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Polishing of polycrystalline diamond by the technique of dynamic friction, part 4: Establishing the polishing map

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ABSTRACT

Through a systematic experimental investigation into the polishing of polycrystalline diamond composites by the dynamic friction technique, this paper identified three major regimes of polishing conditions: the regime capable of a low material removal, that enabling a safe, high removal processing, and that of an unsafe but ultra-high material removal. The study concluded that a higher polishing pressure–speed combination results in a high material removal rate, but with a greater risk of workpiece cracking. At a too low-pressure–speed combination, on the other hand, material removal may not take place. Based on the systematic experimental measurements, the paper established a polishing map to characterise the polishing conditions. It was found that using the polishing parameters determined by this polishing map, a quality surface finish can be obtained efficiently in duration about 10 times shorter than that of the abrasive polishing process currently used in industry.

1. Introduction

As discussed in the previous parts of this series research [1–6], polycrystalline diamond composites (PCDC) could be efficiently polished through an abrasive-free process, a dynamic friction polishing (DFP) technique, by making use of the thermo-chemical reaction induced by the frictional heating between a PCDC specimen and a rotating catalytic metal disk under certain pressure. The research has characterised both the upper and lower boundaries of temperature rise at the polishing interface [1,4], explored the material removal mechanisms [2,3], and discussed the applications of the technique in the polishing of cutting tools and optical elements [5,6]. The theoretical studies were based on thermodynamics and chemical kinetics of interface reactions. Experimentally, SEM, XRD, Raman spectroscopy, TEM, electron diffraction, EDX and EELS were used to clarify the material removal mechanisms. It has been concluded that in a dynamic friction polishing process, temperature and pressure are the key factors that govern the material removal and surface integrity of polished PCDCs. Within the workable range of polishing pressure, the relative sliding speed at the interface of a PCDC specimen and the catalytic metal disk plays a central role. It has been found that during polishing, the diamond at the friction interface will transform to amorphous non-diamond carbon due to the interaction with the catalytic metal at elevated temperature. The transformed amorphous materials became softer and were removed mechanically instantaneously by the continuous rubbing between the disk and PCDC. Meanwhile, both diamond and the transformed non-diamond carbon exposed to the air at elevated temperature would react with oxygen and escape as CO and/or CO_2. Oxidation of carbon accelerates the transformation of diamond to non-diamond carbon and speeds up the material removal in polishing.

Although the material removal mechanisms in dynamic friction polishing have been understood, the process is still hard to control. It has been found that under certain combinations of polishing parameters, PCDC specimens can crack; while under some other conditions, material removal cannot take place.

This paper aims to establish a polishing map to effectively guide an efficient, damage-free polishing. To this end, the relationship among the surface integrity of polished components, polishing efficiency (material removal rate) and polishing parameters, such as polishing time, speed and pressure, will be investigated.

2. Experimental

Two types of thermally stable PCDCs were used for testing. As detailed in Table 1, the Type 1 PCDC contains about 75% polycrystalline diamond particles of ~25 μm in grain size (the rest are SiC and Si) with initial surface roughness of $R_a \approx 1.7\,\mu m$ and R_{max} (value of peak to valley) $\approx 10\,\mu m$. The Type 2 PCDC contains about 65% diamond particles of ~6 μm in grain size with

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an initial surface roughness of $R_a \approx 0.7$ and $R_{max} \approx 5\,\mu m$. The thermal conductivity and density of the materials was ~300 W/m K and 3500 kg/m^3, respectively. A typical specimen was 12.7 mm in diameter and 4 mm in thickness, weighted approximately 1.7 g.

A series of experiments were performed on a polishing machine manufactured in-house as shown schematically in Fig. 1. The polishing, as detailed elsewhere [1–3], was conducted by pressing a PCDC specimen at a specific pressure onto a rotating catalytic metal disk in dry atmosphere. The effect of six levels of polishing pressure 2.2, 2.7, 3.1, 3.8, 5.0 and 7.4 MPa, and a wide range of sliding speed, from 8 to 25 m/s, were investigated.

The surface roughness was measured using the Surftest 402 and Surftest analyser (Mitutoyo). The surface structure and topography were analysed by an optical microscope (Leica DM RXE) and a scanning electron microscope (SEM, Philips 505). The energy dispersive X-ray (EDX) analysis was used to investigate the chemical compositions at an area/spot of interest. The amount of material removed was determined by measuring the weight and thickness changes of a PCDC specimen before and after polishing. The specimen weights were measured on an electronic balance (Sartorius Basic ^{plus} BP210D, resolution of 0.01 mg). The thickness of a specimen was measured by a micrometer and a comparator and slip gauges. The readability of the comparator was 2.5 μm.

Table 1
Specifications of the PCDCs used in experiment.

	Type 1	Type 2
Diamond percentage (%)	75	65
Grain size of the polycrystalline diamond (μm)	25	6
Surface roughness		
R_a (μm)	1.7	0.7
R_{max} (μm)	10	5
Size: diameter (mm) × thickness (mm)	12.7 × 4	12.7 × 4
Thermal conductivity (W/m K)	300	300

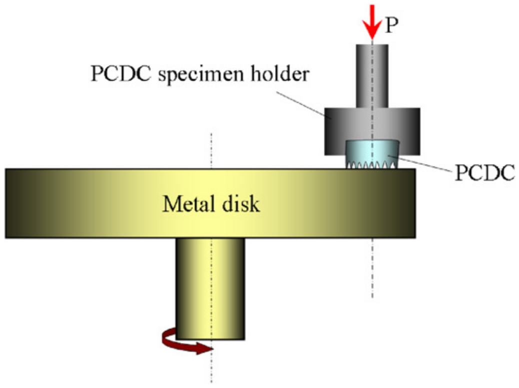

Fig. 1. Schematic illustration of dynamic friction polishing.

3. Results and discussion

3.1. Polishing conditions

3.1.1. Polishing time

The effect of polishing time on the material removal in both thickness reduction and weight loss was studied in detail at a given polishing pressure (3.1 MPa) and sliding speed (25 m/s) for the Type1 PCDC, as shown in Fig. 2.

The material removal increases with the polishing time, but slows down obviously after 4 min, as more clearly demonstrated by the variation of the average polishing rate that reduces from about 3.3×10^{-7} m/s in the first 30 s to about 1.3×10^{-7} m/s in 6 min (Fig. 3). Such a variation is understandable because at the beginning of polishing, the specimen surface was very rough ($R_{max} = 10\,\mu m$) so that the real contact area was small, the contact stresses on the PCDC surface asperities were large, and hence at a constant total polishing load the material removal was faster. As the polishing progressed, the real contact area became greater, the contact stresses on the surface asperities under the same polishing load decreased, and the material removal slowed down.

Fig. 4 shows the change of the average roughness R_a of the polished surfaces, which confirms the above understanding of contact area variation. Within the first 1.5–2 min, R_a decreased from about 1.7 μm R_a to 0.2 μm. Further polishing led to negligible improvement, indicating that with this set of polishing conditions 2 min is sufficient. More interestingly, cracking, if any, usually started to occur when the polishing time was beyond 3 min, which could mean that thermal stresses due to heat accumulation after certain continuous polishing will become critical.

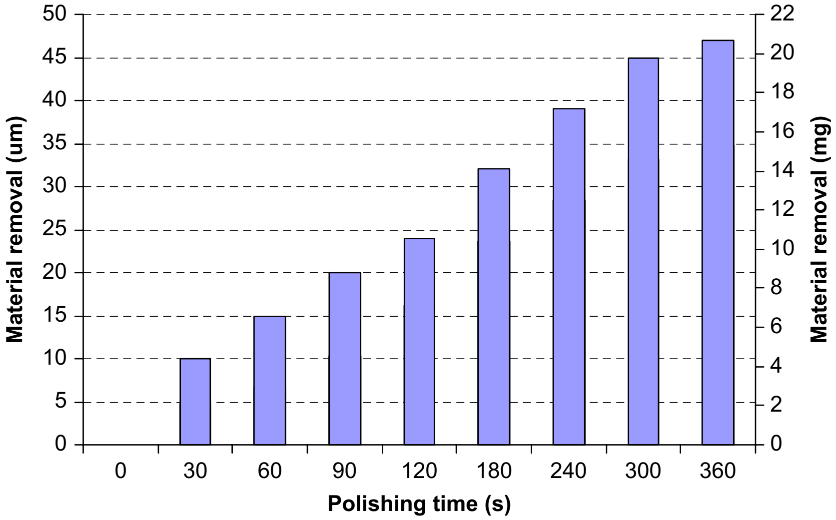

Fig. 2. Effect of polishing time on PCD removal.

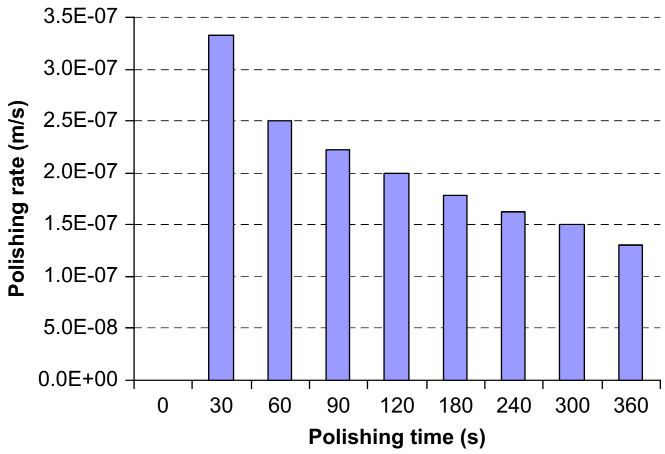

Fig. 3. Changes in average polishing rate with the progress of polishing.

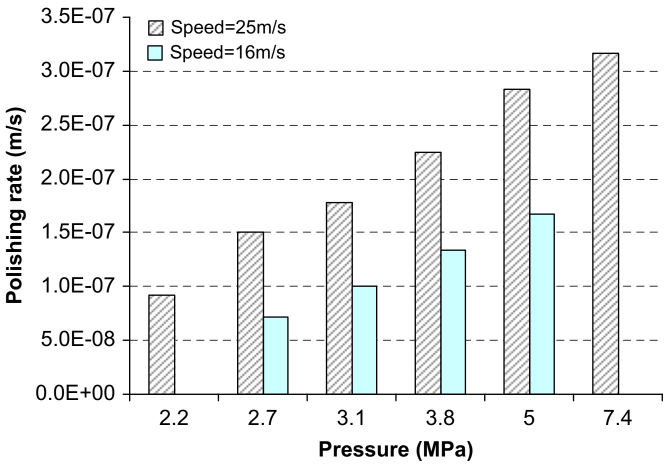

Fig. 5. Effect of pressure on polishing rate.

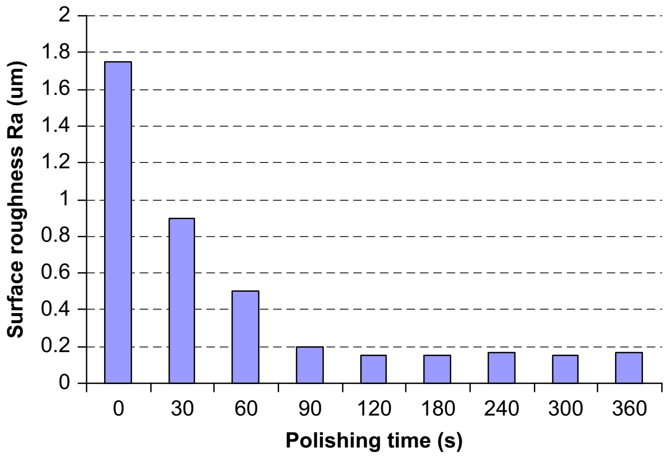

Fig. 4. Variation of average surface roughness with polishing time.

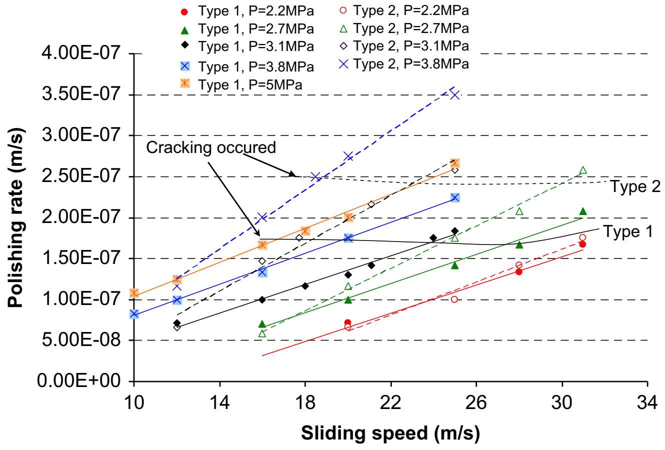

Fig. 6. The variation of removal rate with sliding speed at different pressure.

3.1.2. Pressure

In studying the effect of polishing pressure, the polishing speed was kept constant at 25 m/s or 16 m/s, and polishing time at 3 min for the Type 1 PCDC. As shown in Fig. 5, at a given sliding speed, the material removal rate increases with the pressure rise. Similarly, as to be discussed in detail in Section 3.1.3, a higher speed at a given pressure results in a higher removal rate. It is important to note that at the polishing speed of 25 m/s, no cracks were found when the pressure was below 2.7 MPa. Cracking became detectable when the pressure reached 3.1 MPa. On the other hand, if the sliding speed was reduced to 16 m/s, cracking did not occur until the pressure reached 5 MPa. In addition, under this speed, polishing rate was very low when the pressure was around 2.2 MPa. These results show that cracking was the combined result of mechanical stressing and thermal deformation during polishing.

3.1.3. Sliding speed

To understand the influence of sliding speed on the material removal rate, we varied the speed from 8 to 25 m/s for each polishing pressure (2.2, 2.7, 3.1, 3.8 or 5 MPa) and at a constant polishing time of 3 min for Type 1 specimens and 2 min for Type 2 specimens, as shown in Fig. 6. The symbols represent the experimental results. The solid lines represent the fitted linear regression lines of the Type 1 specimens, while the dotted one represent those of the Type 2 specimens.

For Type 1 specimens, when the sliding speed was lower than 10 m/s, the polishing rate was extremely low and in some cases the material removal were no measurable using the electronic balance available. Under these conditions, the temperature rise at interface by sliding friction is not high enough to stimulate the chemical reactions. At a higher sliding speed ($>$12 m/s), the polishing rate is a function of both the pressure and sliding speed, increasing almost linearly with the speed at every given pressure. However, cracks were observed when the speed–pressure combination is above the solid line, e.g., under the following polishing conditions: pressure = 5 MPa and sliding speed $\geqslant$16 m/s; pressure = 3.8 MPa and sliding speed $\geqslant$20 m/s; pressure = 3.1 MPa and sliding speed $\geqslant$24 m/s; pressure = 2.7 MPa and sliding speed $\geqslant$28 m/s; and pressure = 2.2 MPa and sliding speed $\geqslant$31 m/s.

For Type 2 PCDC, a similar trend can be seen but with different critical values of polishing parameters. In this case, when the speed was lower than 12 m/s, the polishing rate was extremely low, sometime even not measurable. Cracking occurred under the following polishing conditions above the dotted line as shown in Fig. 6: pressure = 3.8 MPa and sliding speed $\geqslant$18.5 m/s; pressure = 3.1 MPa and sliding speed $\geqslant$21 m/s, pressure = 2.7 MPa and sliding speed $\geqslant$31 m/s.

We can see that in general at an identical sliding speed and pressure, the material removal of Type 2 PCDC (smaller grain size particles) is higher than that of Type 1 PCDC. This is because smaller diamond particles have more surface defects and a larger

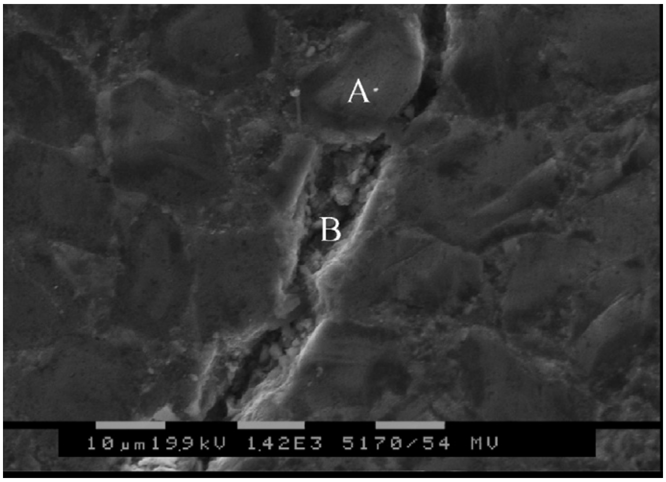

Fig. 7. SEM image of crack in a PCDC specimen after DFP.

surface area in the composite. The chemical reaction starts at the surface defects, thus reacting faster [7]. However, at a low-speed and pressure combination, Type 1 specimens have higher material removal rate. This is mainly due to their much greater initial surface roughness ($R_{\max} \approx 10\,\mu m$) in comparison with the Type 2 PCDC ($R_{\max} \approx 5\,\mu m$), which is a critical factor of temperature rise at the polishing interface [1]. Under such conditions, the material removal is mainly from the surface asperity peaks.

3.1.4. *Workable condition*

According to the theoretical model in Part 1 of this series study [1], a higher pressure/speed produces a higher temperature rise, which will in turn accelerate the chemical reaction at the interface between the metal disk and PCDC and increase the material removal rate. This is because the chemical reaction rate k that determines the material removal rate is a function of temperature according to Arrhenius equation [8], $k = A\exp(-E/RT)$, where T is temperature, R is gas constant (8.31 J/mol K), A is a constant known as the frequency factor which is related to the frequency of collisions between the reactant molecules, and E is the activation energy.

Although a higher pressure/speed increases the material removal rate, it may also result in cracking. The cracking was likely caused by the non-uniform thermal deformation in the PCDC material in which the coefficient of thermal expansion of diamond (1×10^{-6}/K at 300 K [9]) is much lower than that of the binder phase, SiC (3.8×10^{-6}/K at 300 K [10]). When temperature increases, the volume expansion of SiC is much larger than that of the PCD. As a result, cracking takes place along the PCD–SiC boundaries when the thermal stresses are large enough, as confirmed by the experimental observations shown in Figs. 7 and 8 of which the polishing condition was speed = 31 m/s and pressure = 2.7 MPa for Type 1 PCDC. Fig. 8 shows the compositions at different spots around a crack of a polished PCDC surface obtained by EDX analysis in SEM. Over the whole area analysed including the crack, large quantities of carbon and slight quantities of silicon could be detected (Fig. 8a), which is expected to observe on a surface of PCD–SiC composite (the PCDC). On the dark grain spot, Spot A in Fig. 7, only large amount of carbon were found (Fig. 8b), indicating that the grains are diamond grains. At the cracked area, Spot B in Fig. 7, quantities of carbon and silicon detected are close (Fig. 8c), indicating that the cracked area contains large amount of SiC.

The above analysis suggests that to avoid cracking polishing should not be carried out at a very high-speed/pressure combination. However, to obtain a reasonable material removal rate, which is a requirement of production, a too low-speed–pressure combination is not practical, because the frictional heating at a too low-speed–pressure combination cannot generate sufficient temperature rise for chemical reaction and for transforming diamond to non-diamond carbon.

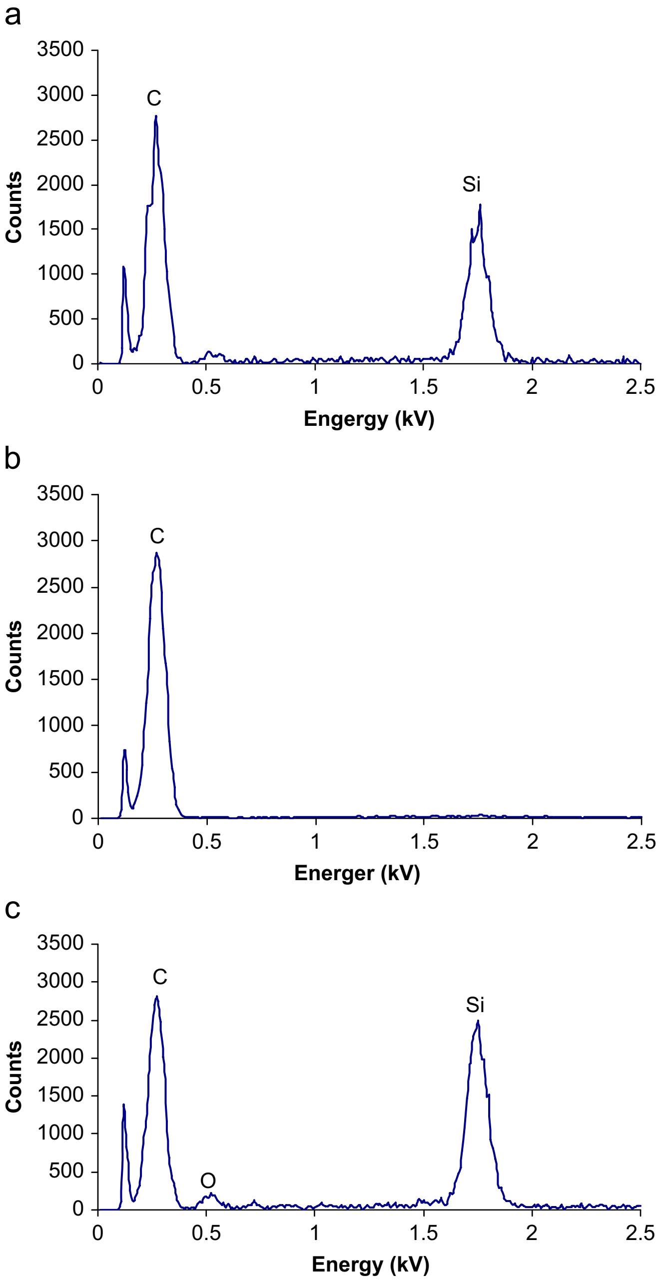

Fig. 8. EDX analysis of a polished PCDC specimen surface. (a) Whole area analysed; (b) on Spot A in Fig. 7; and (c) on Spot B in Fig. 7.

3.2. *Establishing the polishing map*

The results in Fig. 6 can be more easily visualized as a polishing processing map, as shown in Fig. 9 for Type 1 PCDC, a plot of sliding speed vs polishing pressure, where the value of the material removal rate ($\times 10^{-7}$ m/s) measured at a given pressure and sliding speed is indicated next to the data point. A dotted curve extrapolated through these data show a contour of a constant polishing rate.

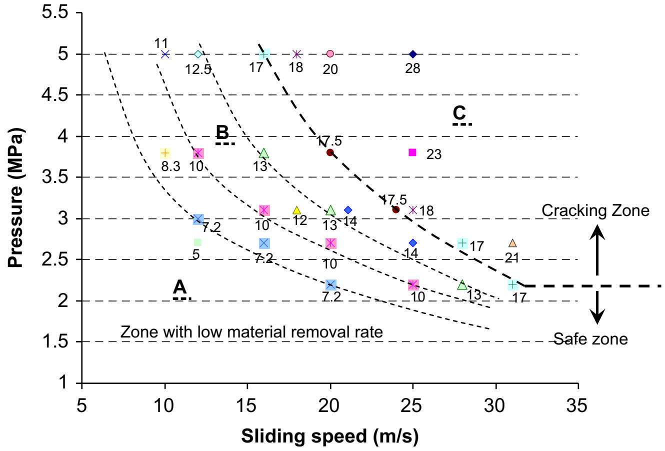

Fig. 9. The material removal map.

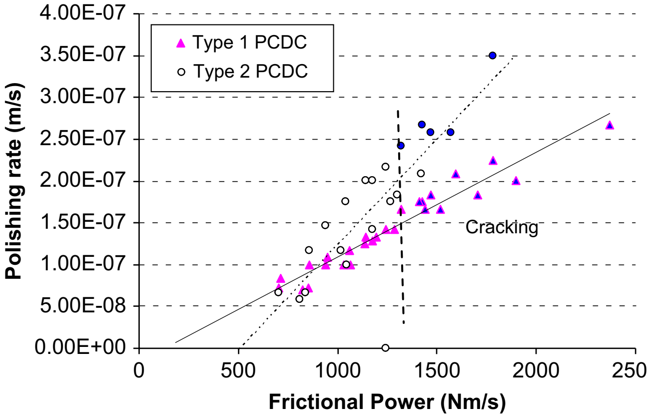

Fig. 11. Effect of frictional power on material removal rate.

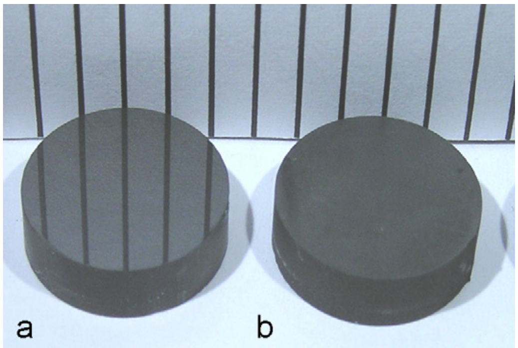

Fig. 10. PCDC surface. (a) After polishing with mirror finish and (b) before polishing.

It can be seen from this polishing map that there are three regimes that characterise the dynamic friction polishing of PCDCs. Region A is a zone associated with a low or negligible material removal rate and hence is not a practical regime for polishing production. Region C is an unsafe zone, in which cracking will occur although the material removal rate can be very high. Region B is a safe and workable zone. When a pressure–speed combination falls into this zone, a damage-free polishing with a reasonable material removal rate can be obtained. For a given pressure (or speed) and a desirable material removal rate, the polishing speed (or pressure) can be easily determined using this polishing map. For example, if the desirable polishing rate is $14\times10^{-7}\,\text{m/s}$, a feasible polishing condition can be speed = 25 m/s with pressure = 2.7 MPa, or speed = 21 m/s with pressure = 3.1 MPa. Using these conditions, the surface roughness can reach to 50 nm R_a in 18 min from 1.7 μm R_a (Fig. 10), which is more than 10 times faster than the mechanical abrasive polishing process currently used in industry.

The above map is useful and scientific, but it still needs certain selection skills. It can be more practical for practitioners if a simpler diagram can be developed.

Using the pressure (P)–speed (V) combination, the frictional power P_f can be determined as

$$P_f = \mu A_s PV,$$

where μ is the coefficient of friction between the contacting bodies and A_s is the surface area of the PCDC specimen. For all the results in Fig. 6, the material removal rate vs the frictional power can be plotted in Fig. 11 where μ was taken as 0.15 in the calculations according to [1]. The solid line represents the linear regression fitting for Type 1 PCDC while the dotted line for the Type 2 PCDC. It can be easily seen that the material removal rate increases almost linearly with the frictional power. At a low frictional power, the material removal rate is small, making the polishing process inefficient. On the other hand, at very high frictional power, such as in the regime occupied by the solid circular dots above the dash line, cracking would occur. Therefore, the frictional power for a crack-free polishing should be $P_f < 1300\,\text{Nm/s}$.

It can be seen from Fig. 11 that the gradient of the regression line of Type 2 PCDC is greater than that of Type 1, and intersect at $P_f = 900$. When the frictional power $P_f > 900\,\text{Nm/s}$, the material removal rate of Type 1 PCDC is lower than that of the Type 2, indicating that the former requires more energy to remove the same amount of PCDC material.

4. Conclusions

This paper has developed a polishing map through a systematic investigation into the dynamic friction polishing of PCDCs. It was found that by selecting a proper polishing pressure and sliding speed, a very high polishing rate with a quality surface finish can be obtained in minutes, which is 10 times faster than the mechanical abrasive polishing process currently used in industry. Using the polishing map, one can determine safe polishing conditions easily at a desirable polishing rate. This method can be extended to the condition selection of other polishing processes.

Since polishing of PCDC is a complex process, including transformation of diamond and SiC to amorphous phases, which were then removed mechanically/chemically, the material removal rate is a function of many variables. A mathematical formulae conducted by simply correlating the experimental data cannot be used for determining the physical phenomena as well as for practical applications. A practical modelling is needed to quantify the material removal rate of dynamical friction polishing of PCDCs, which will be detailed by the forthcoming paper by the authors.

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