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Wear Mechanism of CrN Coating on Aluminum Alloys Deposited by AIP Method

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Abstract : Dry sliding wear and friction test of CrN coating on two types of aluminum alloy substrates, 6061 Al and 7075 Al deposited by arc ion plating, was performed with a ball-on-disk tribometer. The effects of normal load and the mechanical properties of substrate on the friction coefficient and wear-resistance of CrN coating were investigated. The worn surfaces were observed by SEM. The results show that surface micro-hardness of CrN- coated 7075 Al is higher than that of CrN-coated 6061 Al. With an increase in normal load, wear volume increases, while the friction coefficient decreases. The friction coefficient of CrN-coated 6061 Al is higher than that of CrN-coated 7075 Al, while the wear-resistance of CrN-coated 6061 Al is lower than the CrN-coated 7075 Al's, which indicates that the substrate mechanical properties have strong influences on the friction coefficient and wear of CrN coating. The main wear mechanism was fragments of CrN coating, which were caused by apparent plastic deformation of substrate during wear test.

Keywords : CrN coating, wear, tribological behavior, aluminum alloy

Introduction

Aluminum alloys have many excellent properties such as high strength-to-weight ratio, good ductility, light weight and low cost. Thus, they are often used in the automotive and aerospace industries [1]. When applied as tribological machine parts, however, they show poor wear-resistance. This causes the service life of components to decrease [2]. Therefore, it is imperative to enhance their wear-resistance to further increase their service life.

Ceramic coatings are well-known to be the most efficient materials to improve the wear-resistance of machine parts [3-7]. CrN coating, as a new materials coating, has many excellent physical and chemical properties such as high surface micro-hardness [8], high toughness [9], excellent wear resistance [10] and corrosion resistance [11] etc. Thus, CrN coating is applied to milling and turning tools to machine Cu- and Ti-based alloys [12] as well as moulds for the die-casting of Al-based alloys [13]. However, the research works related to the wear properties of CrN coating deposited on aluminum alloy is still limited [14].

In this study, CrN coating was deposited on two types of aluminum alloy substrates, 6061 Al and 7075 Al by using arc ion plating (AIP) method. The tribological behavior of the CrN coating on two different aluminum alloys was investigated at various loads on a ball-on-disk wear tester in dry air. The effect of the substrate mechanical properties on the wear behavior of CrN coating was studied.

Experimental Methods

Substrate materials

Two types of extruded aluminum alloys, 6061 Al and 7075 Al, were used as the substrates. Two types of aluminum alloy bars were machined to 6 small-size tensile specimens of φ 6 mm × 30 m. Uniaxial tensile testing was conducted in an Instron8516 electronic universal tension machine at room temperature with a strain rate of $\sim 5.56 \times 10^{-4}\,\mathrm{s}^{-1}$. The micro-hardness of extruded aluminum alloy was measured by using a Vickers hardness tester (FM-700E), with a load of 10 g. Mechanical testing results of 6061 Al and 7075 Al are shown in Table 1, respectively. Aluminum alloys all were machined to make disc specimens with a 25 mm diameter and 10 mm thickness. The uniform thickness of all specimens was ensured by grinding less than 0.1 mm of tolerance from both sides of the disk surface. One side of disc was polished to remove the grinding damage and any surface irregularities. The surface roughness of the polished surface was 0.1 μm. Surface roughness for specimens was measured by using a profilometer (Mitutoyo Surftest 5000).

Coating deposition

Before the AIP process, the specimens were cleaned ultrasonically in acetone for 30 min, and then put into the deposition chamber of an AIP3000 machine (KOBE Steel LTD), which was subsequently evacuated to a vacuum of 4.2×10^{-4} Pa, and then nitrogen gas (N_2) was introduced to a pressure of 0.053 Pa. For further cleaning, the polished surfaces of specimens were bombarded using an ionized target element

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Table 1. Mechanical properties of aluminum alloys

Materials	Yield strength ó$_s$ (MPa)	Maximum strength ó$_b$ (MPa)	Elongation ä(%)	Microhardness $\mathrm{HV}_{0.01}$
6061 Al	287.26	370.93	19.34	120
7075 Al	351.94	648.2	15.89	194.76

Table 2. Deposition parameters for CrN coating

Bias voltage (V)	Arc current (A)	Deposition temperature (K)	Partial pressure of N_2 (mbar)	Deposition rate (ìm/h)
-38	60	373~423	2.6×10^{-2}	4.0

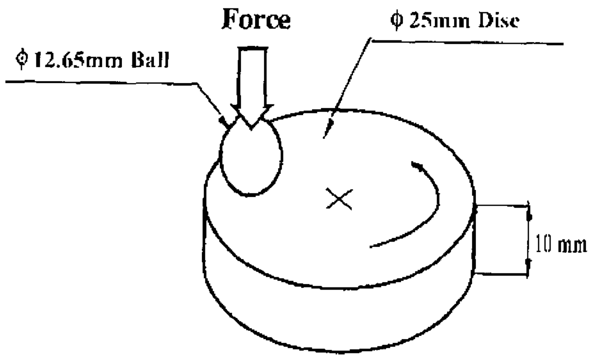

Fig. 1. Schematic illustration of ball-on-disc type wear test.

Cr^+ for 60 min at a bias of 580 V. At that moment, the chamber temperature decreased from 573K to 373K, while the chamber vacuum decreased from 5.3×10^{-2} Pa to 3.4×10^{-3} Pa. When coating deposition started, nitrogen gas was bled rapidly into deposition chamber up to a pressure of 3Pa. If, during deposition, the temperature exceeded 473 (assumed to be the softening point of Al), deposition stopped until the temperature fell to about 403 K. In order to improve the interfacial adhesion, an interlayer of about 0.1 μm Cr was deposited between aluminum alloy substrate and coating. The deposition procedure for CrN coating is: (1) The target was heated to the evaporation temperature and then pure Cr was evaporated and grown on the specimens; (2) nitrogen gas was subsequently introduced into deposition chamber and then CrN began to grow on the pure Cr layer. The thickness of the CrN coating was 6.0 μm, which was controlled by depositing time. The deposition parameters are shown in Table 2.

Ball-on-disc wear test

Prior to each sliding test, the ball and disc were ultrasonically cleaned in acetone for 10 min so as to keep the surface conditions as identical to each other as possible.

Ball-on-disc sliding test was carried out between CrN-coated aluminum alloy disc and polycrystalline alumina ball on the wear test machine, an EFM-3-E (TOYOBALDWIN Co). The physical properties of polycrystalline alumina are shown in Table 3. The contact point was designed at an eccentricity of 5 mm from the center of the rotary motion, which created a round worn track 10 mm in diameter on the disc surface, as shown in Fig. 1. The loads used in this experiment were 2.5, 5 and 10 N. The sliding speed was kept at a constant value of 50 mm/s by adjusting the rotating speed of the disc specimen. The total sliding time was 25 min, generating a total sliding distance of 75m. The experiments were conducted "dry" in an ambient atmosphere (23±1°C and 40±5% RH).

For each disc, the cross-sectional area of the wear track, A, was determined by using a surface profilometer (Mitutoyo Surftest 5000). Thereafter, the disc wear volume, V_d, was calculated using [15]

$$V_d = 2\pi r A \tag{1}$$

where r is the radius of wear track. The disc specific wear rate, K', was calculated using the equation

$$K' = \frac{V_d}{FL} \tag{2}$$

where F is the normal load and L is the sliding distance. The average cross-section area of a wear track was calculated from at least 16 measurements on each specimen. The standard deviation of the cross-section area on a specimen was typically < 10% of its average value.

Analysis of CrN coating surface and wear tracks

The topography of the worn surface for CrN coating was observed by SEM. The surface micro-hardness of CrN coating was measured by using a Vickers micro-hardness tester (FM-700E), with a load of 10 g.

Results

Surface micro-hardness

Fig. 2 shows the surface micro-hardness of the uncoated and CrN coated 6061 and 7075 aluminum alloys, respectively. The

Table 3. Physical properties of polycrystalline alumina ball

Materials	Composition	Diameter (mm)	R_a (ìm)	E(GPa)
Al_2O_3 ball	99.7% Al_2O_3	12.65	0.2	300

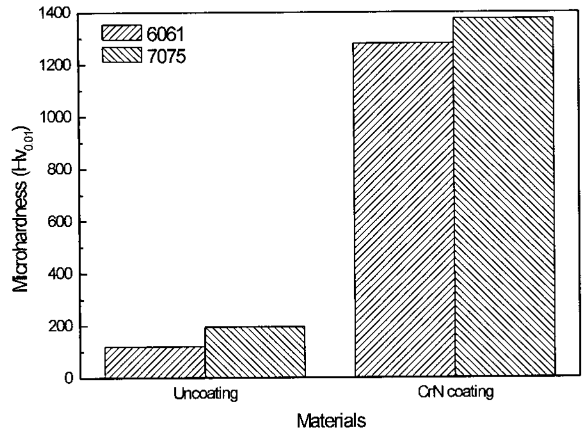

Fig. 2. Surface micro-hardness of the uncoated and CrN-coated 6061 Al and CrN-coated 7075 Al.

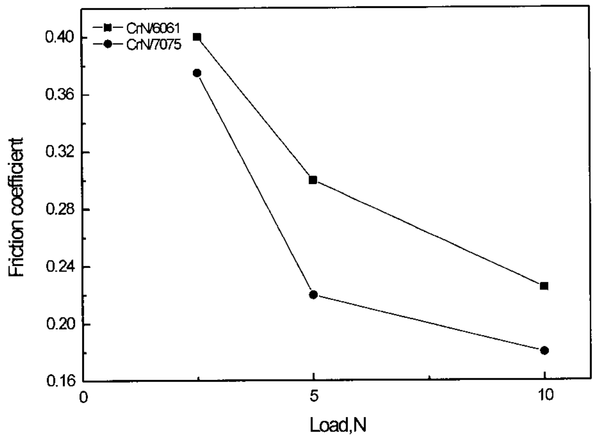

Fig. 3. Effects of normal load on the friction coefficient of CrN-coated 6061 Al and CrN-coated 7075 Al.

results indicate that surface micro-hardness of 6061 and 7075 Al was all enhanced by CrN coating treatment. With an increase in the substrate micro-hardness, the surface micro-hardness of CrN coating also increased. This indicates that the mechanical properties of substrate had main influence on the surface micro-hardness of CrN coating.

Effect of normal load on the friction coefficient of CrN coating

A comparison of friction coefficients of CrN-coated 6061 Al and 7075 Al with different normal loads is shown in Fig. 3. The results show that the friction coefficient decreased with an increase in the normal load. The friction coefficient of CrN-coated 6061 Al was higher than that of CrN-coated 7075 Al. Moreover, with an increase in the normal load, the friction coefficient difference between CrN-coated 6061 Al and CrN-coated 7075 Al increased. This shows that the wear mechanism of the coating depended on the normal load and the mechanical properties of the substrate.

Wear volume and specific wear rate variation with sliding distance

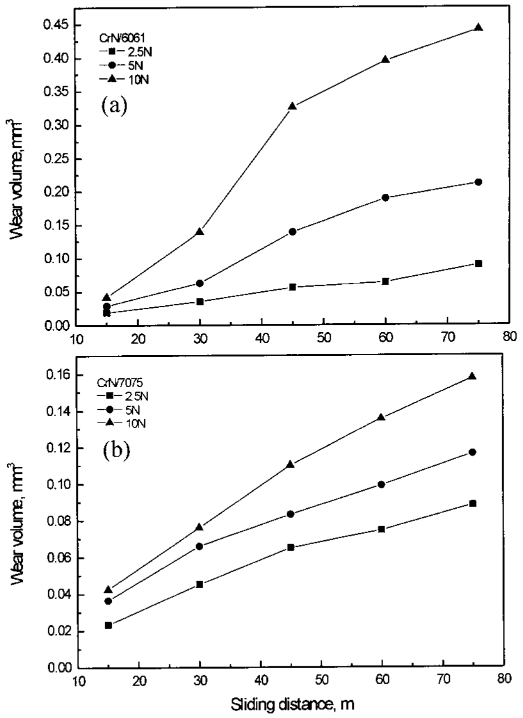

Fig. 4. Variations in wear volume at various normal loads for (a) CrN- coated 606 Al and (b) CrN-coated 7075 Al.

Figs. 4 (a, b) shows the specimen wear volumes versus sliding distance with 2.5, 5 and 10N loads for CrN-coated 6061 Al and CrN-coated 7075 Al, respectively. It is clear that the wear volume increased with increases in sliding distance and normal load. The wear-resistance of the CrN- coated 7075 Al was better than that of CrN-coated 6061Al. As seen in Fig. 4(a), a transition sliding distance (L_c) was observed for CrN-coated 6061 Al specimens, above which the coating was completely fragmented and scrapped off, and then the wear volume increased steeply with a further increase in sliding distance. Fig. 5 shows the effect of normal load on L_c. The results indicate that the transition sliding distance decreased with an increase in normal load. When the normal load was higher than 2.5 N, severe substrate plastic deformation occurred, and caused the anti-wear coating to be invalid early. For the 7075 alloy substrate specimens, their wear volume increased approximately linearly with the sliding distance, yet there was no transition sliding distance when the sliding distance was lower than 75m (Fig. 4 (b)). Fig. 6 (a, b) shows the specific wear rate versus sliding distance with 2.5, 5 and 10 N loads for CrN-coated 6061 Al and CrN-coated 7075 Al, respectively. As seen in Fig. 6 (a), with an increase in normal load , the specific wear rate of CrN-coated 6061 Al decreased as sliding distance lower than 30 m. But it increased after sliding distance longer than 30m. For CrN-coated 7075 Al, its specific wear rate decreased with increases in the normal load and sliding distance (Fig. 6 (b)). The experimental results of CrN-coated 7075 Al was different from those of CrN-coated 6061 Al, which indicates that the wear of the CrN coating/aluminum alloy substrate system was governed by the mechanical properties of the substrate.

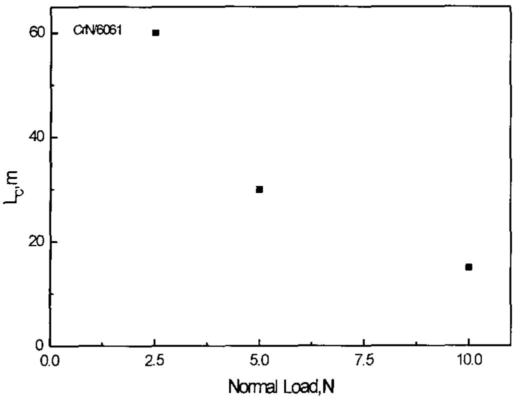

Fig. 5. Normal load effects on the sliding distance transition value.

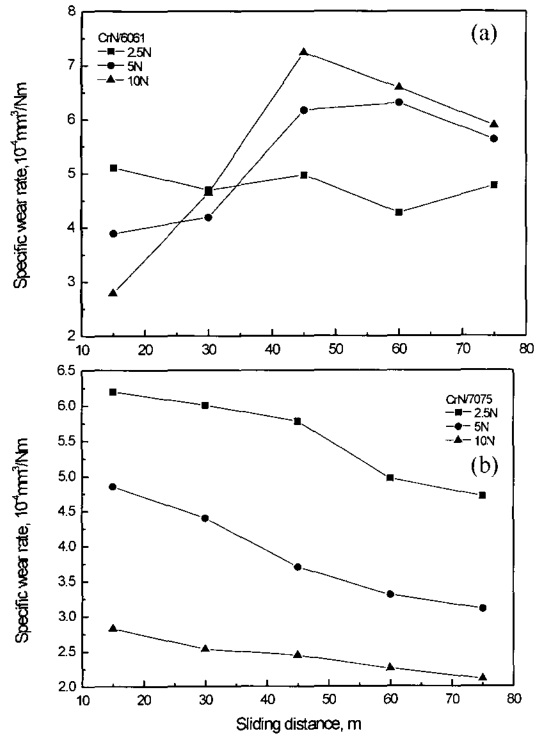

Fig. 6. Variations in specific wear rate at various normal loads for (a) CrN- coated 606 Al (b) CrN-coated 7075 Al.

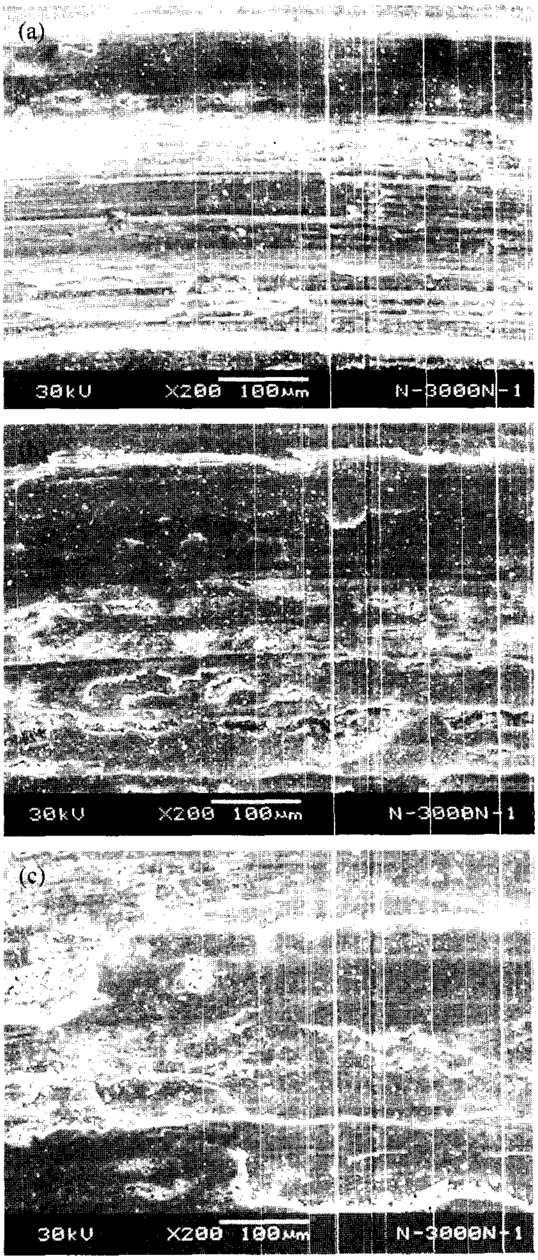

Fig. 7. Characteristics of the wear surfaces for CrN-coated 6061 Al at various loads (a) 2.5 N (b) 5 N (c) 10 N.

Effect of normal load on microstructure of wear track surface

Fig. 7 shows microstructure images of wear track surface for CrN coating deposited on 6061 Al substrate at various loads. At a normal load of 2.5 N, the wear scar surface was covered by fine abrasive grooves and fine powder. The CrN coating surface was slightly burnished (Fig. 7 (a)). When the normal load increased to 5 N, the wear track was covered with a smooth flat layer composed of wear debris particles. Some areas of the CrN coating were partially fragmented(Fig. 7 (b)). At a load of 10 N, heavier deformation occurred in 6061 aluminum alloy substrate, the coating layers were completely scraped off and the wear was more severe (Fig. 7 (c)) Thus, it is known that the wear transition from coating to substrate occurred with an increase in normal load.

The characteristics of wear track surface for CrN-coated 7075 Al substrate at various loads are shown in Fig. 8. At lower loads, there were more fine abrasive grooves and compact layers on the wear track surface (Fig. 8 (a)). When the normal load was 5N, the wear scar surface exhibited a flat surface covered with some fine grooves and wear debris particles (Fig. 8 (b)). At the higher load of 10 N, the wear scar surface showed some compact layers with a relatively smooth surface. Some areas of CrN coating were partially fragmented (Fig. 8 (c)). Fig. 8 indicates that the CrN coatings fragmentation area increased with an increase in normal load.

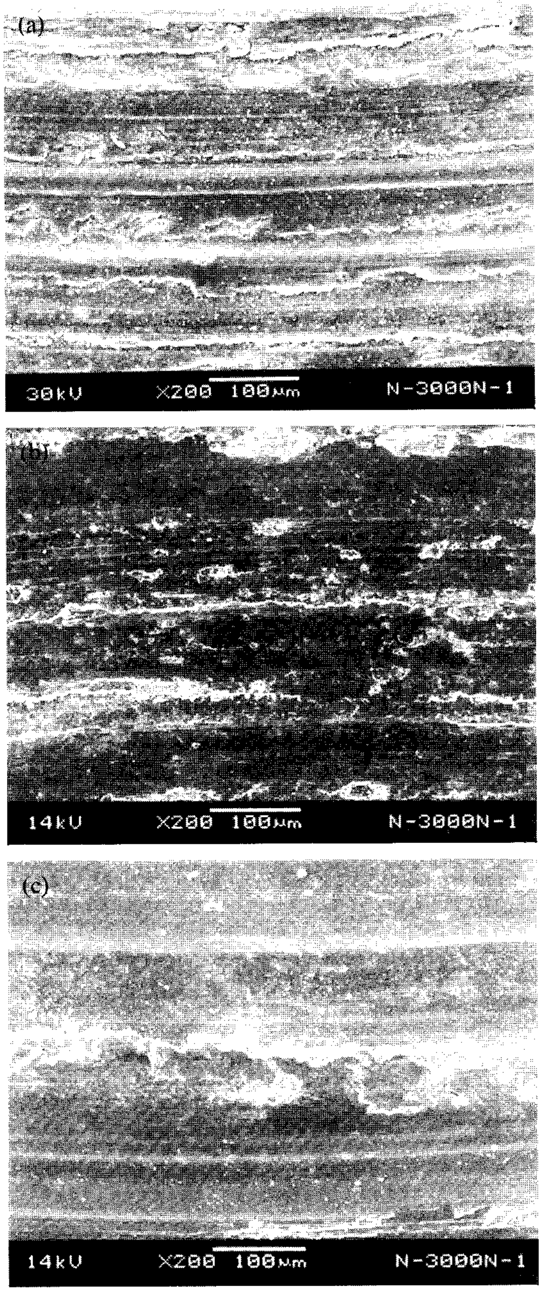

Fig. 8. Characteristics of the wear surfaces for CrN-coated 7075 Al at various loads (a) 2.5 N (b) 5 N (c) 10 N.

Table 4 . Maximum contact pressure P_0 at various loads

Groups	Normal load (N)	P_0 (MPa)
CrN coating /Al_2O_3 ball	2.5	822.90
	5	1036.78
	10	1306.27
6061Al /Al_2O_3 ball	2.5	382.01
	5	481.31
	10	606.41
7075Al/Al_2O_3 ball	2.5	385.53
	5	485.74
	10	611.99

Discussion

The experimental results show that the CrN-coated 6061 Al wear behavior is different from the CrN-coated 7075 Al wear behavior. This difference must arise from the difference in mechanical properties of the substrates. It is known that the hardness of a materials has often been correlated with resistance to abrasive wear and the residual stress level in thin film [16], accordingly, the resistance of a coating to deformation plays an important role in wear characteristics [17]. According to Hertzian ball-on-disk contact mode [17], all the stresses in the contact region are directly related to the maximum contact pressure, P_0, at the contact interface. Based on the data of [18], the maximum contact pressure P_0 for CrN film, 6061 Al and 7075 Al sliding against an Al_2O_3 ball at various loads is shown in Table 4. The maximum contact pressure for CrN film was lower than the micro-hardness of CrN-coated 6061 and 7075 Al. This indicates that CrN coating does not fragment early, and shows excellent wear resistance. However, the maximum contact pressures of 6061 Al and 7075 Al exceed their yield strengths and the substrate materials tend to deform plastically. Thus, the wear volume V_{total} for CrN-coated aluminum alloy substrate can be expressed as

$$V_{total} = V_{CrN} + V_p + V_{Al} \tag{3}$$

where V_{CrN} is the wear volume of CrN coating, V_p is the deformation volume of the substrate induced by contact pressure and V_{Al} is the wear volume of the aluminum alloy substrate after the CrN coating is scraped off. When the normal load is lower and sliding distance is shorter, the CrN coating was not fragmented, so $V_{Al} = 0$. Therefore, V_{total} was governed by V_p. As seen in Table 1, V_p for 7075 Al is lower than that of 6061Al under the same pressure. Thus, V_{total} of CrN-coated 6061 Al was higher than that of CrN-coated 7075 Al. With increases in sliding distance and normal load and the CrN coating scraped off, V_{total} was governed by V_p and V_{Al}. After comparing Table 1 with Table 3, the contact pressure of 6061 Al exceeds the maximum strength of 6061 Al, while the contact pressure of 7075 Al is lower than the maximum strength of 7075 Al. This indicates that plastic fracture occurred in 6061 Al substrate, while plastic deformation occurred in 7075 Al substrate. As a result, the wear volume V_{Al} of 6061 Al is higher than that of 7075 Al under the same conditions. This causes the wear volume of CrN-coated 6061 Al to be higher than CrN-coated 7075 Al.

Moreover, Friction heating also has an influence on tribological behavior and coating failure from sliding, which results in an increased substrate temperature [19]. When CrN coating slid against Al_2O_3 ball, high friction heating was generated at the sliding interface between CrN coating and Al_2O_3 ball. Zhang [20] indicated that severe wear of 6061 Al is characterized by a massive plastic deformation as a result of thermal softening of 6061 Al. The results of cutting test show that 6061 Al softened and adhered to the cutting tool more easily than 7075 Al. When the normal load is higher, CrN coating failure and the severe deformation of 6061 Al are occurred. For CrN-coated 7075 Al, the wear mechanism is CrN coating fatigue fracture due to plastic deformation of substrate. Thus, the wear behavior of CrN-coated 6061 Al is different from that of CrN-coated 7075 Al.

Conclusions

1. In sliding against Al_2O_3 balls, the micro-hardness of CrN-coated 6061 Al was lower than CrN-coated 7075 Al, while the friction coefficient and wear volume for CrN-coated 6061 Al were higher than the CrN-coated 7075 Als.
2. The specific wear rate of CrN-coated 6061 Al increased with higher normal load and longer sliding distance, while that of CrN-coated 7075 Al decreased. Additionally, wear transition was observed for CrN-coated 6061 Al.
3. The wear mechanism of CrN-coated 6061 Al was related to thermal softening and the plastic fracture of 6061Al, while that of CrN-coated 7075 Al was related to the fatigue fracture of CrN coating owing to plastic deformation of 7075 Al.

Acknowledgments

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