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Modelling the Polishing Efficiency of Polycrystalline Diamond Composites by the Dynamic Friction Method

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Abstract. This investigation aims to develop a quantitative model to estimate the material removal of polycrystalline diamond composites by dynamic friction polishing. The model accounts for not only the polishing parameters that govern the material removal mechanisms, but also the constitutive properties of the diamond composites subjected to polishing. The model prediction was justified by relevant experimental measurements.

Introduction

Polycrystalline diamond composites (PCDCs) are an attractive material for making cutting tools due to its ultra high hardness, excellent wear resistant and chemical inertness to most corrosive environment. However, because of their hardness and chemical inertness, polishing of these materials is difficult. In recent years, it has been found that the dynamic friction technique (DFP) can speed up the polishing process significantly [1-3]. This technique is a thermo-chemo-mechanical process which uses the friction heating and catalytic metals in contact sliding to activate chemical reaction to convert diamond to non-diamond matters and hence to ease the consequent material removal mechanically. This technique has been considered as a fast, cost-effective method for polishing PCDCs. Although the polishing mechanisms have been investigated in detail [1-3], a quantitative prediction of the material removal is still unavailable. This paper will develop an approximate analytical model to fill the gap.

Material removal mechanisms

The polishing mechanisms in DFP is that the diamond and SiC in a PCDC at the friction interface with the catalytic metal disk transform to non-diamond and amorphous carbon phases [1-3]. The transformed materials are then removed mechanically by the rubbing between the disk and PCDC. Meanwhile, both the diamond and non-diamond carbon exposing to air at elevated temperature are oxidised and escape as CO and/or CO_2 gases. Depending on the carbon concentration in the metal disk, diffusion of carbon into the metal can also take place. The total material removal (W) is therefore attributed to the chemical reaction (W_c), diffusion of carbon into the metal disk (W_d) and mechanical removal (W_m), i.e.

$$W = W_c + W_d + W_m \tag{1}$$

Chemical reaction. The material removal by chemical reactions includes the transformation of diamond to non-diamond carbon, the transformation of SiC to amorphous phases and the oxidation of carbon. The polishing rate due to chemical reaction, dW_c/dt, can therefore be considered as temperature dependant, represented by the Arrhenius type rate equation:

$$\frac{dW_c}{dt} = A_e \exp(-E_a / RT) \text{, or } W_c = \int_0^t A_e \exp(-E_e / RT)\, dt \tag{2}$$

where R is the gas constant (8.31J/mol.K), A_e is a pre-exponential factor depending on the order of the reaction, E_a is the activation energy and T is the absolute temperature.

Temperature rise in DFP is generated by sliding friction, depending on the frictional force ($F_t = \mu L$) and the thermal properties of the bodies in contact [1]:

$$T = T(\rho_1, \rho_2, K_1, K_2, C_p, V, \mu, L, T_0) \tag{3}$$

where ρ is the material density, K is the thermal conductivity, C_p is the specific heat, the subscripts 1 and 2 stand for the two contacting materials (the PCDC and the metal disk), μ is the friction coefficient, V is sliding speed, L is the normal polishing force and T_0 is the initial temperature.

The activation energy E_a depends on the constitution of materials, i.e.

$$E_e = E_e(\delta, C, \rho_1) \tag{4}$$

in which δ is the characteristic diameter of the diamond particle and C is the composition of diamond in the PCDC.

Mechanical removal. The mechanical removal can be described by the Holm-Archard law [4]:

$$W_m = \frac{C_m L V t}{H} \tag{5}$$

where t is the process time, H the hardness of the PCDC surface, and C_m the wear coefficient depending on some factors such as surface roughness ε and friction coefficient μ [5]

$$C_m = C_m(\delta, C, E_1, E_2, \nu_1, \nu_2, \rho_1, \rho_2, \mu, \varepsilon) \tag{6}$$

The hardness H is a function of PCDC's constitution and temperature [6], i.e.,

$$H = H(\delta, C, E_1, E_2, \nu_1, \nu_2, \rho_1, \rho_2, T) \tag{7}$$

Diffusion. When diamond or non-diamond carbon is in contact with the carbon soluble metal disk at a temperature over 1000 °C, carbon atoms will diffuse into the metal disk until the metal is saturated. The diffusion rate can be calculated as [7]:

$$\frac{dW_d}{dt} = \int_0^y C_d[erfc(y/2\sqrt{D_d t})]dy - C_0 y \tag{8}$$

where C_0 is the initial carbon concentration in the polishing disk, C_d is the interface carbon concentration coefficient, *erfc* is the error function, D_d is the diffusion coefficient, t is the time and y is the thickness of the polishing disk.

Modeling

The aforementioned understanding 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. Therefore, the thickness of the removed PCDC layer, d, can be describes as

$$d = f(L, V, t, \mu, C, C_d, C_0, \varepsilon, \delta, D, D_d, E_1, E_2, \nu_1, \nu_2, h, K_1, K_2, \eta, \sigma, \rho_1, \rho_2, T_0, T_\infty) \tag{9}$$

Because of the complexity of Eq. (9), a simple mathematical formulation cannot reflect the physical process of DFP, and hence, such a simple formula will not be practically useful. To overcome this problem, we will use a dimensional analysis [8, 9].

Based on an energy approach, the heat obtained to stimulate the chemical reactions in polishing is due to the sliding friction between the contacts. The heat absorbed into the PCDC can be [1]

$$q = \frac{\mu L V}{A'} \tag{10}$$

Since the surface of the PCDC prior to the polishing is at a roughness ε_1, there are only a number of asperities in contact. Since the disk metal is much smoother than PCDC, we can assume that the effect of the disk surface roughness on the real contact area can be ignored, i.e.,

$$A' = A'(\varepsilon, D) \tag{11}$$

in which $\varepsilon = \varepsilon_1$

The metal disk is made of stainless steel which contains Fe, Ni and Cr for synergistically catalyzing the chemical reactions [2, 10]. For a given polishing machine using the stainless steel disk, it is assumed that the thermal properties of the disk is constant. The thermal properties of the

PCDC can be described by its thermal diffusivity, χ, i.e.

$$\chi = \frac{K_1}{\rho_1 C_p} \tag{12}$$

The Young moduli of the materials can be defined as an equivalent Young modulus, E [1, 11]:

$$\frac{1}{E} = \frac{1-\nu_1^2}{E_1} + \frac{1-\nu_2^2}{E_2} \tag{13}$$

in which ν is Poisson's ratio.

The effect of the diamond size and its composition can be considered in term of $C\delta$.

The concentration of carbon in the metal disk increases and becomes saturated with the processing time. The material removal due to the diffusion W_d becomes very small after certain polishing time. The parameters C_0, C_d and D_d in Eq. (9) can therefore be ignored.

Eq. (9) now can be rearranged as

$$d = f(\mu L, t, V, C\delta, \chi, E, \varepsilon_1, D, T_0) \tag{14}$$

Following the Buckingham Π theorem in which *E, D* and *t* are used as repeating parameters, the relationship in Eq. (9) can be derived in a dimensionless form as

$$\frac{d}{D} = f\left(\frac{\mu L}{ED^2}, \frac{VD}{2\chi}, \frac{Vt}{D}, \frac{C\delta}{D}, \frac{\varepsilon}{D}, T_0\right) \tag{15}$$

where $\Pi_1 = d/D$, which is a dependent parameter, represents the relative removal height over the size of sample; $\Pi_2 = \mu L/ED^2$ indicates the effect of heat source and mechanical loading to the mechanical strength of material; $\Pi_3 = VD/2\chi = Pe$ is Peclet number reflecting the scale of sliding velocity in moving heat source on the sample; $\Pi_4 = Vt/D$ is the ratio of total sliding distance to the size of the sample; $\Pi_5 = C\delta/D$ represents the effect of particle size and its composition; $\Pi_6 = \varepsilon/D$ is the relative surface roughness of the sample, and $\Pi_7 = T_0$ is the initial temperature.

Model verification and practical implication

Model verification. The experimental setup followed what has been described in [1-3]. The tests were conducted by pressing a PCDC specimen on to a rotating catalytic metal disk in dry atmosphere. The effect of five levels of polishing load 285, 343, 392, 480, 637 and 941 N, and a wide range of sliding speeds, from 8 to 25 m/s, were investigated. Two types of thermally stable PCDC specimens were used. The Type 1 specimen material contains 65% diamond particles (C = 0.65) with grain size δ ~ 6μm (the rest are SiC and Si), and has an initial surface roughness of ε = 0.7μm. The Type 2 PCDC is of *C* = 75%, δ ~25μm and ε = 1.6μm. The size of both types of PCDC is 12.7 mm in diameter and 4 mm in thick. Figure 1 shows the results of the sliding speed and polishing load on the removal rate for both types of PCDCs.

The power law is applied to evaluate Eq. (15) where the coefficient and exponents are obtained using the multi-variable regression of the experimental data [12] with 89.5% confidence level:

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

where units of the variables are in SI units (kg, m, sec, ^{0}K).

Practical implication. The model predictions are in very good agreement with the experimental measurements (Fig. 2) when the relative removal depth (*d/D*) varies in a wide range from 6.3×10^{-4} to 50.4×10^{-4}. The partial differentiations of Eq. (16) with respect to *L*, *V* and *t* give $\partial d/\partial L > 0$, and $\partial d/\partial V > 0$. This finding is consistent with the experimental data (Fig.1) that an increased value of the removal thickness, *d*, can be obtained by increasing the load, *L*, sliding velocity, *V*, and the processing time, *t*. On the other hand, we can see that $\partial Cd/\partial\delta < 0$, showing that it is more difficult to polish PCDCs with larger diamond particles and higher diamond percentage. Eq. (16) can be used as a practical guide for machine design and process planning.

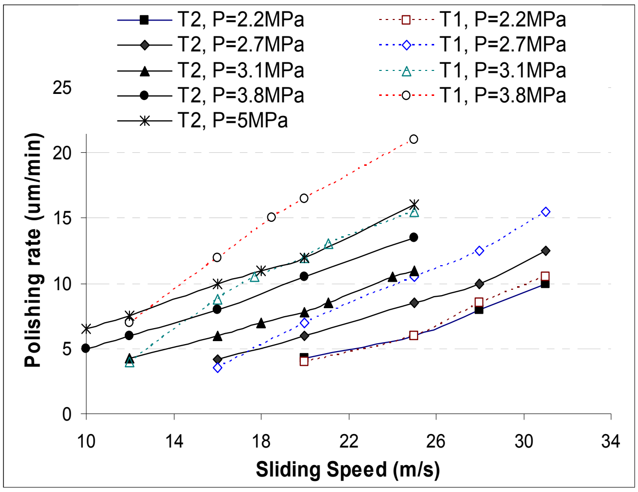

Fig.1 Variation of polishing rate with sliding speed at different pressure for both Types of PCDCs

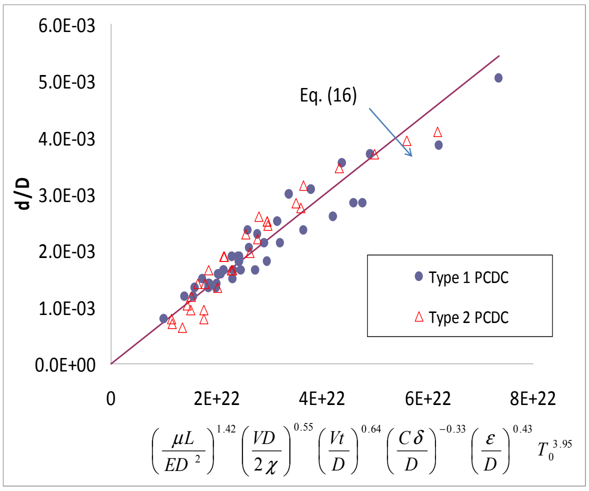

Fig.2 Comparison of model prediction (solid line) and experimental measurements (dots)

Conclusion

Based on the material removal mechanisms in dynamic friction polishing of polycrystalline diamond composites, a parametric model has been developed for estimating the removal thickness. The model prediction is in agreement with the experimental data and can be used as a practical guide for process planning and equipment design.

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