
Polishing of diamond composite cutting tools

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Abstract: This paper presents an effective polishing technology for cutting tools made of thermally stable Polycrystalline Diamond Composites (PCDCs). The research includes: design and manufacture of a special polishing machine; temperature characterisation; comprehensive experimental and theoretical investigation of the material removal mechanism; and the selection of polishing parameters to achieve the required nanometric surface finish.

Keywords: Polycrystalline Diamond Composites; PCDCs; Dynamic Friction Polishing; DFP; temperature characterisation; material removal mechanism.

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1 Introduction

Thermally stable PCDCs, composed of diamond and SiC, are very attractive cutting tool materials because of their excellent properties such as ultra high hardness, thermal conductivity, strength, and chemical inertness to most corrosive environments. For precision machining applications, where PCDC have been widely used, a cutting tool must have excellent surface finish and cutting edge sharpness 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 PCDC cutting tools. This has been compounded by the incorporation of hard-to-polish ceramic material such as SiC as the binder.

Various physical and chemical means have been discussed in the literature to achieve the surface roughness required for a given application (Malshe et al., 1999; Bhushan et al., 1994). These can be broadly classified into contact and non-contact methods using mechanical, chemical or thermal method, or their synergistic combination, such as mechanical polishing, chemo-mechanical polishing, thermo-chemical polishing, Dynamic Friction Polishing (DFP), high energy beam (laser/plasma/ion beam) polishing, and Electrical Discharge Machining (EDM). Each polishing technique has its technological merits but also suffers from one or more disadvantages.

Mechanical abrasive polishing has been widely used in industry (Wilks and Wilks, 1991; Field, 2001; Hird, 2002), which can produce a surface with roughness of the order of $R_a = 0.02 \mu\text{m}$ without drastically changing the chemical quality of the diamond surface (Malshe et al., 1999; Bhushan et al., 1994; Sudarshan, 1995). However, this method needs to use expensive diamond abrasives and diamond wheels, and the polishing rate of the method is extremely low, of the order of a few tens of nanometres per hour.

On the other hand, the chemo-mechanical method can provide a higher material removal rate, better surface finish and less surface damage than mechanical polishing (Bhushan et al., 1993; Ollison et al., 1999; Malshe et al., 1995; Hocheng and Chen, 2006; Graebner et al., 1998). However, the heating of the polishing disk and the requirement of oxidising agents make the polishing process complicated. In addition, to maintain a continuous polishing process, it is essential to remove the chemically reacted products accumulated on the polishing disk.

The thermo-chemical technique (or hot-metal-plate polishing) offers a fine surface finish, and the polishing rate is much higher than mechanical polishing (in the order of a few $\mu\text{m}/\text{h}$) (Yoshikawa, 1990; Tokura et al., 1992; Yoshikawa and Okuzumi, 1996). However, an efficient polishing can only be achieved by heating the polishing disk to a temperature over 750°C , which requires an evacuated/reductive atmosphere to prevent the metal from oxidation, especially when using iron at high temperatures. These, similar to the chemo-mechanical method, require a complicated and expensive setup of equipment.

Another thermo-chemical method, diamond etching, uses the principle of diffusion reactions (Jin et al., 1992). Its advantages are that it is applicable simultaneously to a large number of diamond films, and that it has the flexibility for shaping diamond into non-flat geometries. However, this method does not provide a fine surface finish whose roughness is often of the order of a few micrometers R_a (Sun et al., 2006).

The high energy beam techniques include Plasma/ion beam and laser beam polishing. These non-contact methods generally do not require to apply a force to samples and/or to heat them. Hence polishing of non-planar surfaces and/or small areas can be achieved (Malshe et al., 1999; Silva et al., 2003; Vivensang et al., 1996; Buchkremer-Hermanns et al., 1996; Park et al., 2000). Their major disadvantages are the requirement of a controlled environment, generally a vacuum environment, and expensive equipment.

The EDM polishing method can provide a very high material removal rate (Guo et al., 2001, 2002, 2004; Wang et al., 2002), but the final surface finish is only up to a few microns Ra.

The DFP utilises thermo-chemical reaction induced by dynamic friction between a diamond sample and a metal disk tool rotating at a high peripheral speed to generate dynamic friction, and enables highly efficient abrasive-free polishing (Suzuki et al., 2003; Iwai et al., 2001, 2004). Compared to the methods that utilise thermo-chemical reaction, the DFP method has a higher potential for practical applications, because polishing is carried out at room temperature under dry atmospheric conditions and does not require a vacuum chamber and/or special heating equipment. However, DFP is a relatively new technique and there are only a few reports in the literature. The control and optimisation of the process have not been studied. In order to make the technique suitable for practical application, further investigations are needed.

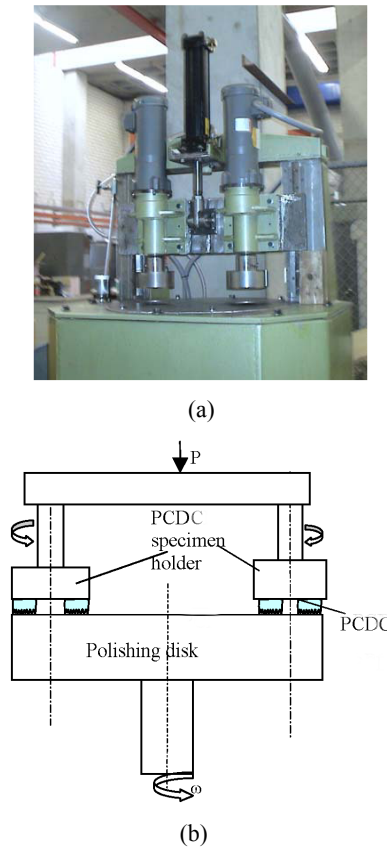
The brief discussion above indicates that it is very important to select a proper polishing technique based on the requirement of a specific application, shape of workpiece, polishing efficiency and cost limitation. For PCDC cutting tools, the authors, based on the DFP technique, have concentrated on establishing a sound methodology to achieve the required surface finish of $Ra \leq 60$ nm.

2 Polishing machine

In the previous research (Suzuki et al., 2003; Iwai et al., 2001, 2004), the DFP experiments have been conducted on a machining centre. This type of setup has limited the range of process parameters such as specimen surface area, applied pressure, etc. and hence has made it difficult to optimise the polishing process. The first step therefore was to develop a machine for carrying out the DFP process for PCDC in a controllable manner.

To polish PCDC cutting tools by the DFP, the interface temperature during polishing must be high enough to activate a chemical reaction between PCDC and a catalytic metal disk by creating appropriate sliding speed and pressure. Based on these requirements, a special polishing machine was designed and manufactured in-house to carry out the DFP efficiently (Zhang et al., 2006). Figure 1 shows an image of the polishing machine and a schematic illustration of the process. The polishing of PCDC specimens was achieved by pressing the specimens at predetermined pressure (1–8 MPa) onto a metal disk rotating at a high speed (10–30 m/s). The material removal rate was controlled by varying the rotational speed of the metal disk and/or the pressure applied on the PCDC specimens.

Figure 1 Dynamic friction polishing of PCDC: (a) the polishing machine and (b) schematic illustration



Source: Zhang et al. (2006)

3 Temperature characterisations

The chemical reactions of carbon and SiC with metals or oxygen play an important role in the material removal of PCDC, and these reactions occur only at elevated temperatures. It is therefore necessary to estimate the temperature during the process, so that the most effective ranges of polishing speed and pressure can be found out. The characterisation of temperature at polishing interface was achieved by combined theoretical modelling and experimental measurement.

3.1 Theoretical modelling

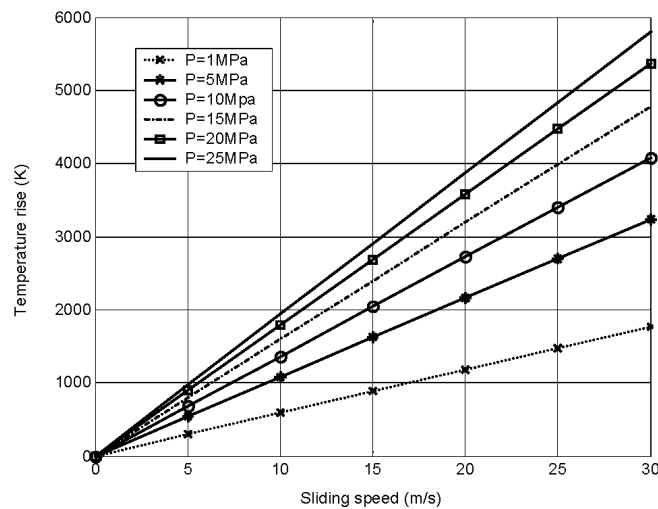
A model was developed to predict temperature rise at the interface of the polishing disk and PCDC asperities (Chen et al., 2006). In this model, the Greenwood-Williamson's statistical asperity model was used to characterise the surface roughness of a PCDC specimen. The result was then used to estimate the contact area and total number of contact asperities under an applied polishing load. The heat generated was taken as the

product of the frictional force and the relative sliding speed between the PCDC asperities and the metal disk surface. Jaeger's moving heat source analysis was then applied to determine the fraction of heat flux flowing into the PCDC asperities and its counterpart at contact sliding during polishing and to predict the average temperature rise on the contact surface.

Figure 2 shows the variations of the calculated average contact temperature rise with the sliding speed at different nominal applied pressure. According to these results, the higher values of pressure and sliding speed correspond to a higher heat flux and higher temperature rise. The temperature rise is seen to increase with increasing pressure and sliding speed. The dependence of temperature rise on speed appears to be linear for a fixed nominal pressure.

The effects of PCDC surface roughness, material properties, polishing speed and polishing pressure on the surface temperature rise were studied using the developed model. Since the model is based on the assumption of no heat loss into the surrounding, the predicted interface temperature rise is the upper bound.

Figure 2 Variation of calculated average temperature rise with sliding speed at different nominal pressures



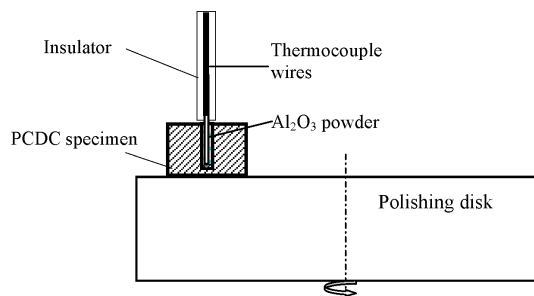
3.2 Experimental measurement

In the current practice, it is almost impossible to measure the interface temperature during PCDC polishing. Although the thermocouple technique has been used in temperature measurement (Kennedy et al., 1997), fitting a thermocouple into a rotating system of DFP is difficult and the temperature at the polishing interface cannot be measured directly. Thus an attempt was made to measure the PCDC subsurface temperature, and then extrapolate it to the polishing surface (Chen et al., 2007a).

Figure 3 shows the schematic setup with the thin thermocouple sensor (Chen et al., 2007a). Once again, polishing was conducted by pressing the PCDC specimen at a given pressure on to the rotating metal disk in dry atmosphere. Polishing parameters were selected to achieve nanometric surface finish, as detailed in Chen et al. (2008).

The temperature rise picked up by the thermocouple was not at the polishing interface, but at a distance from it (approximately 0.6 mm). To obtain the interface temperature, a model of a steady temperature in a semi-infinite cylinder (Carslaw and Jaeger, 1959) was used. The calculation was based on the assumptions that no heat was lost in the process of conduction from the interface to the tip of the thermocouple and no convective heat-losses during the disk/specimen spinning. This is certainly not the case during polishing. Hence, an extrapolated interface temperature rise from the measured result using the experimental setup of Figure 3 gives the lower bound. The actual interface temperature during polishing is between the lower bound from the experiment and the upper bound from the theoretical prediction.

Figure 3 Schematic illustration of the setup for temperature measurement



For comparison, some typical results of the extrapolated interface temperature from the experimental measurement and that from the theoretical prediction are plotted against the variation of sliding speed at a given polishing pressure (Figure 4(a)), and against the variation of the applied polishing pressure at a given sliding speed (Figure 4(b)). It can be seen that the higher the pressure/speed is, the higher the interface temperature. As expected, at any specific combination of sliding speed and pressure, the theoretically predicted temperature rise is always higher than the experimental. Their difference becomes bigger at higher sliding speeds/pressure, possibly due to the stronger convective cooling which was ignored in both the theoretical and experimental modelling.

Figure 4 Variations of interface temperature: (a) with speed at pressure 3.1 MPa and (b) with pressure at speed 22 m/s

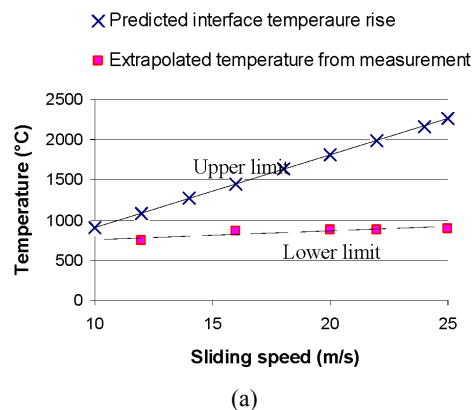
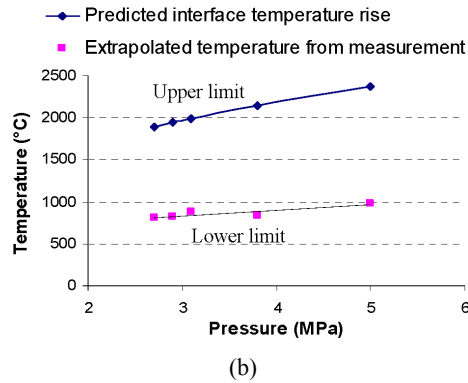


Figure 4 Variations of interface temperature: (a) with speed at pressure 3.1 MPa and (b) with pressure at speed 22 m/s (continued)



4 Investigation of material removal mechanism

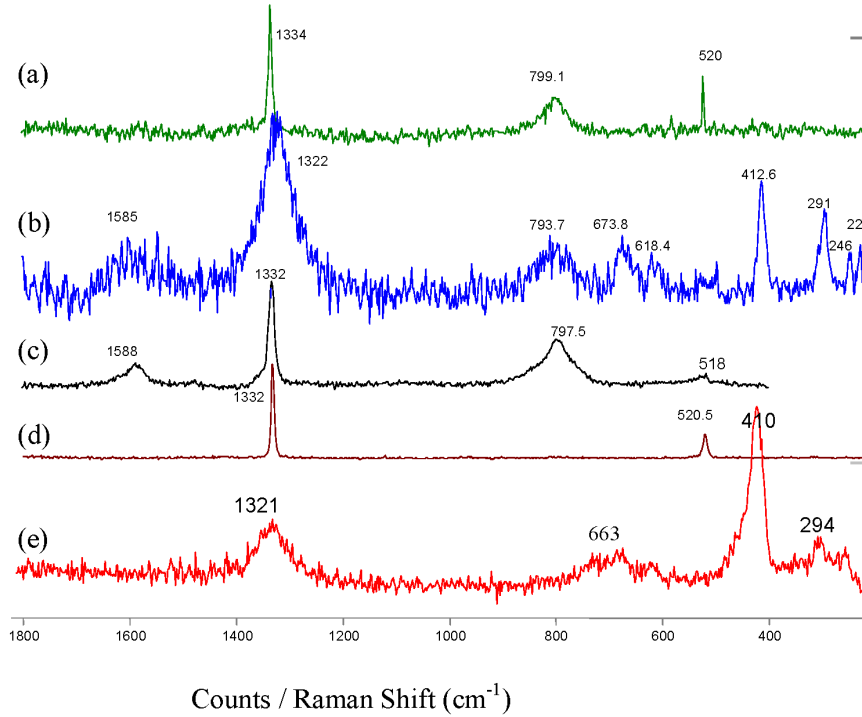
To explore whether chemical reaction and phase transformation had occurred, debris produced during DFP were investigated. To gain a comprehensive understanding of the polishing mechanism, a theoretical study with the aid of thermodynamics and chemical kinetics of interface reactions was also carried out. SEM, XRD, Raman spectroscopy, TEM, electron diffraction, EDX and EELS were used to clarify the material removal mechanisms.

Figure 5 shows the Raman spectra of PCDC specimen surface and polishing debris (Chen et al., 2007b). Non-diamond carbons with Raman peaks at 1585–1588 and 1321–1322 were detected on the polished surface before cleaning (Figure 5(b), (c)) and in the polishing debris (Figure 5(e)), indicating that transformation did occur during polishing.

Based on the EELS and HRTEM analyses (Chen et al., 2007c), it was found that the polishing debris were mainly of amorphous structure, that included different forms of carbon, silicon oxide/carbon, iron oxides, etc. From the free energy theory and low-loss energy spectra (Figure 6), the densities of carbon material in polishing debris were calculated to be much less than that of diamond (Chen et al., 2007c). From high-loss energy spectra, the percentage of sp^2 bonding in the hybridised carbon materials of the polishing debris ranged from 30% to 90%. These results indicate that during DFP, the diamond at surface has transformed to amorphous non-diamond carbon due to the interaction with rotating metal disk at elevated temperature. Meanwhile, another component of PCDC, SiC, also chemically reacted and was transformed to amorphous silicon oxide/carbide during polishing (Chen et al., 2007c).

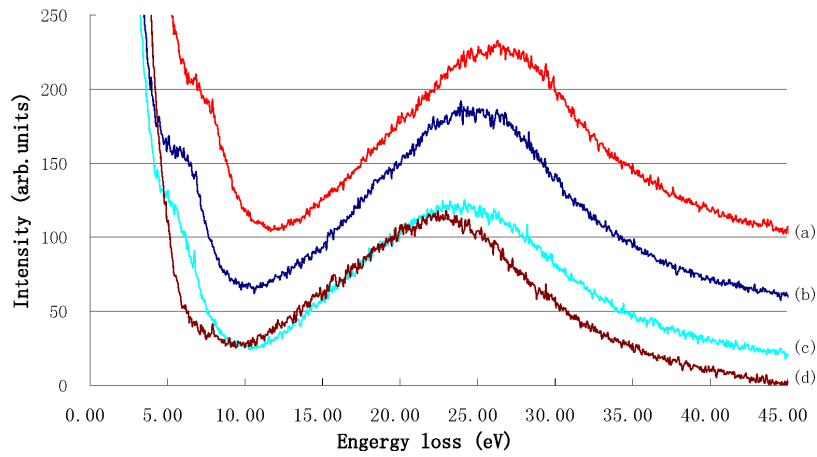
After the transformation occurs, the surface of the contact asperities becomes much softer, which can be easily removed by the sliding motion between the disk and the PCDC surface. SEM and EDX analyses in Chen et al. (2007b) indicate that carbon was removed with catalyst metals/oxide in particle-like debris. In addition, Raman spectroscopy, HRTEM and EELS analyses discussed in Chen et al. (2007c) have confirmed that the non-diamond carbon and amorphous silicon oxide/carbide were removed in polishing debris.

Figure 5 Raman spectra of PCDC specimen surface and polishing debris: (a) before polishing; (b) after polishing with adhered film; (c) after polishing and removal of adhered film; (d) after further polishing with diamond abrasive and (e) polishing debris



Source: Chen et al. (2007b)

Figure 6 Low-energy-loss carbon spectra of polishing debris



Source: Chen et al. (2007c)

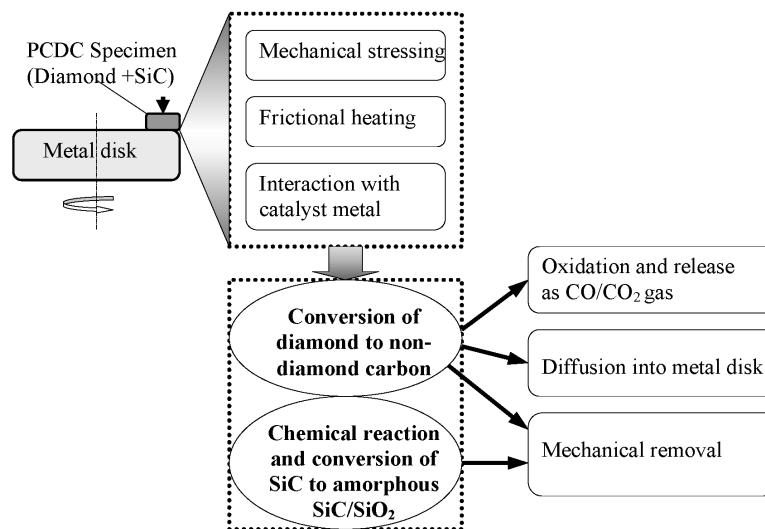
Additionally, on the contact asperities, diamond and its transformed non-diamond carbon were exposed to oxygen at high temperatures. They could easily react with oxygen and escape as CO and/or CO₂ gas. In addition, the oxidation of carbon would be accelerated

by the catalyst metals or metal oxides of Fe, Ni and Cr from the polishing disk. Moreover, diffusion of the carbon from PCDC to metal disk is another process contributing to the material removal.

The basic polishing process involves the interaction of diamond with the rotating metal disk and conversion of diamond into non-diamond carbon, and SiC to amorphous silicon oxide/carbide. After the transformed layer and the removal of the adhered film, new asperities would contact with the metal disk, and the transformation and adhered film removal are repeated during sliding, and hence result in the continuous removal of PCDC.

Figure 7 summarises the material removal mechanisms and the associated chemical reactions in the DFP process. Based on the experimental results and theoretical analyses, the material removal mechanism of DFP can be described as follows: conversion of diamond into non-diamond carbon takes place due to the frictional heating and the interaction of diamond with the catalyst metal disk; then a part of the transformed material is detached from the PCDC surface as it is weakly bonded; another part of the non-diamond carbon oxidises and escapes as CO or CO₂ gas and the rest diffuses into the metal disk. Meanwhile, another component of PCDC, SiC also chemically reacts and transforms to amorphous silicon oxide/carbide, which is then mechanically or chemically removed.

Figure 7 The mechanism map of material removal in dynamic friction polishing



Source: Chen et al. (2007c)

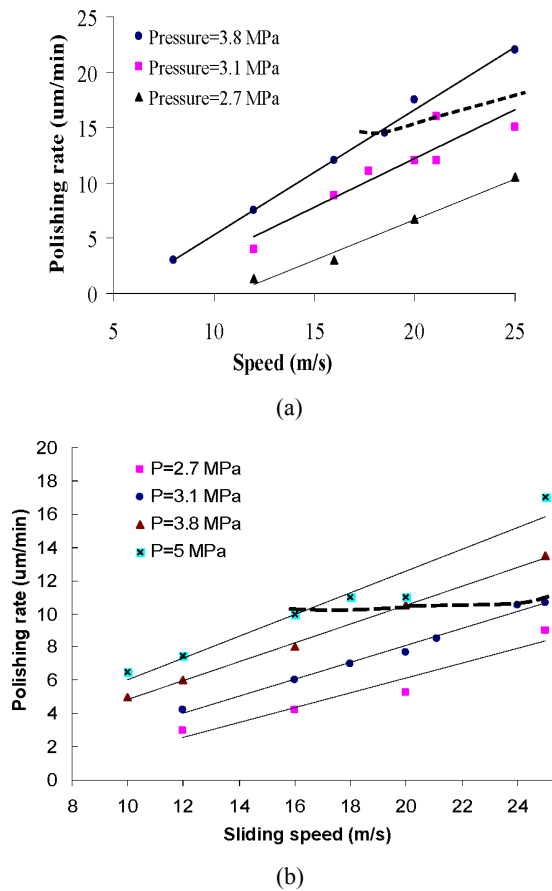
5 Selection of polishing parameters

The ultimate aim is to establish a sound scientific methodology for the effective and efficient polishing of the thermally stable PCDC to obtain a surface roughness down to Ra = 60 nm for cutting tool applications. To achieve this, an attempt is made to optimise the process by investigating the effects of DFP parameters on the material removal rate, surface characteristics and cracking/fracture of polished specimens. These were carried

out by optical microscopy, Atomic Force Microscopy (AFM), Scanning Electron Microscopy (SEM) and its attached Energy Dispersive X-ray (EDX) analyses. Selection of polishing parameters to achieve the required high quality surface finish efficiently will then be considered.

Figure 8 shows the effect of the polishing parameters, pressure and speed, on the material removal rate for two types of PCDC where the symbols represent the experimental results and the lines are the corresponding linear regression fits (Chen et al., 2007). Type 1 PCDC contains approximately 65% diamond particles of 6 μm in grain size with PCDC surface roughness before polishing approximately 0.7 μm Ra, while Type 2 PCDC contains approximately 75% diamond particles of 25 μm in grain size with PCDC roughness 1.6 μm Ra. When the speed is low (e.g., <10 m/s), PCDCs could only be partially polished or not polished at all. That is because the temperature rise is not high enough to activate the phase transformation and chemical reactions at the polishing interface. At a higher sliding speeds (e.g., >12 m/s), the polishing rate increases almost linearly with the increase in sliding speed. At a given polishing speed, a higher pressure resulted in a higher polishing rate. However, cracks could be generated under severe conditions, i.e., above the dashed line.

Figure 8 Effect of sliding speed on polishing rate: (a) Type 1 PCDC and (b) Type 2 PCDC



Source: Chen 2007

To achieve satisfactory polishing, appropriate polishing parameters, i.e., pressure and sliding speed, should be selected to generate the required temperatures at the PCDC-metal interface. The pressure-speed combinations for effective polishing are shown in Figure 8. The dashed line in the figure indicates approximately the boundary of the safe region, below which polishing can be carried out without cracking. Among the conditions tested, the most appropriate parameters for Type 1 PCDC are (Figure 8(a)):

- pressure = 2.7 MPa, sliding speed = 20–25 m/s
- pressure = 3.1 MPa, sliding speed = 16–25 m/s
- pressure = 3.8 MPa, sliding speed = 16 m/s.

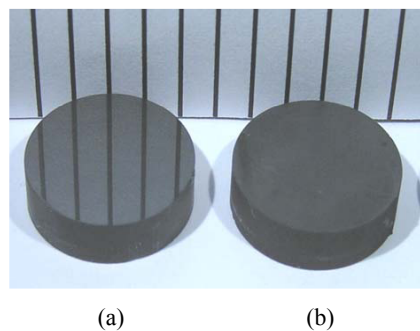
The polishing time for the above pressure/speed combinations is 2 min. The most appropriate parameters for Type 2 PCDC are (Figure 8(b)):

- pressure = 2.7 MPa, sliding speed = 25 m/s
- pressure = 3.1 MPa, sliding speed = 18–25 m/s
- pressure = 3.8 MPa, sliding speed = 16 m/s
- pressure = 5 MPa, sliding speed = 12 m/s.

The polishing time for the above pressure/speed combinations is 3 min.

During DFP, cracks on the PCDC surfaces could be controlled by selecting the appropriate polishing parameters, and the surface roughness was reduced to the range of 0.1–0.2 μm Ra. However, it could not be improved any further because the material removal rate of diamond is faster than that of SiC (Chen et al., 2008). Thus, further mechanical abrasive polishing was applied to remove the protruding SiC and further polish the PCDC to generate the required optical surface finish (Figure 9(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 present work, the specimen relocation was done manually and this introduced considerable tilting of the specimen. Because of this, the polishing of the whole surface of the relocated specimen required about 15 min. If an automatic relocation mechanism is attached, the time will be very much reduced. For comparison, a PCDC specimen before polishing is shown in Figure 9(b). The roughness of the polished surface (Figure 9(a)) was 0.05 μm (50 nm) Ra. The required optical surfaces finish was achieved in 17 and 18 min for Type 1 and Type 2 PCDC specimens, respectively.

Figure 9 PCDC surface: (a) after polishing with mirror finish and (b) before polishing



6 Conclusion

Based on DFP, an effective polishing technology for cutting tools made of thermally stable PCDC has been developed. A special polishing machine was designed and manufactured in house to carry out the polishing. Polishing temperatures were characterised by theoretical and experimental methods. The material removal mechanism has been comprehensively investigated both experimentally and theoretically. For a given type of PCDC, appropriate polishing parameters were determined based on the polishing rate. It was found that by combining DFP and mechanical abrasive polishing, a very high polishing rate and good quality surface could be obtained. The final surface roughness could be reduced to 50 nm Ra for both types of PCDC specimens considered from a pre-polishing value of 0.7 or 1.6 μm Ra. The polishing time required was 18 min, a ten fold reduction compared with the mechanical abrasive polishing currently used in industry.

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