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Polishing of polycrystalline diamond by the technique of dynamic friction—Part 5: Quantitative analysis of material removal

Y. Chen, T. Nguyen, L.C. Zhang *

School of Aerospace, Mechanical and Mechatronic Engineering, The University of Sydney, NSW 2006, Australia

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ABSTRACT

This investigation aims to develop a quantitative model to estimate the material removal of polycrystalline diamond composites (PCDCs) by dynamic friction polishing. The model accounts for the contributions from the constitutive characteristics and thermal properties of the materials and the key polishing parameters. It was found that the material removal was dominated by six dimensionless variable groups involving chemical reaction, diffusion and mechanical wear. A comparison with the experimental measurement showed that the model predicts quantitatively and can be used conveniently for process planning and equipment design.

1. Introduction

Polycrystalline diamond composites (PCDCs) are attractive materials for making cutting tools owing to their ultra high hardness, excellent wear resistance and high chemical inertness to most corrosive environment [1,2]. Meanwhile, also due to these properties, the polishing of PCDCs to a desired surface finish and cutting edge sharpness is difficult. Conventional technology using diamond abrasives needs about 3 to 4 hours to complete a polishing of a PCDC sample of 12.7 mm in diameter. Recently, the authors have developed a dynamic friction polishing (DFP) technique [3–9], which incorporates the thermo-chemo-mechanical material removal mechanism to reduce the polishing time to less than 18 minutes.

Although the mechanisms of the material removal in DFP have been investigated in detail from Parts 1 to 4 of this series study [3–5,9], a quantitative material removal prediction for production use is still unavailable. This is mainly because the dynamic friction polishing of PCDCs involves many processing and material property parameters and as such a conventional modelling technique is hard to apply. The authors noticed that dimensional analysis can often give very satisfactory formulae for quantitative prediction, particularly when it is used in conjunction with some analytical models [10–14].

The purpose of this paper is to develop a parametric model to provide a quantitative guide for the process planning and equipment design for polishing PCDCs using the dynamic friction technique.

2. Critical factors

From their previous studies [3–5,9], the authors have identified that the mechanisms of material removal in dynamic friction polishing of PCDCs can be described by the mechanism map shown by Fig. 1. A PCDC consists of diamond particles and SiC. During polishing, the diamond and SiC at the frictional interface will transform to non-diamond carbon and SiC/SiO_2 due to their interaction with the catalytic metal disk at an elevated temperature. Since their weak bond, the transformed amorphous materials will be mechanically removed easily by the abrasion of the disk in sliding contact with the PCDC. At the same time, diamond and non-diamond carbon exposing to the air at the elevated temperature will be oxidised to form CO and/or CO_2 gases. Depending on the carbon concentration on the metal disk, diffusion of carbon into the metal can also take place.

The above figure of the material removal mechanisms shows that the total material removal (W) in the dynamic friction polishing of PCDCs is attributed to the chemical reaction (W_c), diffusion of carbon into the metal disk (W_d) and mechanical removal (W_m), which can be described as

$$W = W_c + W_d + W_m = \rho_1 A d = \rho_1 \frac{\pi D^2}{4} d \tag{1}$$

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* Corresponding author. Tel.: +612 935 12835; fax: +61 293 517 060.
E-mail address: L.Zhang@usyd.edu.au (L.C. Zhang).

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Nomenclature

A	nominal area of PCDC specimen, m^2
A'	actual contact area between PCDC and disk, m^2
A''	exposed area for heat transfer through conduction and radiation, m^2
A_e	pre-exponential factor
C	composition of diamond in PCDC, %
C_d	interface carbon concentration, kg m^{-3}
C_p	specific heat, J kg^{-1} K
C_m	wear coefficient, kg m^{-3}
D	characteristic length of sample, m
D_d	diffusion coefficient, m^2 s^{-1}
d	material removal thickness, m
E	equivalent Young's modulus, Pa
E_1	Young's modulus of the PCDC, Pa
E_2	Young's modulus of the disk material, Pa
E_a	activation energy, J
H	hardness, N m^{-2}
h	convective heat transfer coefficient, W m^{-2} K
K_1	thermal conductivity of the PCDC, W m^{-1} K
K_2	thermal conductivity of the disk material, W m^{-1} K
$k_0, k_1, \ldots, k_6$	correlation coefficient and exponential factor
L	normal load on PCDC specimen, N
q	total heat flux generated by sliding contact, W m^{-2}
q_{conv}	heat flux due to convection, W m^{-2}
q_{rad}	heat flux due to radiation, W m^{-2}
H	hardness, N m^{-2}
R	gas constant, J mol^{-1} K^{-1}
T	temperature, K
T_0	initial disk temperature, K
T_∞	ambient temperature, K
t	process time, s
V	sliding velocity, m s^{-1}
W_c	material removal by chemical reaction, kg
W_d	material removal by diffusion, kg
W_m	material removal by mechanical action, kg
$\alpha_1, \alpha_2, \alpha_4$	differential coefficient
δ	characteristic diameter of diamond particle, m
ε	surface roughness
ε_1	surface roughness of PCDC sample, m
ε_2	surface roughness of disk, m
ε_f	final surface roughness of PCDC sample, m
μ	coefficient of friction
ν_1	Poisson's ratio of PCDC
ν_2	Poisson's ratio of disk
σ	Stefan–Boltzmann constant, W m^{-2} K^4
η	radiative emissivity
ρ_1	density of PCDC, kg m^{-3}
ρ_2	density of the disk material, kg m^{-3}
χ	thermal diffusivity, m^2 s^{-1}
Y	thickness of disk, m

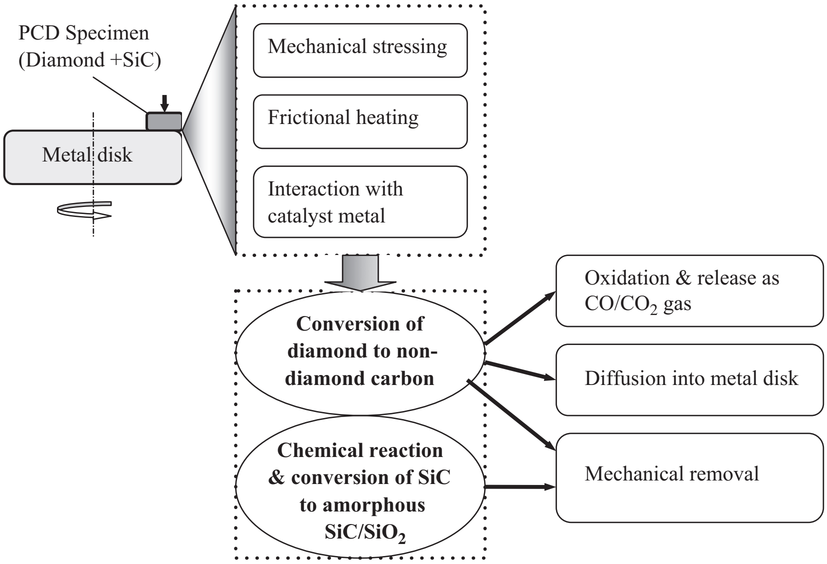

Fig. 1. The mechanism map of material removal in dynamic friction polishing [5].

where ρ_1, A and D are the density, the nominal contact area and the characteristic length of a PCDC sample, respectively; and d is the layer thickness removed from the PCDC. The following sections will discuss the modelling of the contribution from each of the terms in Eq. (1), i.e., W_c, W_d and W_m.

2.1. Chemical reaction

The material removal by chemical reactions includes the transformation of diamond to non-diamond carbon, the transformation of SiC to its amorphous phases and the oxidation of carbon. The material removal rate via these mechanisms, dW_c/dt, is temperature dependant and can be represented by the Arrhenius-type rate equation [15,16]:

$$\frac{dW_c}{dt} = A_e \exp(-E_a/RT)$$

or

$$W_c = \int_0^t A_e \exp(-E_a/RT)dt \tag{2}$$

where R is the gas constant (8.31 J mol^{-1} K), A_e the pre-exponential factor which varies with the order of the reaction, T the absolute temperature, and E_a the activation energy which is the minimum energy required for a chemical reaction to occur. E_a depends on the molecule structure of the reactants which in this study, is a function of crystallite size (δ) and the composition of diamond in the PCDC (C), i.e.,

$$E_a = E_a(\delta, C) \tag{3}$$

For the chemical reactions to take place, heat is needed to elevate the temperature from an initial level, T_0, to the required, T. Based on the energy conservation law, the heat absorbed into the PCDC for the chemical reactions, q_c, can be written as [17]

$$q_c = q_f - (q_{conv} + q_{rad}) = q - A'[h(T - T_\infty) + \eta\sigma(T^4 - T_\infty^4)] \tag{4}$$

where q_f is the heat flux generated by the sliding friction between the contact bodies, q_{conv} and q_{rad} are the heat fluxes due to the convection and radiation, respectively, A'' the exposed area of the sample to the atmospheric ambient, h the convective heat transfer coefficient, η the radiative emissivity ($\eta = 1$ for the black body), σ the Stefan–Boltzmann constant and T_∞ is the ambient temperature. The heat flux q_f is considered as a moving heat source over a semi-infinite solid surface (the disk) [3,18], having the average magnitude:

$$q_f = \frac{\mu L V}{A'} \tag{5}$$

where μ is the friction coefficient, L the normal loading force, and V and A' are the relative velocity and real contact area between the two contact bodies, respectively.

On the other hand, according to the Jaeger's model for a moving heat source [3,18], temperature rise is the result of absorbed heat which is a function of the thermal properties of the contact bodies. Thus the polishing temperature can be expressed as

$$T = T(L, V, \mu, \varepsilon, \delta, E_1, E_2, v_1, v_2, K_1, K_2, \rho_1, \rho_2, T_0) \tag{6}$$

where ρ is the material density, K the thermal conductivity, C_p the specific heat, and E and v are Young's modulus and Poisson's ratio. Subscripts 1 and 2 denote for the two contacting materials, the PCDC and the metal disk, respectively.

2.2. *Mechanical removal*

The mechanical removal can be considered as a wear process, and hence can be approximately estimated by the Holm–Archard law [19], i.e.,

$$W_m = \frac{C_m L V t}{H} \tag{7}$$

where C_m is the wear coefficient, t the process time and H denotes the hardness of the removing PCDC surface. The wear coefficient C_m is a function of properties of the materials in contact sliding, their surface roughness ε and friction coefficient μ [20,21]:

$$C_m = C_m(\delta, C, E_1, E_2, v_1, v_2, \rho_1, \rho_2, \mu, \varepsilon) \tag{8}$$

The hardness H changes during the process and is a function of the PCDC constitution and temperature [22], i.e.

$$H = H(\delta, C, E_1, v_1, \rho_1, T) \tag{9}$$

2.3. *Diffusion*

When diamond or non-diamond carbon contacts 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 carbon concentration of a metal in contact with a carbon source is given by [23,24]

$$C(y) = C_d[erfc(y/2\sqrt{D_d t})] \tag{10}$$

where $C(y)$ is the concentration at a subsurface distance y from the interface, C_d the interface carbon concentration coefficient, *erfc* the error function, D_d the diffusion coefficient, and t the time.

The diffusion rate can be calculated by [24]

$$W_d = \int_0^Y C_d[erfc(y/2\sqrt{D_d t})]\,dy - C_0 Y \tag{11}$$

where C_0 is the initial carbon concentration in the polishing disk and Y the thickness of the disk.

3. Dimensional analysis

The aforementioned understanding shows that the material removal of a PCDC in DFP is a function of the constitutive and thermal properties of materials, and varies with the polishing parameters that generate the frictional heat for chemical reactions. Hence, the material removal in term of average layer thickness removed, d, can be expressed as

$$d = f(L, V, t, \mu, C, C_d, C_0, \varepsilon, \delta, D, D_d, E_1, E_2, v_1, v_2, \\ h, K_1, K_2, \eta, \sigma, \rho_1, \rho_2, Y, T_0, T_\infty) \tag{12}$$

Because of the complex relation of the multi-variables involved in Eq. (12), mathematical formulae conducted by simply correlating the experimental data are unrealistic and cannot reflect well the physics embedded. To overcome this problem, a dimensional analysis will be carried out.

Based on an energy approach, the heat obtained to activate the chemical reactions in polishing is due to the sliding friction. From Eq. (4), it is noted that since the exposed area for the conductive and radiative heat transfer, A'', is too small compared to the nominal area A, the heat absorbed into the PCDC can be approximated as [3]

$$q_c \approx q = \frac{\mu L V}{A'} \tag{13}$$

If the surface of the PCDC prior to polishing has a roughness ε_1, there are only a number of asperities in contact. Since the disk metal is much softer than PCDC, the disk will be eroded faster than the PCDC, resulting in a smooth surface. It is therefore reasonable to assume that the effect of the disk surface roughness on the real contact area can be ignored, i.e.,

$$A' = A'(\varepsilon, D) \tag{14}$$

in which $\varepsilon = \varepsilon_1$.

The metal disk is made of stainless steel containing Fe, Ni and Cr for catalyzing the chemical reactions [4,25]. For a given polishing machine using the stainless steel disk, the thermal properties of the disk are constant. The thermal properties of the PCDC can be described by its thermal diffusivity, χ, i.e.

$$\chi = \frac{K_1}{\rho_1 C_p} \tag{15}$$

Young's moduli of the materials can be grouped into an equivalent Young's modulus, E, defined as [3,26]

$$\frac{1}{E} = \frac{1 - v_1^2}{E_1} + \frac{1 - v_2^2}{E_2} \tag{16}$$

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. Therefore, the material removal due to the diffusion W_d practically become very small after a certain time of polishing [27]. The parameters Y, C_0 and C_d in Eq. (12) therefore can be ignored.

Eq. (12) now can be rearranged as

$$d = f(\mu L, t, V, C\delta, \chi, E, \varepsilon_1, D, T_0) \tag{17}$$

Following the Buckingham Π theorem, the relationship in Eq. (17) can be represented in a dimensionless form as

$$f(\Pi_1, \Pi_2, \Pi_3, \Pi_4, \Pi_5, \Pi_6, \Pi_7) = 0 \tag{18}$$

Using the repeating parameters of E, D and t, the corresponding dimensionless parameters in Eq. (18) can be derived as

$$f\left(\frac{d}{D}, \frac{\mu L}{ED^2}, \frac{Vt}{D}, \frac{\chi t}{D^2}, \frac{C\delta}{D}, \frac{\varepsilon}{D}, T_0\right) = 0 \tag{19}$$

The dimensionless groups in Eq. (19) are rearranged as

$\Pi_1 = d/D$ is the dependent parameter, representing the relative removal height over the size of a sample,
$\Pi_2 = \mu L/ED^2$ indicates the effect of heat source and mechanical loading to the mechanical strength of material,
$\Pi_3' = \Pi_3/2\Pi_4 = VD/2\chi = Pe$ is the Peclet number representing the scale of sliding velocity of the moving heat source on the sample,
$\Pi_4' = \Pi_3 = Vt/D$ 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 disk temperature.

Eq. (18) can now be written as

$$\frac{d}{D} = f\left(\frac{\mu L}{ED^2}, \frac{VD}{2\chi}, \frac{Vt}{D}, \frac{C\delta}{D}, \frac{\varepsilon}{D}, T_0\right) \tag{20}$$

4. Model establishment

4.1. Experimental results

The experimental setup has been detailed elsewhere [4,5,9]. The polishing was conducted by pressing a PCDC specimen at a specific load on to a rotating catalytic metal disk in dry atmosphere. The effect of five levels of polishing load 285, 343, 392, 480 and 637 N conducting at a wide range of sliding speeds, from 8 to 31 m/s, were investigated. Experiments were carried out on two types of thermally stable PCDC specimens containing different percentages of diamond (the rest are SiC and Si), as detailed in Table 1. The variation of the material removal is shown in Figs. 2 and 3 [6,9], where the pressure levels correspond to the load levels listed above.

4.2. Modelling

From the above experiments, the following conditions are considered for the model:

$$d > 10\varepsilon \text{ and } \varepsilon_f < 0.2 \tag{21}$$

Table 1
Specifications of the PCDCs used in the experiment.

	Type 1	Type 2
Diamond percentage (%)	65	75
Grain size of the polycrystalline diamond (μm)	6	25
Surface roughness *Ra* (μm)	0.7	1.6
Size: diameter (mm) × thickness (mm)	12.7 × 4	12.7 × 4
Thermal conductivity ($\mathrm{W\,m^{-1}\,K}$)	300	300

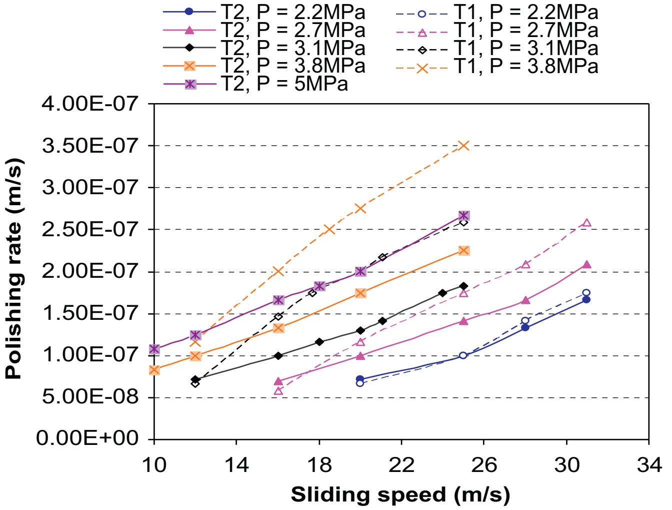

Fig. 2. Variation of polishing rate with sliding speed at different pressure for PCDCs (the polishing time was 3 min).

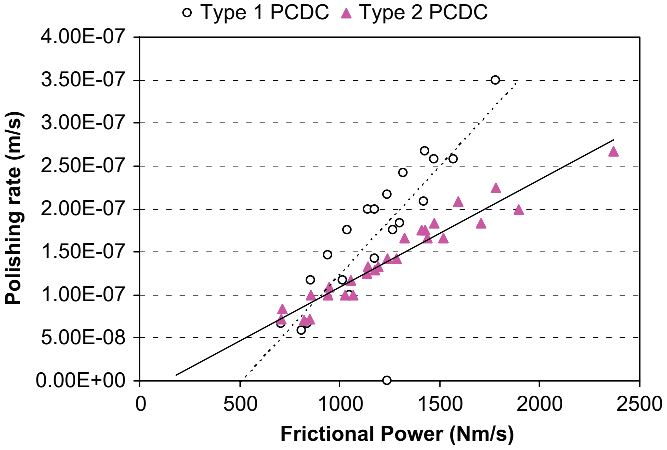

Fig. 3. Effect of frictional power on material removal rate (initial temperature $T_0 = 25\,^\circ\mathrm{C}$).

where ε_f is the surface finish of PCDC sample after polishing

$$3.36 \times 10^6 > \frac{\mu L}{ED^2} > 1.51 \times 10^6 \tag{22}$$

$$4.83 \times 10^4 > \frac{VD}{2\chi} > 1.56 \times 10^4 \tag{23}$$

The conditions in Eq. (21) are associated with the requirement that the surface finish after polishing has to below a certain range. For this requirement, the removed thickness has to be greater than the initial surface roughness. The upper limit in Eq. (22) is made in consideration of the strength of PCDC under static loading without failure. The upper limit in Eq. (23) is to avoid the fracture in the PCDC sample. The lower limits in Eqs. (22) and (23) are associated with the load and sliding velocity of 284 N and 10 m/s, respectively, based on the fact that below these values in the given tested conditions in Table 1 and Section 4, the interface temperature rise will be insufficient for activating the chemical reactions [9].

The power law is applied to evaluate Eq. (22) which gives

$$\frac{d}{D} = k_0 X \tag{24}$$

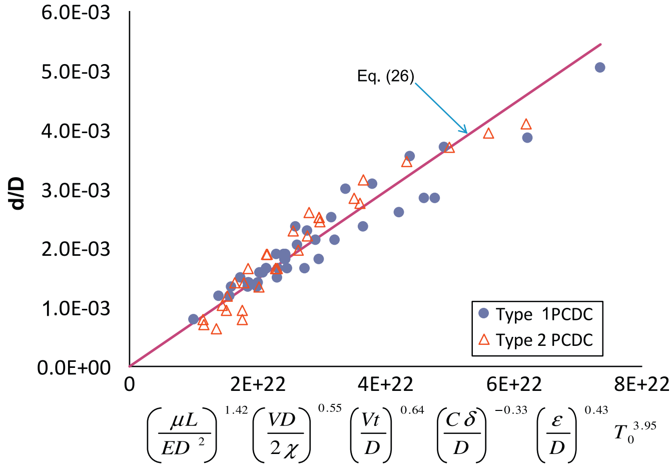

Fig. 4. Comparison of model prediction (solid line) and experimental measurements (dots).

where

$$X = \left(\frac{\mu L}{ED^2}\right)^{k_1}\left(\frac{VD}{2\chi}\right)^{k_2}\left(\frac{Vt}{D}\right)^{k_3}\left(\frac{C\delta}{D}\right)^{k_4}\left(\frac{\varepsilon}{D}\right)^{k_5}T_0^{k_6} \tag{25}$$

In Eqs. (24) and (25), coefficient k_i $(i = 0, \ldots, 6)$ can be obtained using the multi-variable regression of the experimental data [28]. At 89.5% confidence level, Eq. (24) becomes

$$\frac{d}{D} = 7.39 \times 10^{-26}\left(\frac{\mu L}{ED^2}\right)^{1.42}\left(\frac{VD}{2\chi}\right)^{0.55}\left(\frac{Vt}{D}\right)^{0.64} \times \left(\frac{C\delta}{D}\right)^{-0.33}\left(\frac{\varepsilon}{D}\right)^{0.43}T_0^{3.95} \tag{26}$$

where units of the parameters are in SI (kg, m, s and K) as given in the nomenclature of this paper.

Fig. 4 shows the model predictions with the experimental data. It can be seen that the model predictions very well the experimental measurements when the relative removal thickness (d/D) varies in a wide range 6.3×10^{-4}–50.4×10^{-4}. The partial differentiations of Eq. (26) with respect to L, V, t and δ give

$$\frac{\partial d}{\partial L} = \alpha_1 L^{0.42} \tag{27}$$

where

$$\alpha_1 = 1.05 \times 10^{-25} D\left(\frac{\mu}{ED^2}\right)^{1.42}\left(\frac{VD}{2\chi}\right)^{0.55}\left(\frac{Vt}{D}\right)^{0.64} \times \left(\frac{C\delta}{D}\right)^{-0.33}\left(\frac{\varepsilon}{D}\right)^{0.43}T_0^{3.95} > 0$$

$$\frac{\partial d}{\partial V} = \alpha_2 V^{0.19} \tag{28}$$

where

$$\alpha_2 = 8.79 \times 10^{-26} D\left(\frac{\mu L}{ED^2}\right)^{1.42}\left(\frac{D}{2\chi}\right)^{0.55}\left(\frac{t}{D}\right)^{0.64} \times \left(\frac{C\delta}{D}\right)^{-0.33}\left(\frac{\varepsilon}{D}\right)^{0.43}T_0^{3.95} > 0$$

$$\frac{\partial d}{\partial t} = \alpha_3 t^{-0.36} \tag{29}$$

where

$$\alpha_3 = 4.73 \times 10^{-26} D\left(\frac{\mu L}{ED^2}\right)^{1.42}\left(\frac{VD}{2\chi}\right)^{0.55}\left(\frac{V}{D}\right)^{0.64} \times \left(\frac{C\delta}{D}\right)^{-0.33}\left(\frac{\varepsilon}{D}\right)^{0.43}T_0^{3.95} > 0$$

and

$$\frac{\partial Cd}{\partial \delta} = \alpha_4 \delta^{-1.33} \tag{30}$$

where

$$\alpha_4 = -2.43 \times 10^{-26} D\left(\frac{\mu L}{ED^2}\right)^{1.42}\left(\frac{VD}{2\chi}\right)^{0.55}\left(\frac{Vt}{D}\right)^{0.64} \times \left(\frac{1}{D}\right)^{-0.33}\left(\frac{\varepsilon}{D}\right)^{0.43}T_0^{3.95} < 0$$

Since α_1, α_2 and α_3 are greater than zero, $\partial d/\partial L > 0$, $\partial d/\partial V > 0$ and $\partial d/\partial t > 0$. This means that the increase of the removal thickness d can be achieved by increasing the load L, sliding velocity V, or the processing time t. On the other hand, $\alpha_4 < 0$ and $\partial Cd/\partial \delta < 0$ indicate that if a PCDC contains larger diamond particles and a higher percentage of diamond, the material removal will be more difficult. All these are consistent with the experimental observations in Ref. [9].

The above model formula shows that for a given PCDC material of a specific characteristic sample dimension, D, to achieve a higher material removal rate, a greater L and V are generally required; but this is often limited by some technological constraints such as allowable power consumption and available machine capacity. The model established above indicates that this difficulty can be overcome by using a smaller L and V but a longer processing time. Eq. (26) and the limit constraints set in Eqs. (21), (22) and (23) can be used as a practical guide for the machine design and process planning in achieving the balance between production rate and performance.

5. Conclusion

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

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