IN-SITU OBSERVATION OF SINGLE- POINT WEAR OF PM Al-Ti ALLOY①

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ABSTRACT Single-point wear behaviors of PM Al-Ti alloy have been *in-situ* observed with environmental scanning electron microscope. Three micro-wear modes, i. e. ploughing, wedge forming and cutting are observed with increase in the degree of penetration. The region for cutting mode is extended with increasing hardness of the alloy. In addition, the abrasive wear resistance of the Al-Ti alloy does not decrease linearly with decrease in hardness.

Key words Al-Ti alloy wear mode *in-situ* observation

1 INTRODUCTION

The Al-Ti alloys possess high strength, low density and excellent retention of high temperature strength. However, the Al_3Ti dispersoids in the Al-Ti alloys produced by the conventional casting process are coarse and acicular-shaped, which is detrimental to the mechanical properties of the alloys. In recent years, Rapid Solidification Process (RSP) has been used to prepare the fine-grained Al-Ti alloys with spherical Al_3Ti dispersoids, resulting in good mechanical properties. Much attention has been paid to the Al-Ti alloys because of their potential applications in the wear-resistant components of the internal combustion engines. The microstructures and mechanical properties of the Al-Ti alloys have been studied extensively by Lee *et al*[1, 2] and Frazer *et al*[3]. And the dry sliding wear behaviors of the PM Al-Ti alloys have been reported in the previous papers[4- 6]. In order to further understand the wear mechanisms of the Al-Ti alloys, the microscopic wear modes of the PM Al-Ti alloys will be studied in the present work.

In most cases, only the worn surfaces and debris are studied, therefore the dynamic wear process is not well understood. Recently, the dynamic wear behaviors of materials, including SUJ2 bearing steel, stainless steel, brass and SiC ceramics, have been *in-situ* observed using a scanning electron microscope. The results obtained show that the abrasive wear mode can be classified into three types: ploughing, wedge forming and micro-cutting. And an abrasive wear mode diagram has been presented to predict the transformations of the above described wear modes[7- 10]. In addition, the other *in-situ* examination reveals that the sheet-like and flake-like debris are formed during sliding of the copper pins against mild steel disks[11]; adhesion and prow-formation have been found during wear process of aluminum using a ball-on-flat wear tester in SEM. In the present work, an Environmental Scanning Electron Microscope (ESEM) is used to observe the microscopic wear modes of the PM Al-Ti alloys during single-point abrasive wear process.

2 EXPERIMENTAL PROCEDURE

2.1 Preparation of material

The Al-1.4%Ti, Al-3.3%Ti and Al-10%Ti alloy powders were atomized with argon gas. The powders with diameters of 63~ 90 μm were sealed in the pure aluminum cans in vacuum and compacted into 80 mm diameter round rods at

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ambient temperature. The rods were then extruded into bars with rectangular sections of 20 mm × 10 mm. After thermal exposure at 630 ℃ for 10h, the disks with dimensions of d8 mm × 2 mm were machined from the bars by spark eroding and then polished. The metallographic examination showed that the fine Al_3Ti particles (about 0.9 μm in diameter) were dispersed within the α-Al matrix with fine grains. And the mechanical properties of the alloys are listed in Table 1.

Table 1 Mechanical properties of samples

Sample	Hv	σ_s/MPa	σ_b/MPa	δ/%
Al-1.4%Ti	48.5	66.6	146.5	24.4
Al-3.3%Ti	51.6	72.0	149.3	19.7
Al-10%Ti	73.3	93.6	234.0	10.0

2.2 Wear test

The wear test was performed on the Al-Ti alloys with a pin-on-disk tester mounted in the environmental scanning electron microscope (ESEM), as shown schematically in Fig. 1. The disk rotated at a speed of 4 μm/s. The surface of the disk specimen was scratched by a diamond pin (R = 10 μm, Knoop number 70) at a normal load (18.5~ 93.0 μN), which was detected by strain gauges. The surface of the disk was *in-situ* observed with ESEM. The test was carried out at ambient temperature of 26 ℃.

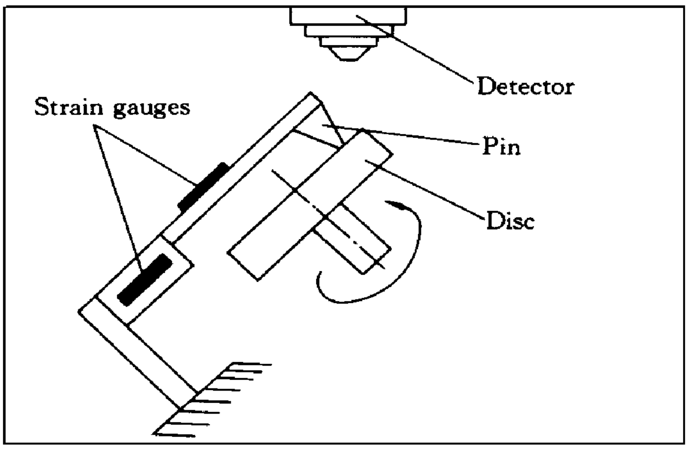

Fig. 1 Schematic diagram for test equipment

In order to determine the contact degree of the pin and the disk specimen, the degree of penetration D_p of the pin is introduced ($D_p = h/a$, where h is the depth of the groove and a is half of the contact width as shown in Fig. 2). It can be expressed by[7]

$$D_p = R \cdot \left(\frac{\pi Hv}{2W}\right)^{1/2} - \left(\frac{\pi Hv}{2W} \cdot R^2 - 1\right)^{1/2}$$

where W is the applied normal load and Hv is the hardness of the disk specimen.

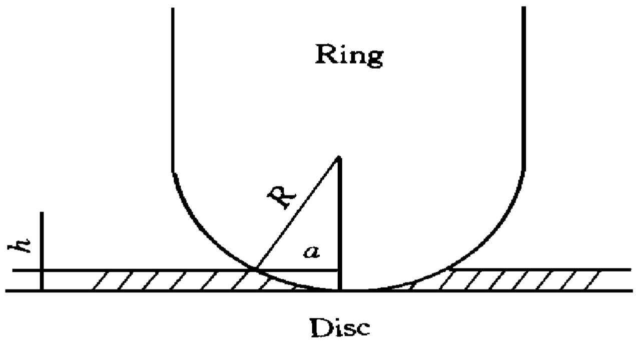

Fig. 2 Definition of degree of penetration

3 RESULTS AND DISCUSSION

3.1 Wear modes

The three wear modes, i. e. ploughing, wedge forming and cutting were observed during the sliding processes of all the samples. For example, Fig. 3 shows the wear morphologies of Al-10% Ti alloy, the grooves are visible in the figures. Evidently, the wear mode changed from ploughing (Fig. 3(a)) to wedge forming (Fig. 3 (b)) with increase of the applied normal load. If the load increased beyond a critical value, the cutting mode occurred (Fig. 3(c)).

At low load, the pin scratched the surface of the disk. Mild deformation occurred and no crack in the surface of the sample was detected. Materials were piled up on both sides of the shallow groove instead of in front of the pin. And no wear debris was formed (Fig. 3(a)). With increase of load, plastic deformation of the alloy became severe. Cracks, parallel to the sliding direction, were found in the shear plate as well as at the interface between the Al_3Ti particles and the α-Al matrix. Propagation of cracks resulted in fracture of material. Most of the fractured plate-like materials were piled up in front of the pin. At this present load range, the wear mode

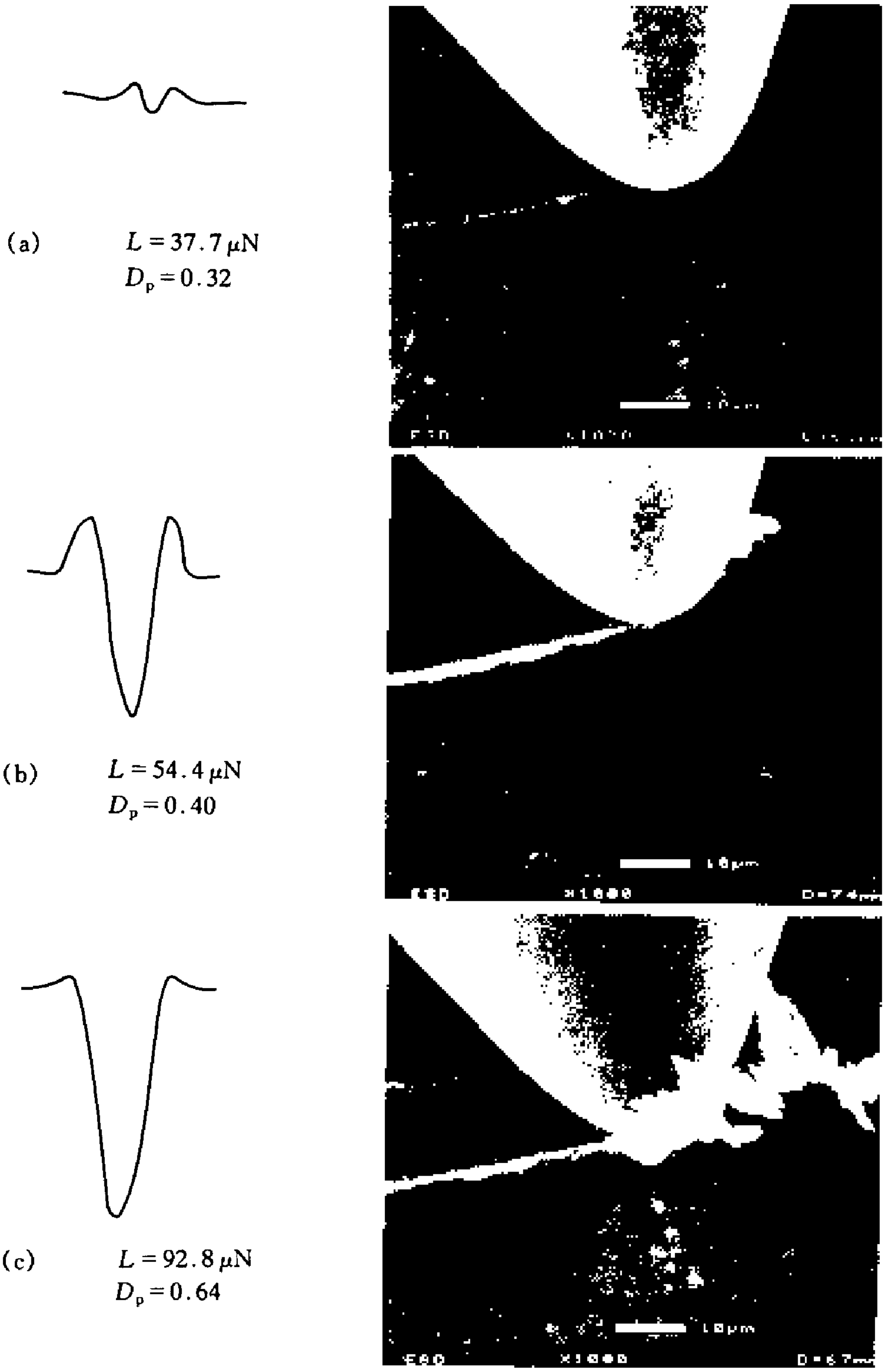

Fig. 3 Wear modes observed in ESEM of Al-10Ti alloy

(a) —Ploughing mode; (b) —Wedge forming mode; (c) —Cutting mode

was characteristic of wedge-forming (Fig. 3(b)). Once the applied load increased to a critical value, pile-up of materials in front of the pin increased and led to detachment of materials from the disk. As a result, ribbon-like wear debris were generated. Much deeper groove with little ridges on both sides was formed (Fig. 3(c)). The cutting mode occurred, leading to large amount of material loss. The ribbon-like wear debris produced on cutting mode, with length of 30 μm, was very similar to that generated in machining with a tool having a negative rake angle.

The wear debris detached from the interface between the pin and disk in three different ways[11]. The debris produced at the leading edge of the pin moved in a direction opposite to the rotating direction of the disk. These particles were piled up in front of the pin and subsequently detached from the matrix. It is visible that the debris produced between the leading edge and the trailing edge escapes from the interface quite readily (Fig. 3(c)). The trailing edge debris tended to deposit on both sides of the groove to form ridges. They were detached from the disk due to following scratching again in the following wear process.

The value of D_p of the three alloys and their corresponding wear modes are summarized in Fig. 4. It can be seen that the wear modes changed from ploughing to wedge forming and then to cutting with an increase in the degree of penetration. If two critical degrees of penetration are designated by D_p^* and D_p^{**}, corresponding to the transition from the ploughing mode to the wedge forming mode and the transition from the wedge forming mode to the cutting mode respectively, the relationship between abrasive wear modes of the Al-Ti alloys and D_p can be summarized as follows:

(1) $D_p < D_p^*$, ploughing mode;

(2) $D_p^* < D_p < D_p^{**}$, wedge forming mode;

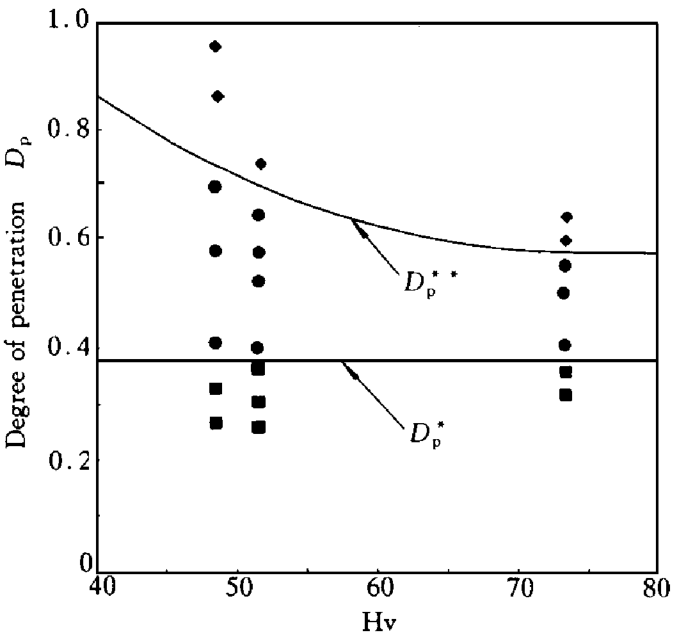

Fig. 4 Wear mode diagram of Al-Ti alloy
■ —Ploughing; ● —Wedge forming; ◆ —Cutting

(3) $D_p > D_p^{**}$, cutting mode.

It can also be seen in Fig. 4 that the value of D_p^* was independent of the hardness of the alloys, while the value of D_p^{**} decreased from 0.69 to 0.56 when the hardness of the Al-Ti alloys increases from 48.5Hv to 73.3Hv. As a result, the region of the wedge forming mode decreased and that of the cutting mode increased with increasing hardness. The similar results have been obtained during sliding of steels harder than 200 Hv using the same method[7]. For quenched bearing steel with the hardness of 250 Hv, D_p^* and D_p^{**} have been determined to be 0.17 and 0.41 respectively, much less than the values for the Al-Ti alloys.

The results obtained can be considered as follows: In the region of ploughing, plastic deformation results in adhesion of the material of the disk to the pin. Cutting occurred due to nucleation and propagation of a lot of cracks parallel to the sliding direction. Rather than the ability to resist plastic yield of materials, the hardness of the alloys has more effective influence on expansion of the cracks. For a harder material, tips of cracks are not easy to passivate and thus cracks propagate readily. As a result, the value of D_p^{**} decreases with increasing hardness, while that of D_p^* remains constant.

3.2 Relationship between width of groove and degree of penetration

During abrasive wear, the width of groove increases with increasing load and decreases with increasing hardness of material[13], because the groove is deepened due to increase of the applied load and decrease of the hardness, leading to increase in the width of groove. If the hardness of materials decreases, the prows on both sides of the groove tend to spread more readily. This fact is visible in Fig. 5 (the width of groove refers to the distance of the two top points of the prows on both sides of the groove). For Al-1.4%Ti and Al-3.3%Ti alloys, the width of groove increases quickly with increase in the degree of penetration up to D_p^{**}. If the degree of penetration is greater than D_p^{**}, the width of groove changes slowly. This can be ascribed to the fact that plastic deformation reaches a constant value and strain hardening of the alloys becomes steady. However, although the hardness of Al-10Ti is larger than that of Al-1.4Ti and Al-3.3Ti alloys, the width of groove formed during wear is smaller than that of Al-3.3Ti alloy, but larger than that of Al-1.4Ti alloy. This indicates that the groove formation during abrasive wear is not only dependent on the hardness of the material. The increase in hardness of materials may improve resistance of plastic deformation, but promote propagation of cracks. This results in rapid detachment of material from the specimen, and thus increases the width of groove. Of all the sliding wear, adhesive wear is most severe, while in single-point microscopic abrasive wear, adhesion is negligible as compared to the cutting mode[7].

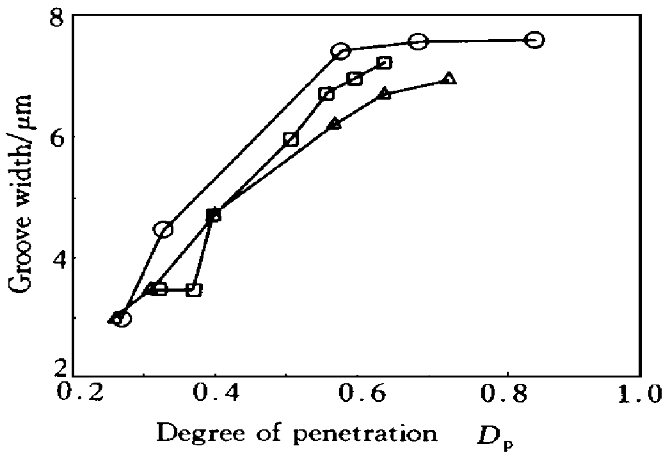

Fig. 5 Relationship between width of groove and degree of penetration

○—Al-1.4Ti; △—Al-3.3Ti; □—Al-10Ti

3.3 Abrasive-wear resistance of Al-Ti alloys

It is often thought that ploughing results in lots of wear debris during abrasive wear. The material with low hardness is poor in resistance of abrasive wear. However, the recent investigations[7, 8] show that wear debris is mainly generated by cutting rather than ploughing. In the case of abrasive wear, the region of the cutting mode is reduced with decreasing hardness. Therefore, wear resistance of materials does not decrease linearly with decreasing hardness.

Hokkigigawa *et al*[7] have proposed that the following modified abrasive wear equation (the action of wedge forming and ploughing is neglected):

$$R = \frac{WL}{V} = \frac{CHv}{\alpha_c \beta_c}$$

where W and L are the applied normal load and sliding distance respectively, C is the shape factor of wear particles, Hv is the hardness of the material, α_c is the critical wear loss when the cutting mode first occurs and β_c is the fraction of contact points where the cutting mode occurs.

To obtain the values of β_c quantitatively, the critical two-dimensional attack angle θ^{**} can be given by[7]

$$D_p^{**} = 0.8\mathrm{tg}\frac{\theta^{**}}{2},$$

$$\theta^{**} = 2\mathrm{arctg}\left(\frac{D_p^{**}}{0.8}\right)$$

Only wear particles with the attack angle larger than θ^{**} contribute to wear loss. For materials harder than 200 Hv, the harder the material is, the less the values of D_p^{**} and θ^{**} are. Thus β_c, the fraction of contact points, which favors the formation of wear debris, increases. Therefore the value of R increases slowly with increasing hardness of materials. For pure metals and annealed steels softer than 200 Hv, the values of α_c and β_c can be taken as constant, the value of R is directly proportional to the hardness of material[7, 14]. However, the present work shows that the relationship between the value of D_p^{**} and the hardness is similar to that of materials harder than 200Hv. Although the value of Hv is low for the Al-Ti alloys, their values of D_p^{**} are much higher than that of steels. Thus the values of β_c are much lower than that of steels correspondingly. The abrasive wear resistance of the Al-Ti alloys doesn't decrease linearly with decrease in hardness.

It is known[13] that the abrasive smaller than 1 μm contacts with materials elastically, and no plastic deformation occurs during the wear process. Sin *et al*[15] have also found that abrasive wear can be prevented by getting rid of the abrasive larger than 0.1 μm in lubricant oil. The diameters of Al_3Ti particles in the Al-Ti alloys are about 0.9 μm, thus abrasive wear is not the predominant mechanism during dry sliding wear[4, 5].

4 CONCLUSIONS

(1) There exist three wear modes during single-point abrasive wear of Al-Ti alloy, i. e. ploughing, wedge forming and cutting. The wear mode changes from ploughing, to wedge forming and then to cutting with the increase in the degree of penetration.

(2) The critical degree of penetration corresponding to the transition from the ploughing mode to the wedge forming mode is independent of the hardness of Al-Ti alloy, while that corresponding to the transition from the wedge forming mode to the cutting mode decreases with increasing hardness, the two values of the Al-Ti alloy are much higher than those of steels.

(3) During abrasive wear, the groove is produced by the combination of plastic deformation, adhesion and fracture of the alloy.

(4) The wear resistance of PM Al-Ti alloy does not decrease linearly with decreasing hardness of the alloy.

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