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Mechanism Analysis and Process Optimization of Micro-Hole Lapping of Hard and Brittle Materials

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Abstract: This research investigates a new micro-hole lapping method by use of the stable zirconia for the material remove model, lapping mechanism and the optimal process parameters. It is assumed that the material is removed in brittle fractures and that the impact force and friction force of a reciprocated piano wire are considered as the major mechanism for removing material. An empirical material remove model including parameters of abrasive size, abrasive concentration of slurry, taper angle of wire, wire tension and pH-value of slurry is derived. The design of experiment and the regression analysis are conducted to formulate the empirical correlation between the significant parameters and the material remove rate. The results show that both the empirical and theoretical models have good agreements with the experimental results and that the material remove rate increases with the abrasive size, wire tension and pH-value of slurry while the material remove rate decreases as the concentration of abrasive or taper angle of wire increases. The experiment result shows that the significant parameters affecting the material remove rate are abrasive size, wire tension and that pH-value of slurry and concentration of abrasive and taper angle of wire are insignificant.

Keywords: Micro-hole lapping; hard and brittle material; response surface method.

1. Introduction

Since the rapid developments of microelectronics, optoelectronics and optical fiber communication industries, more and more micro-hole components as small as 125 μm made of hard and brittle material have been required. Since most of hard and brittle materials are non-metal with high hardness and wear-resisting, the machining process of micro-holes with surface quality has been the interest of researchers.

Pei and Prabhakar [1] adopted the Hertz fracture theory as Wang [2] and assumed that the work piece is an ideal brittle material and the abrasive is a rigid sphere in the analysis of material remove rate by a rotary ultrasonic machining. The result showed that the material remove rate increases with the rotary speed of wire, abrasive size and pressure. Wang and Rajurkar [3] analyzed the mechanism of ultrasonic machining by a dynamic model and found that material remove rate increases linearly with the abrasive size theoretically that matches with the experimental result of the lapping process. Lee and Chan [4] proposed the relation between the impact force and the m-

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aterial remove rate and also studied the effects of the vibrating amplitude, processing pressure and abrasive size on material remove rate and surface roughness with experiments. A plastic deformation and uniform spherical abrasives of equal size are assumed and the volume of material removed by a single abrasive is assumed to be equal to the volume overlapped between the moving track of the abrasive and the work piece in each vibration cycle in the analysis of Pei and Ferreira [5]. It is found that the ultrasonic machining has different material remove models for brittle and ductile materials. Zhang [6] showed that the material remove rate increases with the ultrasonic energy for the abrasive press-in mode in ultrasonic machining. Wiercigroch and Neilson [7] showed that the size of micro-cracks increases with the amplitudes of collisions but the material remove rate decreases under the condition of high working pressure. Wang and Yan [8] applied the ultrasonic vibration lapping to improve the precision of the micro electric discharge machine in drilling a micro-hole with 5 μm in diameter and 0.5mm in depth on a $10\times10\times0.5$mm titanium alloy. Recently the technology of precise manufacture of wafer has been investigated and developed rapidly. Kao [9] investigated the material remove rate of wire saw with slurry but without abrasive. Tsai and Yan [10] investigated the chemical effectiveness of slurry in polishing a surface. Liedke and Kuna [11] investigated the mechanism parameters and the lapping pressure exerted to the work piece by a wire in accordance with Preston's law.

From the above literatures, we find that most of micro-hole lapping processes adopted the ultrasonic machining and the diameter of the machined micro-hole lapped with cylindrical wire is over several millimeters. The usually discussed machining parameters were the abrasive size, the energy of the lapping wire and rotary speed. As compared to the above literatures, the present paper uses a reciprocating piano wire with a very high aspect ratio to lap a micro-hole. The objectives are to investigate the material remove models, the lapping mechanism and the optimal process parameters of the micro-hole lapping.

2. Theoretical model

In order to calculate the material remove rate of micro-hole lapping as shown in Figure 1 (b), the following assumptions are adopted to derive the theoretical model:

(1) The abrasive and the wire are rigid bodies and the abrasive is spherical and has uniform diameter.
(2) The abrasive concentration is uniform in each reciprocating lapping process.
(3) The fracture of removed material is considered to be a brittle fracture.
(4) The fracture of the removed material follows the procedure of Hertz crack as Wang [2].

Calculating the Remove Volume of a Single Abrasive:

A contact force is exerted by the reciprocating wire through the diamond abrasive on the work piece. Wang [8] indicated that the Hertz crack model by Wang [2] could relate the contact force to the maximum depth of the crack as shown in Figure 2. The Hertz crack model is applicable to an ideal brittle fracture cut by an abrasive on a work piece. Pei [12] related the depth δ of crack to the contact force P by use of a formula as the diamond abrasive enters into the work piece:

$$\delta = \left(\frac{9}{16}\frac{P}{d_a/2}\left(\frac{1-\nu^2}{E}\right)^2\right)^{\frac{1}{3}} \tag{1}$$

where, P is the contact force (Newton) exerted on a single abrasive; d_a is the average diameter of the abrasive; E is the Young's modulus of the work piece; ν is the Poisson's ratio of the work piece.

Pei [1] assumed that the abrasive slides a displacement (L_a) and showed that the removed volume V by a single abrasive is the same as the volume of an ellipsoid as shown in Figure 3 and given as:

$$V = \pi(1+\frac{L_a}{d_a})(\frac{d_a}{2}-\frac{\delta}{3})\delta^2 \tag{2}$$

Calculating the Maximum Contact Force F_N:

In the lapping process the contact force is a substantial parameter to the remove volume. The maximum contact force happens at the deepest cut on the surface of the work piece and consists of the impact force and friction force as shown in Figure 4. Assuming that the work piece rotates with respect to the wire, the displacement of the wire surface is given as:

$$\vec{f}=(\frac{d}{2}+z\tan\alpha)\cos\omega t\vec{i}+(\frac{d}{2}+z\tan\alpha)\sin\omega t\vec{j}+z\vec{k} \tag{3}$$

where, $\vec{f}$ is displacement vector of the wire; d is the minimum diameter of the tapered wire; D is the maximum diameter of the tapered wire; z is the axial coordinate; $\tan\alpha=(D-d)/2L$, L is the length of the wire; ω is the angular speed of the work piece with respect to the wire.

The stroke of the wire is

$$z = vt \tag{4}$$

where v is the feeding velocity of wire and t is the time interval of acting.

Substitute (4) into (3) and yield

$$\vec{f}=(\frac{d}{2}+vt\tan\alpha)\cos\omega t\vec{i}+(\frac{d}{2}+vt\tan\alpha)\sin\omega t\vec{j}+vt\vec{k} \tag{5}$$

The speed Vs of the wire surface is given as below:

$$\begin{aligned} V_s &= \frac{d}{dt}\vec{f} \\ &= \left[v\tan\alpha\cos\omega t-\omega\left(\frac{d}{2}+vt\tan\alpha\right)\sin\omega t\right]\vec{i}+\left[v\tan\alpha\sin\omega t+\omega\left(\frac{d}{2}+vt\tan\alpha\right)\cos\omega t\right]\vec{j}+v\vec{k} \end{aligned} \tag{6}$$

By law of conservation of momentum, the impact force can be written as:

$$\begin{aligned} \vec{F}_m &= \frac{M}{\Delta T}V_s \\ &= \frac{M}{\Delta T}\left[v\tan\alpha\cos\omega t-\omega(\frac{d}{2}+vt\tan\alpha)\sin\omega t\right]\vec{i} \\ &+\frac{M}{\Delta T}\left[v\tan\alpha\sin\omega t+\omega(\frac{d}{2}+vt\tan\alpha)\cos\omega t\right]\vec{j}+\frac{M}{\Delta T}v\vec{k} \end{aligned} \tag{7}$$

where M is the mass of wire and ΔT is the time interval when the abrasive is in contact with the wire, basically it is considered as a constant.

The impact force of the abrasive on the work piece can be decomposed to the normal and tangential components to be $\vec{F}_n$ and $\vec{F}_t$ respectively:

$$\vec{F}_n = \frac{M}{\Delta T}\left[(v\tan\alpha)^2+(\omega(\frac{d}{2}+vt\tan\alpha))^2+v^2\right]^{0.5}\cos\alpha \tag{8}$$

$$\vec{F}_t = \frac{M}{\Delta T}\left[(v\tan\alpha)^2 + (\omega(\frac{d}{2} + vt\tan\alpha))^2 + v^2\right]^{0.5} \sin\alpha \quad (9)$$

The tension T of the lapping wire is the sum of the friction force and the tangential component of impact force as shown in Figure 4 and written as:

$$\vec{T} = \mu_k \vec{F}_N + \vec{F}_t \quad (10)$$

where μ_k is the coefficient of dynamic friction and the value is 0.03 in water as Ajayi [13] and F_N is the impact force normal to the surface of the work piece and can be expressed as:

$$\vec{F}_N = \frac{1}{\mu_k}(\vec{T} - \vec{F}_t) \quad (11)$$

The total normal force P_N exerted on the work piece is

$$\vec{P}_N = (\vec{F}_N + \vec{F}_n) \quad (12)$$

The force *P* on a single abrasive is given as:

$$\vec{P} = \frac{1}{N}(\vec{F}_N + \vec{F}_n) \quad (13)$$

where *N* is the effective number of abrasives in lapping area.

From equations (8), the impact force F_n exerted on the work piece is related to the taper angle and the moving speed of the wire. Equation (11) gives the relation among the friction force, impact force and wire tension.

Calculating the Material Remove Rate:

The remove volume *V* cut by a single abrasive can be related to the material remove rate. By assuming that *C* is the abrasive concentration of slurry, the effective number of the abrasives in lapping area is:

$$N = \frac{4SC}{\pi d_a^{\,2}} \quad (14)$$

where *S* is the surface area of the micro-hole and d_a is the diameter of the abrasive.

Then the theoretical material remove rate *MRR**, without considering the effect of slurry, can be written as:

$$MRR^* = Nf_c V = \pi N f_c (1 + \frac{L_a}{d_a})(\frac{d_a}{2} - \frac{\delta}{3})\delta^2 \quad (15)$$

where f_c is the reciprocating frequency of wire.

The property of slurry plays an important role in the lapping process as Marinescu [14]. The remove rate in the water-based slurry is usually larger than that in the oil-based slurry. Therefore, the theoretical material remove rate *MRR** has to be multiplied by a correcting coefficient *k* to obtain the actual material remove rate *MRR* as:

$$MRR = k \times MRR^* \quad (16)$$

where k is determined experimentally and is a function of the pH-value of slurry.

3. Experiment setup and design of experiment

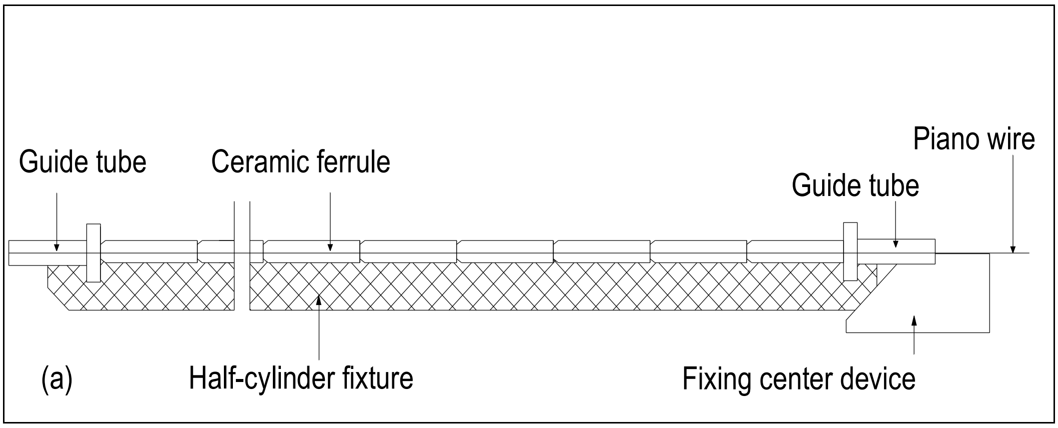
The schematic diagram of micro-hole lapping machine in this experiment is shown in Figure 5. The etched and tapered piano wire passes through the half-cylinder fixing device and is fixed at the left winding reel. The wire moves back and forth until the tension of the wire reaches the set value and zero respectively. While the wire moves back and forth, the slurry is brought to lap the micro-hole to the required diameter. As shown in Figure 1 (b), the left side of the wire is a smooth cylinder and the rolling abrasives are pressed into the clearance of the micro-hole on the work piece for lapping. The wire reciprocates until the required diameter and surface quality of the micro-hole are achieved.

The design of experiment is conducted to relate the parameters, which are the abrasive size, abrasive concentration of slurry, taper angle of wire, wire tension and pH-value of slurry, to the material remove rate. A design of 96 experiments as listed in table 1 is analyzed statistically for the significance of parameters, optimization of parameters and empirical formula of material remove rate.

The material remove rate (MRR) is calculated as:

$$MRR = (W_2 - W_1)/t \tag{17}$$

where W_2 and W_1 are the mass of the work piece before and after lapping respectively and t is the lapping time.



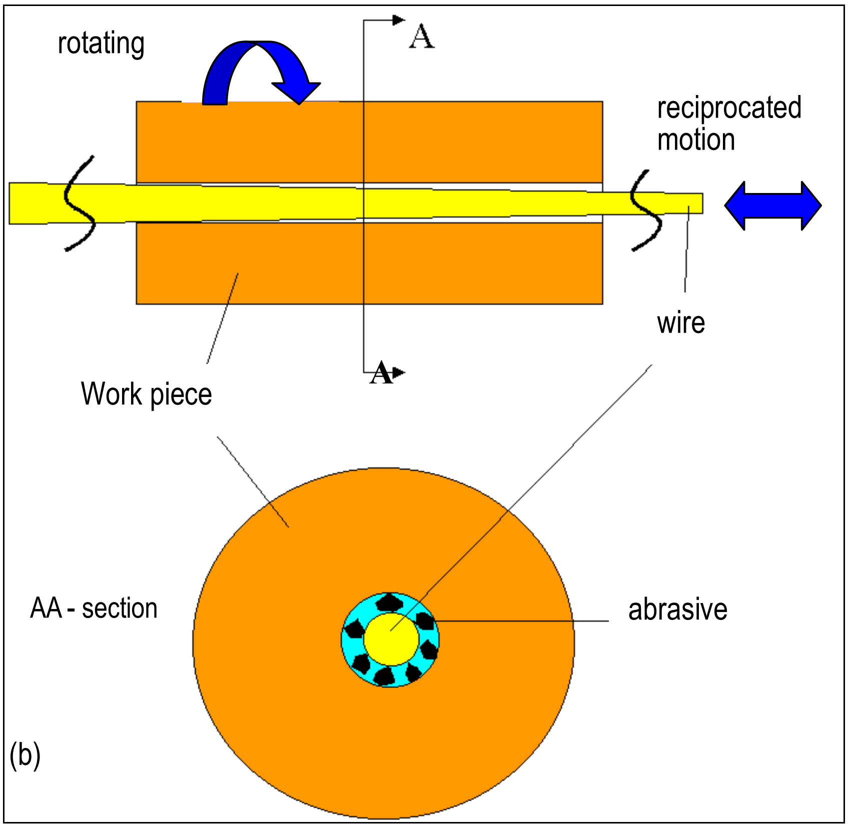


Figure 1. (a) Illustration of fixed ceramic ferrule **(b)** Illustration of micro-hole lapping

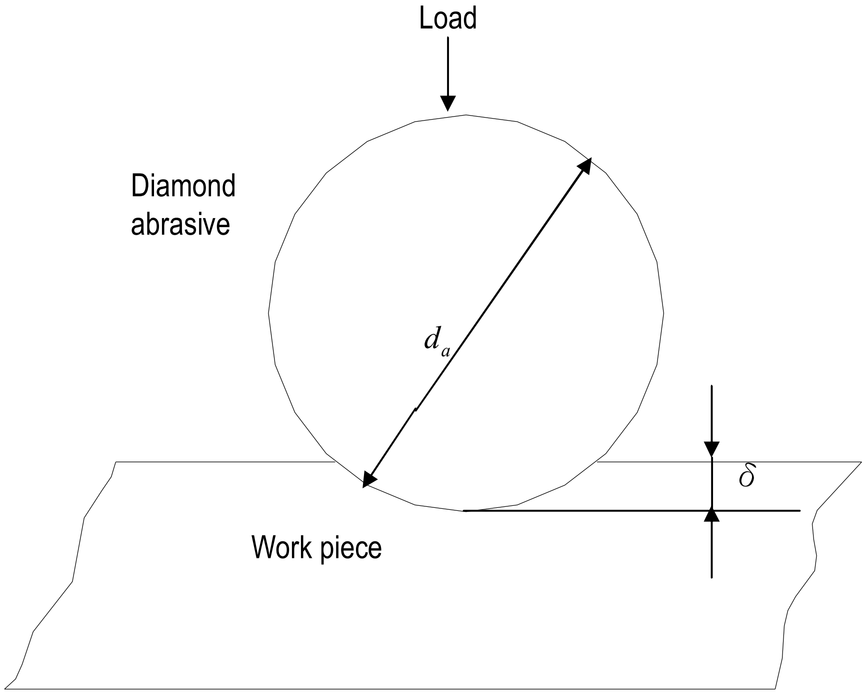


Figure 2. The depth of removed material by an abrasive

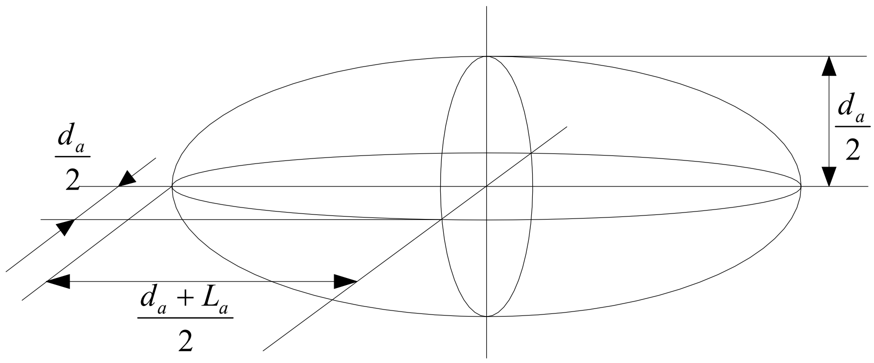


Figure 3. Volume cut by a single abrasive on work piece surface

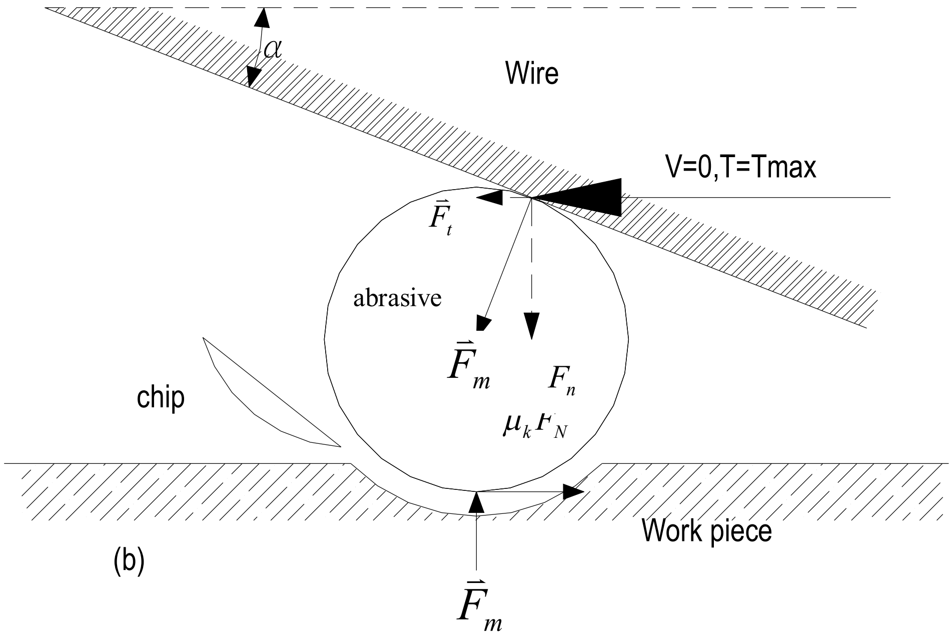


Figure 4. Force exerted mode between abrasive and work piece surface

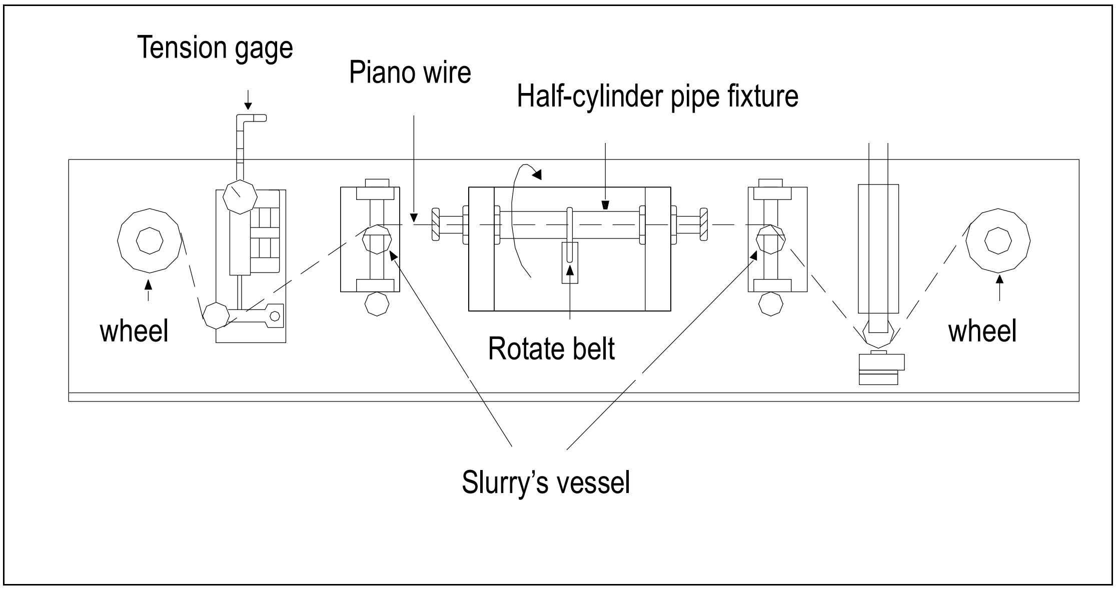


Figure 5. Schematic diagram of micro-hole lapping machine

Table 1. Experiment design for the ceramic ferrule micro-hole lapping

Variable	Abrasive size (A)	Abrasive concentration (B)	Taper angle of piano wire (C)	Wire tension (D)	PH-value of slurry (E)
Level No.	2	2	2	3	4
Actual value and unit	(1). 1μm (2). 3μm	(1). 0.8%wt (2). 1.2%wt	(1). 0.037° (2). 0.03° 8 m long, 80μm and 70μm for two ends' diameters	(1). 300g (2). 400g (3). 500g	(1). PH7 (2). PH8 (3). PH9 (4). PH10

4. Results and discussion

A design of experiment of micro-hole lapping of a hard and brittle material is conducted by analysis of variance to determine the significances of parameters to the material remove rate. Response surface method is applied to evaluate the optimal parameters for lapping. Residual and regression analyses are adopted to determine the empirical correlation. Furthermore, the comparison between the theoretical model and the empirical model is performed.

Optimal Process Parameter Analysis:

Table 2 shows the analysis of variance of the process parameters. It is found that the significant parameters of micro-hole lapping in descending order are the abrasive size (A), tension of the wire (D), pH-value of slurry (E) for their significances. The insignificant parameters are abrasive concentration of slurry (B) and taper angle of the wire (C). Table 3 shows that a linear model is good enough to formulate the empirical equation of the material remove rate through the F-test. By analysis of regression, the empirical model of the material remove rate can be written as:

$$MRR(\mu g/s) = 8.85 + 4.8 * A - 0.31*B - 0.050 * C + 1.60 * D + 2.48 * E \quad (18)$$

Where A is abrasive size; B is abrasive concentration of slurry; C is taper angle of wire; D is wire tension; E is pH-value of slurry.

Figure 6 shows the effects of the parameters on material remove rate. Both Figure 6 and equation (18) indicate that the material remove rate increases with the abrasive size, wire tension, and pH-value of slurry, but decreases slightly as the abrasive concentration of slurry or taper angle of wire increases. The residual of the material remove rate is plotted in the normal distribution probability diagram as shown in Figure 7 in which the statistic analysis of experimental data shows that data points distribute close a straight line as the linear correlations (18) and (19) with the process parameters. The plot of residuals versus predicted material remove rate is shown in Figure 8 in which the experimental data points fall within 3 standard deviations that indicates the close match between experimental data and empirical correlations. From both Figure 7 and 8 it is concluded that a linear empirical model is good enough to correlate the material remove rate. By eliminating the insignificant parameters, the simplified empirical correlation is given as:

MRR(μ g/s) = 8.85 + 4.8 * A + 1.60 * D + 2.48 * E (19)

A further empirical correlation of exponential model can be derived as:

$$MRR = 1.95 \times 10^{-4} A^{1.27} D^{0.8337} E^{2.1056} \quad (20)$$

where, A is the abrasive size (1μm ≦ A ≦ 3μm); D is the wire tension (300g ≦ D ≦ 500g); E is the pH-value of slurry (7 ≦ E ≦ 10).

Figure 9-11 show the response surfaces of the parameters versus the material remove rate. It can be seen that the response surfaces are almost flat planes and there is no interaction between parameters. It is found among Figure 9-11 that the set parameters of average abrasive size (3 μ m), abrasive concentration (0.8wt%) and taper angle of wire (0.03°) give the maximum increase of material remove rate as shown in Figure 11 and can be chosen as the optimal parameters from the available and tested data for lapping with the wire tension (500g) and pH-value of slurry (pH=10).

Correcting coefficient constant k for Material Remove Rate:

The correcting coefficient k in equation (16) is calculated by the least square method for calculating the material remove rate for various pH-value of slurry. Figure 12 shows the ratios k of experimental material remove rate to theoretical material remove rate for various pH-values of slurry. It is observed that the values of k are nearly constants and increase with pH-value of slurry and that the chemical property of slurry affects material remove rate of micro-hole lapping. Therefore, the material remove rate of micro-hole lapping can be improved by chemical reaction.

The material remove rates are calculated by the theoretical model and empirical formula and then compared with that of the experiments by changing the value of one parameter each time. It is found that the deviations of the tested results are within the range of 10% and that the deviations might be caused as:

(1) There might be experimental error in measurements.
(2) The assumption that all abrasives are spherical with a uniform diameter deviates from the practical condition as Winn [15].
(3) The abrasives are assumed to be evenly distributed, but actually might vary with time.

Experimental Verification:

In order to verify the correctness of the theoretical model and empirical formula of the material remove rate, additional experiments are designed for their verification. The average of response values measured in the experiments is calculated. 8 sets of experiment arrangements are designed statistically and sampled randomly. The results show that the deviations of the response value from the value estimated by the empirical formula and the value estimated by the theoretical model fall within 8% and 10% respectively. The theoretical model assumes the ideal conditions and thus has a larger deviation than the empirical formula established by statistical analysis. The deviations in both theoretical model and empirical formula are acceptable by experts and the on-the-spot experience.

Effects of Parameters on Material Remove Rate:

The material remove rate increases with abrasive size by theoretical model and empirical model. A large abrasive diameter gets a less number of abrasives and therefore the average force exerted and gives a deeper crack which makes the remove quantity increase per unit time as Marinescu [14].

The material remove rate decreases

slightly as the abrasive concentration increases by both empirical model and theoretical mode. A higher abrasive concentration might contain a larger number of abrasives in action and give the smaller average force on the work piece and then the smaller crack depth and the less material remove rate.

The material remove rates increase with the tension of wire by both theoretical and empirical formula for the stroke and pressure increase with tension in lapping the micro-hole. As shown in equation (1), the larger pressure gives the deeper crack on the work piece and then increases the remove volume. The tension of wire appears to be a significant parameter.

The material remove rates increase with the pH-value of slurry by both theoretical and empirical formula. The depth of the crack and remove volume increase theoretically as the Young's modulus decreases as in equation (1). The pH-value of slurry might reduce the Young's modulus by etching or softening the surface of the work piece as Sakaino [16] and the coefficient k takes account for the effect of different pH-value of slurry as shown in equation (16) and Figure 12 Fang [17] found that an etching liquid reduces the hardness of the surface of the PSZ zirconia about 5% by dipping the zirconia tested plate into an aqueous solution with potassium hydroxide (pH 12) at 60 °C for 24 hours. This approves that the material remove rate increases with the pH-value of slurry.

Table 2. Results of analysis of variance of the material remove rate

	Coefficient	Standard	t for H0	
Factor	Estimate	Error	Coeff=0	Prob > |t|
Intercept	8.10762	0.384604		
(A)- Abrasive diameter	4.8886	0.330523	14.7905	< 0.0001
(B)- Abrasive concentration	-0.06153	0.128519	-0.47878	0.6333
(C)- Taper Angle of wire	-0.18386	0.334693	-0.54933	0.5841
(D)- Wire tension	0.800672	0.1951	4.10391	< 0.0001
(E)-pH Value	2.44629	0.431157	5.67378	< 0.0001

Table 3. Test model for response value of material remove rate

Source	Sum of Squares	DF	Mean Square	F Value	Prob > F
Mean	7520.09	1	7520.09		
Linear	2755.09	5	551.017	56.5881	< 0.0001
Quadratic	220.734	14	15.7667	1.82767	0.0495
Cubic	282.29	25	11.2916	1.5425	0.0946
Residual	373.337	51	7.32032		
Total	11151.5	96	116.162		

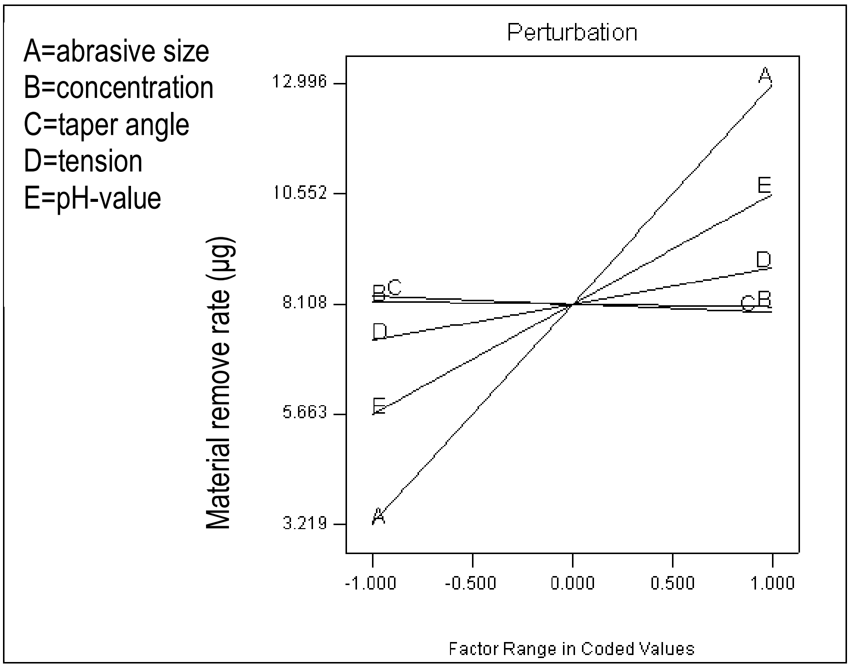


Figure 6. Diagram of material removal rate vs. the experiment parameters of micro-hole lapping of ceramic ferrule

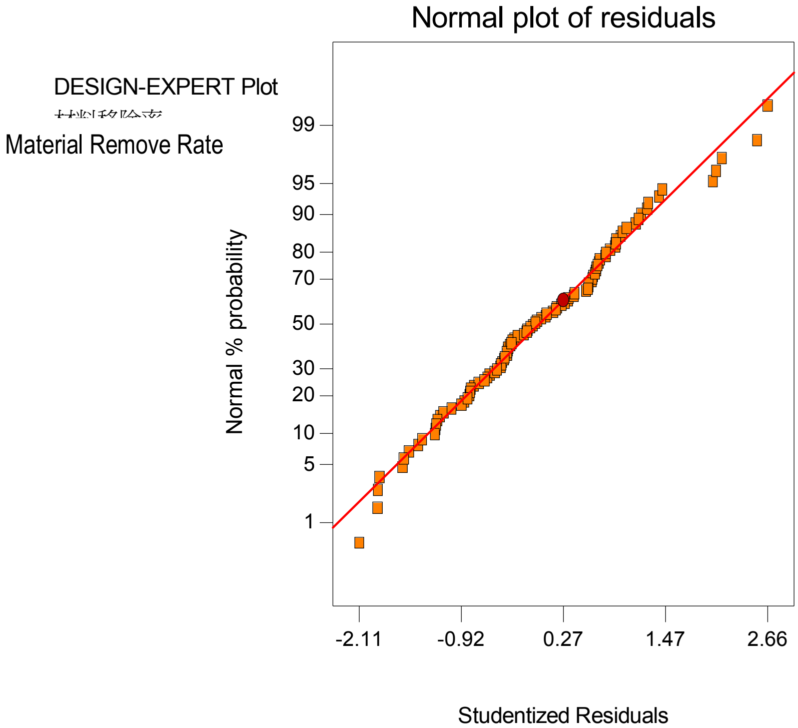


Figure 7. Normal plot of residual probability of material removal rate of micro-hole lapping of ceramic ferrule

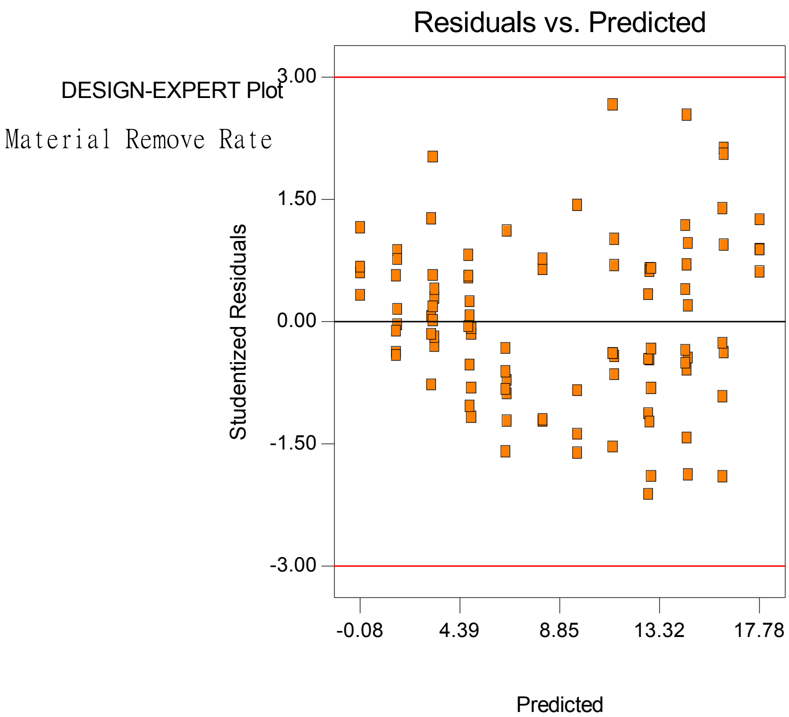


Figure 8. Distribution diagram of residuals vs. predicted material remove rate of micro-hole lapping of ceramic ferrule

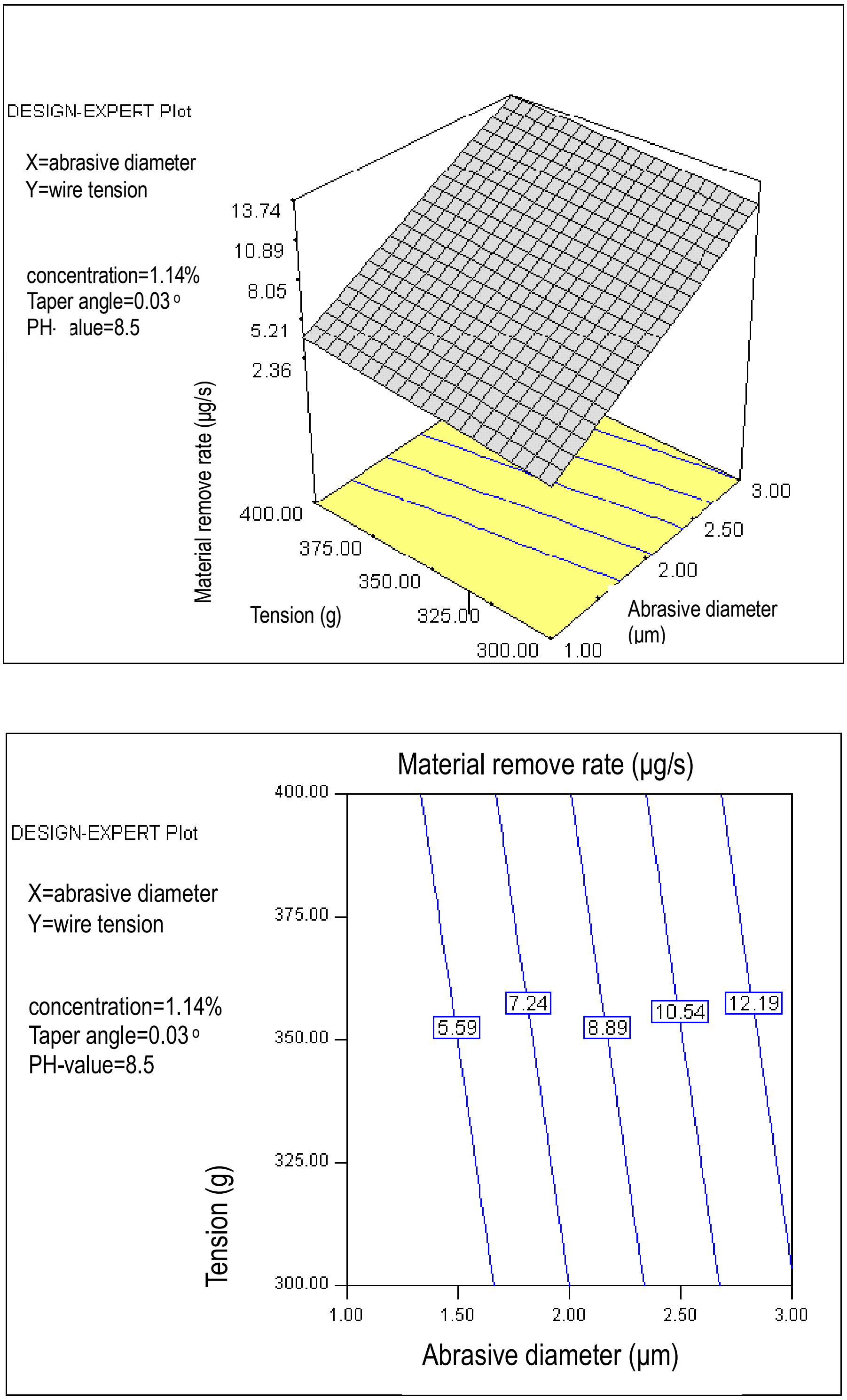


Figure 9. Response material remove rate vs. abrasive diameter and wire tension for ceramic ferrule

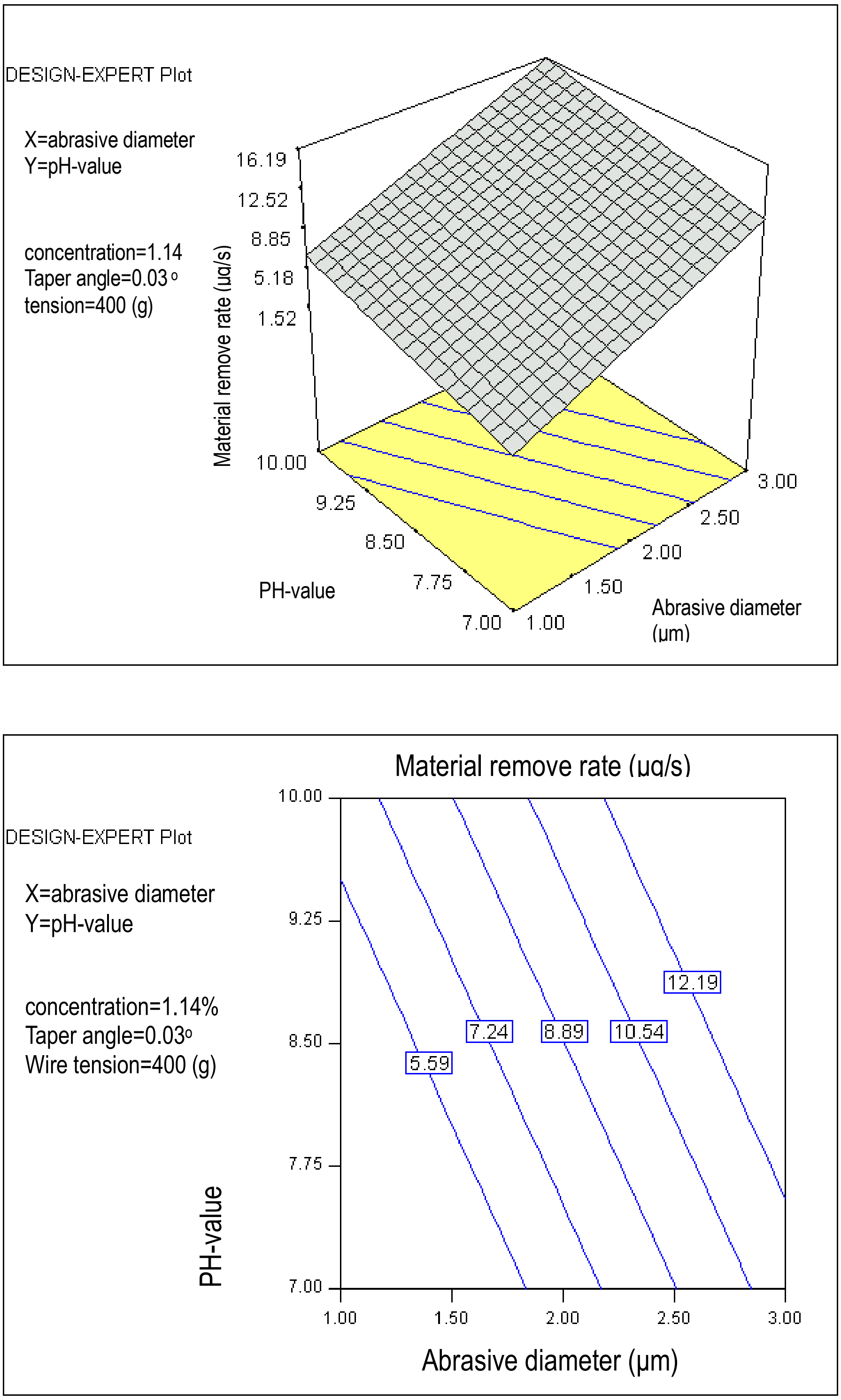


Figure 10. Response material remove rate vs. abrasive diameter and pH value of slurry for ceramic ferrule

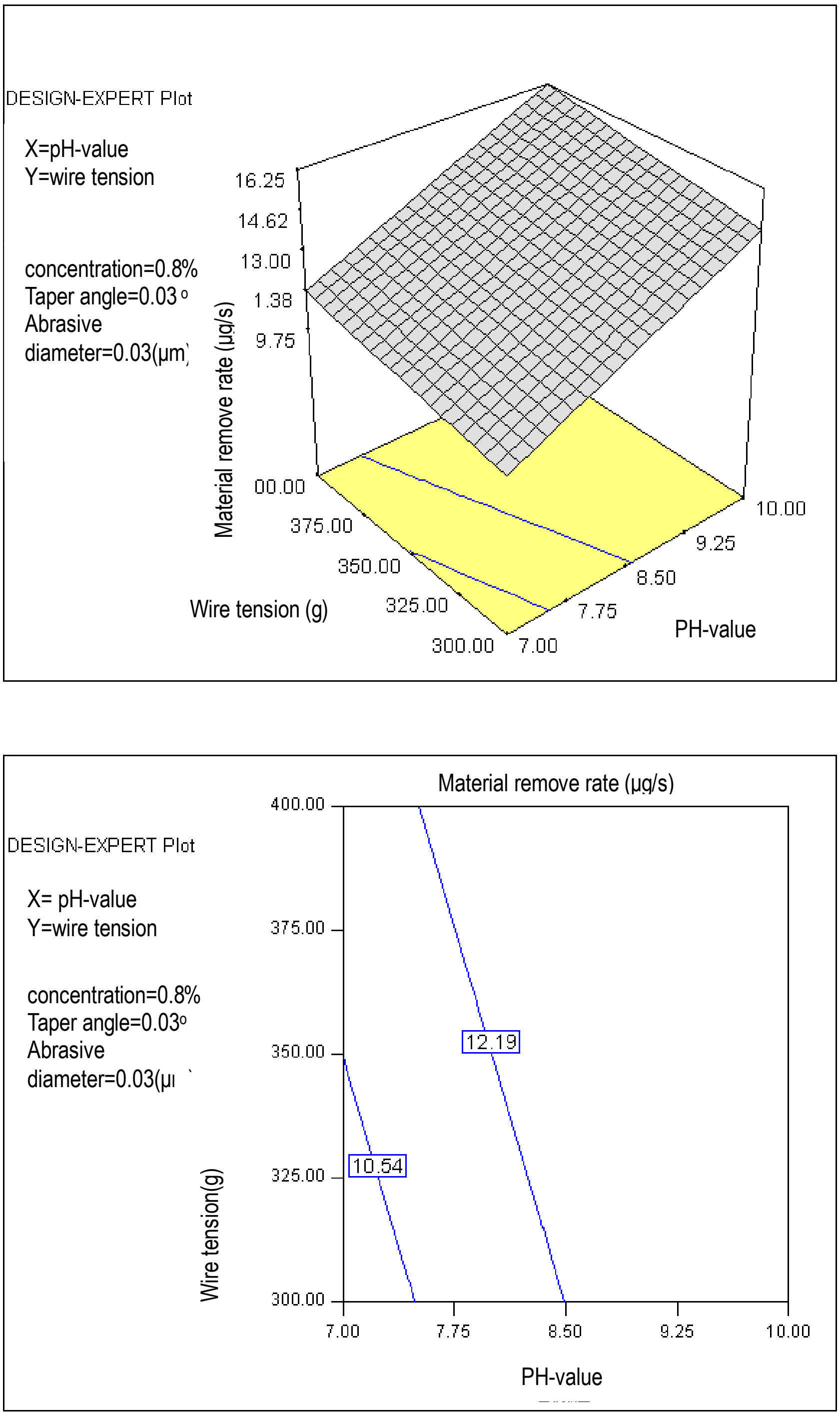


Figure 11. Response material remove rate vs. wire tension and pH value of slurry for ceramic ferrule

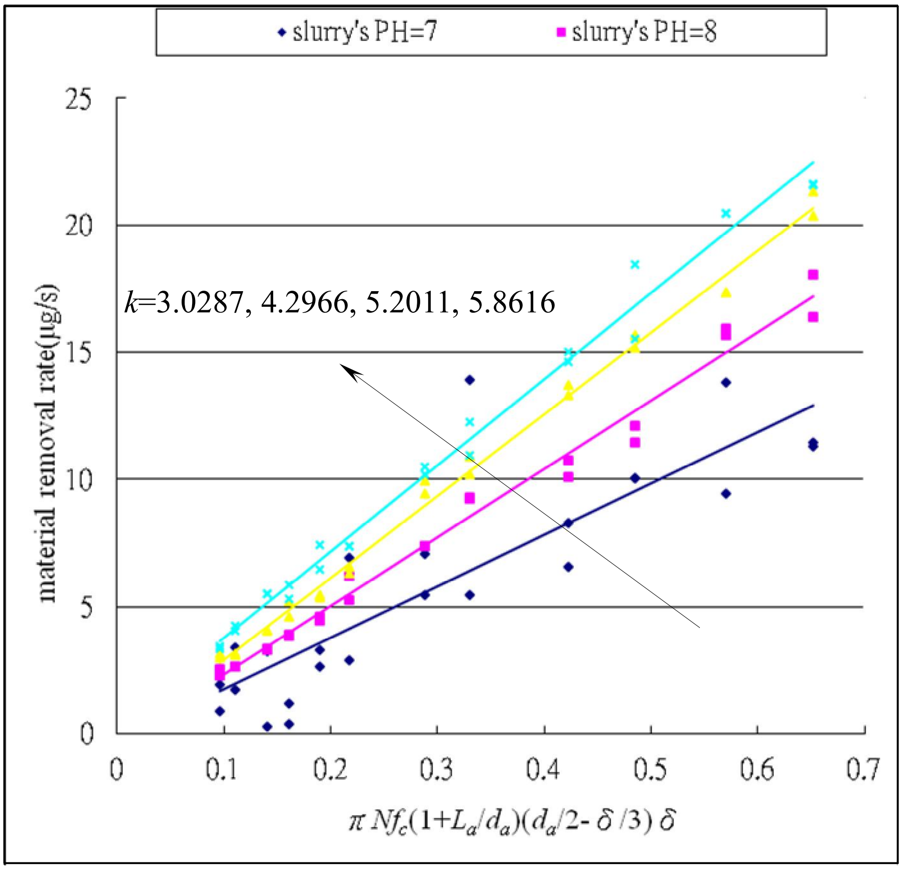


Figure 12. Effect of pH value of slurry on material remove rate

5. Conclusion

A new process of lapping of a micro-hole on the hard and brittle material is investigated based on the model of the brittle fracture. From Eq.(1), the cut depth by the abrasive is estimated to be 0.3 μm 1 order less than the diameter of the abrasive(3 μm) theoretically and a good surface quality can be obtained. The effects of lapping parameters are evaluated by means of theoretical, empirical and experimental analyses on the material remove rate. The following conclusions are obtained:

(1) A new lapping method by use of a piano wire with a taper angle is applied to lap a micro-hole. This new lapping method can lap hard and brittle material such as the insulating ceramic material with precision in diameter and with less limitation of the depth of the micro-hole.

(2) Five parameters of abrasive size, abrasive concentration of slurry, taper angle of wire, wire tension and pH-value of slurry are evaluated on the material remove rate. It is found that the material remove rate increases with abrasive size, wire tension and pH-value of slurry as shown in Figure 6 in which the most significant parameter is abrasive size and then the pH-value of slurry. It is also found that the material remove rate decreases as abrasive concentration of slurry or taper angle of wire increases but both the effects are insignificant as shown in Figure 6.

(3) The friction force is considered to be the main cutting force to remove material and the main material remove mechanism is considered to be the sliding motion drawn by wire tension so

that the effect of taper angle appears to be insignificant and can't match with equation (8) theoretically. However, the main function of the taper angle of wire is to induce the abrasive to enter into micro-hole and pass the wire into the micro-hole easily.

(4) By use of the response surface plot method, a set of optimal parameters are obtained for lapping a micro-hole with abrasive size (3 μ m), abrasive concentration of slurry (0.8wt%), taper angle of wire(0.03 $^\circ$), wire tension (500g), and pH-value of slurry (pH 10).

(5) The theoretical model and empirical formula are established and compared with the results of experiments. The deviations of the predicted material remove rates fall within 10%.

(6) The effect of each parameter of the theoretical model and empirical formula is compared with the experiments for the material remove rate and the deviations fall within the range of 8%. Thus both the models can estimate material remove rate of the stable zirconia for micro-hole lapping efficiently.

The new machining method of wire lapping for a precise micro-hole is satisfying for a hard brittle material. Both the PH-value of slurry and size of abrasive are significant parameters that the extended experimental research of those effects is necessary for improving the material remove rate.

Nomenclatures

C Abrasive concentration of slurry

D Smallest diameter of the tapered wire (m).

d_a Average diameter (m) of abrasive

D The larger diameter of the tapered wire (m).

E Young's modulus (Mpa) of work piece

f Displacement of a reciprocated wire

f_c Frequency of a reciprocated wire

$\vec{F}_n$ Impact force of an abrasive on work-piece in normal direction

$\vec{F}_t$ Impact force of an abrasive on work-piece in tangential direction

$\vec{F}_N$ Normal force on work-piece exerted by an abrasive

k Constant coefficient for material remove rate

L Length of the wire (m)

L_a Displacement of an abrasive driven by the wire (m)

M Mass of the wire (kg)

N Number of effective abrasives in laping area.

P Contact force (N) exerted on a single abrasive

$\vec{P}$ Pressure from single abrasive exerted on work piece

$\vec{P}_N$ Total normal force on work-piece

S Surface area of a micro-hole

$\vec{T}$ Tension of lapping wire

ΔT Time that an abrasive is in contact with a wire (s)

V Volume of a brittle fracture removed by an abrasive (m3)

μ_k Dynamic friction coefficient

ν Poisson's ratio of work piece

ω Angular speed of the work piece with respect to the wire (rad/s)

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