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Tribological Properties of TiC-Based Ceramic/High Speed Steel Pairs at High Temperatures

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Abstract: The tribological properties of three TiC-based ceramics — HM1, HM2 and HM3 — against high speed steel were investigated by using a pin-on-disk tribometer at 25°C and 600°C. The results of the tests indicated that the friction coefficient and wear rate of HM2 were the lowest among the three ceramics. Its friction coefficient was 0.19, and its wear rate was $1.14 \times 10^{-14} m^3/N{\cdot}m$. The examinations of wear scars for ceramics by means of scanning electron microscope (SEM), X-ray diffractometer (XRD) and electron probe analyser indicated that the composition and structure of oxide films formed on the sliding tracks of the ceramics exhibit an important effect on the high temperature self-lubricating behaviour. This investigation also proved that Mo can improve the tribological properties of ceramics, while WC shows a negative effect on them. The different wear mechanisms of HM1 and HM2 were also discussed in this study. © 1997 Elsevier Science Limited and Techna S.r.l

Keywords: ceramic; high temperature; self-lubricating; surface oxide films; wear mechanism.

1 INTRODUCTION

The high hardness, wear resistance and corrosion resistance, combined with relatively low specific gravity of modern ceramics, offer them substantial advantages over metallic materials. In many applications, ceramics have been recognized as having great potential as substitutional materials for a series of rubbing-pairs, such as seal rings, valve seats, extrusion dies, cutting tools, bearings, cylinder liners, etc.[1,2]

Great progress in studying the tribological behaviours of ceramics has been achieved in recent years. The friction coefficient and wear rate of ceramics depend greatly on the experimental conditions, such as sliding speed, load, contact models, temperature and environment situations.[3–5] In an unlubricated sliding condition, the friction coefficient for various ceramics is between 0.1 and 1.0. The effect of temperature on the friction coefficient of ceramics is more complicated. For example, the friction coefficient of an Al_2O_3/Al_2O_3 rubbing pair at 800°C was higher than that at room temperature, but lower than that at 400°C,[2] while the friction coefficient decreased with the increase of temperature for an M-2 tool steel/Al_2O_3 rubbing pair.[6] Generally, the friction coefficient of both ceramic/ceramic and ceramic/steel rubbing pairs in the unlubricated condition is very high for many applications, and the wear rate of ceramics is also several orders of magnitude greater than the permissible value.[7] So the lubrication problems of ceramics must be solved in order to use ceramics in a wider field, especially in high temperature environments. Murray and Calabrese[8] reported that some solid lubricants are very effective in reducing the wear of silicon nitride at temperatures up to 800°C. However, they did not reduce friction. The result of Longson's test showed that a composite of $CaF_2/BaF_2/Ni$ is an effective lubricant for silicon carbides and titanium carbides at room temperature and at 600°C.[9] The solid film and coating lubricants used for high temperature are usually limited because the lubricant films can not reform themselves when they are worn away. The conventional liquid lubricants usually show a poor oxidative and thermal stability. In this paper, the tribological and self-lubricating properties of three TiC-based ceramics were investigated. At high temperature, the lubricating film was formed on the ceramic surface, and it could reform immediately when some part of it was worn away. This ability could solve the lubrication problem of the ceramics at high temperature. The self-lubricating mechanism of the ceramic was examined by using SEM and XRD.

2 EXPERIMENTAL DETAILS

The tests were carried out on a pin-on-disk tribometer at temperatures from 25 to 600°C. The schematic diagram of the tester is shown in Fig. 1. The pin was fixed, made from quenched high speed steel (HRC 62), 5 mm in diameter and 15 mm in length. The disk, made from three different hot-pressed TiC-based ceramics, represented as HM1, HM2 and HM3, respectively, was rotating. Its size was ϕ45 mm×5 mm. The properties of the three ceramics are listed in Table 1. The original surface roughness of both the pins and the disks was $Ra = 0.16\,\mu m$. Before the tests, the specimens were cleaned with acetone in an ultrasonic bath for 15 min. The load was 39.2 N, the sliding speed was 1.0 m/s, and the running time was 60 min for each pair. At least two tests were performed for each condition, with the standard deviation being less than 5%. The friction force was recorded continuously. The wear volumes of specimens were calculated from the weight loss data, which was measured by using a precision balance. In order to correct the weight increase caused by high temperature oxidation, a disk specimen was maintained at the same high temperature for the same time as the friction tests used, its weight increase could then be obtained and used as a reference for other disk specimens in friction tests.

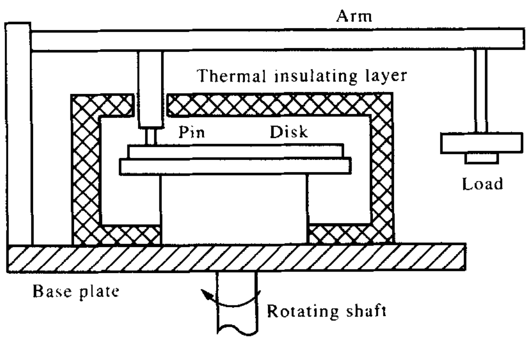

Fig. 1. Schematic diagram of the tester.

3 RESULTS AND DISCUSSION

3.1 Effect of temperature on friction and wear

The friction and wear characteristics of the ceramics were investigated at 25°C and in the range of 300–600°C. The results are shown in Table 2. The mean friction coefficient of the three ceramics at 25°C was 0.45–0.47. It decreased to 0.19–0.29 at 600°C. The variation of the friction coefficient with temperature is shown in Fig. 2. In general, the friction coefficients of the three ceramics decreased slowly with the increase of temperature, but the decrease velocity was different for the three ceramics. The friction coefficient of HM2 at 600°C was the lowest among them. The variation of the wear rate with temperature was similar to that of the friction coefficient. Their wear rates at 600°C were much smaller than those at 25°C (see Table 2).

The examinations on the worn ceramic surfaces by using SEM and XRD indicated that the decrease of friction and wear with temperature was attributed to the oxide films formed on the ceramic surfaces at high temperature. These oxide films were different in thickness, composition and lubricity for different materials. So the three ceramics showed different friction and wear properties at high temperature.

The variation of friction coefficients with sliding time at 600°C is shown in Fig. 3. At a constant temperature, the friction coefficients for all three ceramics were generally stable during the whole running time, a slight fluctuation could be caused by the partial breakdown and reforming of the oxide film on the rubbing surface.

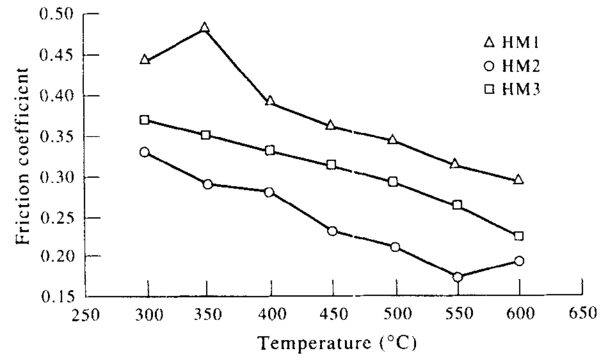

Fig. 2. Variation of friction coefficient with temperature. Temperature increase 8°C/min, load 39.2 N, sliding speed 1.0 m/s.

Table 1. Composition and properties of the three TiC-based ceramics

Materials	Composition (wt%)	Density ($g.cm^{-3}$)	Hardness (HRA)	Impacting strength ($\times 10^4 N.m/m^2$)	Compressive strength (MPa)	
					25°C	600°C
HM1	TiC, Ni(18)	5.67	69	0.86	680	610
HM2	TiC, Ni(13), Mo(5)	5.86	72	1.06	760	680
HM3	TiC, WC(10), Ni + Mo(18)	7.26	78	1.33	900	870

Table 2. Friction and wear properties of the three ceramics at different temperatures

Materials	Mean friction coefficient			Wear rate ($\times 10^{-14} m^3/N.m$)		
	25°C	300–600°C	600°C	25°C	300–600°C	600°C
HM1	0.47	0.38	0.29	19.60	13.70	10.60
HM2	0.45	0.27	0.19	8.39	1.76	1.14
HM3	0.47	0.33	0.21	7.47	2.16	1.38

3.2 Effect of Mo on the friction and wear of the TiC-based ceramics

The components Mo and WC could not only affect the physical and mechanical properties of the TiC-based ceramics, but also cause the difference in the tribological characteristics. The friction coefficients of HM1 at 25°C and 600°C were 0.47 and 0.29, respectively, which indicated that this ceramic shows a certain self-lubricity at high temperature. Generally, the reason for the self-lubricity of some materials at high temperature is considered to be the formation of an oxide film on the rubbing surface. The lower friction coefficient and wear rate of HM1 at high temperature were just due to the formation of nickel oxide (NiO) film (see Fig. 4).

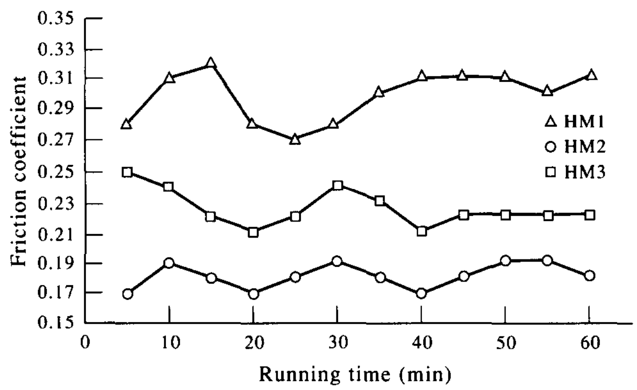

Fig. 3. Variation of friction coefficient with running time. Temperature 600°C, load 39.2 N, sliding speed 1.0 m/s.

Compared with the ceramic HM1, HM2 showed a much lower friction coefficient and wear rate at 600°C. The XRD spectrum of the worn HM2 surface is shown in Fig. 5. The formation of MoO_3 on the rubbing surface made the friction coefficient and wear rate of HM2 much lower.

Both NiO and MoO_3 are good solid lubricants for high temperature application, MoO_3 can be produced more easily than NiO at the same temperature. The differential thermal analysis curves

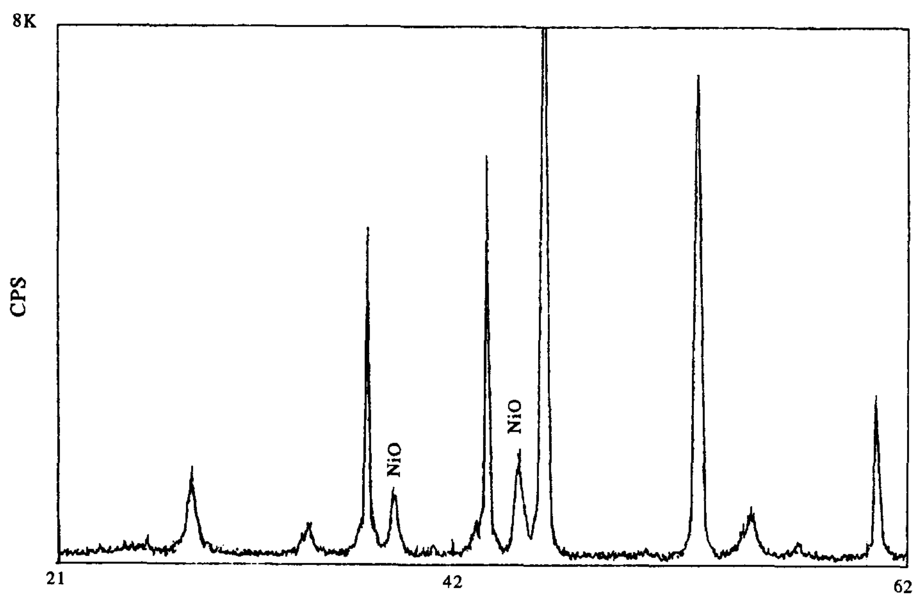

Fig. 4. XRD spectrum of the worn HM1 surface.

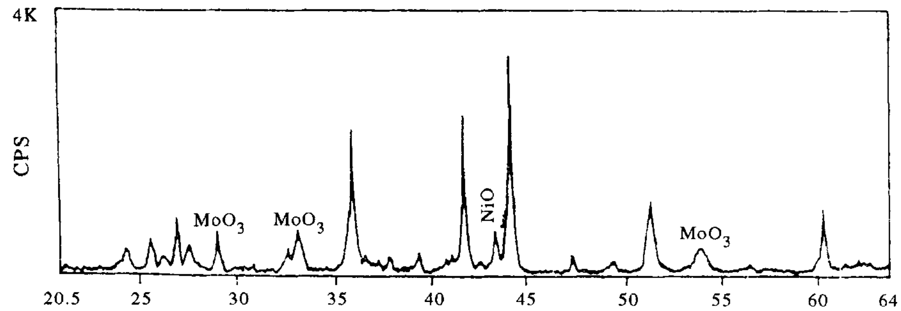

Fig. 5. XRD spectrum of the worn HM2 surface.

of Mo and Ni powders are shown in Fig. 6. The temperature at which Mo begins to be oxidized intensely is about 100°C lower than the temperature for Ni. The standard heats of formation of MoO_3 and NiO are $-745\,kJ.mol^{-1}$ and $-240\,kJ.mol^{-1}$, respectively,[10] which also indicates that Mo can be oxidized more easily than Ni. At high temperature, only a little NiO was produced on the HM1 rubbing surface, the lubricating film of NiO was too thin to reduce the friction and wear. The film could not be self-mended right away when it was worn out, which led to the occurrence of intense adhesive and abrasive wear (caused by ceramic particles). Apart from NiO, quite a large amount of MoO_3 was formed on the surface of HM2, and the oxide film was thick enough to separate the high speed steel and the ceramic surfaces. In this case, the oxide film could be formed easily because of the existence of Mo. So only oxidation wear occurred for the ceramic HM2 at 600°C, and the friction and wear were quite low. The SEM examination of the worn ceramic surfaces proved the wear mechanisms clearly (see Fig. 7). The wear scar of HM1 was much rougher than that of HM2. A complete oxide lubricating film could be found on the SEM micrograph of HM2.

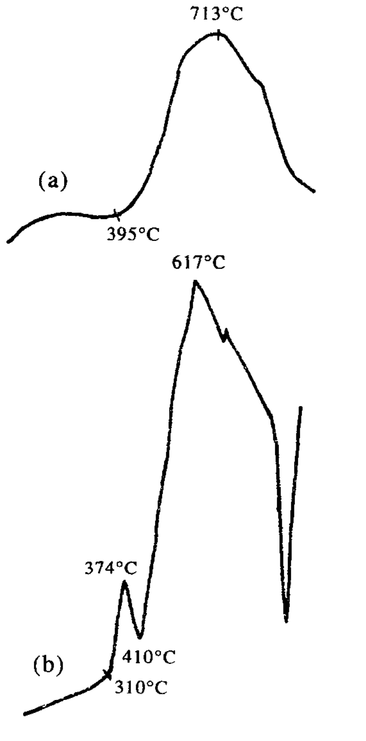

Fig. 6. The differential thermal analysis curves: (a) for Mo powder and (b) for Ni powder.

3.3 Effect of WC on the friction and wear of the TiC-based ceramics

The ceramic HM3 was composed of TiC, WC, Ni and Mo. The addition of WC brought about a

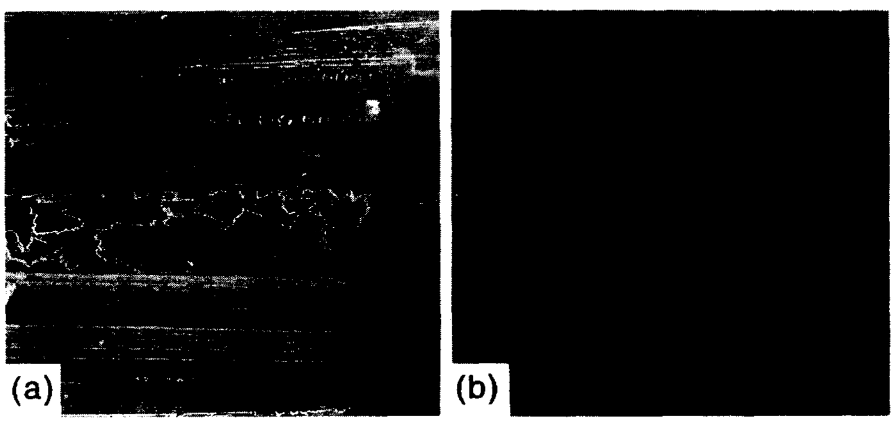

Fig. 7. SEM morphologies of the worn ceramic surfaces (×300): (a) HM1 and (b) HM2. Temperature 600°C, sliding speed 1.0 m/s, load 39.2 N, running time 60 min.

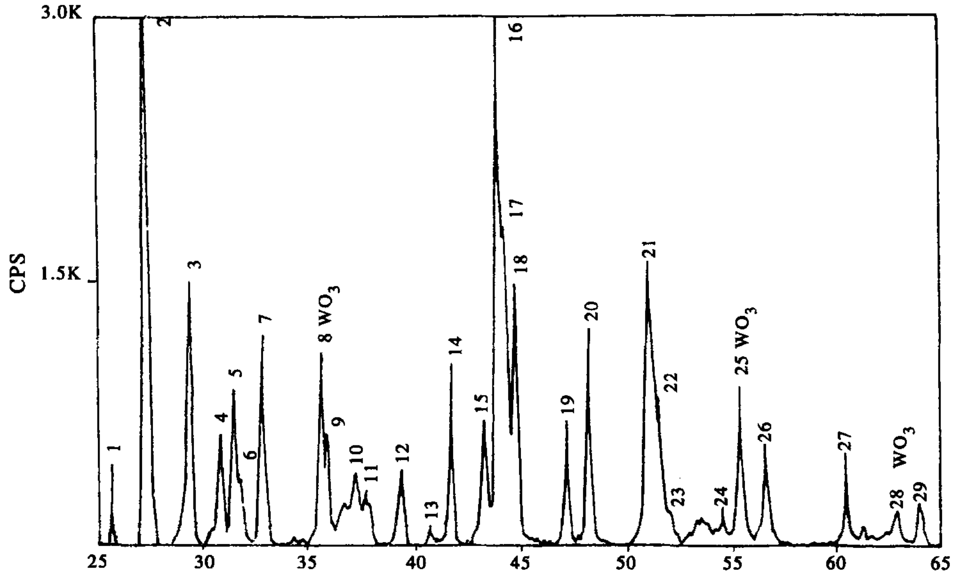

Fig. 8. XRD spectrum of the worn HM3 surface.

harmful effect on its friction and wear. Its friction coefficient and wear rate at high temperature were a little higher than those of HM2. This effect of WC should be attributed to its high temperature oxidation. Figure 8 is the XRD spectrum of the worn HM3 surface. It can be seen that a large amount of WO_3 was produced on the rubbing surface. Reference 11 reported that the friction coefficient of WO_3 at 538°C was 0.55, while the friction coefficient of MoO_3 was only 0.20. In addition, the large amount of WO_3 made the oxide film on the HM3 surface too thick and too loose. Consequently, the film could be broken and worn away easily. So the existence of WC in the TiC-based ceramics deteriorated the friction and wear properties of the materials.

4 CONCLUSION

The following conclusions can be drawn from the results discussed above:

(1) The three TiC-based ceramics showed different self-lubricity at high temperature. Among them, HM2 exhibited the lowest friction coefficient and wear rate.
(2) The self-lubricating property of the ceramics was due to the formation of an oxide film on the rubbing surface. NiO was a very good high temperature lubricant, but the amount of NiO produced on the HM1 surface was too little to lubricate the rubbing surface.
(3) The Mo component of TiC-based ceramics could be oxidized more easily than Ni. A much thicker and denser oxide film was formed on the HM2 rubbing surface at high temperature, which made the ceramic show good friction and wear properties.
(4) Because of the different compositions, the ceramics HM1 and HM2 showed different wear mechanisms at high temperature. The former could be worn away mainly by adhesive and abrasive wear. However, the latter was worn away only by oxidation wear, so the wear rate was quite low.
(5) The formation of WO_3 on the HM3 rubbing surface deteriorated the friction and wear properties of the ceramic because WO_3 showed quite a high friction coefficient at high temperature. In addition, the oxide film was too thick and too loose, and could be broken and worn away easily.

REFERENCES

1. JIAJUN, L., *Wear Principal and Wear Resistance of Materials*. Tsinghua University Press House, Beijing, 1993.
2. ZUM GAHR, K. H., Sliding wear of ceramic/ceramic, ceramic/steel and steel/steel pairs in lubricated and unlubricated contact. *Wear*, **133** (1989) 1–22.
3. WOYDT, M. & SCHWENZIEN, J., Dry and water-lubricated slip-rolling of Si_3N_4- and SiC-based ceramics. *Tribology International*, **26** (1993) 165–173.
4. TOMIZAWA, H. & FISCHER, T. E., Friction and wear of silicon nitride at 150°C to 800°C. *ASLE Trans.*, **29** (1986) 481–488.
5. SKOPP, A. & WOYDT, M., Ceramic composite materials with improved friction and wear properties. *Tribology International*, **25** (1992) 61–70.
6. PETERSON, M. B. & MURRAY, S. F., Frictional behaviour of ceramic materials. *Met. Eng. Q.*, **7** (1967) 22–29.

7. KLAUS, E. E., DUD, J. L. & WU, W. T., Lubricated wear of silicon nitride. *Lubrication Engineering*, **47** (1991) 679–684.
8. MURRAY, S. F. & CALABRESE, S. J., Effect of solid lubricants on low speed sliding behaviour of silicon nitride at temperatures up to 800°C. *Lubrication Engineering*, **49** (1993) 955–964.
9. LONGSON, B., Lubrication of high temperature ceramic materials. *Tribology International*, **16** (1983) 221–225.
10. AYLWARD, G. H. & FINDLAY, T. J. V., *SI Chemical Data*, 2nd edn. John Wiley & Sons, Australia, 1974.
11. FAN, Y., OUYANG, J., ZHANG, X. & XU, J., *Handbook of Solid Lubrication* (in Chinese). Machine Building Industry Press House, Beijing. 1986.