Friction behavior of Al-Cu-Fe-B polycrystalline quasicrystals [①]

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Abstract: Dry sliding friction between the polycrystalline $Al_{59}Cu_{25.5}Fe_{12.5}B_3$ quasicrystals(QCs) and coating of the diamond-like carbon(DLC) was carried out by self-made tribometer under different conditions. The influences of four parameters(temperature, sliding velocity, applied load, atmosphere) on friction of quasicrystal surface were studied. Microstructure of quasicrystal, morphology of worn surface, and wear debris were observed by scanning electron microscope(SEM) . The results show that for QCs, the friction coefficient and the roughness of worn surface is influenced by the parameters, especially greatly by the temperature. With increasing the applied load and sliding velocity, the friction coefficient decreases. The dominant wear mechanism at 350 ℃ is delamination for QCs. The cracks forms on the worn surface during friction. Moreover, phase transformation is not observed on worn surface of QCs at 350 ℃.

Key words: polycrystalline quasicrystal; dry sliding; temperature; crack

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1 INTRODUCTION

Due to their aperiodical structure, quasicrystals (QCs) have a series of unusual physical and chemical properties(for example, high hardness, low surface energy and low frictional coefficient)[1]. However, most of QCs are very brittle at room temperature. The fracture toughness of Al-Cu-Fe-B QCs was enhanced by adding small amount of boron in Al-Cu-Fe[2]. As well known, wear resistance is not a materials property. When two surfaces slide against each other, the tribological performances not only depend on the properties of the materials involved but also on the geometry of the contact both on gross scale and fine scale, on sliding velocity, applied load, the temperature and the ambient environment, presence of lubricants. Stebut et al[3] reported that for Al-Cu-Fe polycrystalline quasicrystal, the general friction behaviour of scratch test depends on the counter materials. For Al-Cu-Fe polycrystalline coating[4], the addition of a relatively ductile Fe-Al phase improved abrasion resistance in reason of the transition of wear mechanism from brittle fracture to plastic flow. Furthermore, under high temperature, Al-Cu-Fe quasicrystals were detected to produce the oxidation process and involved phase transformation. Phase transformation may possibly occur during the sliding friction and oxidation wear. In conclusion, it is difficult to attribute a single mechanism operating for friction of two mating surfaces between the quasicrystal and DLC coating.

The aims of this work are to study the friction coefficient of $Al_{59}Cu_{25.5}Fe_{12.5}B_3$ under different sliding conditions. Moreover, the morphology of the worn surface was observed, and the wear mechanisms were discussed.

2 EXPERIMENETAL

2. 1 Materials

Two materials were used in the friction test. One was single phase $Al_{59}Cu_{25.5}Fe_{12.5}B_3$ bulk polycrystalline quasicrystal, with dimension of d 30 mm × 12 mm. It was prepared by sintering the powders of the icosahedral phase(the maximum particle size, 25 μm) at 780 ℃. The surfaces of samples must be carefully polished with grid 1200 emery paper under water, and by standard diamond with 6 μm and 1 μm particles. The other was 40CrMoV3 steel of shape d 70 mm × 5 mm. The cylinder surfaces were well polished(R_a= 0. 02 μm) , and then deposited with DLC coating.

2. 2 Friction and wear test

The friction tests were carried out on a self-made tribometer in France. The equipment includes the friction apparatus, the controller, and the recorder. Fig. 1 shows the schematic diagram of the friction tester.
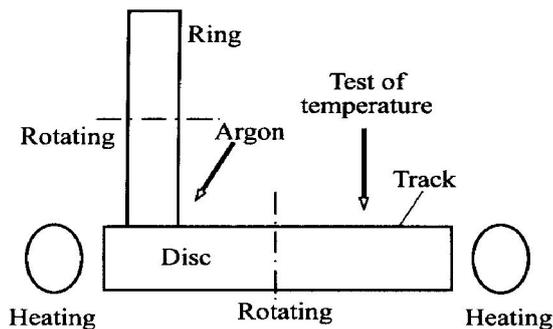

Fig. 1   Diagram of ring-on-disc tribometer

The disc(QCs) and the ring(40CrMoV3 with DLC coatings) were matched un-lubricated to rotating altogether by two electrical motors. Under the argon atmosphere, the disc was heated with an inductor. The temperature was measured with Ircon infrared thermometers (200 – 600 ℃). In present study, the relative sliding velocity of discs was 1 and 0. 1 ms^{-1}. The temperature was at room temperature and 350 ℃, and the applied load was 15 N and 35 N, respectively. The experiment time was 10, 20, and 40 min, respectively. The coefficient of friction(μ) was calculated by the tangential force and normal force(ie $\mu = F_T/F_N$). The working conditions are listed in Table 1.

2. 3   Analysis method of surfaces

Scanning electron microscope (SEM) JEOL 840A was used to observe the sliding surface. With an energy-dispersive spectrometers(EDX), the composition of the wear debris and part of surface was analyzed. The surface roughness of quasicrystals before wear and after wear was studied by means of Talyprofile(Taylor/Hobson pneumo), while the phase structures were evaluated using X-ray diffraction(XRD).

3   RESULTS AND DISCUSSION

3. 1   Friction coefficient

As shown in Fig. 2, the friction coefficient varies with sliding time at given condition(T1 and T3). It is seen that the average friction coefficient decreases from 0. 151 down to 0. 094, as the sliding velocity increases from 0. 1 ms^{-1} upto 1. 0 ms^{-1}. It means that, the coefficient of friction of QCs is essentially dependent on the sliding velocity.
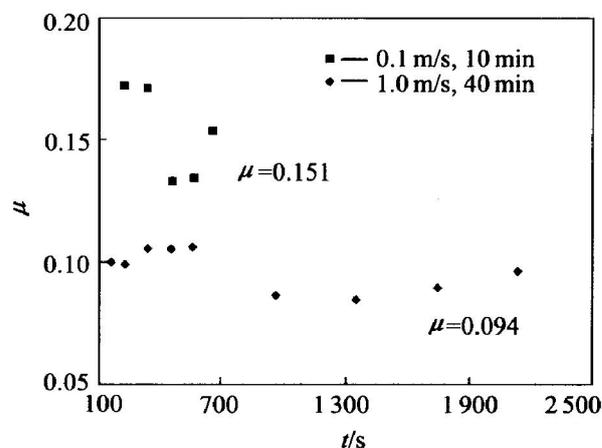

Fig. 2   Friction coefficient as a function of sliding time(T1 and T3)

Fig. 3 indicates that at 350 ℃, the average value of friction coefficient was obviously higher than that at room temperature. As sliding time increases it increases upto peak value 0. 32, then decreases rapidly, and finally, reaches to a constant value.

Effect of the applied load on friction coefficient is illustrated in Fig. 4. The average coefficient of friction increases with increasing the applied load. The values of the steady state coefficient of friction under the load of 35N are significantly lower than those of 15N, which are about 0. 056 and 0. 094, respectively. Compared the sliding tests under argon atmosphere(T3) with air atmosphere (T2), it is listed in

Table 1   Experimental conditions

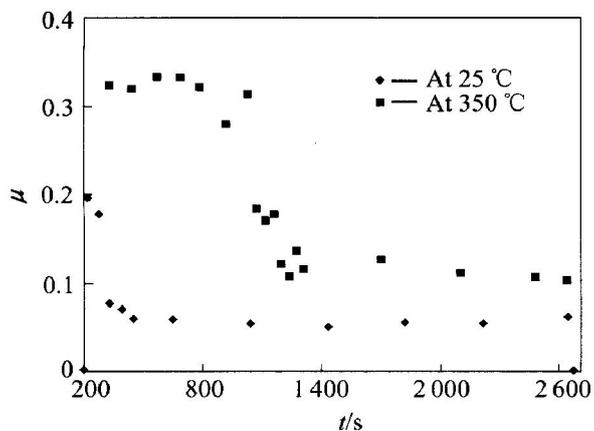| Test condition	Applied load/ N	Sliding velocity/ $(m \cdot s^{-1})$	Temperature/ ℃	Atmosphere	Sliding time/ min	Average coefficient of friction, μ
T1	15	0. 1	25	Argon	10	0. 151
T2	15	1. 0	25	Air	40	0. 100
T3	15	1. 0	25	Argon	40	0. 094
T4	35	1. 0	25	Argon	40	0. 056
T5	35	1. 0	25	Argon	20	0. 089
T6	35	1. 0	350	Argon	40	0. 325 – 0. 118

T0 —Before wear

Fig. 3 Friction coefficient as a function of sliding time(T4 and T6)
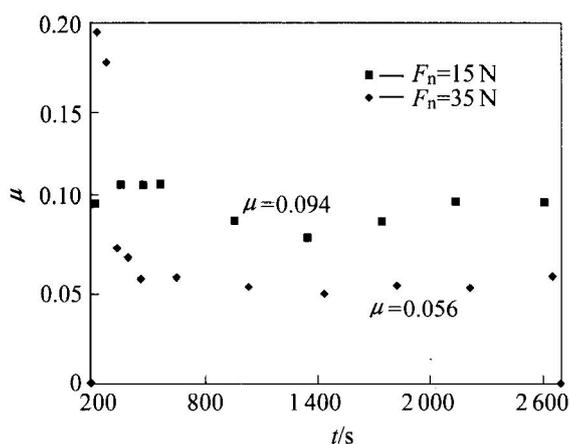

Fig. 4 Friction coefficient as a function of sliding time(T3 and T4)

Table 1 that the friction coefficient of the former(μ= 0. 094) is almost the same as the latter(μ= 0. 100) . The result implies that for QCs, coefficients of friction are seldom affected by the sliding condition with argon or air atmosphere.

It is noted that the friction coefficient is higher at the early stage, then decreases sharply and remains constant. Moreover, the friction coefficient of QCs is obviously lower than that of conventional metal materials[5]. As a rule, the temperature influences extremely on the friction coefficient of QCs.

3. 2 Morphology of worn surface

Fig. 5 exhibits the worn surfaces of QCs under different sliding conditions. There are very regular ploughing grooves along the direction of sliding at room temperature(Fig. 5(a) and Fig. 5(b)) , that is, abrasive wear is clearly observed on the worn surface. In addition, the adhesion on the worn surface can be seen. Cracks were observed, as shown in Fig. 5(c) and 5(d) , which were branched or almost perpendicular to the sliding direction. The different kinds of cracks were observed, for example, fine sub-crack. It might be related with the characterization of QCs. For the friction of QCs, there were two types of wear debris. One was the fine debris, as shown in Fig. 6. Its compositions examined by energy-dispersive spectrometer(EDS) demonstrated that those are made up of the Al and Fe-rich oxide. The fine debris scatters randomly on the worn surface. The other are larger
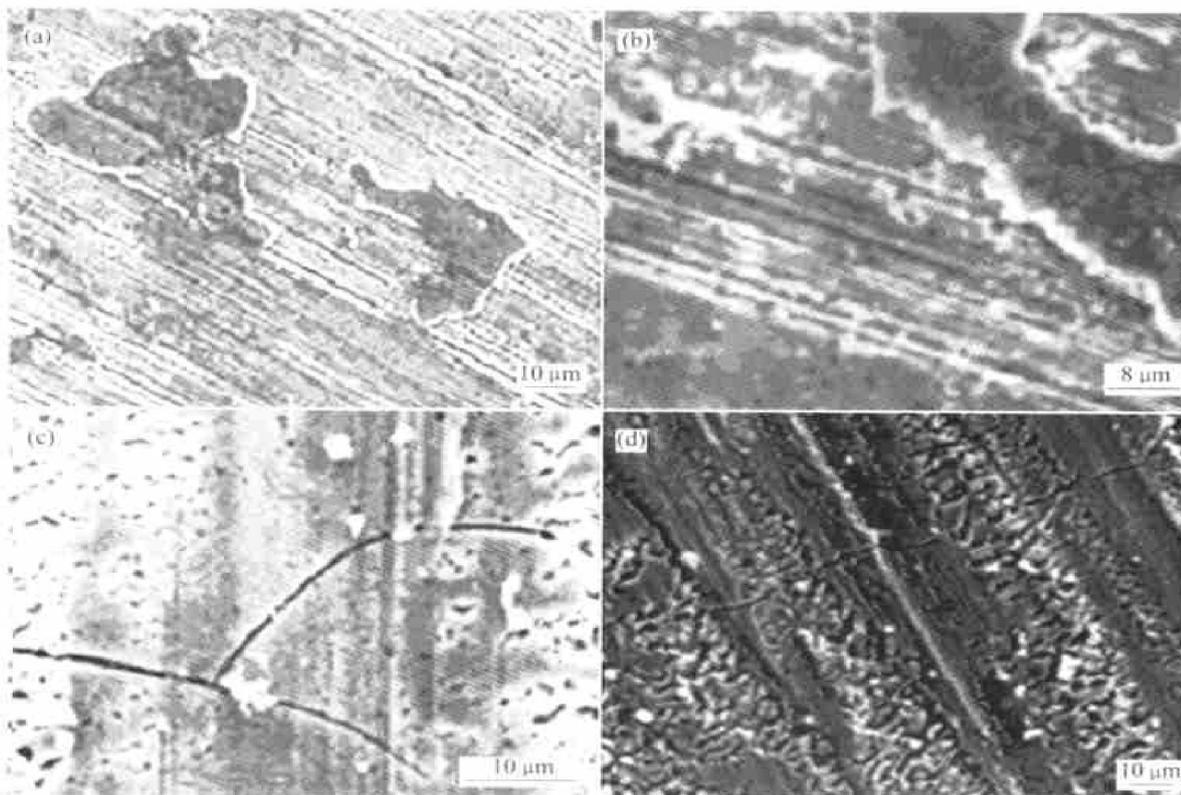

Fig. 5 SEM morphologies of worn surface
(a) —Under T3 test condition; (b) —Under T2 test condition; (c) —Under T6 test condition;
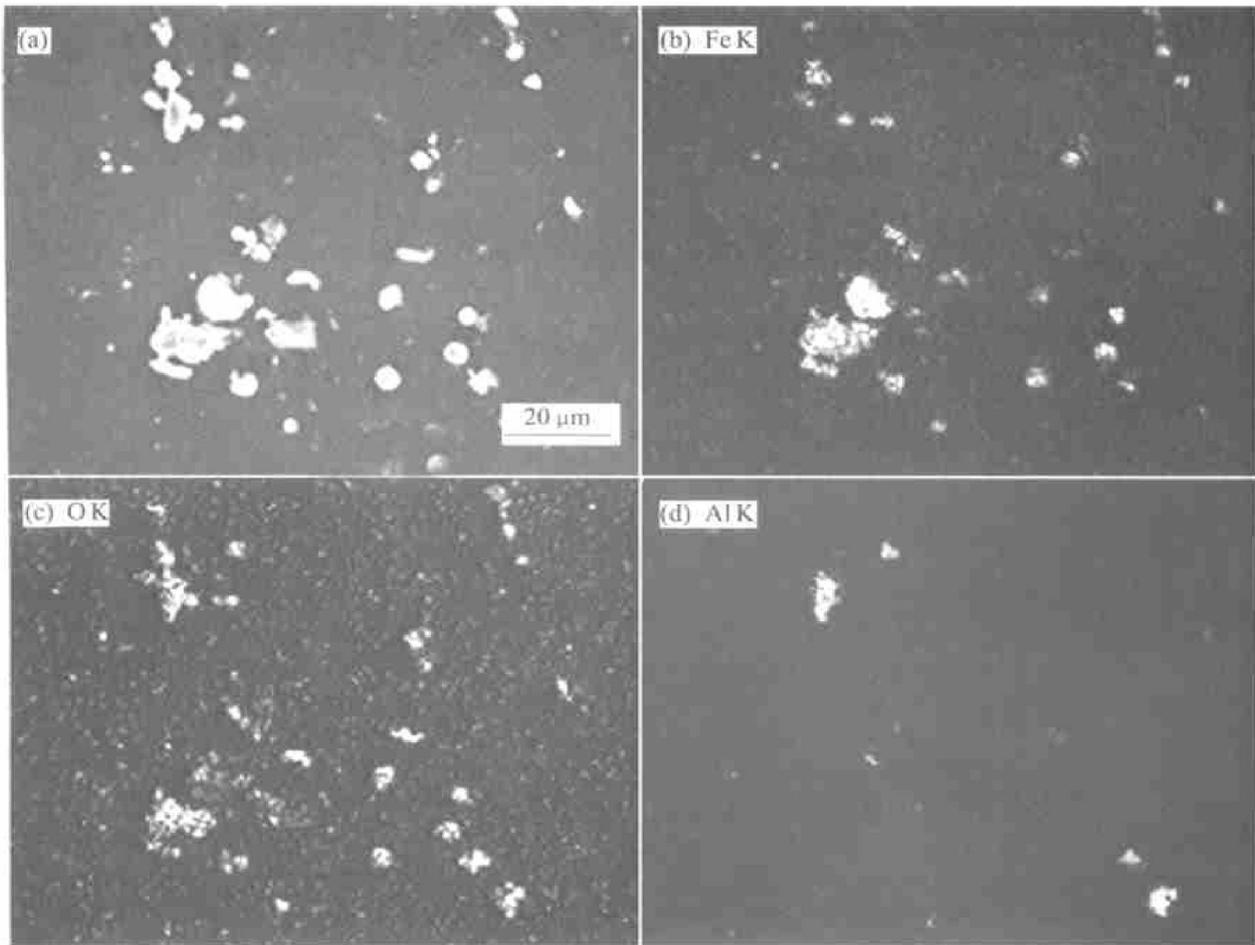(d) —Under T6 test condition showing area of delamination

Fig. 6　Morphologies of fine debris and related composition under T 3 test condition
(a) —All element; (b) —Fe; (c) —O; (d) —Al

sheet debris, having layered structure(Fig. 7). The composition examination of three areas(1, 2, 3 point in Fig. 7) showed that they have the same composition as QCs. Therefore, larger debris can be thought to form directly due to delamination from the surface of QCs. It is noted that, large debris are only produced under sliding friction at 350 ℃. Fig. 8 shows two states of wear debris to be peeled off and being peeling off. Morphologies of worn surface illustrate that the surface of QCs suffers the plastic deformation, and delamination takes place during the sliding
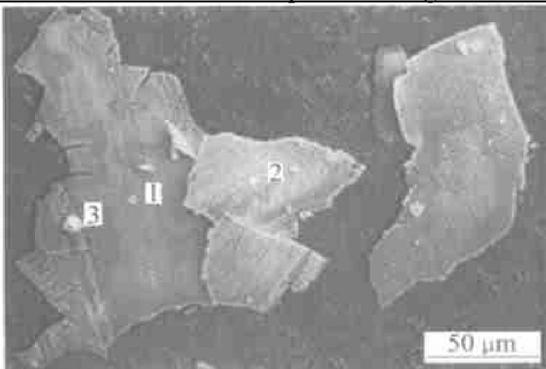

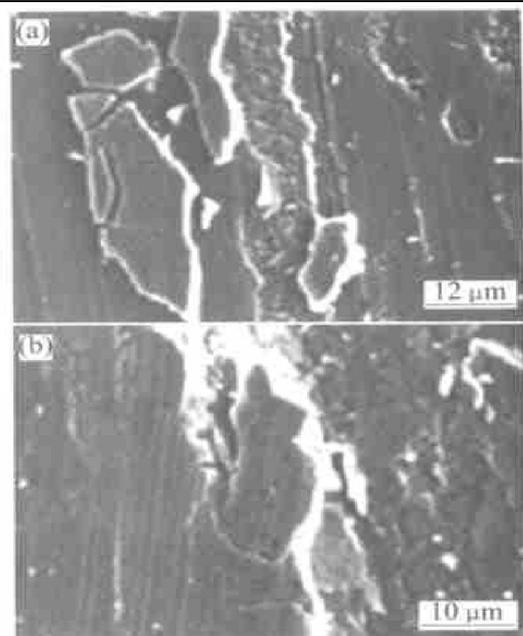
Fig. 7　Morphology of larger sheet debris at 350 ℃

Fig. 8　Morphologies of larger debris under T 6 test condition
(a) —To be peeled off; (b) —Being peeled off

friction at 350 ℃.

3. 3 Microstructure and roughness of worn surface

Fig. 9 shows the X-ray diffraction patterns of quasicrystals before and after friction under T6 condition at 350 ℃. The phase structural analysis illustrates that there are two phases(icosahedral phase and β_2 phase). The result was completely consistent with the data which suggested by ZHOU[6] for Al-Cu-Fe QCs, α-Al$_2$O$_3$ formed above 700 ℃. In this experiment, the basic structure did not significantly change after wear and before wear[7]. This probably related to the absence of oxygen under the argon atmosphere.
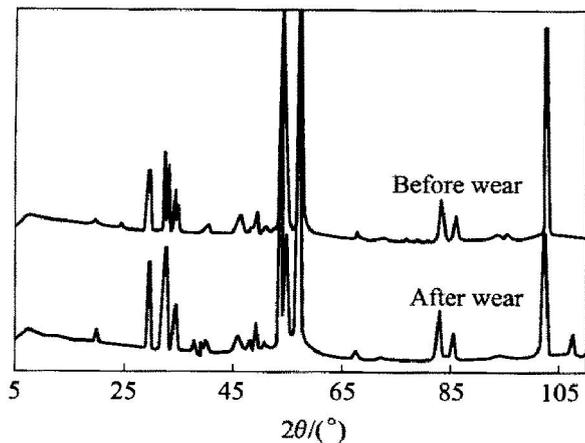

Fig. 9 X-ray diffraction patterns of QCs before wear and after wear at 350 ℃

It is shown that the surface roughness varied with sliding conditions(Fig. 10). The temperature had the greatest influence on the roughness of worn surface(under T6 test condition). Under the different applied load(T3 and T4) and atmosphere(T3 and T2), the surface roughness changed slightly. The roughness of QCs increased with increasing the sliding time, compared T4 with T5 test condition. That means, the sliding time had apparent effect on roughness.
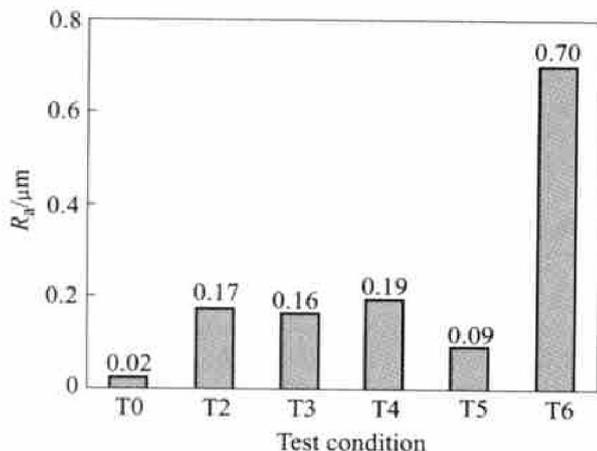
3. 4 Discussion

Fig. 10 Surface roughness(R_a) of QCs under different sliding conditions

It was reported[8,9] that the friction coefficient of two mating surfaces sliding against each other is given by addition of three main factors:

$$\mu = \mu_r + \mu_{ad} + \mu_{ab}$$

where r, ad, ab refer to the influence of roughness, adhesion, and abrasion, respectively. In this study, all roughness of QCs specimen were the same as that in the early wear stage. Higher value of friction coefficient in the early stage, which is frequently encountered for metallic and ceramic materials[10], was attributed to the initial polishing of mating surface(Fig. 3 and Fig. 4). So the coefficient of friction depends on the identification of tribological mechanism under different sliding conditions in running-in periods. When the applied load increases, the coefficient of friction decreases. The explanation was as follows: one was alteration of wear mechanism which adhesion was prevailed. The other was the increase of real surface area of friction as the load increased according to the Hertzian contact model[11].

With the increase of sliding velocity, the coefficient of friction decreases too. It can be inferred[12] that friction mechanism of worn surface is adhesion to prevail. The higher friction coefficient of 40 min sliding test could be associated to the presence of adhesion compared to the 20 min sliding test(Table 1). As a rule, the reasons that the friction coefficient is much lower than that of the other alloys are contributed to low surface energy of QCs and the surface roughness ($R_a \leqslant 0.02$ μm) before sliding. During sliding with argon and without argon, the morphology of worn surface has a little difference. Dominant wear mechanism of the former was abrasion; in contrast, the latter formed by partial oxygen adhesion. Flowing argon gas not only cooled continually the mating surface of QCs, but also prevented the surface from oxidation by decreasing the possibility of oxygen adhesion. Therefore, under argon atmosphere, the abrasive wear prevailed to take place.

The wear processes of QCs were generally described in term of one or more mechanisms, for example, adhesive and abrasive processes, microfracture, plastic deformation, delamination or fatigue. Any one of those mechanisms can predominate, or several of them can combine to develop the wear surface and subsurface. Generally, the dominant wear mechanism changes with the materials, or with varying the load or sliding velocity[13].

Delamination mechanism[14] on worn surface of QCs is illustrated in Fig. 11. Plastic deformation of the surface layer of these smooth surfaces led to the generation of subsurface cracks due to surface traction. Under cyclic loading, the cracks initiate or nucleate at defects of sintering QCs[15]. They propagated parallel to the surface for some distance before eventually branching to the surface and forming loose
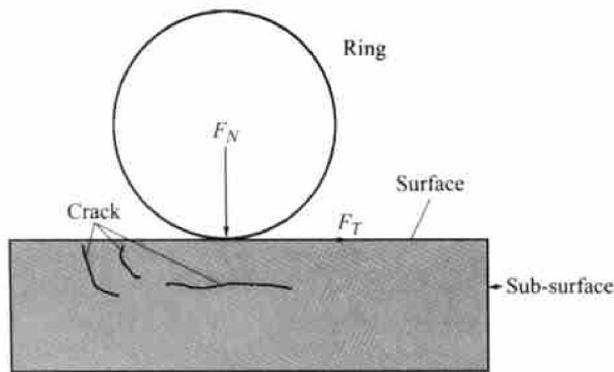
and larger debris(Fig. 7) .

Fig. 11　Schematic of formation of larger debris due to delamination mechanism

　　The higher value of friction coefficient at 350 ℃ was attributed to the generation and interposition of this wear debris, which acted as abrasive particles and contributed to enhance the materials removal. Furthermore, surface roughness of worn QCs at 350 ℃ was another reason to increase coefficient of friction.

4　CONCLUSIONS

　　The polycrystalline $Al_{59}Cu_{25.5}Fe_{12.5}B_3$ quasicrystals exhibit very low friction coefficient compared with the same types of metal materials. Temperature has the greatest influence on the friction coefficient. With increasing the temperature, the friction coefficient of QCs increases greatly. Increases of applied load and sliding velocity decrease the friction coefficient. This is due to the changes of wear mechanism under different conditions. The cracks are observed to form on the worn surface. Delamination is the dominant wear mechanisms at 350 ℃. Phase transformation is not observed on worn surface of QCs at 350 ℃.

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