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Optical Surface Finish of PCD Composites by Dynamic Friction Polishing

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Abstract. This paper presents a cost-effective technique for achieving optical surface finish of thermally stable polycrystalline diamond (PCD) composites using dynamic friction polishing (DFP). The effect of polishing parameters on the material removal rate and surface characteristics of polished specimens were studied. The surface characterisation was carried out by optical microscopy, atomic force microscopy (AFM), scanning electron microscope (SEM) and its attached energy dispersive X-ray (EDX) analysis. It was found that optical surface finish of PCD with roughness Ra = 50 nm could be obtained efficiently with nearly a ten fold reduction in polishing time compared to the currently used method in industry.

Introduction

Polycrystalline diamond (PCD) possesses excellent physical and chemical properties, such as ultra high hardness and thermal conductivity, good resistance to chemical erosion, and transmitting electromagnetic radiation over a wide wavelength range. These properties make PCD very desirable for a wide range of mechanical, electrical, optical, chemical and thermal applications. For most of these applications, PCD must have excellent surface finish and hence a requirement for polishing. However, because of the above properties, it has been difficult to develop an efficient and effective polishing technique for PCD. According to the literature, various physical and chemical methods such as mechanical polishing [1,2], chemically assisted mechanical polishing [3,4], thermo-chemical polishing [5,6], laser/plasma/ion beam polishing [7] and dynamic friction polishing [8-12] have been explored to achieve the surface roughness required for a given application. Nevertheless, no single method has been able to provide completely satisfactory results so far [7,13].

In dynamic friction polishing (DFP), a PCD compact is polished by pressing at a predetermined pressure onto a special metal disk rotating at a high speed to generate dynamic friction. It utilizes the thermo-chemical reaction induced by the dynamic friction between PCD and metal disk, and enables a highly efficient abrasive-free process of material removal. Chen et al [10-12] developed a model to predict the temperature rise of the PCD surface and investigated the material removal mechanisms during DFP. The above research used thermally stable PCD compacts composed diamond and silicon carbide (SiC).

The present paper presents an efficient and effective polishing technique for such thermally stable PCD compacts to obtain an optical surface finish of Ra ≈ 50 nm. The two major constituents, diamond and SiC, have very different properties, eg., hardness, chemical reactivity, etc. Hence the material removal rates for diamond and SiC will be different. In order to obtain the required finish both efficiently and economically, a combination of dynamic friction and mechanical process will be used. The paper also investigates the effect of DFP parameters on material removal rate and surface characteristics.

Experiment

The PCD specimens contain approximately 65% diamond particles of 6 μm in grain size (the rest are SiC and Si), 12.7 mm in diameter and 4 mm in thickness, weighting approximately 1.7 grams. The surface roughness of a specimen before polishing was approximately 0.7 μm Ra. The thermal conductivity of the specimen material was 300 W/m.K.

The dynamic friction polishing experiments were carried out on a polishing machine manufactured in-house, as illustrated in Fig.1. Polishing was conducted by pressing a PCD specimen at a predetermined pressure on to a rotating catalytic metal disk in dry atmosphere. The sliding speed between the specimen and the metal disk was varied from 8 to 25 m/s. The polishing pressure used was 2.7, 3.1, 3.8, 5.0 and 7.4 MPa respectively.

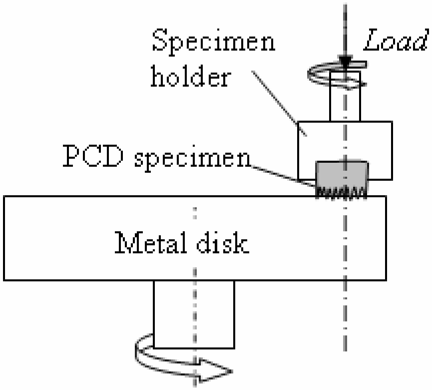


Fig.1 Scheme of dynamic friction polishing of PCD

The surface roughness was measured using Surftest 402 and Surftest Analyzer (Mitutoyo). Surface topography including micro-cracks was examined by an optical microscope (Leica DM RXE). The surface structure and topography were also studied using a scanning electron microscope (SEM) Philips 505; at the same time, energy dispersive X-ray (EDX) analysis was used to investigate the chemical compositions. The atomic force microscopy (AFM) was used to study the fine detail and determine the surface roughness of the polished PCD specimens. The AFM studies were carried out on a PicoSPM multi-purpose scanning probe microscope, operating in AFM contact mode.

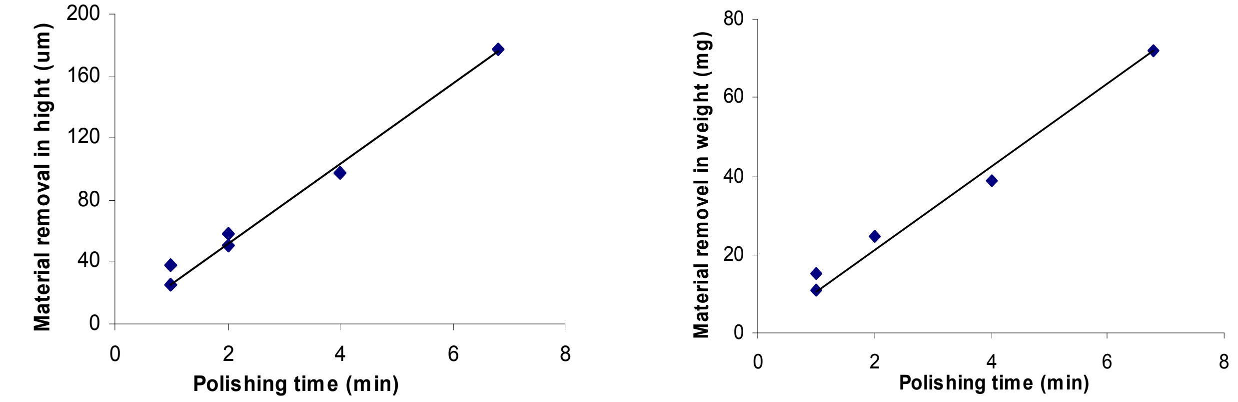
The amount of material removed was determined by measuring weight and thickness of PCD specimen before and after polishing. The specimen weights were measured by an electronic balance (Sartorius Basic ^{plus} BP210D) with resolution 0.01 mg. The thickness of the specimens was measured by a micrometer, and by a comparator and slip gauges. The comparator allowed the thickness to be measured within ±1.25 μm.

Results and discussion

Effect of DFP parameters on the material removal and cracks generated

Polishing time. When the sliding speed and polishing pressure were fixed at 25 m/s and 7.4 MPa, respectively, the effect of the polishing time on the PCD removal could be observed, as shown in Fig.2. The symbols represent the experimental results and the lines represent the corresponding linear regression lines.

It can be seen that the removal height (Fig. 2(a)) and weight (Fig. 2(b)) of the PCD specimen increases almost linearly with the polishing time. Thus, the removal rates of the PCD could be calculated as the height or weight of removed material divided by the polishing time, which gives a polishing rate of 26 μm/min in height or 11 mg/min in weight. Compared to the traditional mechanical abrasive method with polishing rate of the order of 10 nm/h [14], the increase in polishing rate achieved in the present tests is more than thousands of times.



(a) Polished depth (b) Removed weight

Fig.2 Effect of polishing time on PCD removal

Pressure. The pressure dependency of the removal rate was investigated by changing the pressure on the specimens while the polishing speed and time were kept constant at 25 m/s and 2 minutes respectively. The levels of the polishing pressure used were 2.7, 3.1, 3.8 and 7.4 MPa. Fig. 3 shows the effect of polishing pressure on the material removal rate, which demonstrates that the PCD removal rate increases with the increasing pressure up to about 4 MPa. Further increase in pressure does not result in a significant increase in removal rate. The relation between removal rate and pressure seems to follow a power law.

It was noticed that, when the pressure was 2.7 or 3.1 MPa, no cracks were found. However, when the pressure was increased to 3.8 MPa, cracks in PCD could sometimes appear; when it was further increased to 7.4 MPa, cracking or fracture of PCD occurred.

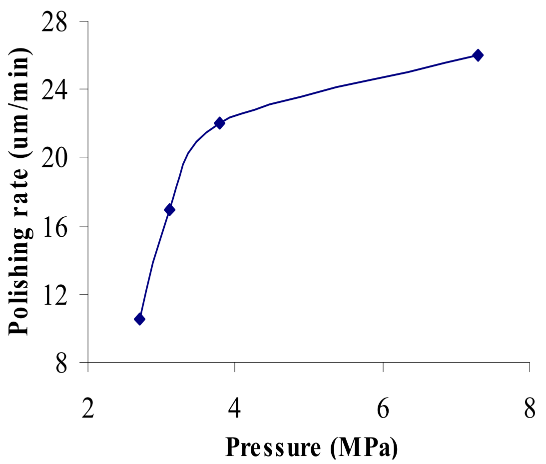


Fig.3 Effect of pressure on polishing rate

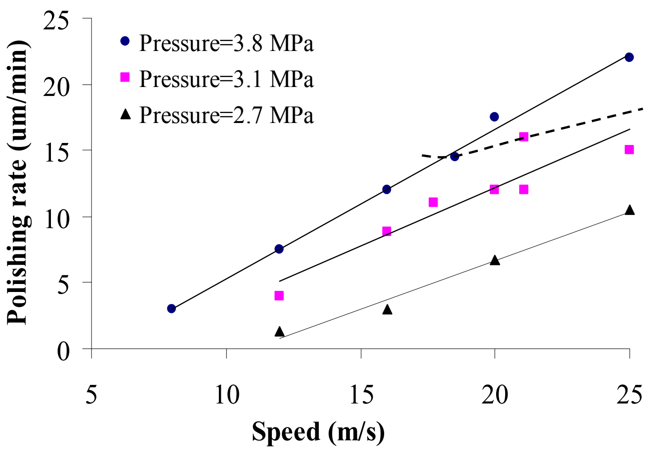


Fig.4 Effect of sliding speed on polishing rate

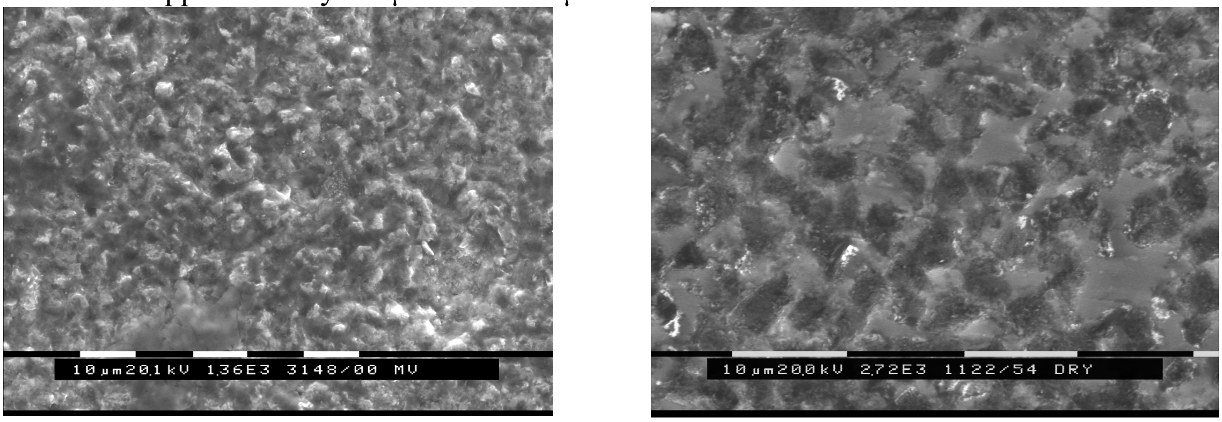
Sliding speed. The effect of the sliding speed on the removal rate was investigated by varying the sliding speed between 8-25 m/s while the pressure was kept a constant at 2.7, 3.1 or 3.8 MPa. The polishing time was maintained constant at two minutes for all the conditions except at pressure 2.7 MPa and speed 12-20 m/s where a longer time of three minutes was necessary to obtain a measurable material removal. The fitted lines for the experimental results are given in Fig. 4. When the speed was low (8 m/s), PCD could not be polished at all at pressure = 2.7 MPa. The PCD could only be partially polished at pressure = 3.1 MPa. At a higher sliding speed, the polishing rate increased almost linearly with the increase in sliding speed. Even a higher polishing rate can be expected by further increasing the speed. At a given polishing speed, a higher pressure also resulted in a higher polishing rate. However, cracking occurred in PCD under the following polishing conditions: pressure = 3.8 MPa, and sliding speed = 18.5 to 25 m/s; pressure = 3.1 MPa and sliding speed = 21 m/s.

These results show that an increase in sliding speed will increase material removal rate and thus reduce polishing time. However, cracks can be generated under severe conditions (e.g., very high pressure/speed).

The results presented in Fig. 4 are based on limited experiments, i.e., one test for each condition. This may represent a degree of non-repeatability. Additionally, sufficient time was allowed (at least four hours) in between the tests. We found that if consecutive tests under identical conditions were conducted one after another with a very short time interval, e.g., a few minutes, the material removal rate would vary in the consequent tests. The mechanism responsible for such a rate change is unclear yet. Further research is being carried out to understand whether it is due to the rise in polishing temperature and/or some unknown changes of conditions at the specimen-disk interface.

Surface topography

Fig.5 shows the SEM images of the surface topography of a typical PCD specimen before and after dynamic friction polishing. Before polishing, the surface was rough (Fig.5 (a)) and could not be seen clearly under light microscopy due to its short depth of field. The surface roughness of the specimen was approximately 0.7 µm Ra and 5 µm Rmax.



(a) Before polishing (b) After polishing at 3.1MPa and 20 m/s

Fig.5 SEM image of PCD specimen surface before and after polishing

After polishing, the surface of PCD specimen improved, the roughness Ra value of these specimens were measured to be in the range of 0.1-0.2 µm, which has decreased markedly. However, under high magnification on SEM (2720 times, Fig.5 (b)), it was found that the bright grains were higher than the dark "cavities". The fine details of polished surface could be observed more clearly by AFM, as shown in Fig. 6. It can be seen that the surface after DFP was not flat but has peaks and valleys, but without scratching marks, indicating that the material was not removed by mechanical abrasion, but by chemical reactions, as reported in [11,12]. The asperity peaks were sharp (Fig. 6), and the Rmax value was about 0.5 µm, which had reduced markedly from 5 µm Rmax before polishing.

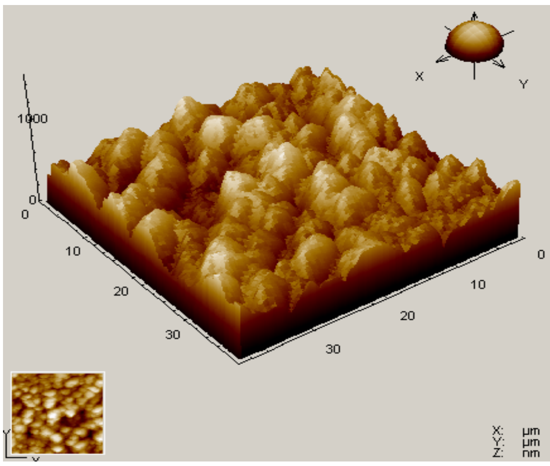
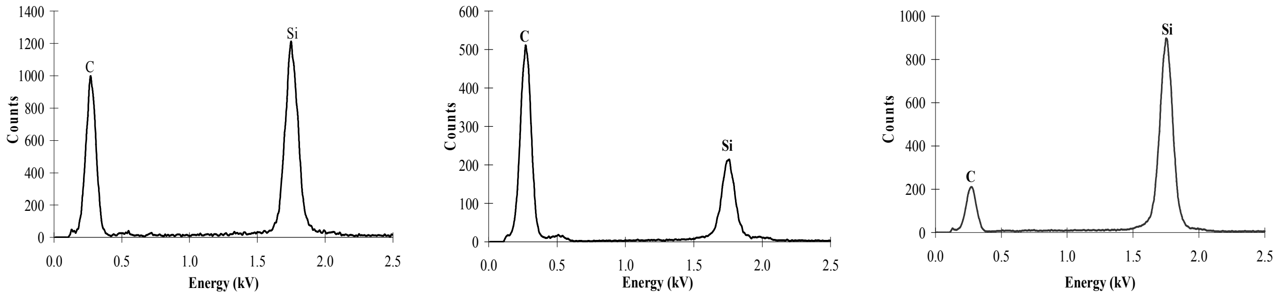


Fig.6 AFM image of PCD specimen after DFP

Such surface topography could be generated by different material removal rates of diamond and SiC during polishing. To confirm this, EDX in SEM was applied to find out the composition at the peak and valley areas. Fig.7 shows the typical components on polished PCD surface obtained using EDX analysis under high magnification of SEM. On the whole area analysed, similar quantities of carbon and silicon were detected on the surface (Fig.7 (a)). On the dark cavity spot, which was under the surface, a small quantity of silicon and a large amount of carbon were found (Fig.7 (b)). At the white bright spots, a large quantity of silicon and small carbon were detected (Fig.7 (c)). These results indicate that the material removal rate of diamond is faster than that of SiC during polishing. Therefore, further processing is required to reduce the surface roughness and improve the PCD surface quality.



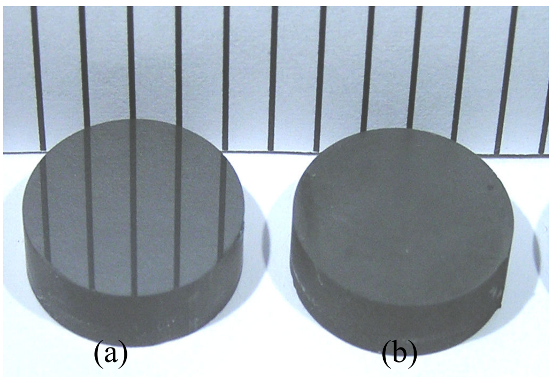
(a) Whole area analysed (b) on a dark cavity spot (c) on a bright surface spot

Fig. 7 EDX analysis of DFP polished PCD surface

Polishing parameters for optical surface finish

Using DFP, in order to obtain a crack free PCD surface, lower pressure and higher sliding speeds seem suitable. The pressure/speed combinations that were tested to determine the effective ones for DFP are shown in Fig. 4. Among the conditions tested, it was found that the most appropriate ones are: (1) pressure = 2.7 MPa, sliding speed = 20 to 25 m/s; (2) pressure = 3.1 MPa, sliding speed = 16 to 25 m/s; and (3) pressure = 3.8 MPa, sliding speed = 16 m/s. The dotted line in the figure indicates roughly the boundary of the safe region below which polishing can be carried out without cracking.

During DFP, the cracks on the PCD surfaces could be controlled by varying the polishing parameters, and the surface roughness was reduced to the range of 0.1 to 0.2 μm Ra. However, it could not be improved further because the material removal rate of diamond is faster than that of SiC.



(a) After polishing with mirror finish
(b) before polishing

Fig.8 PCD surface

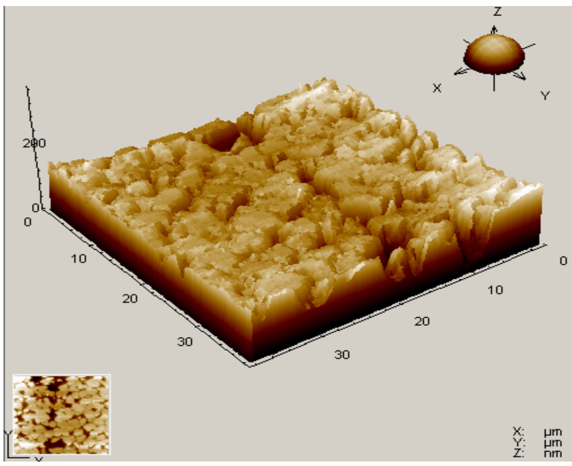


Fig. 9 AFM image after DFP and a subsequent mechanical abrasive polishing

Thus, further mechanical abrasive polishing was applied to remove the protruding SiC and further polish the PCD to generate an optical surface finish (Fig.8 (a)). The abrasive polishing time required depends on the accuracy of relocating the specimen from the DFP machine to the abrasive polishing machine. In the authors' lab, the specimen relocation was done manually and thus introduced a high tilting of the specimen. Because of this, the polishing of the whole surface of the relocated specimen required about 15 minutes. If an automatic relocation mechanism is attached, the time will be very much reduced. For comparison, a PCD specimen before polishing is shown in Fig.8 (b). The roughness of the polished surface (Fig.8 (a)) was 50 nm Ra. Fig.9 shows the AFM images of this surface which shows that the top surface has become flat with Rmax value approximately 0.12 μm.

Conclusion

By combining dynamic friction polishing and mechanical abrasive polishing, a very high polishing rate and good quality surface can be obtained. The final surface roughness can be reduced to 50 nm Ra easily. The polishing time required is a ten fold reduction compared with the mechanical abrasive polishing currently used in industry.

Acknowledgements

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