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Friction and wear properties of mullite/ZrO_2/Al_2O_3 composites①

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Abstract: The friction and wear properties of ZrO_2 and Al_2O_3 cooperatively toughened mullite composites-mullite/ZrO_2/Al_2O_3(MZA) were studied. The tribological tests were performed in a line-reciprocating tribometer using a GCr15 steel ball on a MZA disk under different dry reciprocating sliding conditions at room temperature. A wide range of normal loads and sliding speeds were chosen to investigate the relationship between the wear mechanisms of MZA and the testing conditions. The wear mechanism diagram of MZA is constructed, it contains two typical regions. It suggests that the wear mechanisms of MZA in each of the region change from one to another depending on the wear conditions. In the mild wear region, the wear rate of MZA is 10^{-6} mm^3/m, and the wear mechanism of MZA is plastic deformation accompanied by a little micro-cracking. In the severe wear region, the wear rate of MZA is 10^{-5} mm^3/m and the dominant wear mechanism in this region is brittle fracture.

Key words: mullite/ZrO_2/Al_2O_3; friction and wear; ceramics; wear mechanism
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1 INTRODUCTION

Mullite-based composites have been regarded as one of the most important structural ceramics and widely used as heat-resistant and anti-wear materials in engineering fields[1-8]. The effective application of mullite-based composites as anti-wear components requires detail information on friction coefficient and wear rate under various conditions so as to ensure their efficient and reliable performance[9-11]. Furthermore, the understanding of the wear mechanisms of these materials is needed to develop new materials with improved performance. Unfortunately, the study on the tribological characteristics of these materials is insufficient for their applications. Therefore, zirconia and alumina cooperatively toughened mullite composites (MZA) were prepared, and the friction and wear behavior of the composites reciprocally sliding against steels under a wide range of loads and speeds was examined. In this paper, the friction and wear test results of the MZA in a wear-map form were dealt with, which can be used to guide the engineering application of these composites.

2 EXPERIMENTAL

2.1 Materials and properties

The MZA composites were sintered at the normal pressure state. The nominal composition of MZA is 68% mullite, 12% ZrO_2 and 20% Al_2O_3 (volume fraction). The main physical and mechanical properties of the MZA are listed in Table 1. The counterpart materials are GCr15 steel balls with diameter of 9.53 mm, surface roughness R_a of 0.03 μm, hardness HRC of 62 - 63, Poison's ratio ν of 0.25 and elastic modulus E of 206 MPa.

Table 1 Physical and mechanical properties of MZA

Hardness (HV)/MPa	ρ/ ($g \cdot mm^{-3}$)	K_{IC}/ ($MPa \cdot m^{1/2}$)	σ_f/MPa
8.5	3.8	5.5	382

ν	E/GPa	R_a/μm
0.2	206	0.03 - 0.05

2.2 Friction and wear test

The friction and wear behavior of the MZA composites against GCr15 steels was examined on an Optimol-SRV tribometer. The size of the MZA specimen is 19 mm × 19 mm × 3 mm. The tests were performed at an ambient temperature of 25 ℃

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and a relative humidity of 30% - 50%.

3 RESULTS AND DISCUSSION

3.1 Tribological properties

Fig. 1 shows the friction coefficient vs load curve for the MZA/GCr15 couple. It can be seen that the friction coefficient increases with increasing load and it is in the range of 0.48 - 0.58. Fig. 2 shows the variations of the wear rate of MZA with load and speed. The wear rates of MZA change from 10^{-6} mm^3/m to 10^{-5} mm^3/m depending on speed and load. Two typical wear regions, i. e. a mild wear region corresponding to a wear rate level of 10^{-6} mm^3/m and a severe wear region corresponding to a wear rate level of 10^{-5} mm^3/m can be identified in Fig. 3. Fig. 4 shows the wear rates of the counterpart GCr15 steel balls. It shows that the wear rates of the GCr15 steel balls also depend on both the load and speed and are at a level of 10^{-4} mm^3/m in the whole tests.

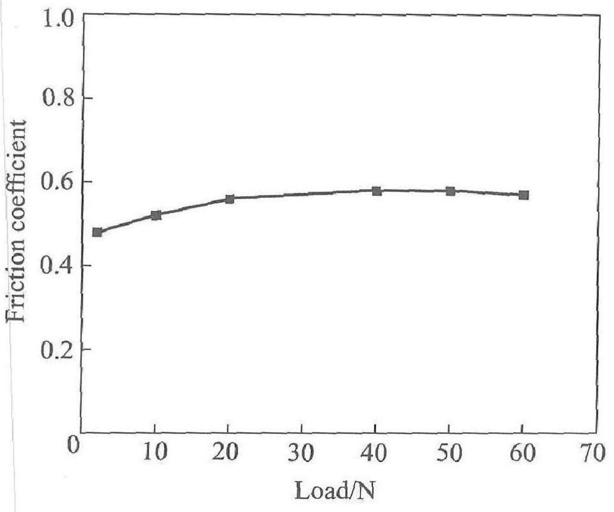

Fig. 1 Curve of friction coefficient vs load

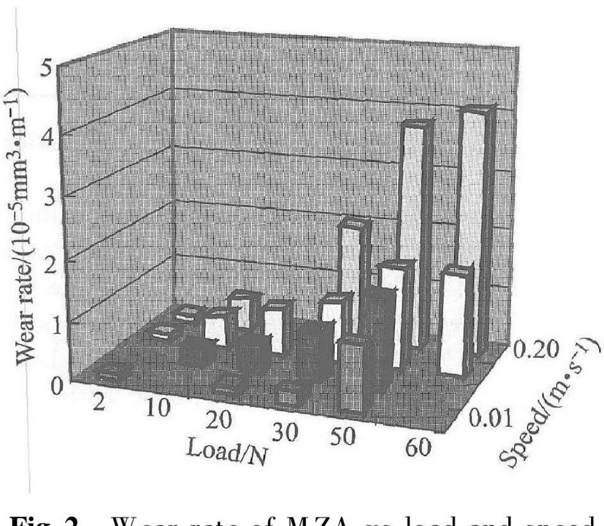

Fig. 2 Wear rate of MZA vs load and speed

3.2 Surface analysis

Fig. 5 shows the SEM image of the worn surface of MZA in the mild wear region in which the wear rate is in the level of 10^{-6} mm^3/m. It is found

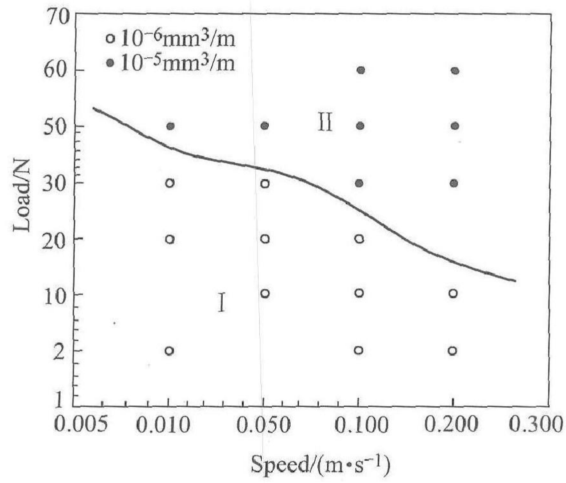

Fig. 3 Wear map of MZA

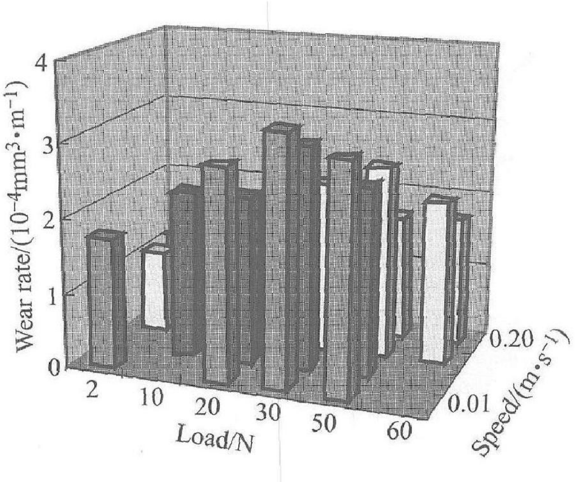

Fig. 4 Wear rate of GCr15 vs load and speed

that the worn surface in this region is relatively flat and characterized by slight ploughing, which indicates that MZA suffers mild plastic deformation under a small load. In the reciprocal friction process, plastic deformation was gradually developed to an extent and then caused the distortion of the crystal lattice on MZA surface. When the material could not be further deformed to absorb energy, it would experience the destruction of the crystal lattices and result in wear-away of the surface material. Subsequently, brittle fracture could be caused at some locations on MZA surface owing to the stress concentration.

Fig. 6 shows the SEM images of the worn surface of MZA in the severe wear region where the wear rate is at the level of 10^{-5} mm^3/m (load 50 N, speed 0.1 m/s). It can be seen that the worn surface in this region is relatively rough and characterized by brittle fracture with many micro-cracks and pits (Fig. 6(b)). Therefore, it is supposed that MZA is dominated by micro-crack and brittle fracture in the severe wear region.

In the whole testing range, the worn surface of the counterpart GCr15 steel balls shows the

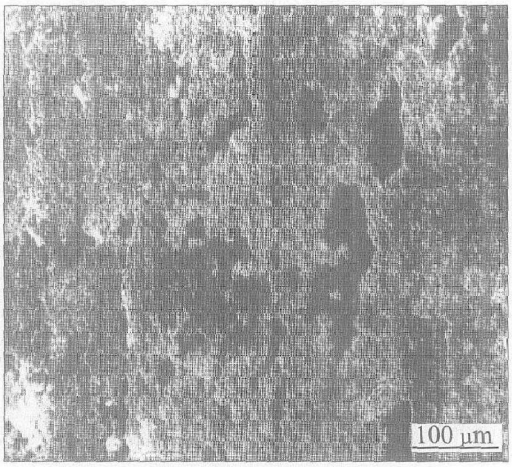

Fig. 5 SEM image in mild wear region

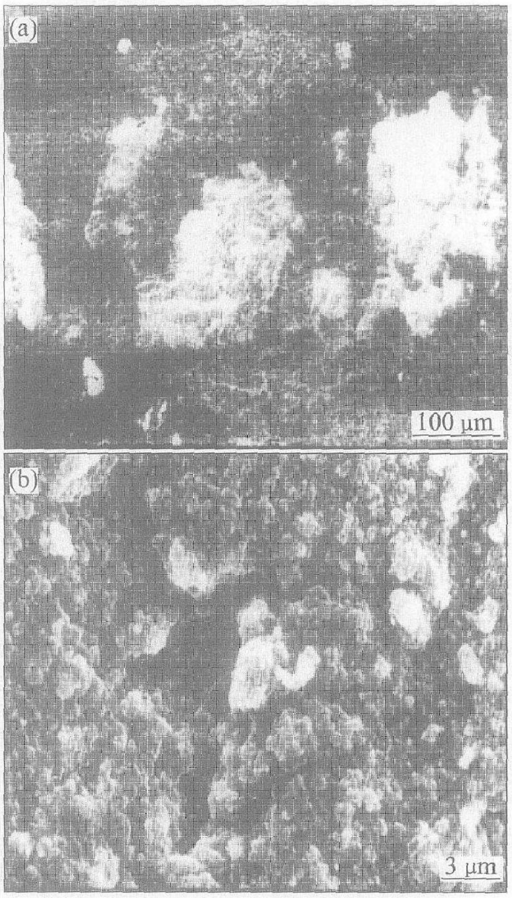

Fig. 6 SEM images in severe wear region

same features and are dominated by micro-cutting and plastic deformation.

3.3 Effect of normal load on wear behavior of MZA

According to the theory of elastic mechanics, the tensile stress(σ_0) between the frictional pair in a ball-on-disc contact configuration can be expressed as

$$\sigma_0 = \frac{2P}{2\pi}\left[\frac{3PR}{4}\left[\frac{1-\nu_1^2}{E_1}+\frac{1-\nu_2^2}{E_2}\right]^{\frac{1}{3}}\right]^{-2} \qquad (1)$$

where P is normal load; R is radius of the ball; ν_1 and ν_2 are the Poisson's ratios of the ball and the disc respectively; E_1 and E_2 are the elastic moduli of the ball and the disc.

The maximum tensile stress (σ_{max}) in the contacting area can be calculated as

$$\sigma_{max} = \frac{1-2\nu_2}{3}\sigma_0 \qquad (2)$$

In the presence of sliding in the side direction, the σ_{max} in the contacting area will be changed because of the existence of friction[12],

$$\sigma_{max} = \sigma_0\left[\frac{1-2\nu_2}{3}+\frac{\pi(4+\nu_2)}{8}f\right] \qquad (3)$$

where f is friction coefficient.

So the σ_{max} on the MZA surface can be obtained by introducing Eqn.(1) into Eqn.(3),

$$\sigma_{max} = \frac{3P}{2\pi}\left[\frac{3PR}{4}\left[\frac{1-\nu_1^2}{E_1}+\frac{1-\nu_2^2}{E_2}\right]\right]^{-2/3}\cdot \left[\frac{1-2\nu_2}{3}+\frac{\pi(4+\nu_2^2)}{8}f\right] \qquad (4)$$

The values of σ_{max} on the MZA surface at a fixed sliding speed of 0.1 m/s and loads of 2−60 N are calculated and listed in Table 2. It shows that at a light load of 2 N, the σ_{max} is 383.6 MPa. The fracture of the MZA can not to be initiated at such a small σ_{max}, therefore the MZA is dominated by plastic deformation, the worn surface is relatively flat (Fig.5), and the wear rate is as small as 10^{-6} mm^3/m. When the normal load reaches a certain value (50 N), the σ_{max} increases to as large as 1 327.4 MPa. Micro-cracking is initiated on the MZA surface, the material is worn away owing to brittle fracture (Fig.6), and the corresponding wear rate in this region is as large as 10^{-5} mm^3/m.

Table 2 Maximum tensile stress (σ_{max}) on surface of MZA

Load/N	σ_{max}/MPa	Load/N	σ_{max}/MPa
2	383.6	30	1 103.5
10	699.7	50	1 327.4
20	936.5	60	1 370.5

3.4 Effect of sliding speed on wear behavior of MZA

When the speed increases, the friction-induced heat is increased and so is the surface temperature, which in turn leads to change in the surface structure, hardness and the wear mode of MZA as well. ZrO_2 in MZA composite has three phases, i.e. m-ZrO_2, t-ZrO_2 and c-ZrO_2. The phase transformation among them can be expressed as[13]

$$m\text{-}ZrO_2 \xrightarrow{1\,170\ ^\circ C} t\text{-}ZrO_2 \xrightarrow{2\,370\ ^\circ C} c\text{-}ZrO_2 \qquad (5)$$

Under a certain critical speed at which the friction-induced temperature is high enough, the phase transformation from t-ZrO_2 to c-ZrO_2 may be initiated, which causes the volume decrease of the

ZrO_2 grains by 9% (volume fraction) [14, 15] and results in the tensile stress among the grains. Therefore, the surface fracture inclination on the worn surface of MZA will be greatly improved and the wear rate of MZA increases. For example, at a fixed load of 10 N, the wear rate of MZA is at 10^{-6} mm^3/m level as the speed is 0.05 m/s, but it increases to the level of 10^{-5} mm^3/m when the speed rises to 0.1 m/s.

4 CONCLUSIONS

The friction and wear behavior of MZA composites sliding against GCr15 steels in a ball-on-disc contact under dry reciprocal sliding mode was studied as a function of normal load and sliding speed. The wear modes of MZA can be summarized with a wear-map (Fig. 3). In region Ⅰ, MZA experiences mild wear and the corresponding wear rate is in the range of 10^{-6} mm^3/m, the wear mechanism is plastic deformation with slight micro-cracking. In region Ⅱ, MZA experiences relatively severe wear with the wear rate as high as 10^{-5} mm^3/m and the wear mechanism is dominated by brittle fracture. In the whole tests, the counterpart GCr15 steels have a wear rate level of 10^{-4} mm^3/m and the wear mechanism is characterized by micro-cutting and plastic deformation.

REFERENCES

[1] Schneider H, Okada K, Pask J. Mullite and Mullite Ceramics [M]. England: John Wiley & Sons Ltd, 1994. 232 - 245.

[2] Aksay K, Dabbs I A, Sarikaya M, et al. Mullite for structural, electronic, and optical application [J]. J Am Ceram Soc, 1991, 74(10): 2343 - 2358.

[3] Yuan Q, Tan J, Yang Z, et al. Preparation and properties of zirconia toughened mullite ceramics [J]. J Am Ceram Soc, 1986, 69: 265 - 267.

[4] XU Chong-hai, AI Xing, HUANG Chuan-zhen. Fabrication and performance of an advanced ceramic tool material [J]. Wear, 2001, 249: 503 - 508.

[5] CAI Shu, YUAN Qi-ming, MENG Jia-hong, et al. Study on the behavior of ZTM composites at low-temperature [J]. Journal of the Chinese Ceramic Society, 2001, 29(3): 221 - 225. (in Chinese)

[6] Prochazka S, Wallace J S, Claussen N. Microstructure of sintered mullite-zirconia composite [J]. J Am Ceram Soc, 1983, 66(8): 125 - 127.

[7] JIN Xi-hai, GAO Lian, KAN Yan-mei, et al. Influence of Nb_2O_5 on the mechanical performance and toughening mechanism of ZrO_2 in ZTM-Al_2O_3 [J]. Journal of Inorganic Materials, 2000, 15(6): 153 - 156

[8] MENG Jia-hong, CAI Shu, YANG Zheng-fang, et al. Microstructure and mechanical properties of mullite ceramics containing rodlike particles [J]. Journal of the European Ceramic Society, 1998, 18: 1107 - 1114.

[9] Tan Y, Wang Y, Yu A, et al. Effects of grinding on the wear resistance of ZTM composites [J]. Key Engineering Materials, 2004, 259 - 260: 366 - 369.

[10] Dogan C P, Hawk J A. Role of zirconia toughening in the abrasive wear of intermetallic and ceramic composites [J]. Wear, 1997, 212: 110 - 118.

[11] Lim S C, Ashby M F. Wear mechanism maps [J]. Acta Metall, 1987, 35: 1 - 24.

[12] Braza J F, Cheng H S. Mechanical failure mechanisms in ceramic sliding and rolling contacts [J]. Tribology Transaction, 1989, 32(1): 1 - 8.

[13] LI Ren-yu. New Finite Ceramics [M]. Shanghai: Tongji University Press, 1990. 65 - 78. (in Chinese)

[14] Woydt M, Klaffke D. Tribological transition phenomena of ceramic materials [J]. Wear, 1990, 136 (2): 373 - 381.

[15] WANG Xi-bi, SHI Han-min, REN Jing-xin. An investigation on the transformations in grinding affected layer of ZTC [J]. International Journal of Machine Tools & Manufacture, 2000, 40: 165 - 172.

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