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Effect of load on tribological properties of silicon nitride/steel under rolling-sliding contact condition

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ABSTRACT

The tribological behaviors of Si_3N_4/GCr15 tribo-pair under dry rolling-sliding friction condition at different loads were investigated by using a modified rolling-sliding contact device. The pure sliding friction under the same condition was executed as a comparison test. The results showed the friction coefficient and the wear rate at rolling-sliding contact condition were below that at pure sliding contact condition. For the rolling-sliding contact condition, when the loads were 10 N and 20 N, the wear mechanisms of Si_3N_4/GCr15 tribo-pair were adhesive wear and abrasive wear. Hence, the friction coefficients were higher (0.58 and 0.4 respectively). With the load continuously increased from 30 N to 100 N, the dominant wear mechanisms were the combination of adhesive wear, delamination wear and contact fatigue, and the friction coefficient decreased with an increase in the load. In addition, it also can be seen that the rotational number of the ball showed an increasing trend with the increase of the load with the aid of high-speed camera. At the loads of 30 N and 50 N, a discontinuous tribofilm was formed on the worn surface and the friction coefficients were 032 and 0.23 respectively. At the loads of 70 N and 100 N, the friction coefficients were as low as 0.14 and 0.08, the wear rates of both ball and disk were the order of magnitude of 10^{-7} $mm^3N^{-1}m^{-1}$, and the worn surfaces were quite smooth with a handful of spalling zone, which can be attributed to the tribo-chemical reaction products. For the pure sliding contact condition, the wear mechanisms of Si_3N_4/GCr15 tribo-pair were mainly dominated by mechanical wear at the loads of 10 N, 20 N and 30 N, and when the load was 50 N the dominating wear mechanism was tribo-oxidation reaction.

1. Introduction

Structural ceramics have been widely used in a variety of engineering fields because of their high strength, high hardness, low density, excellent thermal and chemical stability, and good corrosion resistance [1–3]. For rolling contact applications, silicon nitride (Si_3N_4) ceramics have become the preferred materials of rolling elements, and it has been successfully applied in all-ceramic and hybrid ball bearings [4–9]. In addition, silicon nitride is also a potential candidate of meshing element materials in non-clearance precision ball transmission, which the active balls engage with a cycle groove to transmit movement and force [10,11]. In fact, the ball usually undergoes non-conforming contact (i.e. Hertzian contact) in aforementioned applications, and suffers combined rolling and sliding friction.

To the best of our knowledge, the vast majority of studies on silicon nitride ceramics materials were mainly focused on rolling contact fatigue [1,12,13], failure mechanism [6,7,14–16], lifetime prediction [17–19], or wear characteristics [5,20–23]. Most of test rig types were twin-disk rig, ball-on-rod rig, disk-on-rod rig, or modified four-ball rig, etc., nevertheless, the data about ball-on-disk rolling-sliding contact tests were still lacking [24–26]. It was worth noting that the actual friction condition of the circumferential ball-on-disk tester was the most consistent with the motion of these mechanisms, for example, thrust bearing, cycloid ball planetary transmission. In addition, those conventional types of test rig inevitably increased the geometry complexity and manufacturing cost of silicon nitride ceramic materials, and those tests were usually achieved at a higher contact stress or higher speeds. Thus the ball-on-disk rolling-sliding contact device showed the potential application for rolling contact test, and especially in rolling wear tests.

Generally speaking, many external factors such as contact stress, rolling velocity, number of cycles, or lubrication state could affect the wear characteristics of silicon nitride ceramic ball. At present, the study of researchers was mainly carried out at high loads and speeds. Under the conditions of very high contact stress and speed, the damage mode of silicon nitride ball could be the fatigue spalling or subsurface cracking. However, the evolution of worn surface caused by the contact fatigue damage and surface wear under the conditions of low contact

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stress and low rolling velocity was completely different from that under the conditions of high contact stress and high rolling velocity, due to the effect of random slippage. Furthermore, under non-lubricated conditions, the rolling wear was an unavoidable factor for the rolling-sliding friction with the low contact stress and speed.

The hot isostatically pressed silicon nitride (HIPSN) balls are the most potentially used for hybrid ball bearings. However, the high manufacturing costs, especially the cost of the final surface-finishing methods, and the complex preparation technologies are still one of the important factors that limit the application of HIPSN [27,28]. Nowadays, the gas pressure sintered silicon nitride (GPSN) balls receive more attention due to their lower manufacturing cost and reliable sintering process [15]. So this paper mainly selected the gas pressure sintered silicon nitride balls as one pairing material.

In this work, we present a rolling-sliding contact device that could acquire an orbital rolling-sliding motion of a ball on a disk, following the ball-on-disk testing principle. We have chosen the gas pressure sintered silicon nitride balls as the rolling element, and the GCr15 steels as the matching disc. The tribological properties of Si_3N_4/GCr15 tribo-pair under dry sliding and rolling-sliding contact friction with different contact stress were investigated. The wear characteristics were analyzed by measuring the friction coefficient and wear rate, observing the worn surface morphology and analyzing the composition of the tribo-film. In addition, this paper firstly employed a high-speed camera to record and research the rolling movement of the ball on the disk.

2. Experimental descriptions

2.1. Test materials

The gas pressure sintered silicon nitride (GPSN) balls were employed in this paper for friction and wear test and commercially obtained from JunKeNaXin special ceramic Co. Ltd (China). The physical and mechanical properties of the GPSN are shown in Table 1.

The disk specimens were GCr15 steel. The main compositions of GCr15 steel are given in Table 2. The microstructure and XRD analysis result of the GCr15 steel are depicted in Fig. 1. As shown in Fig. 1(a), the granular pearlite is uniformly distributed on the ferrite matrix. Fig. 1(b) shows that the phase structure of the disk is composed of $Cr_{0.03}Fe_{0.97}$, Fe and Fe_3C.

2.2. Experimental methods

In this study, ball-on-disk rolling-sliding contact tests were carried out on a MMW-1 vertical universal friction and wear tester. Fig. 2(a) depicts the new rolling-sliding contact device that uses modified pin-on-disk test fixture. In this tribometer, a block specimen was firmly placed in the rectangular slot attached to the lower surface of the rotary upper fixture. A bushing was mounted in the bore of the middle fixture assembled with the upper fixture to fit a ball specimen. A disk specimen was firmly placed in the stationary bottom fixture which had been loaded by the loading system. The data of the friction torque and the friction coefficient were automatically monitored at 5 s intervals in all tests by the data processing software.

The block (with the size of 5 mm × 6 mm × 10 mm) and the bushing were made of PTFE [29], in order to eliminate the wear of the fixture to the ball. The ball specimen was made of Si_3N_4 ceramic with diameter of 9.525 mm, and surface roughness (R_a) of 0.012 μm. The disk specimen was made of GCr15 steel with the dimensions of 44 mm in diameter and 6 mm in thickness, surface roughness (R_a) of 0.04 μm, and hardness of 63 HRC. As the load was applied with simultaneous rotary movement of the upper fixture, the Si_3N_4 ball was forced to circumferentially roll and slide between the GCr15 disk and the PTFE block, and the axis of circumferential motion was the axis of spindle. In this case, two kinds of movements arose during the rolling friction [30]: one was circumferential translation along the circular path, and the other was the rotation around its axis, as shown in Fig. 2(b). The rotating axis of the ball was parallel to the contact surface of the disk. These movements were similar to those in an axial bearing or a precision ball transmission. Thus the original contact geometry of Si_3N_4/GCr15 tribo-pair was circular contact (Fig. 2(c)), and the contact increased to the full width throughout the test as a consequence of wear.

Table 1
Physical and mechanical properties of GPSN.

Material	Density (g/cm^3)	Elastic Modulus (GPa)	Hardness (HV)	Fracture Toughness (MPa·m$^{1/2}$)	Compressive Strength (GPa)
Si_3N_4	3.23	320	19	8	> 3500

Table 2
Main chemical compositions of GCr15 steel.

Grade	Components (wt. %)						
	C	S	Si	P	Mn	Ni	Cr
GCr15	0.95	≤0.020	0.27	≤0.027	0.36	≤0.30	1.49

According to the Hertzian contact stress theory for ball-on-plane contact type, the maximum contact pressure p_{max} can be calculated by the following equations [31]:

$$p_{max} = 0.578 \times \left(\frac{F_N \times E'^2}{r^2}\right)^{1/3} \quad (1)$$

$$a = 0.909\left(\frac{F_N \times r}{E'}\right)^{1/3} \quad (2)$$

$$\frac{1}{E'} = \frac{1-\nu_1^2}{E_1} + \frac{1-\nu_2^2}{E_2} \quad (3)$$

$$\tau_{max} = 0.31 \times p_{max} \quad (4)$$

$$h_m = 0.47 \times a \quad (5)$$

Where F_N is the normal applied load, r is the radius of the ball. E_1 and E_2 are the Young's moduli of the ball and the disk, ν_1 and ν_2 are the Poisson's ratios of the ball and the disk, respectively. a is the radius of the contact circle. τ_{max} is the maximum subsurface shear stress. h_m is the depth from the maximum subsurface shear stress to the surface. Table 3 lists the corresponding computing results for different loadings.

All the experiments were performed at ambient temperature without lubrication. The normal loads were 10 N, 20 N, 30 N and 50 N, corresponding to maximum contact pressures of 0.737 GPa, 0.929 GPa, 1.063 GPa and 1.261 GPa, respectively. The rotation velocity was 300 rpm. The rolling-sliding distance of all tests was 1000 m. Every test was repeated at least three times. Before each test all specimens were ultrasonically cleaned with ethanol for 10 min. The friction coefficient curve was automatically recorded by the tribometer, and the value of the friction coefficient in the paper refers to the average value during the steady state. In addition, the wear rate K (mm^3/Nm) of the ball or the disk was given by $K = \triangle m/\rho FS$, where $\triangle m$ is the mass loss (mm^3) weighed by a microbalance with an accuracy of 0.1 mg, ρ is the density (g/cm^3), F is the normal load (N), S is the total friction distance (m). For comparison, the ball pure sliding against the disk was implemented in the ball-on-disk test mode under the aforementioned experiment conditions. Moreover, the normal loads (70 N and 100 N) were chosen to further investigate the effect of the load on the friction and wear characterization of Si_3N_4/GCr15 under rolling-sliding contact condition.

At the same load range a high-speed camera (FastCAM MINI UX100, Photron, Japan) was employed to find out how the ball roll over the