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Effect of sliding mating materials on vacuum tribological behaviors of sintered polycrystalline diamond

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ABSTRACT

The comparative tribological behaviors of the sintered polycrystalline diamond (PCD) sliding against SiC, Si_3N_4, GCr15 and Al_2O_3 mating balls have been investigated by a ball-on-disk tribometer under vacuum conditions. Scanning electron microscope (SEM), energy dispersive X-ray spectrum (EDS) and Raman spectroscopy were performed to study the morphologies and chemical composition of the worn surfaces on the PCD and mating balls. The results showed that the coefficients of friction (COFs) of PCD/SiC and PCD/Si_3N_4 tribopairs were about ten times as high as those of PCD/GCr15 and PCD/Al_2O_3 tribopairs. The EDS and Raman spectroscopy results demonstrated that the higher friction and wear of PCD/SiC and PCD/Si_3N_4 tribopairs were attributed to serious adhesion caused by the formation of C–C and Si–C bonds at the contact interface. Some diamond grains were found in the wear scar of GCr15 mating ball, which indicated that the embed diamond grains spalling from the PCD surface resulted in abrasive wear by plowing mechanism. Sliding against Al_2O_3, the low ultimate surface roughness and chemical inertness maintained the super low COF and minimal wear of both the PCD disc and mating ball. These results proposed that the vacuum tribological behaviors of the PCD were significantly affected by mating materials.

1. Introduction

The polycrystalline diamond (PCD), sintered under high temperature and high pressure, is composed of diamond micro-powders and a "binder phase" of Co [1,2]. It is one of the potential materials for space drilling bits and aerospace components, including thrust bearings, due to its extremely high hardness, toughness and thermal conductivity, and high wear resistance [3–7]. The much-needed comparative study for tribological mechanism on variant mating materials in vacuum can offer engineering reference for proper mate selection, and make it more effectively applicable in aerospace field [8,9].

The vacuum tribological behaviors of diamond materials vary when sliding against dissimilar mating materials [10–12]. Liu et al. [10] examined the friction and wear behaviors of diamond-like carbon films sliding against GCr15, bronze, ZrO_2, Al_2O_3, SiC, WC, and Si_3N_4 mating balls under high vacuum conditions, and the contact radius and the contact pressure were introduced to explain the diverse friction behaviors. Yu et al. [11] studied the vacuum tribological behavior of chemical vapor deposition (CVD) diamond films sliding against Si_3N_4, and observed a mass of transferred layers on the worn track of diamond. Zeiler et al. [12] investigated the friction behaviors of CVD diamond sliding against different ceramic materials. And the results show that Al_2O_3 and Si_3N_4 exhibit excellent wear behaviors accompanied by very low friction, and SiC and ZrO_2 show somewhat inferior wear and friction behaviors. The different tribological behaviors of diamond materials result from diverse tribological mechanisms. Adhesion was proposed explaining diamond friction in vacuum [13–16]. Grillo et al. [13] investigated the vacuum tribological properties of self-mated natural diamond, and suggested that adhesion plays a fundamental role in diamond tribological behavior in vacuum. Bowden and Tabor [14] proposed that vacuum friction resulted from atomic bonding between diamond surfaces. Under vacuum conditions, the surfaces are not passivated by adsorbed molecules and therefore the dangling σ bonds of the carbon atoms on diamond surfaces are free to join at the sliding interfaces. Such interactions can cause strong adhesion and hence high friction [15,16]. Besides, the effect of mate surface roughness on tribological behaviors of diamond materials has been investigated [17–19]. Schade et al. [17] announced that the self-mated fine-grained CVD diamond coatings with low surface roughness and good flatness were best for dry sliding, and they indeed revealed in some cases longer running-in times. Similar speculation on the role of roughness was made by Hayward et al. They concluded that running-in period depended on surface roughness, and that the friction would decrease only after the interface had been

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smoothed by abrasive wear [18,19]. Based on previous work, the diamond materials exhibit significantly various vacuum tribological behaviors by different tribological mechanisms when sliding against diverse mating balls. The study on friction and wear behaviors of the PCD sliding against Si_3N_4 ball indicated that the friction coefficients obtained under vacuum are much higher than those under ambient air, and Zhao et al. [2] attributed it to the serious adhesion between counter surfaces and weak bonding strength among diamond grains. Nevertheless, few researches have been performed on the influence of mating materials on the tribological behavior of PCD under vacuum conditions.

Therefore, in the present paper, vacuum sliding wear tests were carried out using SiC, Si_3N_4, GCr15 and Al_2O_3 mating balls, to investigate the role of mating materials on the tribological behaviors of the PCD. The wear track and wear scar were examined using scanning electron microscope (SEM)/energy dispersive X-ray spectrum (EDS) and Raman spectroscopy to explore the vacuum tribological mechanisms of the PCD when sliding against different materials.

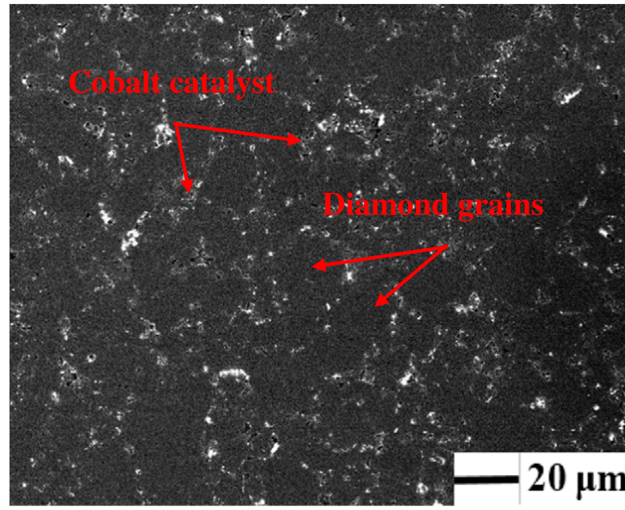

Fig. 2. SEM morphology of the PCD surface.

2. Experimental details

2.1. Materials

The flat samples used in this work are commercial grade polycrystalline diamond compacts (PDCs), which contain coarse grain (half-content diameter, D50 = 25 μm) diamond, and WC-Co (16 wt.% Co) substrate. The diamond grains are typically placed adjacent to WC-Co substrate that provides a source for catalyst metal. The PDC disc was polished to make the surface roughness reach a value of 3–4 nm. The cross-sectional image and optical photo of the PDC are shown in Fig. 1. It can be seen that the dimensions of the disc are 45.0 mm in diameter, 2.9 mm in thickness, and 540 μm in thickness of the PCD layer and 2.37 mm in thickness of WC-Co substrate. Fig. 2 presents the surface morphology of the PCD. It is identified that the binder phase corresponded to the bright regions distribute along the grain boundaries of diamond corresponded to the dark ones.

In this study, SiC, Si_3N_4, GCr15 and Al_2O_3 balls were used as mating samples. The physical properties of the PCD and mating balls are listed in Table 1 [2,9,20].

2.2. Tribological tests

The tribological tests were performed in vacuum (~7.0×10^{-4} Pa) by a ball-on-disk space tribometer (MSTS-1) [21]. The PDCs were used as the disks. The ball specimens were SiC, Si_3N_4, GCr15 and Al_2O_3 balls with diameter of Φ 9.525 mm. During the tests, the mating ball was fixed while the PDC disc was rotating with a turning radius of 10 mm, and the duration of tribological test was 30 min. The friction forces were measured by the dynameter and then converted into friction coefficients throughout the tests. Prior to the tribological test, both the PDC discs and mating balls were rinsed with hexane, and then ultrasonically cleaned in fresh hexane, finally cleaned by ultrasonic with acetone for 30 min. The investigation aims to study the effect of mating materials on vacuum tribological behaviors of the PCD. Generally, the tribological behaviors of the PCD should be affected by the applied load and revolution speed. Therefore, the impact of applied load (30 N and 45 N) on the vacuum tribological behaviors of the PCD was investigated under a constant revolution speed of 100 r/min. Moreover, the applied load was constant at 30 N to evaluate the effect of revolution speed (100 r/min and 150 r/min) on the tribological behaviors of the PCD in vacuum. The selected parameters of the applied load and revolution speed were based on previous tribotests under diverse applied loads and revolution speeds.

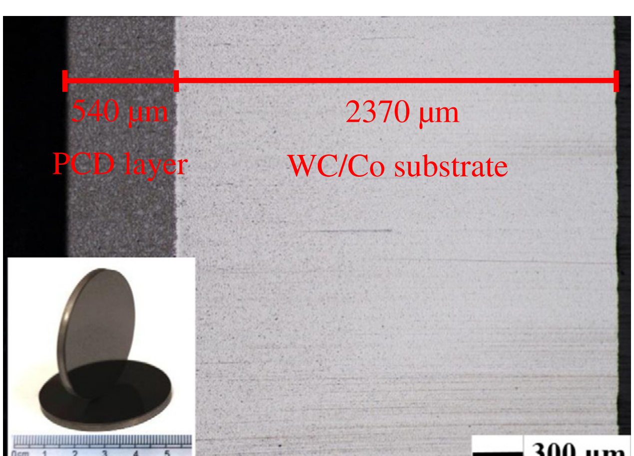

Fig. 1. The cross-sectional image and optical photo (the inset) of the polycrystalline diamond compact.

2.3. Surface analysis

The surface analysis of the PCD discs and mating balls tested under 30 N and 100 r/min was carried out to study the vacuum tribological mechanisms. Because the tribological behaviors of the PCD sliding against different mating materials under various applied loads and revolution speeds present a similar trend. The three-dimensional wear profiles across wear tracks of the PCD were measured by NanoMap-D three-dimensional white light interferometer. The wear scar morphologies of mating balls were observed using the Olympus BX51M optical microscopy and VK-X100K confocal microscope. The surface roughness of the mating balls before and after tribological tests were measured by VK-X100K confocal microscope. The CS3400 scanning electron

Table 1
Physical properties and surface roughness of test specimens.

Materials	Hardness (GPa)	Young's modulus (GPa)	Surface roughness (nm)	Thermal conductivity (W/(m·K))	Poisson's ratio
PCD	40–50	810	3–4	700.0	0.07
SiC	25–27	440	30–40	33.0–33.4	0.17
Al_2O_3	15–17	370	300–350	25.2–32.9	0.27
Si_3N_4	14–16	300	20–30	16.2–29.5	0.25
GCr15	6–8	210	20–30	45.2–51.3	0.30