism that promotes cracking. A particular combination of strain rate and temperature occur in surface which results in deleterious strain rate response where crack is nucleated and propagated. In titanium it was experimentally observed that wear rate reduces with increase in sliding speed. This is due to reduction in the intensity of ASB in near surface region of titanium pin (Kailas S V and Biswas S K, 1997). ASB depends on many factors such as abrasive particles, tempering temperature, number of impact etc.

Figure 1: Microstructural Response Map for Titanium

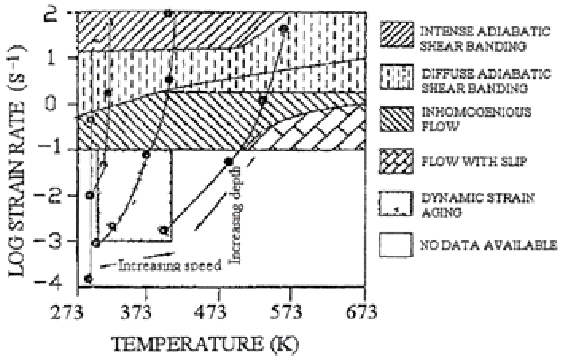


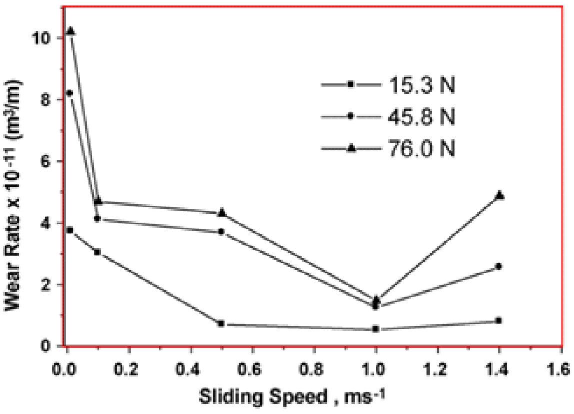
Figure 1 shows the strain rate microstructural response map for titanium obtained from the uniaxial compression tests done at various constant true strain rates and temperatures. The curves represent the strain rates and temperatures estimated in the subsurface of the titanium pin at various sliding speeds and depths.

In case of titanium, Kailas and Biswas (1995) observed experimentally that wear rate reduces with an increase in sliding speed. This was postulated to be due to the reduction in the intensity of ASB (microstructural instability) in near-surface regions of the titanium pin. Strain rate response approach made a good correlation between the wear rate and microstructural evolution in the near-surface region (Kailas S V, 2003).

Under ambient condition, the material responds to the increase in potential energy due to friction by thermal oxidation. For many metals and alloys, there is a transition temperature (either ambient temperature or surface temperature due to frictional heat) above which the wear rate in the mild wear regime becomes very low compared with the corresponding rate at lower ambient or surface temperatures (Stott F H *et al*., 1985; Smith A F, 1986; Newman P T and Skinner J, 1986). This is due to the establishment of a continuous oxide layer (sometimes known as a 'glaze') which gives reduced resistance to sliding and good protection against wear damage.This oxide layer acts as a solid lubricant and prevents further metal to metal contact thus reducing co-efficient of friction and wear rate. In titanium presence of TiO_2 layer reduce the co-efficient of friction from 0.75 to 0.40 by avoiding direct contact between titanium and other surface (Hong H *et al*., 1988). I.I Garbar showed that as normal load increases, tribo-oxidation is accompanied by the mechanism of plastic deformation (Garbar I I, 2002).

Mao et al. (Cui *et al*., 2012) explained that Tribo-layer, a mechanical mixing layer existed on worn surfaces under various conditions. However, the protective role of tribo-layer depended on whether more oxides appeared or not. The Mechanically Mixed Layer with more oxides gave an obviously protective role due to its high hardness. In the case of material like titanium alloys, most wear mechanism observed are consistent with Archard adhesive wear characteristics by plastic ploughing and transfer of material from the counterface. With respect to friction and wear behavior, numerous authors(Perrin and Rainforth, 1995, Leonard et al., 1997, Jiang and Tan, 1996, How and Baker, 1997 and Rigney, 1998) have concluded that the tribological behavior is influenced by the mechanical, physical and chemical properties of these near-surface materials. In all case, a mechanically mixed layer (MML), otherwise called Tribo layer, was present in most dry worn wrought titanium alloys due to the repetitive sliding.(check continuity of para

Figure 2: Shows Wear Rate of Pure Ti with Sliding Speed for Normal Load of (a) 15.3N (b) 45.8N (c) 76N under Ambient Conditions [24]



The purpose of this paper is to come to the general understanding of wear mechanisms by reviewing the characteristics of wear CP Ti and summarizing the factors affecting the wear mechanisms of Ti.

WEAR BEHAVIOR OF TI

Figure 2 shows the variation of wear rate with sliding speed of CP Ti sliding against alumina disk under ambient conditions. Under ambient conditionsthey noticed that wear rate is high at speed of 0.01m/s; this can be attributed to the high intensity of ASB due to low temperature which initiates crack nucleation and propagation and lack of tribo oxidation. But at 0.1m/s, 0.5m/s and 1.0m/s wear rate is found to be low. This is due to the tribo oxidation and MML formation. As speed increases, the flow of ASB become in homogenous manner and interface temperature increases which result in tribo oxidation. In tribo oxidation a thin oxide layer of several micron thicknesses produced over metallic surface in sliding contact. This oxide layer acts as a solid lubricant and prevents further metal to metal contact thus reducing wear rate. The protecting nature of oxide is due to its high thermal stability and better hardness compared to that of base materials. The presence of oxide at these speeds is confirmed by surface micrograph of Ti pin along the sliding direction at constant load as shown in Figure 5. During sliding of metals Mechanically Mixed Layer formation is caused by the chemical reaction and mechanical mixing of oxides and base materials. The hardness of MML depends upon the amount of oxides present in it. It is seen that amount of oxides increases with the speed which is the reason for increase in its hardness and protecting nature. This is due to the mixing of oxides and base material at higher temperature induced because of higher speed. Thus we can say that more amount of oxide compound in Mechanically Mixed Layer, for eg TiO_2, will increase the hardness of MML hence will improve the wear property of the material. The amount of oxides and hardness of Mechanically Mixed Layer depends upon the temperature, which in turn is a function of speed and load. Figure 4 shows the EDS line analysis of tribo-layer of Ti–6Al–4V alloy sliding under various conditions (Cui *et al*., 2012). It can be noticed that various oxide such as TiO_2 and Fe_2O_3 exists on the pin surface of Ti-6Al-4V. The hardness and material properties of oxide and MML layer is different from that of base metal which results in better wear behavior. Thus oxide amount and hardness of MML play main role in friction and wear behavior.

Figure 3: Shows Wear Rate of Pure Ti with Sliding Speed for Normal Load of (a) 15.3N (b) 45.8N (c) 76N under Vacuum Conditions [24]

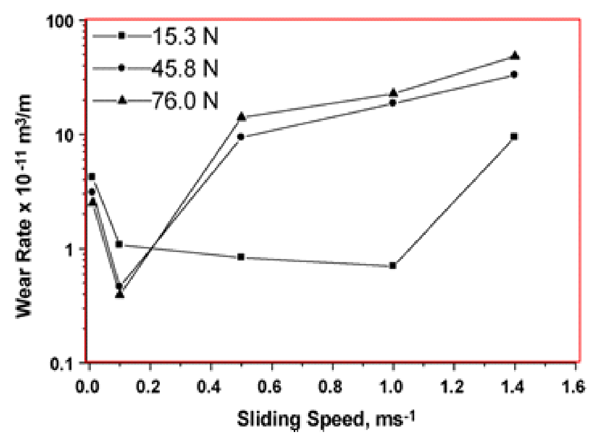


Figure 4: EDS Line Analysis of Tribo-layer of Ti-6Al-4V Alloy Sliding Under Various Conditions:(a)25 1C, 100N;(b)200 1C, 100N;(c)400 1C, 100N; and (d)500 1C, 100N. [23]

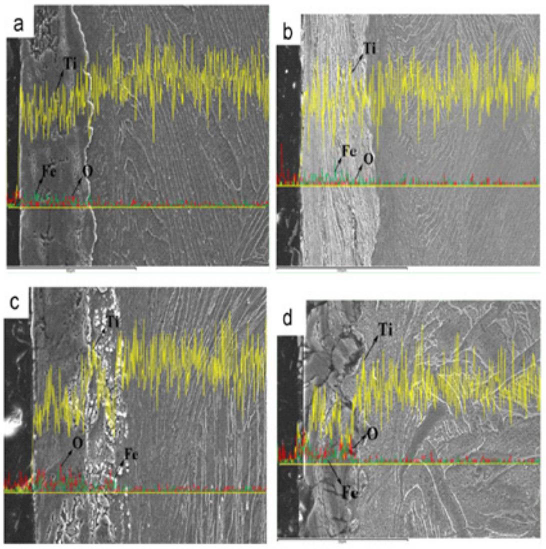


Figure 3 shows the wear rate of Pure Ti with sliding speed for different normal load under vacuum conditions. Under vacuum conditions they noticed that the wear rate is quiet higher compared to that in ambient conditions for all speeds; this can be attributed to the lack of tribo oxidation and MML, high temperature

Figure 5: Worn Surface of Pure Ti Slid with Normal Load of 15.3N Under Ambient Conditions at Sliding Speed of (a) 0.01m/s and (b) 1.0m/s[24]

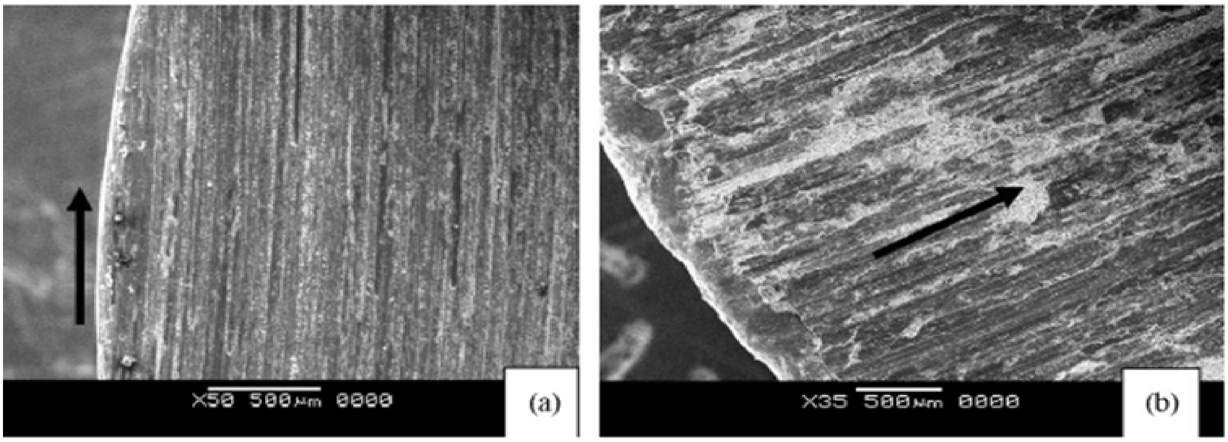


Figure 6: Wear Debris of Ti Slid at Normal Load of 45.8N with Sliding Speed of (a) 0.01m/s and (b) 1.0m/s [24]

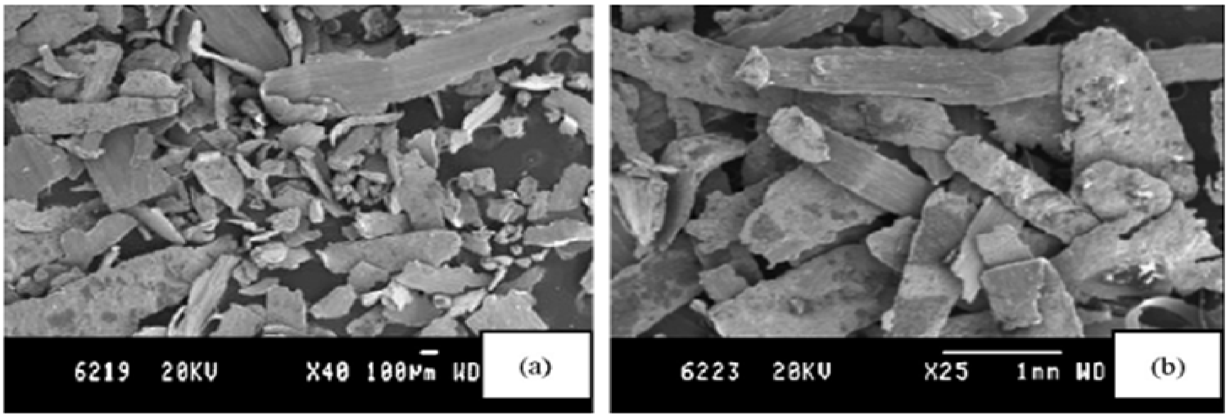
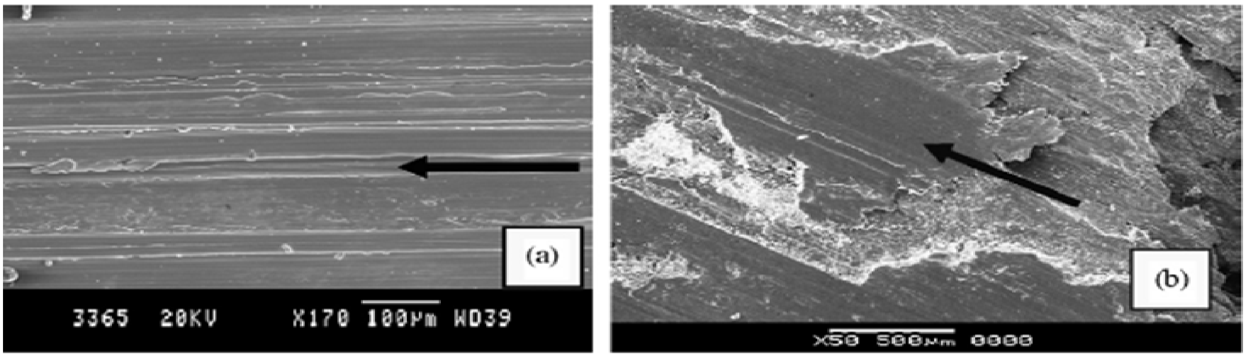


Figure 7: Worn Surface of Pure Ti Slid with Normal Load of 45.3N Under Vacuum Conditions at Sliding Speed of (a) 0.01m/s and (b) 1.0m/s [24]



which will cause large plastic deformation and high surface energy of adhesion in vacuum conditions. The clean surface in vacuum conditions results in high surface energy of adhesion. Hard asperities, plowing over a softer surface of the pin without cutting will produce ridges. Ridges can then be flattened by further contact. As a result extrusions or lips are formed. These lips are broken off and become flat wear flakes. One of the feature in subsurface micrograph under vacuum conditions that is different from the subsurface micrograph under ambient conditions is that at 1.0m/s a 'beard' is seen under vacuum conditions (Figure 7). This 'beard' like feature is a clear indication of very large plastic deformations near the surface regions. The squeezing of the high temperature material results in the formation of the 'beard' and the wear debris with large size.

FACTORS AFFECTING WEAR BEHAVIOR

Effect of normal load

Rabinowicz [25] showed experimentally that wear loss of copper is proportional to applied normal load when sliding against steel. He reasoned that increasing the normal load results in an increase in the number of adhesive junctions and an increase in wear rate of copper. It was observed by Archard [26] that, there was a transition from mild to severe wear, when the contact pressure reached to value of about one third of hardness of metals. This was attributed to the interaction of plastic zones that occurred beneath the contacting asperities. In high load regime, mechanical damage of material occurs due to high surface stresses. It was observed that an increase in load results in monotonic increase in interface temperature, which led to the reduction of the yield stress of a material. Hence, it could be concluded that the wear rate of material was a linear function of normal load. However, it was also observed that rate of increase in wear rate did not remain constant over the long range of normal load.

Effect of Sliding Velocity

Experiments were conducted by Suh et a1 [27] under ambient conditions on commercially pure titanium using pin on-ring geometry. A decrease in wear rate of Ti was observed with the increase of sliding speed. He reasoned that due to the increase in temperature, the drop in wear rate occurred as there was an increased resistance of the material to crack nucleation and propagation. The amount of frictional heat that is generated during dry sliding condition, with the increasing sliding speed increases, this leads to the tribo-oxidation, which forms an oxide layer at the interface. This oxide film serves as lubricant which reduces the wear rate of metals. In the case of lubricated condition, at higher sliding speed, the formation of hydrodynamic lubricant film at the interface minimizes the wear rate. Generally, wear rate of metals shows a decreasing trend with sliding speed in dry as well as lubricated sliding conditions. However, if interfacial temperature reaches the melting point of a metal, it lowers the hardness of the metals drastically and causes severe wear.

Effect of Temperature

The temperature is an important parameter, which influences the wear response of metal in the following way.

1. It accelerates the chemical reactivity of a metal surface.
2. The physical and the mechanical properties of the metals are altered.
3. It changes the microstructural response too.

Deanley P A and Dahm K L (2004) studied the wear behavior of thermally oxidized and untreated pure titanium's samples. He found that wear rate of untreated titanium is greater than that of thermally oxidized titanium. Thus he reached to a conclusion that the generation of the TiO_2 layer provided protection by interfacial fracture. Hence it is understood that thermal induced oxidation reduces the wear rate of metals. Rabinowicz (1980) performed sliding tests on cobalt-steel pair at different temperatures. He observed the wear rate at 653 K to be nearly 100 times than that observed at 553K. The reason attributed to this increase is the phase transformation from HCP to FCC structure.

In dry sliding, temperature is a function of speed and load. Higher speed or/and higher load result in high temperature. Thus we can say that wear behavior is governed by temperature which in turn is a function of speed and load.

Effect of Environment

Hutching *et al*. (Hutching I M, 1992) studied the influence of environment on wear behavior of commercially pure titanium. He observed that titanium exhibited a linear wear behavior under ambient conditions, but a linear behavior was not observed in inert gas atmosphere. He observed that titanium exhibits high wear rate in an inert atmosphere which was due to severe adhesion and material transfer. In ambient conditions, the wear rate of metals can be lower than in inert atmosphere only if the oxide film is strong enough to prevent the direct contact between metal-metal surfaces. One could expect that wear rate of metals is higher in vacuum than in air. But the opposite is also true. Rigney[30] observed that wear and friction of lead and babbit alloys are high in vacuum than air. He concluded that formation of fine-grained layer in air induces non-uniform sliding which causes high friction and wear.

Effect of Hardness

According to the Archard model (Rigney D A, 1997), the wear rate of metals is an inverse function of their hardness. Harder materials can provide better resistance to cutting and penetration. In the case of abrasive wear, it is easy to correlate hardness with wear rate as it involves penetration process. Kruschov *et al*. [32] studied the relative wear resistance of pure metals and cold worked steels as a function of hardness in two-body abrasion. There was no effect of prior work hardening reported on wear rate. The effect of hardness on sliding wear is quite complex to understood. Transfer of metal and mechanical mixing are one of the few complex processes that occur during sliding wear, and these processes modify the relative hardness of sliding metals, which makes the effect of hardness on wear process difficult to understand.

The hardness of the mixed material may be greater or lesser than that of parent metals. The heterogeneous nature of the mixed material varies hardness locally. Kato et a1 [33] indicated that the sliding behavior of different metal pairs correlates well with a simple hardness ratio given by R = Hd / Hp (*Hd,Hp*-Hardness of disc and pin, respectively) He observed that severe wear occurs when R value is below 1 and mild weal occurs when R at any time during the sliding test has a value above 1.

Effect of Elastic Modulus

Obeile *et al*. (1951) pointed out that a better measure of abrasive wear resistance is the amount of elastic deformation that surface can sustain. He related the abrasive near resistance of a material to elastic modulus by H/E ratio. Thus, the wear resistance of material can increased by either by increasing the hardness or decreasing the elastic modulus. The high elastic modulus produces high contact stresses, which decreases the wear resistance of a material. On the other hand, Khrushov (1974) anticipated Oberle et al's model and assumed that wear resistance of a material is directly related to elastic modulus in accordance with adhesive theory of wear. He explained that metals, which have high elastic modulus result in decrease of real area of contact leading to low adhesion and wear.

Effect of Fracture Toughness

Brittle materials like ceramics have a high good wear resistance owing to the high fracture toughness. During interaction of asperities, crack growth occurs with critical amount of strain. If the applied strain is smaller than critical strain, the wear rate of a metal is independent of fracture toughness. Once the critical strain is reached, there is an increased probability of crack growth and wear rate of metals depends up on fracture toughness. Hornbogen [35] proposed the model that there are three regions of wear behavior as a function of fracture toughness. In first region, wear is not affected by toughness in which Archard's law is obeyed Second region involves transition from mild to severe wear. Increase in pressure, strain rate or a decrease in fracture toughness are the factors which induce such a transition. Third region involves a highly brittle condition which shows high wear rate because of low fracture toughness.

Effect of Crystal Structure

Sliding of metals produce large plastic deformation, which in turn forms dislocation cell wall structures near the surface region Since cell walls serve as pathway for subsurface cracks, metals with limited number of slip systems (HCP) exhibit lower wear rate than metals with large number of slip systems (FCC). Buckley (1978) showed experimentally that cubic crystals wear at about twice the rate of hexagonal crystals. While most hexagonal metals have good friction and wear properties, however Titanium, although a hexagonal metal, exhibits relatively high friction and wear. This high friction may be related to a difference in the slip mechanisms for Titanium; titanium unlike most hexagonal metals slips on the {101^{-}0} planes rather than on the (0001) basal plane

Effect of Thermal Diffusivity

Low thermal diffusivity makes the dissipation of heat from the interface difficult. The mechanical strength of the metals is degraded by the thermal accumulation and this in turn leads to high wear.Wear and thermal diffusivity are inversely related. Abdel-Aal (2000) related the heat dissipation capacity of metals with wear transition. He postulated that transition from mild to severe wear occurs once the quantity of heat generated is higher than the quantity of heat dissipated. He also noted that if the amount of thermal accumulation reaches a critical value, delamination of oxide flake results in higher wear rate.

CONCLUSION

From this study we can conclude that wear behavior of CP Ti is not its material property. It depends on operating conditions such as sliding speed, normal load, temperature, environment conditions etc. and material parameters such as hardness, elastic modulus, crystal structure etc. One interesting thing to be noted in dry sliding behavior of Ti is that under ambient conditions at higher load and higher speed tribo oxidation and Mechanically Mixed Layer (MML) formation take place which protects the surface but the same condition under vacuum conditions leads to large deformation and large wear out of surface. Thus in industrial application we can improve the tribological behavior of Ti by selecting proper operating conditions.

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