Int. Journal of Refractory Metals and Hard Materials 64 (2017) 66–74

Contents lists available at ScienceDirect

Int. Journal of Refractory Metals and Hard Materials

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

Effect of vacuum annealing temperature on tribological behaviors of sintered polycrystalline diamond compact

Tianyang Yue [a], Wen Yue [a,b,*], Jiansheng Li [a,c], Chengbiao Wang [a,b]

[a] School of Engineering and Technology, China University of Geosciences (Beijing), Beijing 100083, PR China
[b] Key Laboratory on Deep Geo-drilling Technology of the Ministry of Land and Resources, China University of Geosciences (Beijing), Beijing 100083, PR China
[c] Nano Structural Materials Center, School of Materials Science and Engineering, Nanjing University of Science and Technology, Nanjing 210094, PR China

ARTICLE INFO

Article history:
Received 18 September 2016
Received in revised form 18 January 2017
Accepted 22 January 2017
Available online 24 January 2017

Keywords:
Polycrystalline diamond compact
Si_3N_4 balls
Tribological behavior
Annealing temperature

ABSTRACT

The sintered polycrystalline diamond compacts (PDCs) were annealed at 200 °C, 300 °C, 400 °C, 500 °C, 600 °C, 700 °C, and 800 °C under vacuum environment. The friction and wear behaviors of the annealed PDCs sliding against Si_3N_4 balls were evaluated by a ball-on-disc tribometer in ambient atmosphere. The compositions, microstructures and surface morphologies of PDC discs and wear scars on Si_3N_4 balls were characterized by energy dispersive spectroscopy (EDS), Raman spectroscopy, and scanning electron microscopy (SEM), respectively. The experimental results demonstrated that the steady friction coefficient decreased at the annealing temperature of 200 °C and increased with annealing temperature increasing. While, the wear rate of PDCs and Si_3N_4 balls increased at 200 °C, and sharply decreased from 300 to 800 °C. The surface morphologies and Raman spectra revealed that the variation law of friction coefficient curves at different annealing temperatures was attributed to carbonaceous transfer films formed on Si_3N_4 balls. The residual stress on PDC surface was reduced after the annealing treatment, thus fine diamond grains were easily extracted from PDC surface onto the contact area during the tribotest which led to the wear of PDC and abrasive wear for both counter parts. These results revealed that the friction and wear behaviors of PDC were significantly affected by the vacuum annealing temperature.

1. Introduction

The sintered polycrystalline diamond compact (PDC) has been widely used for machine tools, drilling bits and thrust bearings [1,2]. High temperature is inevitably produced during the manufacturing and working process, which will affect the physical and chemical properties of PDC. Li et al. [3] found that spalls appeared on PDC surface as annealing temperature attained to 500 °C and the surfaces were totally damaged at 900 °C both in ambient air and vacuum. Previous references [4–6] showed that thermal damages like graphitization and micro cracks resulted from the high temperature under vacuum or inert environment. In addition, other diamond related materials will suffer the similar thermal damages including graphitization and micro cracks under the high temperature condition in manufacturing and working process. Because the chemical and physical properties have great influence on the mechanical behaviors in the engineering application, it is of important significance to understand the effect of high temperatures on diamond related materials.

Numerous researches had revealed the connection between high temperature and the performance of diamond related materials. Under the high temperature environment, the grain boundaries of nanocrystalline diamond (ND) film were preferentially etched away by oxygen at high-temperatures, which eventually led to a sponge structure [7]. The initial stage of oxidation for ND film carries on with a faster rate, which is probably due to the oxidation along the phases of non-diamond carbon and graphite. Graphite phase was formed when ND was annealed in Ar atmosphere, but oxidation mainly occurred when the ND material was annealed in O_2 condition [8]. The diamond and some carbon films prepared by chemical vapor deposition (CVD) were annealed in ambient air, the oxidation appeared but was absent in inert environment [9]. Sun et al. [10] found that the hard polymer phenyl carbyne films heated (from 400 to 600 °C) in Ar environment resulted in the formation of sp^2 carbon phase. Graphitization, oxidation, cracks and other substances formed in high temperature physically and chemically damage the surface structures of diamond related materials.

These thermal damages have serious influence on the friction and wear behaviors of diamond related materials. Deng et al. [11] found the friction coefficient decreased with the increase of temperature under ambient air, and the lowest friction coefficient appeared at 700 °C. Jaworska et al. [12] confirmed the similar results. It was found

* Corresponding author at: School of Engineering and Technology, China University of Geosciences (Beijing), Beijing 100083, PR China.
E-mail addresses: cugbyw@163.com, yw@cugb.edu.cn (W. Yue).

http://dx.doi.org/10.1016/j.ijrmhm.2017.01.007
0263-4368/

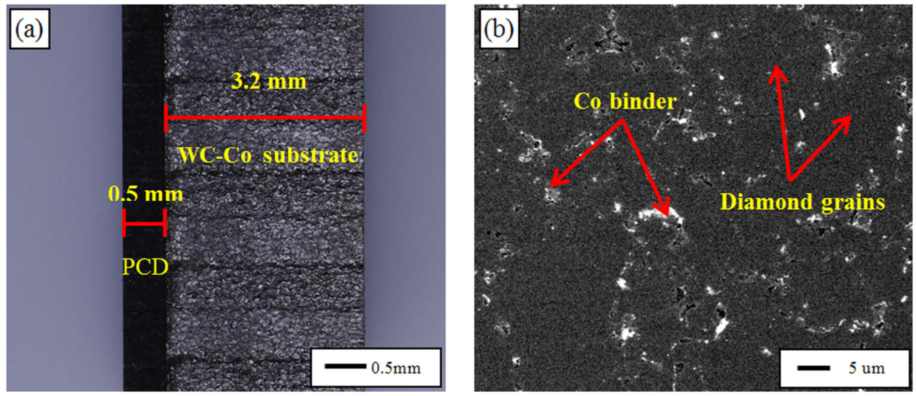

Fig. 1. The image of PDC disc (a) optical cross-section image of the PDC discs, (b) SEM image of PDC surface.

that high temperature bonding phase for diamond composites guarantees higher hardness and low coefficients of friction at elevated temperatures. At the annealing temperature of 650 °C, the residual stresses in the PDC specimens were quite negligible and their mechanical and fracture properties were nearly the same [13]. The wear resistance of Diamond-like carbon (DLC) films decreases after annealing at 400 °C due to the drop of the local adhesion [14]. However, the tribological property of DLC multilayer films is almost the same as that of original DLC films at the annealing temperature of 250 °C [15]. Niakan et al. [16] revealed that the lower annealing temperature (200–300 °C) hardly influenced the friction and wear behaviors of DLC films, but the higher annealing temperature (600 °C) can lead to the transformation from sp^3 to sp^2, which degraded the tribological properties of DLC films. From all above, it is obvious that the annealing temperature would affect the properties of these diamond materials to change the friction and wear behaviors.

The PDC materials have been widely applied in the drilling and cutting industrial field. The PDC tools are usually heated in vacuum or inert environment in the manufacturing process. For example, PDC materials are bonded to the metal matrix of drills and cutters by vacuum brazing [17]. The high temperature would affect the microstructures and properties of PDC surface, leading to degraded friction and wear properties and poor mechanical performances. It is important to reveal that the mechanism of the effects of high temperature on tribological properties of PDCs.

The PDC samples were annealed at 200 °C, 300 °C, 400 °C, 500 °C, 600 °C, 700 °C, and 800 °C under vacuum environment to simulate the manufacturing process. The ball-on-disc tribotest were carried out by using the annealed PDC discs and Si_3N_4 mating balls to investigate the effect of annealing temperatures on friction and wear properties of PDC.

2. Experimental details

2.1. Materials

The PDC were fabricated by Zhongnan Diamond Co. Ltd. The samples were consisted of a PCD layer and a WC-Co substrate. The diamond grains in the PCD layer have a mean size of 25 um. The substrate was made of WC-16 wt% Co cemented carbide. The images of the original PDC surface observed by scanning electron microscopy (SEM) are shown in Fig. 1. Fig. 1a and b show the cross-section image and the secondary electron image of PDC, respectively. The PDC disc with the total thickness of 3.7 mm, consists of 0.5 mm-thick PCD layer and 3.2 mm-thick WC-Co substrate. The cobalt binder on the surface of PCD layer is shown in Fig. 1b, which can bond the diamond grains to form PDC [1, 2]. The surface roughness of the PDC is 4.3 nm. In the tribotest, Si_3N_4 balls with diameter of 6 mm were used as the mating samples.

2.2. Annealing tests

The PDCs, capsulated in quartz tubes with the vacuum degree of ~1×10^{-5} Pa [3], were annealed at 200 °C, 300 °C, 400 °C, 500 °C, 600 °C, 700 °C, and 800 °C in a muffle furnace (SX-8-10) for 30 min to get thermally damaged. The annealing temperature has an error of ±20 °C. Then, these specimens were cooled down in ambient air.

2.3. Ball-on-disc tribotests

The tribological tests were performed on a ball-on-disc rotated tribometer of CSM TRN system in ambient air. The PDCs were used as the discs, while the upper samples were Si_3N_4 balls. Prior to the test, the balls and the discs were firstly purged with hexane and then ultrasonically cleaned in alcohol liquid for 30 mins. During the sliding process, the Si_3N_4 ball was fixed and the PDC disc continuously rotated. The revolving speed of the disc was 100 r/min with a turning radius of 2.5 mm (the liner sliding speed of 1.57 m/min). The duration time of the sliding process was 30 min with the sliding distance of 47.1 m. The applied load was 20 N which corresponds to the mean Hertz contact pressure of 2.39 GPa. The friction forces were measured by applying a dynameter in the tribometer system. The friction coefficients were calculated by using Amonton's law (the friction force = the friction coefficient × the applied load). The wear rates of PDC and Si_3N_4 balls

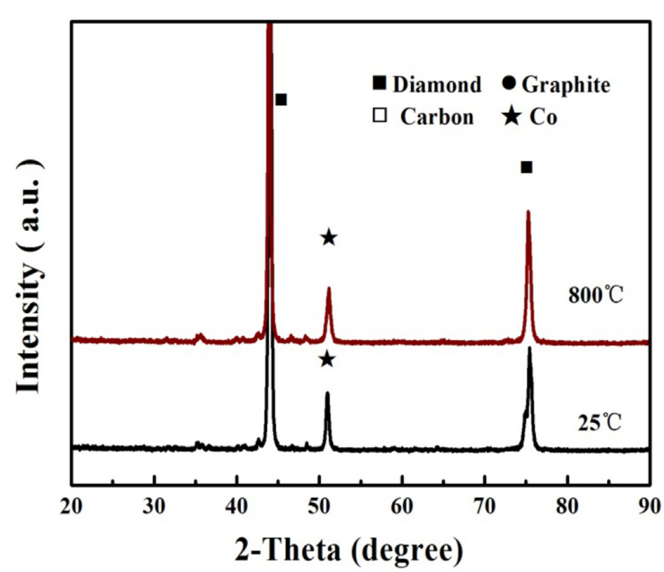

Fig. 2. XRD patterns of original PDC surface and PDC surface at 800 °C under vacuum environment.