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Improved vacuum tribological properties of sintered polycrystalline diamond compacts treated by high temperature annealing

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A B S T R A C T

The sintered polycrystalline diamond compacts (PDC) can be used in drilling in outer space with its excellent tribological properties such as low friction coefficient and high wear resistance. However, an unsatisfactory adhesion resistance behavior should be brought to the forefront, which may be the main factor resulting in the failure of PDC under vacuum environment. Consequently, we make the first attempt at improving the vacuum tribological behaviors of PDC. The effects of annealing on the vacuum tribological behavior of PDC are discussed in view of experimental studies using complementary analytical techniques (Raman, SEM&EDS, AFM). Raman spectra revealed that the degree of graphitization of PDC was increased with the temperature. The wear mechanism of the PDC under vacuum condition varied from adhesion to the abrasive wear when the annealing temperature was increased from 25 °C (RT) to 700 °C in ambient air. It was found that the friction coefficient of the compacts under vacuum can be minimized to lower than 0.015, while the wear can hardly be seen. Therefore, the vacuum tribological behavior of PDC can be largely improved after annealing treatment.

1. Introduction

The polycrystalline diamond compact (PDC), consisting of a diamond layer on a WC-Co substrate, has been successfully applied in the manufacture of antiwear parts, especially such as the drilling bits, thrust bearing, and cutting tools [1–5]. Nowadays, with the rapid development of the outer space exploration, the materials of drilling bits with superior vacuum tribological performances are strongly required. PDC is one potential material for outer space drilling due to its unique properties such as high hardness, thermal conductivity and perfect wear resistance [2–7]. However, the frictional and wear behaviors of PDC under the vacuum condition are non-ideal [8–11]. It is imperative to improve the vacuum tribological performances of PDC in both scientific researches and practical applications.

The effects of vacuum condition on the tribological behaviors of diamond materials have been reported [10–12]. Under high vacuum conditions, the friction heat cannot be released because of no gas convection, which may result in an increase of the local flash temperature. Many researches have demonstrated that the local flash temperature is the dominant factor which can cause graphitization of diamond. Moreover, due to the absence of contaminated layer which plays a role of surface dangling passivation in vacuum condition, two solid surfaces can immediately contact with a strong covalent interaction. Gardos et al. pointed out that, the adhesion between the surfaces of the films caused a higher friction coefficient for chemical vapor deposition (CVD) self-mated diamond films under vacuum compared with that in ambient environment [9]. Zhao et al. found that the friction coefficients of the PDC under vacuum are much higher than that under ambient air. This is due to the strong adhesion caused by the desorption of the absorbed film formed on the frictional surface under vacuum [10]. Miki et al. found that the friction coefficient of the nanocrystalline diamond coatings under high vacuum (1.33×10^{-5} Pa) can be kept at 0.35 [11]. All above studies have manifested that the direct contact of two sliding surface under vacuum can lead to a serious adhesion which results in higher friction coefficients and more serious wear.

Simultaneously, some researchers made a further understanding of adhesive wear [12–18]. Achard et al. proposed that adhesive

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wear occurred by fracture and the creation of debris particles [15], and the idea was extensively confirmed by experimental observations at different scales [16,17]. Previous atomistic modeling studies of the adhesive wear predicted a new mechanism of continual smoothing of surfaces [18]. Aghababaei et al. designed atomistic simulations and elaborated two experimentally observed adhesive wear mechanisms [19]. They explicated that hard materials with large asperities and strong adhesive bonding at the asperity contact junctions favored the debris formation mechanism over the asperity smoothing mechanism. Consequently, the size and existing state of debris severely affect the contact regime of asperities, thus influence the adhesive interactions across sliding interfaces. On the basis of those, we suppose that transforming the form and shape of wear debris via changing the interface physical and chemical properties may affect the tribology performance of PDC.

Although the technological benefits of PDC is tremendous, alleviating the adhesion phenomena of PDC under vacuum condition remains one of the most major challenge for the applications in the outer space exploration. The annealing treatment with the advantage of convenience and efficiency has been widely used to improve the mechanical properties of metallic materials, such as grain refinement and distressing [20–23]. Alternatively, this conventional method can also be considered to improve the tribological performances of diamond relative materials. Amazingly, Berman et al. successfully transferred the polycrystalline diamond into high quality graphene layers on the wafer scale using a rapid thermal annealing process facilitated by a Ni thin film catalyst on top [24]. It indicated that on certain conditions the annealing method can achieve the transition of diamond materials, which can seriously affect the tribological behavior. Amounts of researchers pointed out the effect of heat treatment on diamond related materials [20–24]. Deng et al. evaluated the friction and wear behavior of PDC in ambient air at temperatures up to 700 °C, and found that the friction coefficients of PDC decreased with the increase of temperatures and reached the lowest value at 700 °C, due to its surface graphitization [20]. Masina et al. used laser heating of nanodiamonds to study temperature induced changes to the diamond structure, and indicated that thermal induced stresses in the diamond are sufficient to radically alter its physical properties [22]. Microstructures and thermal damage mechanisms of PDC in ambient and vacuum at temperatures up to 1000 °C were described by Li et al. [23]. Thus, whether vacuum adhesive behavior of PDC treated by high temperature annealing can get improved is still unknown, and the beyond mechanism is worth to be understood.

Motivated by the annealing effects of diamond, in this study we designed tribological experiments in vacuum using a ball on disk tribometer to systematically research the effect of annealing temperature on the vacuum tribological properties of PDC. Complementary analytical techniques are used to reveal the vacuum tribological mechanism.

2. Experimental details

2.1. Fundamental characteristics of specimens

Commercial sintered polycrystalline diamond compact (PDC) from Zhongnan Diamond Co., Ltd. was used in this work. The polycrystalline diamond layer composed of diamond with coarse grain (most diamond particles' size ~ 25 μm) and Co binder was sintered to a thickness of ~0.5 mm onto the circular face of the WC-16 wt% Co cemented carbide substrate (diameter ~ 45 mm). The optical and the cross-sectional images of the PDC layer are shown in Fig. 1. The PDC layer is compact and smooth due to mechanical polishing. The surface roughness of polished PDC can reach a value of 3–4 nm. Silicon nitride (Si_3N_4) balls were used as counter mates in the tribotests, with the diameter of 9.525 mm and the surface roughness of 15–20 nm.

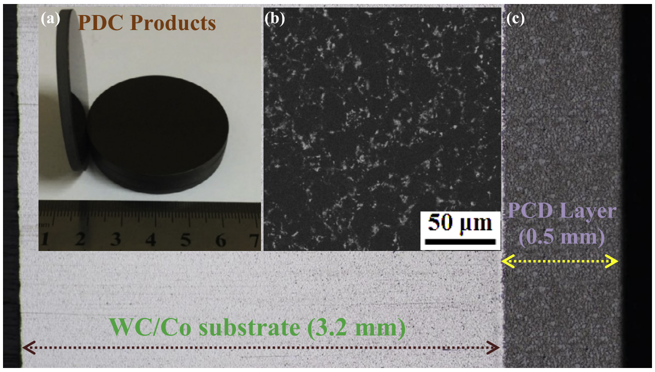

Fig. 1. The characteristics of PDC: (a) profile of PDC, (b) back scattering morphology of PDC surface, (c) cross-sectional image. (A colour version of this figure can be viewed online.)

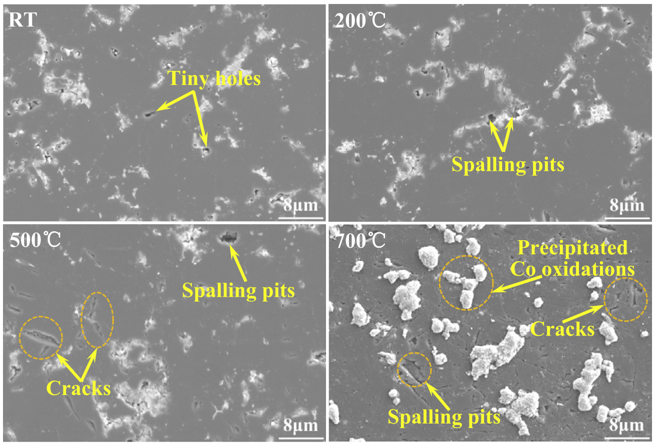

Fig. 2. SEM images of annealed PDC surfaces. (A colour version of this figure can be viewed online.)

2.2. Annealing tests

Before annealing treatment, the PDC samples were ultrasonically rinsed with acetone for 30 min and then alcohol for 15 min, respectively. Then they were dried by using a blower at room temperature. Subsequently, the PDCs were annealed in a muffle furnace (SX-8-10) for 30 min under ambient air conditions at 200 °C, 500 °C and 700 °C, respectively. The untreated sample (RT) is used for comparison. The three temperatures are chosen based on the previous experiments [23]. For 200 °C, although the morphology of PDC surface was almost the same as that of the original one, the relief of residual compressive stress affected the experiment results. As for 500 °C, physical changes appeared on PDC surface. For the temperature up to 700 °C, the transition of diamond to amorphous carbon and graphite as well as the emerge of cobalt oxides might also change the friction status. As a consequence, three temperatures are selected, basing on the morphology change and chemical transition of PDC during the process of annealing, to purse a further understanding of annealed PDC's vacuum tribological mechanism. The temperatures can be detected by a thermocouple with a deviation of ± 20 °C. All the samples were analyzed after they had thoroughly been cooled down in air.