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A model to simulate surface roughness in the pad dressing process

T. L. Horng

Associate professor, Department of Mechanical Engineering, Kun-Shan University, Tainan, Taiwan

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Abstract

Pad dressing, which is one of the most important planarization processes, is widely used in CMP. The estimation of surface roughness under various machining parameters (such as dressing force, diamond density of the dresser, rotational speed of the dresser, different machining paths, etc.) is essential to the pad dressing process. In this study, elastic-plastic theory and the wear model are used to construct the expression for the magnitude of material removal as a function of the indentation depth. The deformation of the pad is obtained by using elastic-plastic theory, and the material removal caused by individual micro-contacts is calculated with the help of wear theory. Finally, the macroscopic wear volume is found by summing the volumetric wear of each individual micro-contact. A parametric study is conducted to explore the influence on the surface roughness results and the pad dressing interfacial phenomena of operational parameters. The results reveal that a rapid initial improvement followed by a leveling off, manifesting a saturation effect. Moreover, the model shows that a higher dressing force with a dresser speed close to the pad speed and a moderate translation speed increase the material removal rate corresponding with a lower surface roughness dressing.

Keywords: Pad dressing process; Planarization processing; Material removal; Surface roughness; Elastic-plastic model

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1. Introduction

Pad dressing, which is one of the most important planarization processes, is widely used in CMP. In the pad dressing process, the magnitude of surface roughness plays a pivotal role in the time-taken, the abrasive efficiency, and the wear of abrasive particles [1]. Xie [2] presented the mechanisms of material removal in the free abrasive polishing process and recommended that when polishing a pad, in order to achieve a high material removal rate and a smooth surface, it is preferable to use diamond as the polishing material because of its high deformation resistance. Except for the model presented by Horng [3-4], previous models derived from abrasive wear theory ignored the role played by surface deformation in the contact area, and micro-contact elastic-plastic phenomena seem to be essential in the pad dressing process [5]. Therefore, the current study employs the micro-contact elastic-plastic model to simulate surface roughness in the pad dressing process. Moreover, simulation of the process was conducted under various machining parameters, such as abrasive force, rotational speed of the dresser, and various machining paths. The abrasive depth was obtained by summing the abrasive quantities of every abrasive particle attached to the dresser and the surface roughness was obtained using the statistical method. In this study, there is no material removal when the indentation was made in the elastic region. If the indentation depth of an abrasive particle on the pad interface is calculated and the magnitude of indentation is greater than the transition depth, the

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*Corresponding author. Tel.: +886 6 205 3522, Fax.: +886 6 205 0509
E-mail address: hortl@mail.ksu.edu.tw

elastoplastic state has been reached. Then, the volumetric wear can be evaluated by using the indentation depth difference.

The results reveal that the material removal rate increases with increasing dressing force magnitude, decreasing abruptly with small dressing force, and increasing abruptly with large dressing force. This occurs because for a large dressing force, a higher percentage of the plastic state is approached. Similarly, a small dressing force results in a higher percentage of the elastic state. Moreover, roughness is similar for different translation speeds of the holder and for all angular speeds of the dresser, except for the rpm around near the angular the speed of pad (20 rpm). In conclusion, a higher dressing force with a dresser speed near the pad speed and a moderate translation speed are the best machining parameters for the pad dressing process. In other words, the goal of increasing material removal corresponding with a lower roughness dressing is valid by using these parameters in the pad dressing.

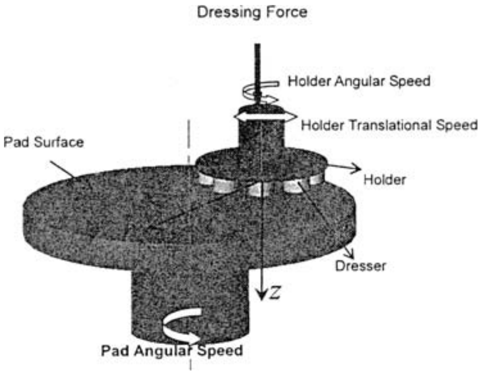

Fig. 1. Schematic diagram of the pad dressing process.

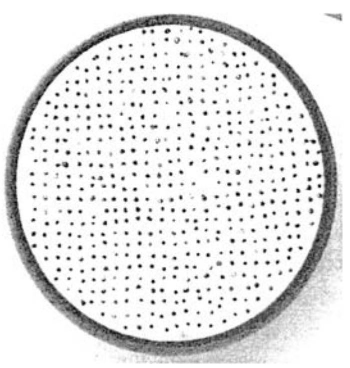

Fig. 2. View of the abrasive grains embedded on the dresser.

2. Modeling the pad dressing process

2.1 *Theoretical contact model between the abrasive grains and a pad*

The pad dressing processes shown in Fig. 1 were simulated by the abrasive effect between diamond particles bound to the dresser (see Fig. 2), which is symmetrical to the center of the holder, with dressing forces applied to the dresser equally. A micro-contact can be represented by a rigid protuberance in contact with a deforming surface. The shape of abrasive grains is represented by hemispheres as shown in Fig. 3. In this section, an elastic–elastoplastic–plastic contact model is derived for the contact between a moving abrasive particle and a deforming surface. The contact model provides a relationship between the contact load subjected to a single grain and the indentation depth on the flat part of the pad.

The indentation depth of a pad from the center of a dresser supporting a uniformly circular load was developed by Horng [3], and the superposition method is introduced to calculate the deformation that has resulted from the dressing force. Thus, indentation depth, as shown in Fig. 4, can be shown as:

$$d_{gp} = \sum_{i=1}^{N_d} u_i(r) \tag{1}$$

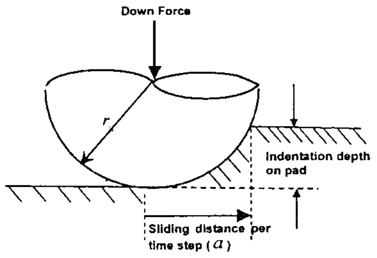

Fig. 3. Degree of penetration between an abrasive grain and pad.

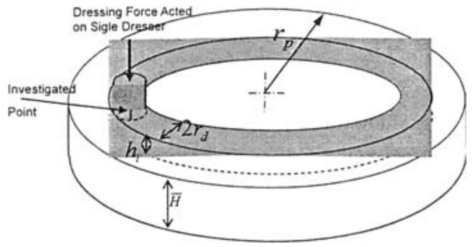

Fig. 4. Configuration of abrasive depth to calculate non-uniformity.

Where $u_i(r)$ is the indentation depth of a pad from the center of a dresser supporting a uniformly circular load, and r is the radial distance from the center of the calculated dresser.

For the contact between a rigid abrasive grain with radius r_g and an elastic smooth pad, the contact area is given by Eq. (2):

$$A_e = \pi r_g d_{gp} \tag{2}$$

and the elastic contact load according to Hertz is given by

$$N_e = \frac{2}{3} d_{gp}^{3/2} E' \sqrt{r_g} \tag{3}$$

where $E' = 2 \times \frac{E}{1-\nu^2}$, ν Poisson's ratio, and E Young's modulus of the pad.

The onset of plastic deformation occurs when $\bar{p} = kH$, where $\bar{p}$ is the average contact pressure, H is the hardness of the pad and k the average contact pressure factor as introduced by Tabor [7]. A good approximation for most metals is k =0.4, and in a plastic contact where the average contact pressure equals the hardness of the deforming material, k is equal to 1.0.

The relationship between the contact area, A_P, and indentation depth, d_{gp}, is based on the truncation of the contacting cap and can be written as:

$$A_P = 2\pi r_g d_{gp} \tag{4}$$

Furthermore, a relationship for the carried load N_P is obtained by multiplying the contact area with the hardness:

$$N_P = 2\pi r_g d_{gp} H \tag{5}$$

As the elastoplastic regime extends from the onset of plastic deformation at $d_{e,trans}$ to the beginning of fully plastic deformation at $d_{p,trans}$, the relative elastoplastic indentation depth δ can be defined as

$$\delta = \frac{d_{gp} - d_{e,trans}}{d_{p,trans} - d_{e,trans}} \tag{6}$$

With this, the elastoplastic contact area can now be expressed as [6]:

$$A_{ep} = A_e + (A_p - A_e)(-2\delta^3 + 3\delta^2) \tag{7}$$

The average elastic contact pressure can be obtained as

$$\bar{p} = N_e / A_e = \frac{2}{3\pi} \times E' \times \sqrt{d_{gp} / r_g} \tag{8}$$

Substituting the contact pressure at the onset of plastic deformation, gives the transaction indentation depth, $d_{e,trans}$, yield:

$$d_{e,trans} = \frac{9\pi^2}{4} \times \frac{k^2 \cdot H^2}{E'^2} \times r_g \tag{9}$$

According to Johnson [8], the transition to fully plastic deformation occurs when the contact load equals 400 times the load at initial yield. In terms of the indentation depth d, this gives:

$$d_{p,trans} \approx 80 \cdot d_{e,trans} \tag{10}$$

2.2 Wear Model

Based on the experimental work of Jiang and Arnell [9], the degree of wear, ξ, between an abrasive grain and the pad is given in Eq. (11):

$$\xi = c \times \tanh(12.3 \times \frac{d_{gp}}{a} - 3.0) + c \tag{11}$$

where a is the sliding length carried by one time step, and c is a fraction of displaced material which becomes loose debris and is a constant related to the material property. In this study, the fraction of displaced material c is set to 0.4.

The contact model between abrasive grains and a pad comprises of three deformation regimes: elastic, elastoplastic, and fully plastic. If the indentation depth d_{gp} of an abrasive particle on the pad interface is calculated using Eq. (1), as shown in Fig. 3, and the magnitude of d_{gp} is greater than the transition depth $d_{e,trans}$, the elastoplastic state has been reached. Simultaneously, the sliding contact between a rigid abrasive and the pad results in a wear area A_{ep} on the pad. Then, the volumetric wear can be evaluated by using the indentation depth difference d_{gp}.

There is no material removal when the indentation is made in the elastic region. As soon as elastic-plastic state is reached, the volumetric wear $M_{g_i p/ep}$ for a single particle can be expressed according to Eq. (12):

$$M_{g_i p}(t) = \xi \times A_{ep} \times a \tag{12}$$

where a is sliding length carried by one time step. Subsequently, the contact area, A_p, occurs as soon as the pad indentation is equal to depth $d_{p,trans}$, meaning that the fully plastic deformation state of asperities has been reached. Finally, the total volumetric wear, say $M(t)$, is conducted by the summation of the contact partners between abrasive particles and the flat part of the pad, which can be expressed according to Eq. (13):

$$M(t) = \sum_{i=1}^{N_g} M_{g_i p}(t) \tag{13}$$

where N_g is number of abrasive grains.

2.3 Surface Roughness Estimation

By using the material removal model mentioned above and assuming that the volume of material removal conducted by the single dresser is uniform, the abrasive depth h_i at the investigated point i on the pad surface shown in Fig. 4, can be expressed as:

$$h_i(t) = \frac{M(t)}{\pi r_d^2} \tag{14}$$

Then, the mean abrasive depth of the surface of pad denoted by $\bar{h}$, can be written as:

$$\bar{h}(t) = \sum_{i=1}^{N_c} h_i(t) \Big/ N_c \tag{15}$$

where Nc is the number of investigated points on the pad. Finally, the averaged method is introduced to describe the roughness. Index Ra, which is a function of time t, can be defined as:

$$Ra(t) = \frac{h_{\max}(t) - h_{\min}(t)}{\bar{h}(t)} \tag{16}$$

where $h_{\max}(t)$ and $h_{\min}(t)$ are the maximum and the minimum abrasive depths on the pad, respectively.

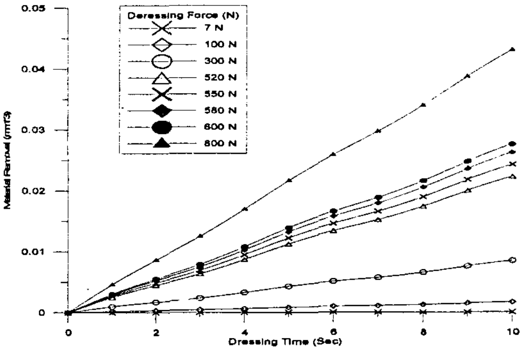

Fig. 5. Material removal histories with a constant angular-speed of the holder, as a magnitude for various dressing forces.

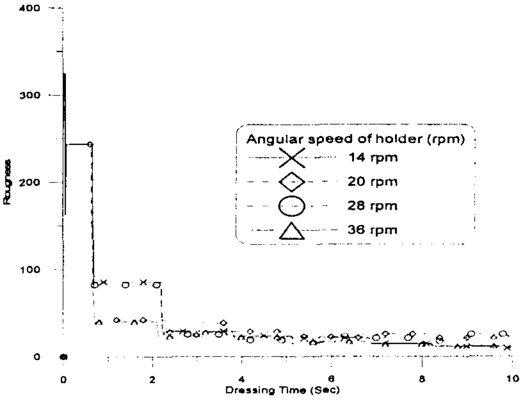

Fig. 6. Roughness (Ra) histories for the pad dressing process with different angular speeds of the holder ω_d .

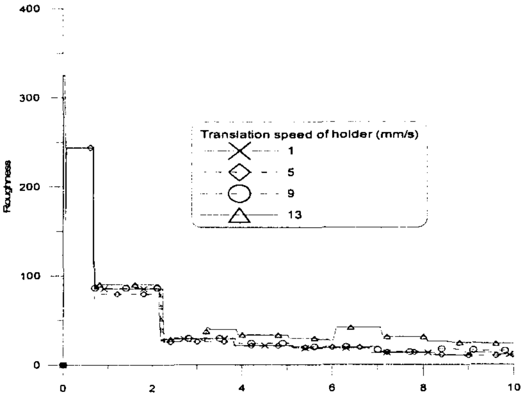

Fig. 7. Roughness (Ra) histories for the pad dressing process with different translation speeds of the holder V_d .

Table1. Operational parameters adopted in the analysis of the pad dressing process.

Abrasive grain parameters	
Density of abrasive grains	200 (No./cm**2)
Radius of abrasive grains	0.01 mm
Elastic Modulus of abrasive grains	Infinite
Radius of holder, Radius of dresser	50 mm, 10 mm
Number of dressers	8

Pad and abrasive grain parameters	
Height of pad, Radius of pad	4 mm, 400 mm
Elastic modulus of pad	139.47 Mpa
Poisson ratio of pad	0.3
Hardness of pad	50 Mpa

Other parameters	
Down force on pad	7,100,300,520,550,580,600,800 (N)
Angular velocity of holder	14,20,28,36 (rpm)
Translation velocity of pad	1,5,9,13 mm/sec
Angular velocity of pad	20 rpm
Eccentric length	200 mm
Processing time step, Processing time	0.01 sec, 10 sec

4. Results and discussion

Pad dressing [3 and 10], which is one of the most important planarization processes is widely used in CMP. The pad dressing processes shown in Fig.1 were simulated by the abrasive effect between a pad and diamond particles bound to the dresser. In this study, the modified rotary dressing path [11 and 12] was used for the tool path of the dresser in the pad dressing process shown in Fig. 6. If the contact surface between the dresser and polishing pad is assumed as a flat plane, then the dressing model can be simplified as a pad subjected to a multi-uniformly circular load. In the dressing process, the holder and polishing pad revolve on their own axis with angular speeds ω_d and ω_p, respectively. Simultaneously, the holder translates to and from the pad surface with a constant speed V_d.

The material removal analysis in the pad dressing process, using grinding technology with the help of a micro-contact elastic-plastic model, was conducted on a pad. Fig. 1 shows this model and its dimensions. Table 1 presents the relevant operational parameters. A number of simulations were carried out to investigate the relationship between the material removal and roughness with respect to machining parameters such as the dressing forces, the rotational speed of the dresser, and the translation speed of the holder. Fig. 5 shows the variation in the material removal rate on the pad surface with a constant angular-speed of the holder, as a magnitude for various dressing forces. The simulation results indicate that for a constant holder angular speed, the material removal rate increases with increasing dressing force magnitude, decreasing abruptly with a small dressing force, and increasing abruptly with a large dressing force. Fig. 6 and Fig. 7 show the histories of roughness with different angular speeds of the holder, and different translation speeds of the holder, respectively. These figures indicate an initial rapid improvement is followed by a leveling off, manifesting a saturation effect. Fig. 6 shows that roughness is also similar for different translation speeds of the holder and Fig. 7 shows that roughness is similar for all different angular speeds of the dresser, except when the rpm are near the angular the speed of the pad (20 rpm).

A higher dressing force with a dresser speed near the pad speeds and a moderate translation speed are the best machining parameters for the pad dressing process. In other words, the goal of increasing material removal corresponding with a lower roughness dressing is valid by using these parameters in the pad dressing.

5. Conclusions

This study presented a surface roughness model which is based on contact mechanics and which considers elastic-plastic effects during the wear mechanism. In contrast to previous models, the current model considers the machining parameters relating to the dressing force, translation speed of the holder, and the holder angular speed. The model was successfully applied and used on the pad dressing process to analyze surface roughness. The results provide a detailed description of the interface phenomena and yield an insight into the physical effects of the operating parameters in the pad dressing process. In conclusion, the model shows that a higher dressing force with a dresser speed close to the pad speed and a moderate translation speed increase the material removal rate corresponding with a lower surface roughness dressing.

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