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Microstructures and thermal damage mechanisms of sintered polycrystalline diamond compact annealing under ambient air and vacuum conditions

Jiansheng Li [a], Wen Yue [a,b,*], 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

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ABSTRACT

The microstructures and thermal damage mechanisms of sintered polycrystalline diamond compact (PDC) were studied in ambient air and vacuum at the temperature up to 1000 °C. The microstructures and compositions of the annealed PDC were characterized by white light interferometer, X-ray diffractometry (XRD), Raman spectroscopy and scanning electron microscopy (SEM). The results showed that no visible change in the morphologies of surface of PCD layers (PDC surfaces) was observed at 200 °C both in ambient air and vacuum. After annealing at 500 °C, numbers of spalling pits appeared on the PDC surface, and the stress-induced spall mechanism was the dominant thermal damage mechanism in ambient air and vacuum. With the temperature up to 800 °C, the annealed PDC surface in ambient air was seriously damaged with a mixed thermal damage mechanism such as graphitization, oxidation and stress-induced micro-cracks. Whereas, the thermal damage mechanism in vacuum was nearly the same as that at 500 °C. At 900 °C, only a dendritic phase of Co_3O_4 was contained on the annealed PDC surface due to extensive graphitization and oxidation in ambient air. When it comes to vacuum environment, many cracks were observed on the PDC surface and some fine diamond grains near the cracks spalled, which demonstrated that the thermal damage mechanisms consisted of stress-induced crack and spall mechanisms caused by the different thermal expansion coefficients between the diamond and Co phase. Compared with that at 900 °C, the degree of thermal damage reduced at 1000 °C in vacuum because of the diffusion of unevenly distributed Co.

1. Introduction

Sintered polycrystalline diamond compact (PDC) is a kind of ultra-hard materials that involved sintering a polycrystalline diamond (PCD) layer to a cemented carbide (WC–Co) substrate during a high pressure/high temperature (HP/HT) process [1,2]. PDC possesses the characteristics of diamond (high hardness, excellent wear resistance) as well as the advantages of WC–Co substrate (excellent impact toughness, good machinability). Due to these excellent properties, PDC has been widely used in cutting tools and drilling bits. Moreover, PDC is considered as an excellent material for space drilling for its outstanding physical and chemical properties under vacuum condition [3–6]. However, a high temperature, during the processes of cutting and drilling, will accelerate the formation of thermal damage such as graphitization and micro-cracks [7–9], which rapidly leads to failure of PDC tools. Cobalt, as a binder existing in the gaps among diamond grains as well as the interface between PCD layer and WC substrate [8,10], plays a very important role in graphitizing and initiating of micro-cracks of diamond at high temperature (above 600 °C) [11,12].

As numbers of previous experimental results showed, the microstructures and thermal damage mechanisms of PDC were affected by the temperature and environment. Mehan et al. [13] proposed that the thermal damage of PDC, with a pregnant period, was associated with graphitization in nitrogen. Micro-cracks initiated from the edge of diamond grains and eventually developed into transgranular cracks. Miess et al. [14] studied the stability of three kinds of PCDs (diamond grain sizes of about 4 μm, 10 μm and 30 μm, respectively) in oxygen, nitrogen and hydrogen at the temperature from 600 °C to 800 °C, and observed the second phase of WC–Co extruded out of all kinds of PCD as well as micro-cracks induced by thermal stress. Wang et al. [15] further studied the effect of distribution of binder Co on the cracks, and demonstrated that the various distributions of Co directly led to different kinds of cracks at 700 °C in nitrogen. The mechanisms of thermal damage of PCD, at the temperature from 800 °C to 900 °C in ambient air, were concluded by Wang et al. [16], which confirms that the four forms of thermal damage are micro-cracks, micro-wrinkles, ball-like bugles, and micro-holes. When PCD was heated above 800 °C, diamond grains were converted into CO_2 and CO, and micro-cracks and micro-

* 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).

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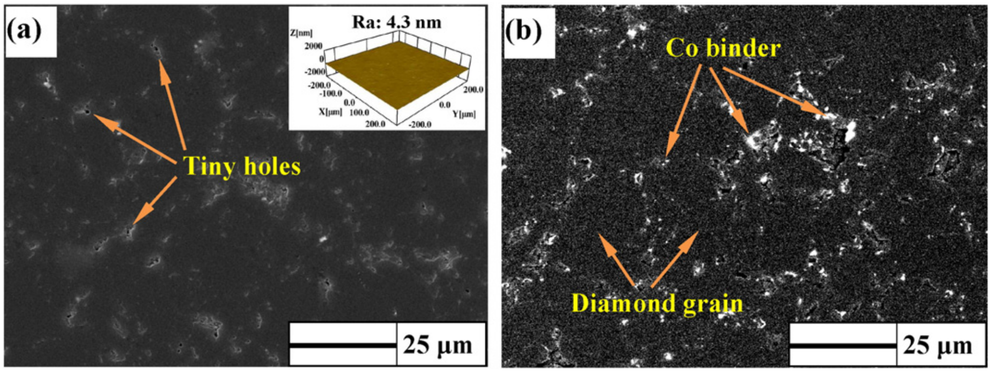

Fig. 1. SEM image of the original PDC surface: (a) secondary electron image and (b) back scattering image.

wrinkles occurred on the surface of diamond due to thermal stress. With the disappearance of diamond and increasing of Co_3O_4, ball-like bugles and micro-holes eventually appeared. Recently, Masina et al. [17] heated PDCs by laser in ambient air to explore the thermally induced defects. It presented that the diffusion of Co and W resulted in the formation of Co_xO_y and W_xO_y on PDC surface, but no graphitization of diamond was found. Up to now, researchers only have paid attention to the microstructures and thermal damage mechanisms of annealed PDC around the induced phase transition temperature (700–850 °C). The thermal damage below the induced phase transition temperature is associated with the progress of cutting and drilling with low speed. However, few researches on lower temperature (below 700 °C) and higher temperature (above 850 °C) have been reported. For better understanding of the thermal damage of cutting and drilling tools, it is vital to systematically study the microstructures and thermal damage mechanisms from room temperature (RT) to 1000 °C under ambient air condition. In addition, as a kind of potential material for space exploration, the microstructures and thermal damage of PDC will affect its service life in vacuum conditions. Some works have been performed to study the thermal stability of PDC with a nonmetal binder in vacuum [18,19], whereas the microstructures and thermal damage mechanisms of PDC with Co binder have been rarely studied under vacuum condition.

In this work, annealing experiments were performed in ambient air and vacuum to explore the mechanism of thermal damage of PDC samples so as to further realize the thermal failure mechanism of PDCs in cutting and drilling under ambient air and vacuum conditions.

2. Experimental details

2.1. Materials

The commercially sintered PDC produced by Zhongnan Diamond Co., Ltd. was used. It consisted of a PCD layer and a substrate. In the PCD layer, the mean size of diamond grains was 25 μm and the content of the cobalt binder was about 5 wt.%. The substrate was cemented carbide (WC–16 wt.% Co). The commercial PDC samples were cut into 8×8 mm^2 samples by wire-electrode cutting with a polished cross section. The SEM images of original PDC surface are shown in Fig. 1. Fig. 1a and b shows the secondary electron image and back scattering image of

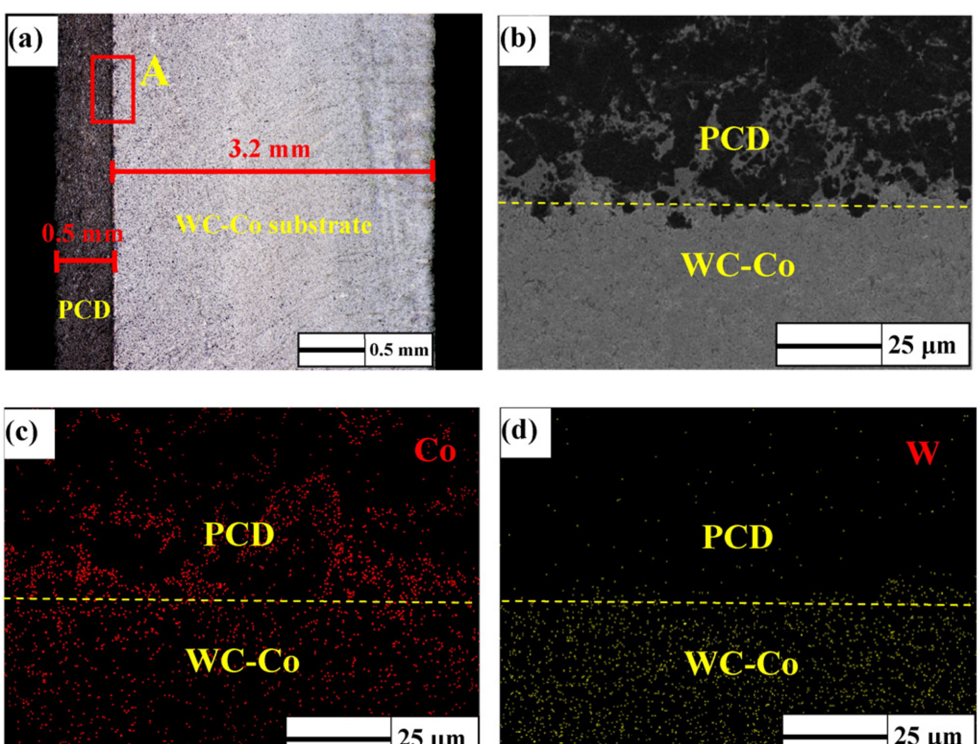

Fig. 2. Cross section image of the PDC: (a) optical image, (b) SEM image of selected region A in (a), and panels (c) and (d) are the corresponding EDS mapping images of (b).