Int. Journal of Refractory Metals and Hard Materials 44 (2014) 12–18

Contents lists available at ScienceDirect

Int. Journal of Refractory Metals and Hard Materials

journal homepage: www.elsevier.com/locate/IJRMHM

Effect of the counterpart material on wear characteristics of silicon carbide ceramics

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ARTICLE INFO

Article history:
Received 23 September 2013
Accepted 20 January 2014
Available online 24 January 2014

Keywords:
Silicon carbide
Counterpart material
Coefficient of friction
Wear resistance

ABSTRACT

The pin-on-disc dry sliding friction and wear experiments have been made on SiC ceramics in contact with Si_3N_4, Al_2O_3, and ZrO_2 ceramic balls and WC-Co ball at 5 N load in an ambient environment. Coefficient of friction and specific wear rate were measured, and wear damage mechanisms were identified. The friction coefficient of SiC varied in the range of 0.5–0.65 against Al_2O_3 ball, between 0.62 and 0.67 against Si_3N_4, in the range of 0.45–0.54 against ZrO_2, and between 0.46–0.59 against WC-Co ball. The SiC materials with fine globular microstructure had lower COF and wear rate than SiC materials with coarser rod-like microstructure. The results showed that with the ZrO_2 and WC-Co counterpart the wear rate of SiC decreased while with the Si_3N_4 ceramic counterpart the wear rate of SiC was about one order of magnitude higher. The main wear mechanism was similar for all studied materials in the form of mechanical wear (micro-fracture) and tribochemical reaction (creation of coherent layers composed mainly of a large amount of oxygen).

1. Introduction

Ceramics are hard and stiff, which makes them very attractive materials for use in contact-mechanical and tribological applications [1]. The high hardness and relatively good toughness give an excellent abrasion resistance, adding further to the good tribological properties of silicon carbide (SiC) [2]. SiC is an important engineering structural material and is widely used in applications like bearings, valves and seals. Therefore, friction and wear properties of SiC are investigated to a greater depth.

Wear is a complex problem, which cannot be easily predicted from basic mechanical properties (hardness and fracture toughness), and tribological studies of the developed materials are indispensable [3]. Tribological performance of the sliding pairs depends on many factors: environmental conditions, sliding velocity, load, surface quality, and microstructure of the mated materials. Values of COF > 0.5 and wear rate > 10^{-5} mm^3/Nm are unacceptable for most technological applications [4].

The tribological behaviour of silicon carbide is reported in several works for a wide range of sliding speeds, load and temperatures [5–13]. Tribological behaviour of SiC is determined by oxidation reactions in the presence of oxygen and/or humidity in the surrounding atmosphere [5]. Tribochemical reactions often take place during sliding leading to the formation of a protective layer. Absorption of water on sliding surfaces may increase friction and wear or decrease them depending on the nature of ceramics, applied load and sliding speed [6]. Sliding couples of ceramic materials like silicon carbide, silicon nitride, alumina or zirconia normally have high friction coefficients in unlubricated conditions [7]. Rani [8] investigated the tribological behaviour of ceramic materials in water by varying the test conditions. He found that, for self-mated Si_3N_4 and SiC ceramics, the tribochemical reaction resulted in surface smoothening with low friction coefficient at high load and speed. Sasaki [9] clearly showed that COF of Si_3N_4 and SiC ceramics dropped as low as 0.01 when they slid against themselves in water. Chen [10] reported that the wear rate of Si_3N_4 and SiC was in the same magnitude of 10^{-9} mm^2/N. Cho [11] investigated liquid-phase-sintered (LPS) SiC and mentioned that an abrupt transition in the wear mechanism from an initial grooving process to a grain pullout process occurred during the test. Takadoum et al. [6] carried out a sliding test in humid air and reported the formation of hydrated silicon oxide on the worn surface of SiC. When the silica debris was removed and the test was continued, coefficient of friction (COF) increased. Murthy [12] studied the effects of relative humidity and doping elements on the COF and wear of SiC in unlubricated condition. At higher humidity, the COF is low and is independent of doping elements.

The effect of microstructure on the sliding wear was studied by Borrero-López et al. [13]. It has been shown that elongated-grain LPS SiC has improved sliding-wear properties over equiaxed-grain LPS SiC, which has been attributed to the interlocking network of elongated grains. Wang [14] studied ultra-fine-grained ceramics and reported that wear resistance decreases with increasing grain size and with decreasing hardness. Kim [15] reported that the wear resistance improved

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http://dx.doi.org/10.1016/j.ijrmhm.2014.01.006

with a decreasing Si_3N_4 grain size despite the decreased fracture toughness. However, only very few papers have been focused on the investigation of the influence of counterpart material on the wear characteristics of SiC or Si_3N_4 materials [16,17]. Guicciardi [16] noted that the friction coefficient decreased when the ceramics were not self-mated. In particular, the self-mated SiC coupling had the highest COF and the coupling Si_3N_4/n-SiC the lowest.

The aim of this work was to study the tribological properties of sintered and heat treated SiC materials and to determine the influence of counterpart material on the coefficient of friction and wear.

2. Experimental

2.1. Experimental materials

β-SiC powder (HSC-059, Superior Graphite) was mixed with Al_2O_3 (A 16 SG, Alcoa) and Y_2O_3 (grade C, H.C. Starck). The weight ratio of nonoxide matrix to oxide sintering additives SiC: Y_2O_3 + Al_2O_3 was kept constant, 91:9. The weight ratio of particular oxides Y_2O_3:Al_2O_3 was 6:3 for all compositions. The powder mixtures were ball milled in isopropanol with SiC balls for 24 h. The suspension was dried and subsequently sieved through a 25 μm sieve screen in order to avoid hard agglomerates. The samples were sintered by hot pressing at 1850 °C/1 h under mechanical pressure of 30 MPa in N_2 atmosphere. The hot pressed samples were subsequently annealed under various temperature conditions given in Table 1. After sintering and annealing the specimens were cut, polished to a 1 μm finish using routine ceramographic methods, and then plasma etched. The microstructures were then studied using an SEM (JEOL JSM-7000F).

2.2. Hardness and fracture toughness

The densities of the sintered and annealed specimens were measured according to Archimedes' principle in water. Mechanical properties were investigated using indentation methods. Microhardness was determined by Vickers indentation (hardness testers LECO 700AT) under a load of 9.81 N with a dwell time of 10 s. In order to determine the indentation toughness at least 15 Vickers indentations per specimen were introduced with the load of 49.05 N. The indentation toughness was calculated from the lengths of radial cracks and indents diagonals using a formula valid for semi-circular crack systems as proposed by Anstis et al. [18]:

$$K_{IC} = 0.016\left(\frac{E}{H}\right)^{1/2}\left(\frac{P}{c^{3/2}}\right) \quad (1)$$

where K_{IC} — indentation toughness ($MPa \cdot m^{1/2}$); 0.016 — material-independent constant for Vickers-produced radial cracks; E — Young modulus (GPa); H — Vickers hardness (GPa); P — indentation load (N); c — half-length of the radial crack (m).

2.3. Sliding-wear testing

Wear testing was carried out at room temperature on a high temperature tribometer (CSM Instruments) using the ball-on-disc technique. Wear behaviour of the prepared SiC materials was studied in dry sliding where tribological partner was a highly polished ball with 6 mm diameter made out of commercial ceramics — Si_3N_4, Al_2O_3, ZrO_2 and WC-Co (Spheric-Trafalgar Ltd.). Normal load of 5 N and sliding speed of 0.1 m/s were applied. Total sliding distance was 500 m. The tests were performed in air with relative humidity of 30 ± 5%. The friction coefficients were continually recorded and wear volume on each specimen was calculated from the surface profile traces across the wear track and perpendicular to the sliding direction using the confocal microscopy (SENSOFAR).

The worn volume of the disk was calculated according to the following equation [19]:

$$V_d = 2\pi R\left(\frac{S_1 + S_2 + S_3 + S_4}{4}\right) \quad (2)$$

where R (mm) and S (mm^2) are the sliding radius and the cross section area of the worn track, respectively.

The worn volume of the ball was calculated according to the following equation

$$Vb = \frac{\pi A^3 B}{32D} \quad (3)$$

where A and B are the longer and shorter diameters (mm) of the worn area of the top of the ball, respectively, and D is the ball diameter (mm).

The wear surfaces were studied using SEM to identify the wear mechanisms.

The specific wear rate is given by

$$W_S = \frac{V}{F_N.L} \quad (4)$$

where W_s is the specific wear rate (mm^3/Nm), V the volume of removed material (mm^3), F_N the normal load (N) and L the total sliding distance (m).

3. Results and discussion

3.1. Microstructures

Representative SEM micrographs of a polished and plasma etched surface of the SiC materials are shown in Fig. 1A–C. The microstructures of hot pressed materials (Fig. 1A) and materials annealed at 1650 °C (Fig. 1B) consist of fine submicron-sized equiaxed SiC grains with a low aspect ratio (~1). No visible effect of the heat treatment at 1650 °C was observed on the microstructure of the material. The microstructure of the SiC material significantly changed after their post-sintering high temperature treatment at 1850 °C (Fig. 1C). It has a bimodal distribution and consists of elongated SiC grains with a higher aspect ratio (4.4) and of smaller equiaxed SiC grains. The mentioned results clearly demonstrate that β → α phase transformation is key for the growth of SiC grains with a high aspect ratio [20].

3.2. Mechanical properties

All ceramic samples were well densified. The specimens with oxide additives have a value of relative density above 97.2% and the density was decreased by increasing the annealing temperature. In Table 1 it can be seen that the hardness values for SiC materials are almost the

Table 1
Heat treatment regimes and mechanical properties of the investigated materials.

Samples	Heat treatment	Density (g/cm^3)	HV5 (GPa)	$K_{IC,ind}$ ($MPa \cdot m^{1/2}$)	E (GPa)
SiC-HP	HP (1850 °C/1 h)	3.220	20.4 ± 0.9	2.90 ± 0.2	450
SiC-1650	HP (1850 °C/1 h) + AN (1650 °C/5 h)	3.220	19.4 ± 0.3	3.35 ± 0.2	420
SiC-1850	HP (1850 °C/1 h) + AN (1850 °C/5 h)	3.189	20.6 ± 0.3	4.54 ± 0.4	422