

Temperature Characterization for Nano-polishing of PCD Composites

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Abstract. This paper discusses the temperature characterization for nano-polishing of polycrystalline diamond composites (PCDCs) by combined experimental and theoretical modelling. It was found that a higher polishing pressure-speed combination results in a higher temperature rise and material removal rate. To optimize the nano-polishing of PCDCs and achieve a surface roughness of $R_a = 50$ nm, the interface temperature at polishing needs to be maintained at an appropriate level.

Introduction

Nanometric surface finish of thermally stable PCDCs, composed by polycrystalline diamond and SiC, has been achieved with the aid of the technique of dynamic friction polishing (DFP) [1,2]. This technique utilizes the thermo-chemical reaction induced by the dynamic friction between a PCDC specimen and a metal disk rotating at a high peripheral speed to enable an efficient, abrasive-free polishing. Under appropriate polishing conditions, temperature rises dramatically at the interface, and chemical reactions of carbon and SiC at elevated temperatures play an important role in the material removal. To control the polishing rate at the nano-scale and optimize the process, it is essential to be able to manipulate the variation of the interface temperature. Although a theoretical model has been developed to predict the interface temperature rise during polishing [3], it is necessary to understand the effect of temperature variation on the material removal rate.

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 [4], fitting them into a rotating system of DFP is difficult and the temperature measured cannot be directly at the polishing interface.

This paper aims to understand the relationship among the interface temperature rise, polishing conditions, and the polishing rate of PCDCs by combined experimental and theoretical modelling.

Characterization of Interface Temperature Rise at Polishing

Upper Bound. The authors have established a theoretical model to predict the interface temperature rise during the polishing of PCDC specimen [3]. In this model, the Greenwood-Williamson's statistical asperity theory was used to characterize the surface roughness of a PCDC specimen. The result was then used to estimate the contact area and the total number of contact asperities under an applied polishing load. The heat generated was taken as the product of the friction force and the relative sliding velocity between the PCDC asperities and the metal disk surface. The Jaeger's moving heat source theory was applied to determine the fractions of heat flowing into the PCDC asperities and their counterpart at contact sliding in polishing and to give rise to the average temperature rise at the polishing interface. Since the model is based on the assumption of no heat loss into the surrounding, the predicted interface temperature rise is the upper bound.

Lower Bound. The interface temperature rise can also be estimated indirectly experimentally. Fig.1 shows the schematic setup using thin thermocouple sensors. In this case, 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 scale surface finish, as detailed in [2].

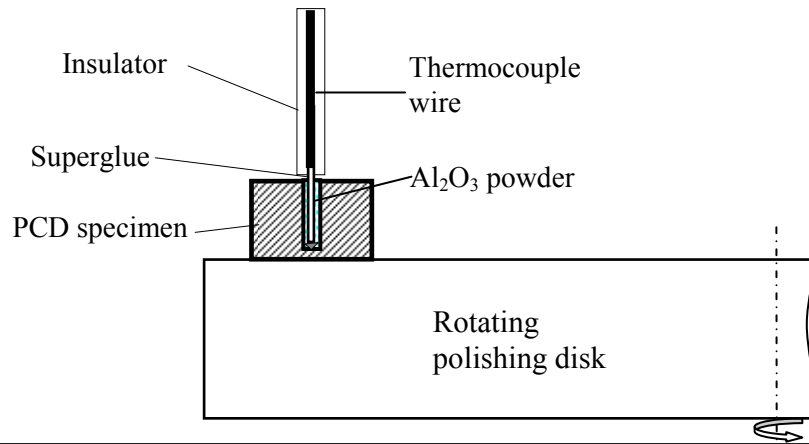
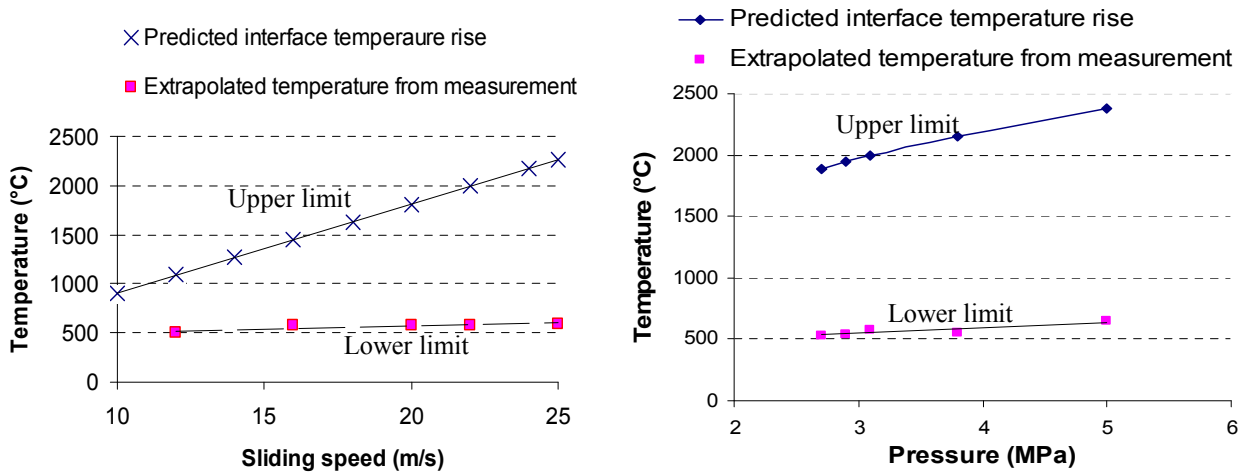


Fig. 1 Schematic illustration of the setup for temperature measurement

The temperature rise picked up by the thermocouple was not at the polishing interface, but at a distance from it. To obtain the interface temperature, a model of steady temperature in a semi-infinite cylinder [5] was used. The calculation was based on the assumption that no heat was lost in the process of conduction and convection from the interface to the tip of the thermocouple during the disk/specimen spinning. This is certainly not true in DFP. Hence, an extrapolated interface temperature rise from the measured result using the experimental setup of Fig.1 gives the lower bound. The actual interface temperature during polishing is between the lower bound from the experimental modelling and the upper bound from the theoretical prediction.

Results and Discussion



(a) With speed at pressure 3.1 MPa

(b) with pressure at speed 22 m/s

Fig. 2 Variations of interface temperature

For comparison, some typical results of the extrapolated interface temperature T_s from the experimental measurement and that from the theoretical prediction T_r are plotted against the variation of sliding speed at a given polishing pressure (3.1 MPa), and against the variation of the applied polishing pressure at a given sliding speed (22 m/s) (Fig.2). It can be seen that at a given speed, the

higher the pressure/speed is, the higher the interface temperature. As expected, at any specific combination of speed and pressure, the theoretically predicted temperature rise is always higher than the experimental. Their difference becomes bigger as the sliding speed/pressure increases, possibly due to the actually stronger convection cooling ignored in both the theoretical and experimental modeling.

Polishing Condition Selection

The material removal mechanism in a DFP is as follows [1,6]: when the PCDC is being polished under appropriate conditions, on the contact asperities of the surface, the interface temperature increases to above the critical point (about 700°C) for fast transformation of diamond to non-diamond carbon. The contacting catalyst metal accelerates such transformation. Thus the diamond that is in contact with the catalytic metal at elevated temperatures loses its lattice structure and converts to non-diamond carbon. Moreover, surface graphitization of diamond is accelerated by oxygen-containing compounds in the gaseous phase, and the diamond or transformed non-diamond carbon, exposed to oxygen, would react with oxygen to form CO and/or CO₂ gas at elevated temperatures at the polishing interface. The chemical reaction rate that determines the material removal rate k is a function of temperature according to Arrhenius equation,

$$k = A \exp(-E / RT)$$

where T is temperature, R is gas constant (8.31 J/mol.K), A is a constant (frequency factor) and E is the activation energy. All these indicate that the interface temperature at polishing plays a key role in the material removal, which becomes more straightforward when referring to the following analysis.

Fig.3 shows the effect of the polishing conditions, pressure and speed, on the material removal rate, where the symbols represent the experimental results and the lines are their corresponding linear regression fittings. It is noticed that when the speed was lower than 10 m/s, PCDCs could only be partially polished or not polished at all. That is because the temperature rise was not high enough to activate the phase transformation and chemical reaction at the polishing interface.

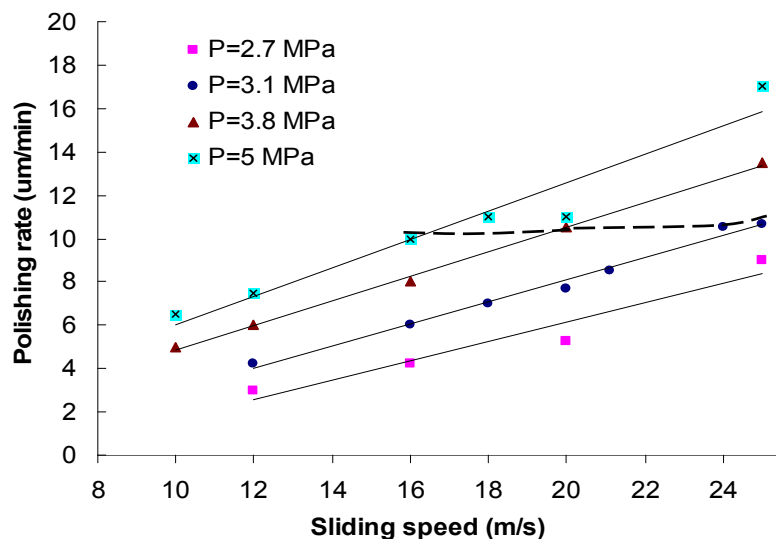


Fig.3 Effect of polishing parameters on material removal rate

At a higher sliding speed (>12 m/s), the polishing rate increased 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 also be generated, e.g., at a state above the dashed line. When a PCDC specimen was polished at a too high sliding speed and pressure combination, both the interface and

subsurface temperature rose above the critical point of fast transformation of diamond, whose density is 3.5 g/cm^3 , to non-diamond carbon, whose density is much lower in the range from 1.8 to 2.5 g/cm^3 [6]. Meanwhile, such a temperature increase caused significant thermal distortion of the PCDC as well. As a result, the marked increase in volume and thermal distortion could significantly increase the stress in the PCDCs and lead to cracking.

The above discussion clearly shows that to achieve satisfactory polishing quality, appropriate polishing parameters, pressure and sliding speed, should be selected to generate suitable temperatures. The pressure-speed combinations to determine the effective polishing parameter in this study are shown in Fig. 3. 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, it was found that the most appropriate parameters are: (1) pressure = 2.7 MPa, sliding speed = 25 m/s; (2) pressure = 3.1 MPa, sliding speed = 18 to 25 m/s; (3) pressure = 3.8 MPa, sliding speed = 16 m/s; and (4) pressure = 5 MPa, sliding speed = 12 m/s. With these, a surface roughness of PCDC surfaces down to $R_a=50 \text{ nm}$ could be achieved.

Conclusions

This paper discussed the temperature characterization for nano-polishing of PCDCs by combined theoretical and experimental modelling. The theoretically predicted interface temperature gave an upper bound and that by the experimental modelling led to a lower bound. The method and model developed provide a useful guide for selecting the nano-polishing process for obtaining a surface roughness of PCDC surfaces down to $R_a = 50 \text{ nm}$.

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