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Chapter 3

POLISHING OF DIAMOND SURFACES

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ABSTRACT

Since the successful synthesis of diamond, especially the rapid development of chemical vapour deposition (CVD) diamond technology, diamond has been used extensively in industry and the effective polishing of diamond surfaces has become increasingly important. Over the years, various techniques using a mechanical, chemical or a thermal method, or their synergistic combinations have been developed, of which the dynamic friction polishing (DFP) method is relatively new and appears to be an attractive alternative to provide the efficiency that the conventional methods cannot achieve. In addition, the DFP is an abrasive free technique, requires simple machinery, and can be implemented in a normal ambient environment.

This chapter reviews the latest development on DFP of diamond surfaces, which includes polishing equipments, estimation of interface temperature, exploration of the material removal mechanism, modelling of material removal rate, establishment of polishing map for nanometric surface finish and characterization of surface integrity. It also presents the applications of the method to single crystalline diamond, polycrystalline diamond composites, and CVD diamond films.

1. INTRODUCTION

Since the successful synthesis of diamond, especially the rapid development of chemical vapour deposition (CVD) diamond technology, diamond has been used extensively in industry and the effective polishing of diamond surfaces has become increasingly important. Over the years, various physical and chemical methods have been developed to polish the

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diamond surfaces. Comprehensive reviews on these techniques have been available in the literature [1-4]. The diamond polishing techniques using a mechanical, chemical or a thermal approach, or their synergistic combinations can be broadly classified into contact and non-contact methods, including mechanical polishing, chemo-mechanical polishing, thermo-chemical polishing, high energy beam (laser/plasma/ion beam) polishing, electrical discharge machining (EDM) and dynamic friction polishing.

Mechanical abrasive polishing has been practised for many centuries, and has been widely used in industry [5-7]. This technique can produce a surface with a roughness of the order of Ra = 0.02 μm without drastically changing the chemical quality of the diamond surface [3-4,8]. The process is straightforward and scalable, and there is no requirement for heating the substrate or using reactive gases. However, the polishing time can be quite long, up to several days, and the applied pressure on the substrates can cause microcracking on CVD diamond films [9]. The polishing rates are extremely low and depend on the quality of the diamond, its lattice orientation and polishing direction.

The chemo-mechanical method [10-14] uses mechanical polishing with the aid of chemicals to enhance the removal rate and to obtain a better surface finish (~ Ra =20 nm) [15-16]. This method exploits the high temperature oxidation property of diamond [3,11] and the compound effect of mechanical abrading, where oxidant etching plays a main role in the material removal process. The processing time is of the order of several hours [17]. However, the heating of the polishing disk and the requirement of oxidizing 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 polishing (or hot-metal-plate polishing) is a process using a hot metal plate, and is based on the thermo-chemical reaction between a diamond surface and a hot metal plate at an elevated temperature (730 – 950 °C). It offers a fine surface finish, and the polishing rate is much higher than that of mechanical polishing (in the order of a few μm/h) [18-20]. 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.

Another thermo-chemical method, diamond etching, uses the principle of diffusion reactions [21]. Metals or alloys (Fe, Mn or molten rare earth metals/alloys such as Ce or La) foils are placed in contact with the diamond films under load at an elevated temperature (600 - 900 °C) in an argon atmosphere [22-27]. An etching rate of approximately 60 μm/min [53] has been achieved by using rare-earth/transition-metal alloys. The advantages of this method 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 Ra is often of the order of a few micrometers [26].

The high energy beam techniques include Plasma/Ion beam and laser beam polishing. Asperities on a diamond surface are removed by the high energy beam via sputtering, etching, localized heating, high-temperature graphitization and/or oxidation. These non-contact methods generally do not require the application of a force to samples, or do not need to heat them. Hence polishing of non-planar surfaces and/or small areas can be achieved [3,28-31]. Their major disadvantages are the cost of expensive equipment and for maintaining a controlled environment, generally a vacuum environment.

EDM removes materials by harnessing thermal energy produced by pulsed spark discharges which generates a very small plasma channel having a high energy density and a very high temperature (up to 10,000 °C) that melts and evaporates a small amount of diamond surface material. The EDM polishing can provide a very high material removal rate [32-35], but the finial surface finish is only up to a few microns Ra.

Dynamic friction polishing (DFP) is a relatively new method proposed and studied [36-39]. This technique utilizes the thermo-chemical reaction induced by the frictional heating between a diamond specimen and a rotating catalytic metal disk under certain pressure, and enables highly efficient abrasive-free polishing. It appears as an attractive alternative to supplement the deficiency of the conventional polishing methods, because the DFP can obtain very high polishing rate and effectively use the friction energy. The equipment required is simple, and the process can be implemented in a normal ambient environment and does not require a vacuum chamber and/or special heating.

This chapter reviews the latest development on dynamic friction polishing of diamond surfaces, which will include polishing equipments, estimation of interface temperature, exploration of the material removal mechanism, modelling of material removal rate, establishment of polishing map for nanometric surface finish, and characterization of surface integrity. It also presents the applications of the polishing technology in single crystalline diamond, polycrystalline diamond composites (PCDC), and CVD diamond films.

2. Polishing Equipments

A typical DFP process is schematically illustrated in Figure 1. The polishing was conducted by pressing a rotating diamond specimen at a predetermined pressure onto a catalytic metal disk rotating at a high speed in dry atmosphere. The metal disk used in DFP can vary, provided that it consists of catalytic elements. For example, some used nickel or stainless steel [36-37,40] but some others used titanium allay [41] or an intermetallic compound consisting of one or more elements selected from the group of Al, Cr, Mn, Fe, Co, Ni, Cu and Pt and one or more from the group of Ti, V, Zr, Mo, Ta and W [42-44].

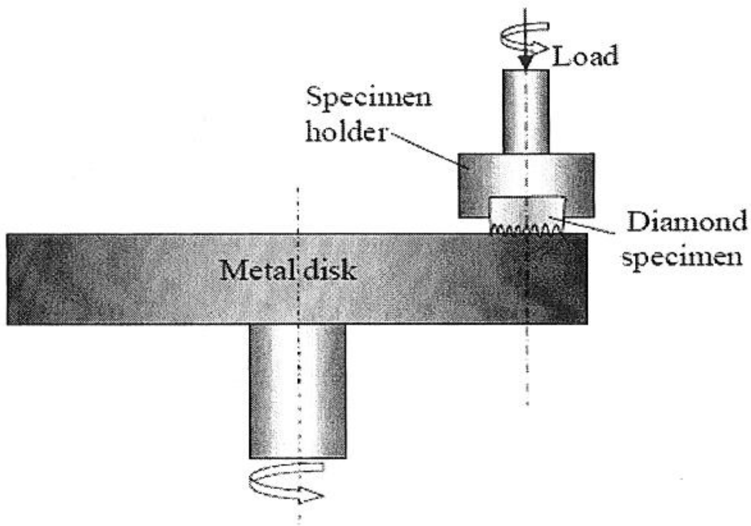


Figure 1. Schematic illustration of a typical dynamic friction polishing.

Another advantage of DFP is that polishing can be carried out on various machines. The polishing metal disk and diamond specimen can be mounted on to a CNC machine centre, universal milling machine, normal polishing or grinding machine, or specifically designed diamond polishing machine for better and stable control of the process. The key requirement is that the equipment needs to provide high combination of pressure and sliding speed to generate adequate dynamic friction heating between diamond and the catalytic metal disk to generate sufficient interface temperature to activate phase transformation or/and chemical reactions during polishing. In addition, the equipment needs to carry out the DFP process efficiently and in a controllable manner to ensure precise and uniform polishing of diamond surfaces.

A wide range of parameters, such as a pressure in the range of 1 to 100 MPa and sliding speed in the range of 10 to 167 m/s at different combinations have been used for polishing. DFP has been conducted at both room temperature and in a heated environment such as 100 to 800 °C. Some techniques were developed by heating the polishing disk or diamond specimens with the intention that the effective polishing can be conducted at a lower pressure or sliding speed.

3. Interface Temperature

The chemical reactions and phase transformation of diamond play an important role in the material removal of diamond, and these reactions only occur at elevated temperatures. It is therefore important to estimate the temperature during the process. The temperature at polishing interface has been characterized by theoretical modelling and experimental measurement.

Iwai et al used FEM analysis to predict the temperature at single crystalline diamond surface [45]. The results of estimated surface temperature *vs* sliding speed at different pressure are shown in Figure 2. In the simulations, the friction coefficient was selected according to previous experiment, and the high coefficient of 0.2 and low coefficient of 0.08 were used and the results are presented in Figure 2 (a) and (b), respectively.

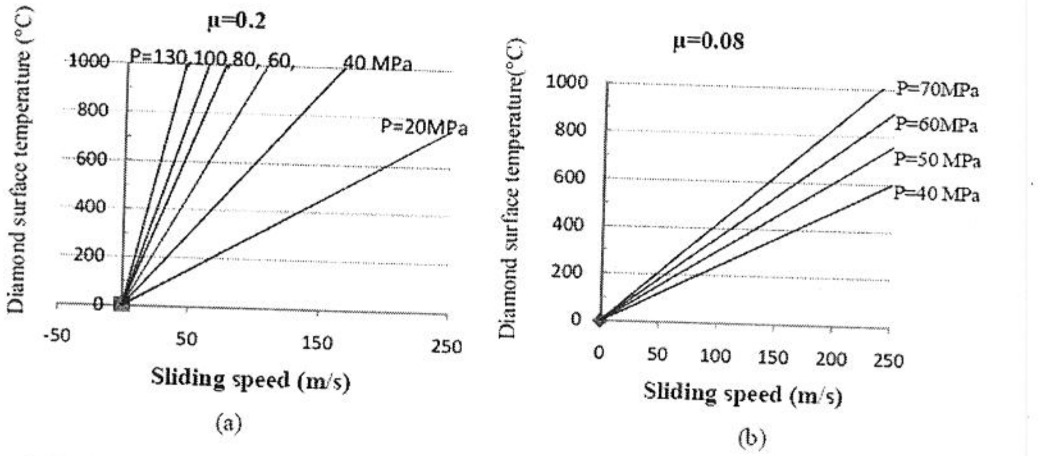


Figure 2. Estimated diamond surface temperature *vs* sliding speed at different nominal pressures [45]. (a) Coefficient of friction μ=0.2. (b) Coefficient of friction μ=0.08.

It can be seen that the higher pressure and sliding speed resulted in higher surface temperature, and the temperature increased lineally with the sliding speed at a given pressure. Since these predicted temperatures are on the nominal diamond surface whose area is much larger than the actual contact area, the predicted temperatures could be lower than the actual interface temperature. The required pressure and speed to achieve the minimum surface temperature of 700 °C for polishing is likely higher than that actually needed.

Chen et al [38] developed a model to predict temperature rise at the interface of the polishing disk and polycrystalline diamond composites (PCDC) asperities. 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 asperities and the metal disk surface. Jaeger's moving heat source analysis was then applied to determine the fraction of the heat flowing into the asperities and its counterpart at contact sliding during polishing and to predict the average temperature rise on the contact surface.

Figures 3 shows the variations of the calculated average contact temperature rise with the sliding speed at different nominal pressure applied. The coefficient of friction μ used in the calculation was 0.15. 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 increases with increasing pressure and sliding speed. The dependence of temperature rise on speed appears to be linear for a fixed nominal pressure. Since the model is based on the assumption of no heat loss into the surrounding, the predicted interface temperature rise is the upper bound.

In the current practice, it is almost impossible to measure the interface temperature during diamond polishing. Although the thermocouple technique has been used in temperature measurement [46], 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 PCD subsurface temperature, and then extrapolate it to the polishing surface [47].

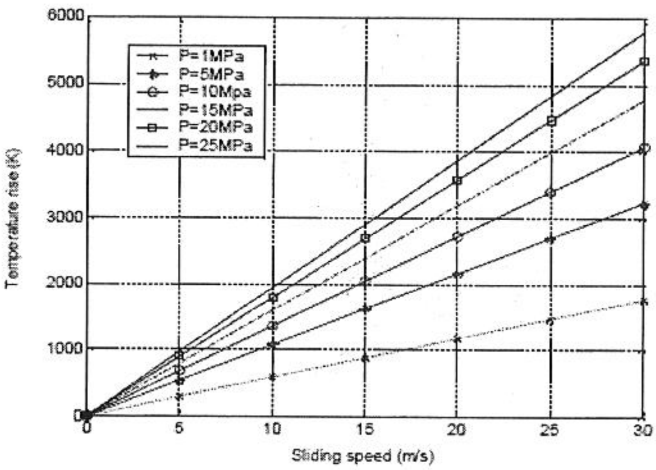


Figure 3. Variation of calculated average temperature rise with sliding speed at different nominal pressures [38].

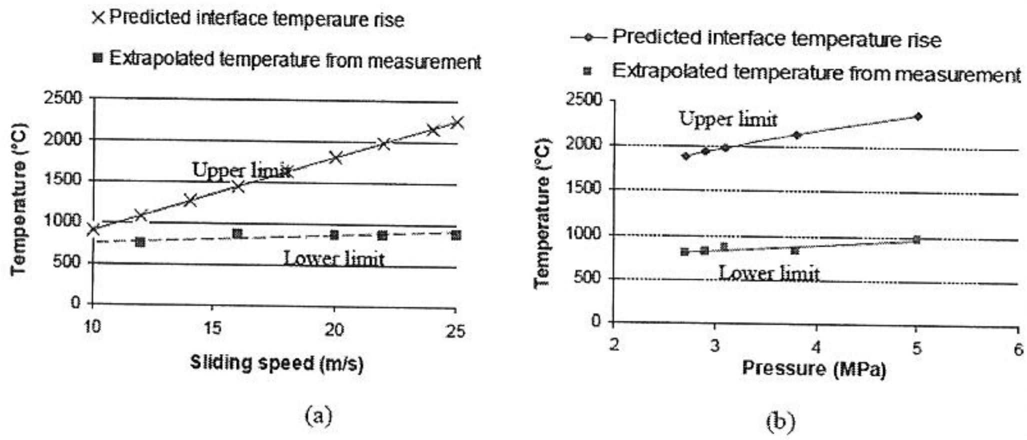


Figure 4. Compare of interface temperature from theoretical prediction and extrapolated from measurement [47]. (a) with speed at pressure 3.1MPa. (b) with pressure at speed 22 m/s.

The temperature picked up by the thermocouple was not at the polishing interface, but at a distance (approximately 0.6 mm) from it. To obtain the interface temperature, a model of a steady temperature in a semi-infinite cylinder [48] 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 not the same during actual polishing. Hence, an extrapolated interface temperature from the measured result 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.

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)) [47], and against the variation of the applied polishing pressure at a given sliding speed (Figure4 (b)). It can be seen that at a given speed, the higher the pressure, 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.

4. Material Removal Mechanisms

The material removal mechanisms of DFP have been studied by a number of research groups. Iwai et al [37] and Suzuki et al [36] investigated the material removal mechanism based on the polishing efficiency in various atmospheres, and carried out x-ray diffraction analyses of the polishing debris and the surface of metal disk. They found that the mechanisms were rapid diffusion of carbon from the diamond to the disk and then evaporation of carbon by oxidization. Huang et al [41] analysed the element composition and chemical state of the diamond film and polishing titanium disk after polishing by using x-ray photoelectron spectroscopy (SPX). They suggested that the chemical reaction between carbon and titanium and the diffusion of carbon atoms into the polishing plate were the material removal mechanisms.

To gain a comprehensive understanding of the polishing mechanism, Chen et al [39-40] combined theoretical and experimental investigations to explore whether chemical reaction and phase transformation had occurred. A theoretical study was carried out with the aid of thermodynamics and chemical kinetics of interface reactions. Scanning electron microscopy (SEM), x-ray diffraction (XRD), Raman spectroscopy, transmission electron microscopy (TEM), electron diffraction, energy dispersive x-ray analysis (EDX) and electron energy loss spectroscopy (EELS) were used to analyse the debris produced during DFP and diamond specimens before and after polishing to clarify the material removal mechanisms.

Figure 5 shows the Raman spectra of diamond specimen surface and polishing debris [39,49]. Non-diamond carbons with Raman peaks at 1585-88 and 1321-22 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 [40], it was found that the polishing debris were mainly of amorphous structure, that included different forms of carbon and 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 [40]. From high-loss energy spectra, the percentage of sp^2 bonding in the hybridized 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 [40].

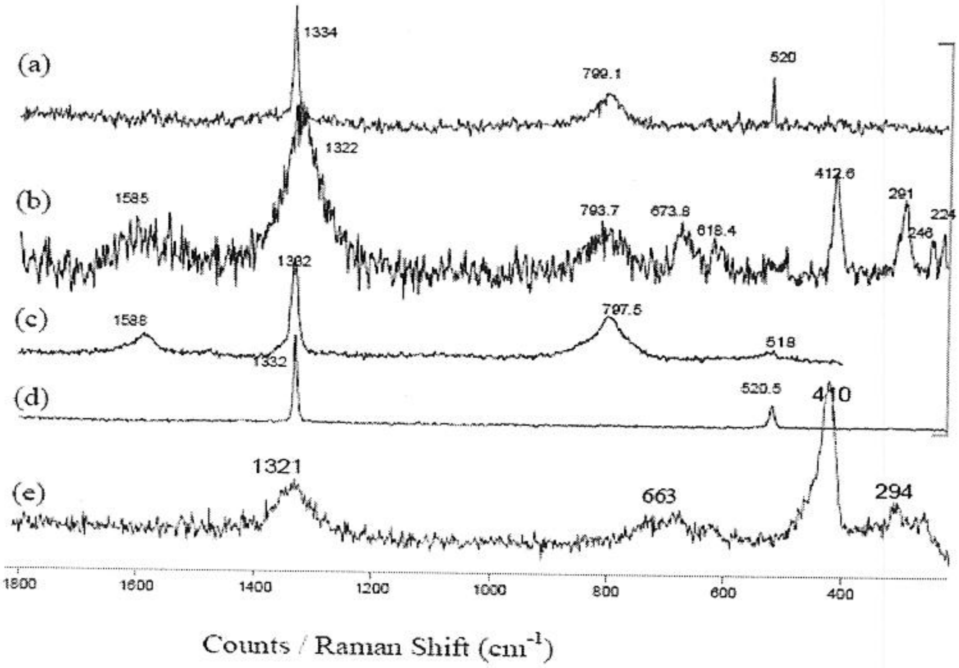


Figure 5. Raman spectra of PCDC specimen surface and polishing debris [39] (a) Before polishing, (b) After polishing with adhered film, (c) After polishing and removal of adhered film, (d) After further polishing with diamond abrasive (e) Polishing debris.

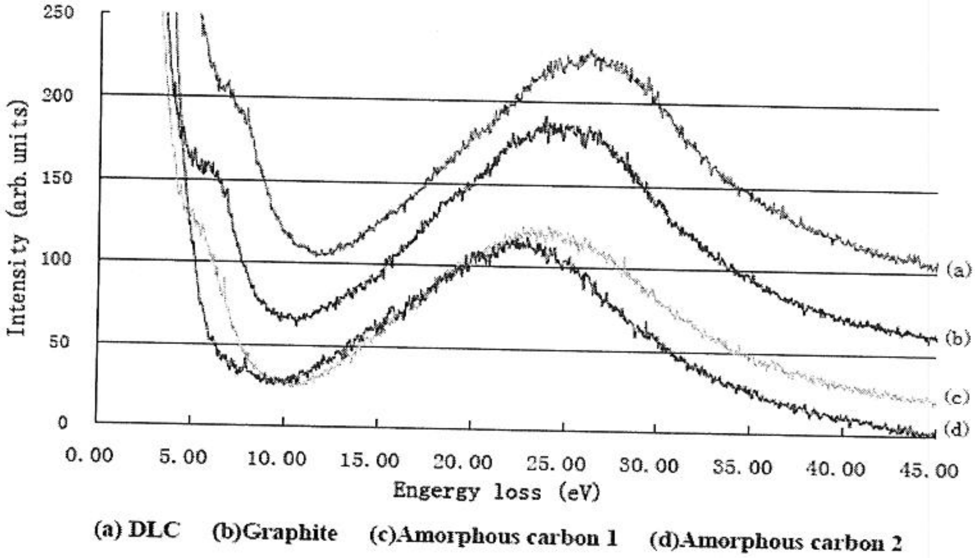


Figure 6. Low-energy-loss carbon spectra of polishing debris [40].

After the transformation, the surface of the contact asperities becomes much softer, which can be easily removed mechanically by the continuous sliding between the disk and the diamond surface. SEM and EDX analyses in [39] indicate that carbon was removed with catalyst metals/oxide in particle-like debris.

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 CO_2 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 diamond surface to metal disk is another process contributing to the material removal.

Figure 7 summarizes the material removal mechanisms and the associated chemical reactions in the dynamic friction polishing process [40].

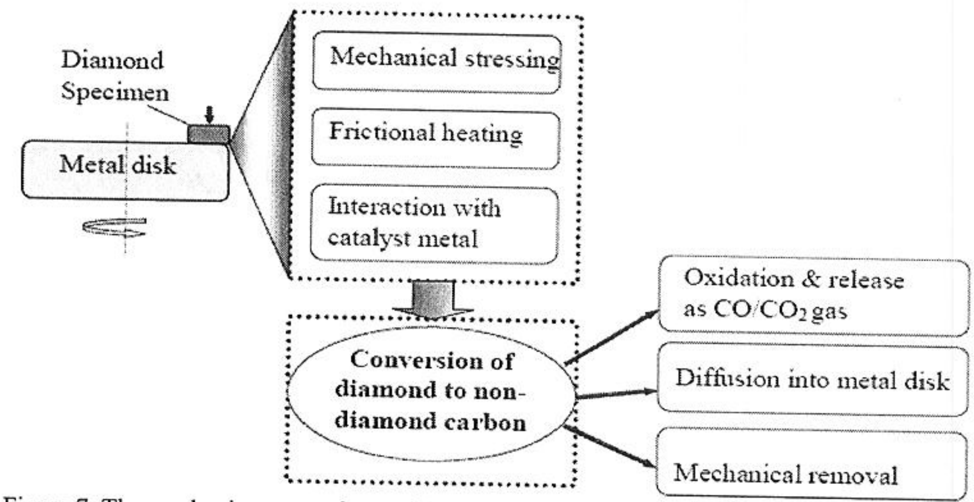


Figure 7. The mechanism map of material removal in dynamic friction polishing [40].

Based on the experimental results and theoretical analyses, the material removal mechanism 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 removed mechanically from the diamond surface as it is weakly bonded; another part of the non-diamond carbon oxidizes and escapes as CO or/and CO_2 gas; and the rest diffuses into the metal disk. After the phase transformation and the removal of the adhered layer, new asperities would contact with the metal disk, and the transformation and removal are repeated during sliding, and hence result in the continuous removal of diamond.

5. Material Removal Rate

From the aforementioned understanding, there are various material removal mechanisms involved in DFP and many factors can influence the material removal rate. These include the polishing parameters such as polishing pressure and sliding speed, surrounding gas environment, diamond workpiece material and its initial surface condition, polishing disk material and initial disk temperature etc. By selecting proper polishing conditions, very high material removal rate can be obtained.

Iwai et al [45] studied the material removal rate on DFP of single crystalline diamond, and reported that a very high material removal rate of 520 μm /min (equal to 0.182 mm^3/min) was achieved at the polishing speed of 167 m/s and pressure of 100 MPa. The polishing time used was only 0.5 second; this had reduced dramatically from the other diamond polishing method whose polishing time was in the order of hours and days. For CVD diamond, material removal rate of 12 μm/h could be obtained at the polishing speed of 60 m/s and the pressure of 0.31 PMa on a titanium polishing disk [41].

In general, the research found that the pressure and speed needed to be high enough to generate sufficient frictional heating to a critical temperature to trigger the chemical reaction. A high polishing pressure and sliding speed resulted in a high material removal rate. Compared to a normal ambient environment, the material removal rate increases in an oxygen environment but decreases in nitrogen gas [36]. This is because oxidation of carbon accelerates the transformation of diamond to non-diamond carbon and speeds up the material removal in polishing.

Chen et al [50] has systemically studied the material removal rate of two types of thermally stable polycrystalline diamond composites (PCDC). The Type 1 PCDC contains about 75% polycrystalline diamond particles (C=75%) with grain size $\delta \sim 25$ μm (the rest are SiC and Si), and has an initial surface roughness of $\varepsilon = 1.6$ μm. The Type 2 PCDC is of C = 65%, $\delta \sim 6$μm and $\varepsilon = 0.7$μm. The size of both types of PCDC is D =12.7 mm in diameter and 4 mm in thick. To understand the influence of polishing parameters on the material removal rate, the speed V was varied from 8 to 25 m/s for each polishing pressure of 2.2, 2.7, 3.1, 3.8 or 5 MPa (corresponding to load 285, 343, 392, 480 and 637 N) and at a constant polishing time of 3 minutes for Type 1 specimens and 2 minutes for Type 2 specimens, as shown in Figure 8, where the symbols represent the experimental results, the solid lines represent the fitted linear regression lines of the Type 1 specimens, and the dotted one represents those of the Type 2 specimens.

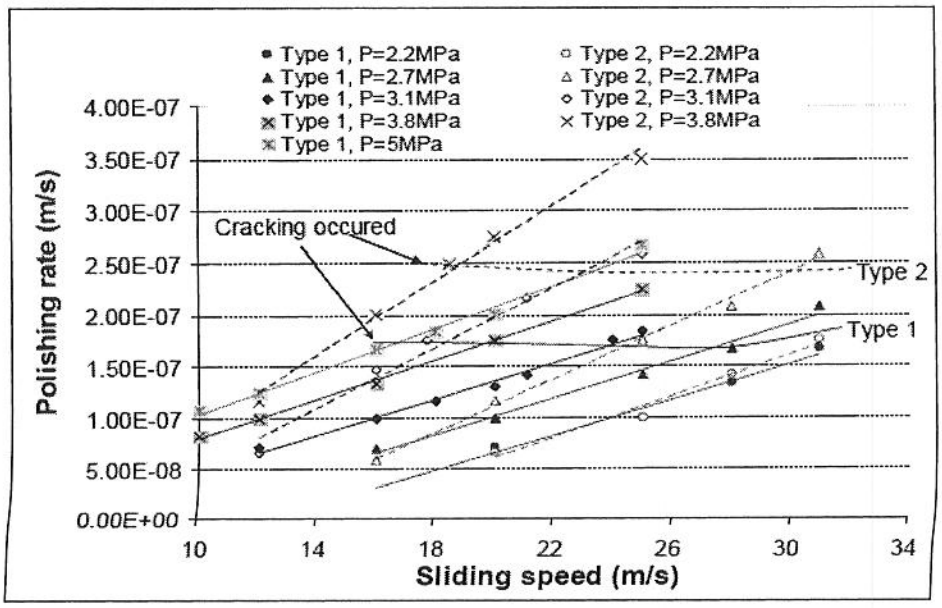


Figure 8. The variation of removal rate with sliding speed at different pressure for both types of PCDC [50].

As shown in Figure 8, at a given sliding speed, the material removal rate increases with the pressure rise. Similarly, a higher speed at a given pressure results in a higher removal rate. 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 was no measurable using the electronic balance available. This means that 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. For Type 2 PCDC, a similar trend can be seen but with different critical values of the polishing parameters. In this case, when the speed was lower than 12 m/s, the polishing rate was extremely low, sometime even not measurable.

We can see that in general at an identical sliding speed and pressure, the material removal of the Type 2 PCDC (smaller grain size particles) is higher than that of the Type 1 PCDC. This is because smaller diamond particles have more surface defects and a larger surface area in the composite. The chemical reaction starts at the surface defects, thus reacting faster [51]. However, at a low speed and pressure combination, the Type 1 specimens have a higher material removal rate. This is mainly due to their much greater initial surface roughness (Rmax ≈10 μm) in comparison with the Type 2 PCDC (Rmax ≈ 5 μm) 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.

The aforementioned study shows that the material removal of the PCDC in DFP polishing is a function of the constitutive and thermal properties of materials, and also varies with the polishing parameters that generate the frictional heat for chemical reactions. There are multi-variables that influence the material removal rate. Therefore Chen, et al. [52] carried out a dimensional analysis to try to describe quantitatively the material removal thickness *d*. They found that the following dimensionless formula can fairly accurately estimate *d*:

$$\frac{d}{D} = 7.39\times10^{-26}\left(\frac{\mu L}{ED^2}\right)^{1.42}\left(\frac{VD}{2\chi}\right)^{0.55}\left(\frac{Vt}{D}\right)^{0.64}\left(\frac{C\delta}{D}\right)^{-0.33}\left(\frac{\varepsilon}{D}\right)^{0.43} T_0^{3.95} \quad (16)$$

where the units of the variables are in SI units (kg, m, sec, ^{0}K), and the nomenclatures are shown in Table 1. A comparison of the formula estimation with experimental measurements is presented in Figure 9 [52].

The formula shows that to achieve a higher material removal rate, a greater load *L* and sliding speed *V* are generally required; but this is often limited by some technological constraints such as power the consumption allowable and machine capacity available. This difficulty can be overcome by using a smaller *L* and *V* but a longer processing time. The formula also indicates that if a PCDC contains larger diamond particles and a higher percentage of diamond, the material removal will be more difficult, while the higher initial disk temperature will increase the material removal rate. The formula can be used as a practical guide for designing a polishing machine or for planning a polishing process to achieve the balance between production rate and performance.

Table 1. Nomenclature

C	composition of diamond in PCDC, %	D	characteristic length of sample, m
d	material removal height, m	E	equivalent Young's modulus, Pa
L	normal load on PCDC specimen, N	q	total heat flux generated by sliding contact, W m^{-2}
T_o	initial temperature, K	t	process time, s
V	sliding velocity, m s^{-1}	δ	characteristic diameter of diamond particle, m
ε	surface roughness	μ	coefficient of friction
χ	thermal diffusivity, m^2 s^{-1}		

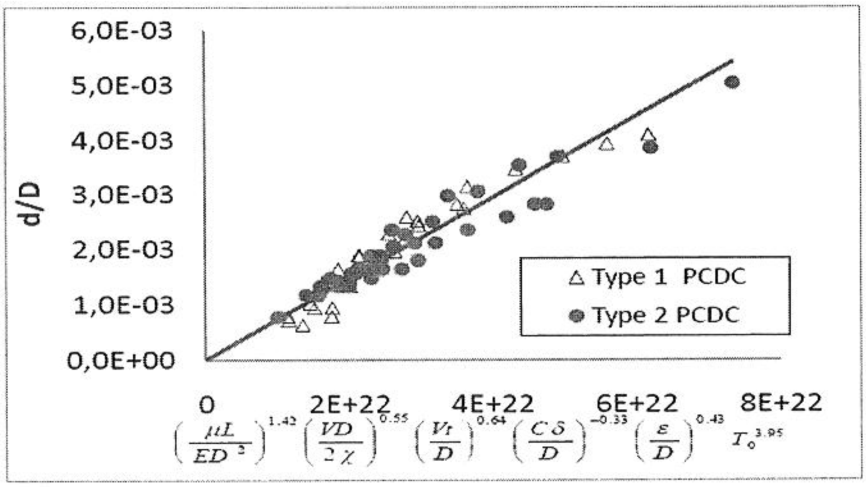


Figure 9. Comparison of model prediction (solid line) and experimental measurements (dots) [52].

6. Polishing Map and Surface Integrety

During the dynamic friction polishing of PCDC, although a higher pressure/speed increases the material removal rate, it may also result in cracking [50]. According to Figure8, cracks were observed when the speed-pressure combination is above the solid line for the Type 1 specimens, e.g., under the following polishing conditions: pressure = 5 MPa and sliding speed ≥ 16 m/s; pressure = 3.8 MPa and sliding speed ≥ 20 m/s; pressure = 3.1 MPa and sliding speed ≥ 24 m/s; pressure = 2.7 MPa and sliding speed ≥28 m/s; and pressure = 2.2 MPa and sliding speed ≥31 m/s. For the Type 2 PCDC, cracking occurred under the following polishing conditions above the dotted line as shown in Figure 8: pressure = 3.8 MPa and sliding speed ≥ 18.5 m/s; pressure = 3.1 MPa and sliding speed ≥ 21 m/s, pressure = 2.7 MPa and sliding speed ≥ 31 m/s.

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 x 10^{-6} /K at 300 K [53]) is much lower than that of the binder phase, SiC (3.8 x 10^{-6} /K at 300 K [54]). 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 [50].

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.

The results in Figure 8 can be more easily visualized as a polishing processing map, as shown in Figure 10 for Type 1 PCDC, a plot of sliding speed *vs* polishing pressure, where the value of the material removal rate (x 10^{-7} m/s) measured at a given pressure and sliding speed is indicated next to the data point [50]. A dotted curve extrapolated through these data show a contour of a constant polishing rate.

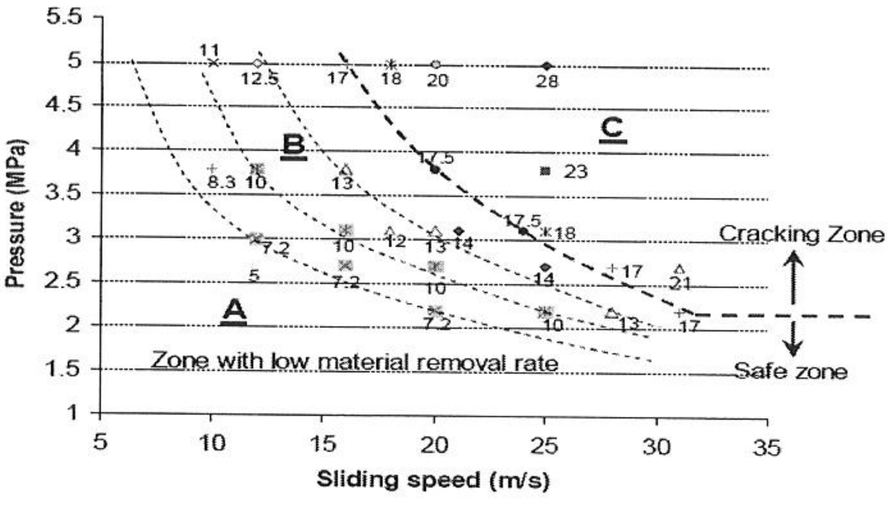


Figure 10. The material removal map [50].

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 the polishing map described above. For example, if the desirable polishing rate is 14×10^{-7} m/s, a feasible polishing condition can be taken as speed = 25 m/s with pressure = 2.7 MPa, or speed = 21 m/s with pressure = 3.1 MPa. Using these conditions and further mechanical abrasive polishing was applied to further polish the PCDC, the surface roughness can reach 50 nm Ra in 18 minutes from 1.6 μm Ra (Figure 11), which is more than 10 times faster than the mechanical abrasive polishing process currently used in industry.

In addition, Raman mapping was used to analyse the polished PCDC surface [55]. Figure 12 (a) shows the macro-Raman spectrum which was obtained by averaging the 2943 spectra collected from the rectangular area marked in Figure12 (b). No graphite, metal oxide or non-diamond carbon was detected.

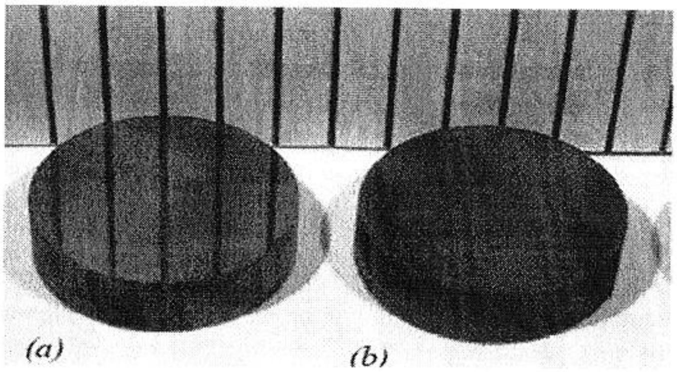
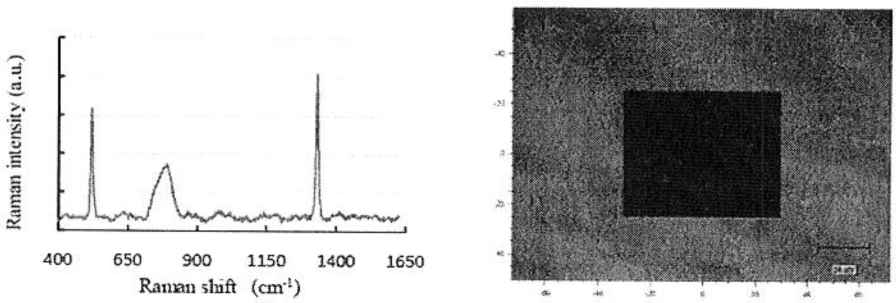


Figure 11. PCD surface [50]. (a) After polishing with mirror finish. (b) before polishing.



(a) (b)

Figure 12. Raman mapping of the final polished PCDC surface [55]. (a) Macro-Raman spectrum (by averaging the 2943 spectra). (b) Raman map of phase distribution (red: diamond, cyan: Si, blue: SiC. No graphite was detected).

The sharp narrow diamond line centred at 1332.4 cm^{-1} indicates a high quality of the completely polished surface. The average spectrum contains deformed amorphous SiC band centre at ~799 cm^{-1} and a high intensity of Si peak at ~521 cm^{-1}. The Raman map (Figure 12(b)) provides the location of the three phases. It can be seen that pristine diamond phase was predominant within the gain areas, as demonstrated in red in Figure12 (b), while SiC and Si (shown as blue and cyan, respectively) distributed along the grain boundaries. All the intermediate soft materials including metal oxide, non-diamond and amorphous graphite which may degrade the quality of the PCDC had been removed from the surface. This verifies that the DFP will not only achieve fast polishing of PCDC, but also maintain high material quality.

7. APPLICATIONS

The DFP method has been used for polishing single crystal diamond, polycrystalline diamond composites (PCDC) and CVD diamond films.

Compared to polishing PCDC and CVD diamond, polishing single crystal diamond using DFP method is the most straightforward. By selecting a proper polishing pressure and sliding speed, e.g., 17 MPa and 35 m/s, a very high polishing rate at 170 μm/min with a high quality surface finish at the roughness ~0.05 μm Ra can be obtained in a minute [56]. This is hundreds times faster than the other polishing techniques reported in the literature [2-3]. In addition, Iwai et al [45] reported that the material removal rate could reach 480 μm/min when polishing at the speed of 167 m/s and pressure of 50 MPa, with an ended surface roughness of Rz = 0.05 μm. This method can be used to manufacture diamond products include diamond jewelry, and to repair worn diamond components such as diamond cutting tools and dressers for grinding wheels.

The polishing became more complicate when applying DFP on thermally stable PCDC which contained diamond, SiC and Si. The two major constituents, diamond and SiC, have very different properties, eg., hardness, coefficient of thermal expansion and chemical reactivity, etc, and the material removal rates for diamond and SiC will be different. Cracking may occur when polishing at a very high speed-pressure combination due to the different coefficient of thermal expansion of diamond and SiC. As detailed in Section 6, by selecting proper polishing parameters, a high polishing rate with a quality surface finish can be achieved in minutes.

DFP has not yet directly been applied to CVD diamond thin films, because the films are often very thin, are of high hardness but weak adhesion to substrate. These make a CVD diamond thin film easy to delaminate, damage and crush during polishing. To date, the DFP has only been applied on the polishing of free stand CVD diamond thick films (~ 0.5 mm) with a low polishing pressure [45]. However, it has shown that DFP is promising in the thick film polishing. For instance, under the condition of speed = 167 m/s and pressure = 1 MPa with blowing oxygen gas, polishing rate obtained was 45 μm/min.

8. SUMMARY

This chapter has reviewed briefly the commonly used techniques for polishing diamond and its related materials. The focus of discussion has been on the latest development on the dynamic friction polishing method, including polishing temperature and its modeling, material removal mechanisms, surface integrity, and material removal rate and its prediction. The discussion has concluded that pressure-speed combinations are the most important. The polishing map developed by Chen, et al [50] provides a useful guide for the design of a DFP process/machine and for a proper selection of polishing parameters. A DFP process is simple, does not require complicated machinery, and can be implemented in a normal ambient environment. By selecting proper polishing parameters, a very high polishing rate with a quality surface finish can be achieved in minutes. The DFP method can be used in polishing single crystalline diamond, polycrystalline diamond and its composites, and CVD diamond thick films. However, its application to diamond thin films is still at infancy.

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