Prediction of Material Removal Rate in Ductile–Mode Micro Ultrasonic Machining

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Abstract: This paper presents a model to predict Material Removal Rate (MRR) in Micro Ultrasonic Machining (micro-USM). The proposed model is developed based on the ductile-mode of material removal in micro-USM process. The correlation between ductile material removal rate and process parameters including frequency and amplitude of the ultrasonic vibration, particle size, and slurry concentration is presented. The proposed predictive model is verified by performing micromachining experiments using two types of workpiece materials including silicon and quartz at various process parameters levels. The results show that the MRR increases with a rise in vibration amplitude for both silicon and quartz materials. The experimental MRR values follow a trend similar to that of predicted MRR values. However, the predicted MRR values are higher than the measured MRR values for both silicon and quartz materials. The measured MRR values for ductile removal mode were found to have a considerable increase at vibration amplitudes of 2 μm and 2.4 μm for silicon and quartz, respectively, which is in favour of increasing the accuracy of the model prediction.

Keywords: Ductile-Mode Machining, Material Removal Rate, Micro Ultrasonic Machining, Process Modelling

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Research paper

1 INTRODUCTION

Micro Ultrasonic Machining (micro-USM) is a competent micro machining process with a considerable potential for microscale material removal to generate microstructures in various hard and brittle materials at low cost. Several innovative strategies such as on-machine tool preparation, tool rotation, workpiece vibration, and force adaptive control to stabilize the material removal characteristics have been proposed to improve the machining accuracy and process performance of the micro-USM process [1-4]. Machining of microfeatures with a desired level of surface and edge quality, minimum sub-surface damage, high dimensional and geometrical accuracy, and acceptable material removal rate are key factors that influence the success of micro-USM process [5]. Although micro-USM is considered a promising technique to meet increasing demand in micromachining, a lack of knowledge base in underlying process mechanisms and predictive process modelling as well as sub-optimal process parameters puts obstacles on introducing this technique to practical micromanufacturing and industrial applications. Despite the similarities of USM and micro-USM, theoretical models for USM may not be directly applicable to micro-USM process.

Factors such as rotation of the abrasive particles with tool as well as particles distribution in the machining zone that come into play in micro-USM may not be considered influential in conventional USM [6]. Furthermore, slurry supply to the small machining zone between micro tool bottom and workpiece surface becomes difficult in micro-USM due to the capillary effect [2], which may impair the machining efficiency, machined surface quality and achievable material removal rate [7-8]. The sensitivity of the process performance to process parameters coupled with the distinct differences in process conditions between USM and micro-USM suggests that their process characteristics are also different. Such factors may not only create diverse process performance, but also may generate contrasting process modelling results between USM and micro-USM [9]. Therefore, although the results of USM process modelling may be relied on to suggest similar trends in micro-USM, specific studies under micro-USM process conditions are still required to elucidate the actual process characteristics.

Existing models for predicting the process performance in micro-USM are limited. Yu et al. [6] developed a model to describe the correlation between MRR and process parameters, namely, static load, frequency and amplitude of vibration, particles size and tool rotation. The volume of the material removed by a particle in one cycle of vibration is estimated from the amount of elastic deformation under particle indentation [10]. A decrease in MRR over a threshold value of static load, similar to the phenomenon in conventional USM was identified, which differed from the trend proposed by the theoretical model.

A model was presented in [6] to understand and analyze quantitatively the trend of decreased MRR over a certain static load. It was suggested that the trend observed was mainly due to the accumulation of debris around the crater in a short period of time, which brings about the micro tool to impact on debris instead of the abrasive particles within the slurry, thereby resulting in the low machining efficiency. While the basic assumptions made for modelling of MRR resemble to those in rotary ultrasonic machining where abrasive particles are fixed to the rotating tool, in actual machining conditions particles move freely inside the machining zone. Also, abrasive particles have been mostly assumed to have a spherical shape in the process modelling while the particles used for the experiments were irregular shaped bodies with a distributed size [11]. Actual machining in micro-USM process may be contributed by different material removal modes comprising plastic deformation and brittle fracture [12-13].

This feature necessitates making appropriate assumptions in accordance with the material removal mode under which machining is performed. Thus, the conformity and adaptability of process modelling to the conditions of material removal in micro-USM could be enhanced by incorporating the material removal mode into modelling procedure [11].

The review of the existing models for prediction of the material removal rate in conventional USM and micro-USM reveals that none of these models conform to the resulting material removal mode in the process whether ductile or brittle. Therefore, one issue in micro USM is to provide the models in accordance with the prevalent material removal mode in the process. This study endeavours to model the material removal rate for ductile material removal mode in micro-USM. The importance and novelty of the present work compared to existing literature lies in providing a predictive model for material removal rate, in which the conditions required for ductile mode of the material removal in micro-USM process is incorporated into the analysis.

2 METHODOLOGY FOR DEVELOPMENT OF THE MATERIAL REMOVAL RATE MODEL

As illustrated in “Fig. 1”, the predictive modelling for material removal rate in micro-USM consists of two main parts: First, the number of abrasive particles in the machining zone is specified (N-number model). Process parameters including particle size, abrasive particles density, slurry liquid density, slurry concentration, tool diameter, and machining gap are employed for calculations. Second, a process model to predict MRR for ductile removal mode is presented based on the kinetic energy of particles and volume of the plastic indentation zone beneath the impinging particles.

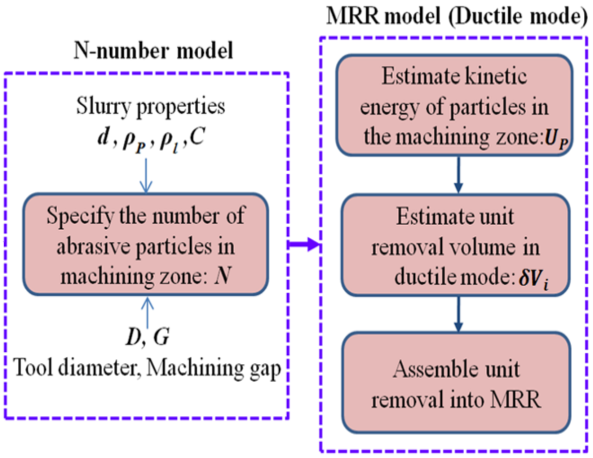


Fig. 1 The approach for modelling the material removal rate in ductile-mode micro-USM.

3 THE NUMBER OF ABRASIVE PARTICLES IN THE MACHINING ZONE (N-NUMBER MODEL)

In order to estimate the average number of particles in the machining zone, it is necessary to make a few assumptions. Abrasive particles are assumed cubes with side length of d. Besides, the micro tool is considered as a solid cylinder. It is also assumed that the average number of abrasive particles is constant during the micro-USM process. It is due to the delivery of the abrasive slurry to the gap between the workpiece and micro-tool at a constant flow rate as well as continuous transfer of the utilized slurry from the machining zone by vacuum system. The expression for total volume of the abrasive slurry, contributing to the machining process is as follows:

$$V = \pi \frac{D^2}{4} G \qquad (1)$$

Where, D and G represent the micro-tool diameter and the machining gap, respectively. The expression for volume of the machining zone in terms of the volume of particles and liquid can be written as:

$$V = V_P + V_l = N d^3 + \frac{M_l}{\rho_l} \quad \Rightarrow \quad V = N d^3 + \frac{M_P}{\rho_l C} \qquad (2)$$

Where, V_P and V_l are the volume of the particles and liquid in the machining zone, respectively; N is the total number of abrasive particles; d is the particle size; M_l and M_p are the mass of the liquid and particles in the machining zone respectively; ρ_l is the density of the slurry liquid, and C is the slurry concentration. Equation (2) can be rewritten as:

$$V = N d^3 + \frac{N \rho_P d^3}{\rho_l C} \qquad (3)$$

Where ρ_P is the density of the abrasive particles. By considering equations (1) and (2), total number of abrasive particles in the machining zone can be expressed as:

$$N = \frac{\pi D^2 G}{4 d^3 \left(1 + \frac{\rho_P}{C \rho_l}\right)} \qquad (4)$$

4 MODELLING OF MATERIAL REMOVAL RATE IN DUCTILE MODE CONDITION

When a hard angular particle impacts the surface of a brittle material, a plastic deformation occurs in the impact site and underneath the indented surface. If the kinetic energy of the particle does not exceed the threshold kinetic energy required for the initiation of lateral cracks, material removal takes place in a ductile mode without creating lateral cracks beneath the plastic zone. Under these conditions, the volume of the material removed by an impacting particle can be estimated based on the volume of indentation zone shown in “Fig. 2”.

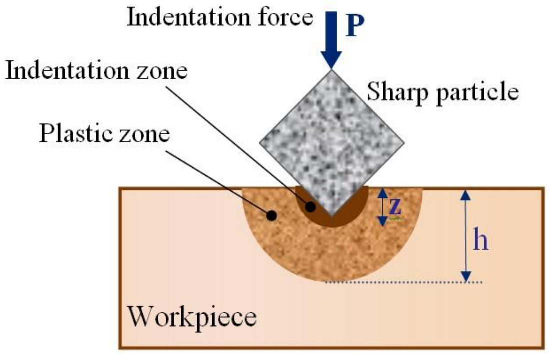


Fig. 2 Indentation and plastic zones beneath a sharp particle during indentation on the surface of a brittle material.

Kinetic energy of the impacting particle, U_p is converted to plastic work at the indentation zone upon the particle impact. Therefore, the volume δV_i of the indentation zone, produced by the impacting particle, can be given as:

$$\delta V_i = \frac{U_P}{H} \qquad (5)$$

Where, H is the hardness of the intended workpiece and U_p is the kinetic energy of the incident particle. Equation (5) can be considered to represent the volume of the material removed per particle impact per cycle of the vibration when machining under ductile mode in the micro-USM process. The value of Up can be calculated from the expression below [14]:

$$U_P = \frac{1}{2} d^3 . \rho_P (2\pi a f + v_c)^2 \tag{6}$$

Inserting the expression (6) for the calculation of U_p into equation (5) gives:

$$\delta V_i = \frac{d^3 \rho_P (2\pi a f + v_c)^2}{2H} \tag{7}$$

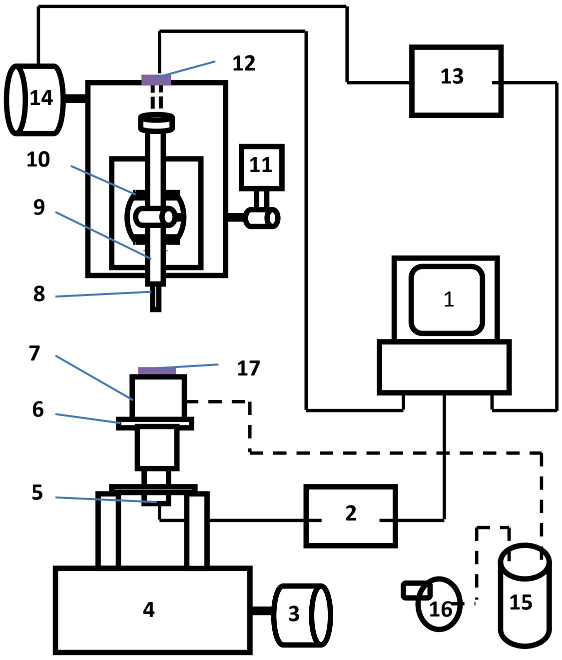
Where, a and f are the amplitude and frequency of vibrations respectively, and v_c is the velocity of the particle arising from cavitation collapse in the slurry. The removal volume per particle impact (δV_i) in the ductile mode, calculated from Equation (7), can be aggregated into MRR by incorporating the number of abrasive particles inside the machining zone as well as the frequency of ultrasonic vibrations. Thus, the expression for MRR in ductile mode is presented as:

$$MRR = N . f . \delta V_i \tag{8}$$

5 MODEL VALIDATION EXPERIMENTS

Figure 3 shows the schematic diagram of the micro-USM system used for conducting the experiments. The ultrasonic vibration with frequency of 50 kHz is generated through a power generator and ultrasonic transducer. Then, the mechanical vibration is transmitted to the workpiece through booster and horn. A force sensor is mounted on the tooling system and connected to the computer to measure the machining force i.e. the contact load between micro-tool and abrasive slurry. The machining force is maintained within a specified range by controlling the infeed motion of the micro-tool via computer interface. The amplitude of vibration is adjusted by setting the output voltage of the ultrasonic generator. Fresh abrasive slurry is delivered continuously into the machining zone throughout the process.

Micro-USM experiments were performed using silicon and quartz materials to validate the MRR model for ductile removal mode. Process parameters are presented in "Table 1" . The amplitude of ultrasonic vibration was set at values ranging from 0.8 μm to 4 μm. These values were selected to provide conditions required for ductile mode machining in silicon and quartz whereby kinetic energies below the threshold values for crack initiation are generated. Three replications were considered for each experimental run.



1. Personal computer
2. Ultrasonic generator
3. X and Y-axis actuator
4. Electronic balance
5. Ultrasonic transducer
6. Booster
7. Ultrasonic horn
8. Micro-tool
9. Mandrel
10. V-shaped bearing
11. DC motor
12. Precision force sensor
13. Piezomotor controller
14. Z-axis actuator
15. Liquid separator
16. Vacuum pump
17. Workpiece

Fig. 3 Schematic diagram of the experimental micro-USM system.

Table 1 Experimental conditions used to validate the MRR model for ductile removal mode

Machining parameters	Value
Amplitude, *a* (μm)	0.8; 1.2; 1.6; 2.0; 2.4; 2.8; 3.2; 3.6
Frequency, *f* (kHz)	50
Gap distance, *G* (μm)	50
Workpiece material	Silicon <100>, Quartz
Tool material	Tungsten
Tool diameter, *D* (μm)	293.3
Particles type	PCD
Particles size, *d* (μm)	3
Slurry concentration, *C* (% wt)	0.02

6 RESULTS AND DISCUSSION

The diameter and the depth of micro holes machined at various vibration amplitudes were measured by PL□ confocal imaging profiler. The data was then used to calculate the volume of micro holes and subsequently the material removal rate at each parameter setting. The average measured values of MRR were plotted together with the theoretical MRR values for silicon and quartz materials, as shown in "Fig. 4" and "Fig. 5", respectively.

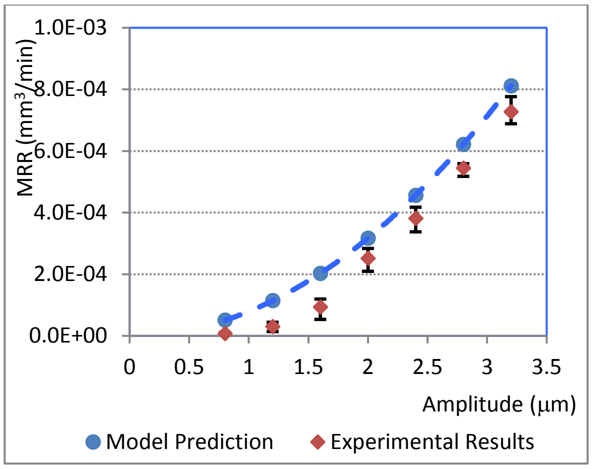


Fig. 4 Comparison of the calculated and experimental values of MRR at different vibration amplitudes for ductile mode machining of silicon; particle size=3 μm.

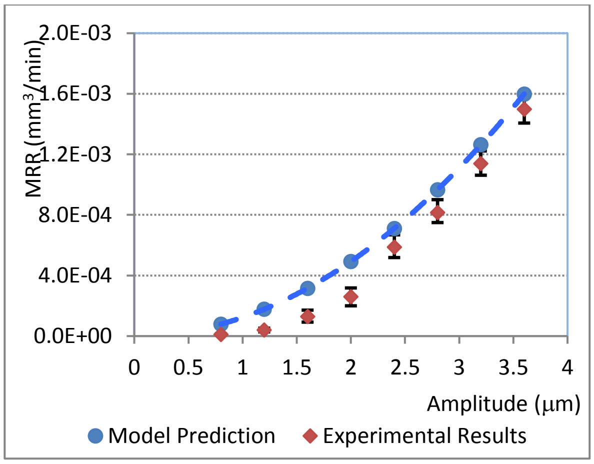


Fig. 5 Comparison of the calculated and experimental values of MRR at different vibration amplitudes for ductile mode machining of quartz; particle size=3 μm

As shown in the figures, the MRR values increases with increasing vibration amplitude for both silicon and quartz materials. The measured MRR values are found to follow a trend similar to that of theoretical MRR values, predicted by the proposed model. However, the predicted MRR values are higher than the measured MRR values for both silicon and quartz materials. The deviation between theoretical and experimental MRR values could be attributed to inter-particle collisions inside the machining zone that dissipate the kinetic energy of accelerated particles.

Factors such as variations in actual vibration amplitude of the ultrasound transmitted to the slurry medium during the machining process as well as distribution in the shape and size of the particles may also contribute to deviations observed.

A relatively sharp increase in the measured MRR values is also found at amplitudes of 2 μm and 2.4 μm for silicon and quartz, respectively, which leads to a lower deviation between measured and predicted MRR values. These trends can be explained by considering the criteria for transition between material removal modes. The kinetic energy of the particles at amplitude of 2 μm and 2.4 μm is about 0.190 nJ and 0.274 nJ, respectively. These values are close to threshold kinetic energies for radial cracks in silicon and quartz, respectively. Thus, abovementioned trends could be attributed to the occurrence of transition between purely ductile removal to a partially ductile removal mode where radial cracks are formed at the particle impact site.

7 CONCLUDING REMARKS

A process model was presented to predict the material removal rate for ductile removal mode in micro-USM. The proposed MRR model was found to predict the trends of experimental MRR results reasonably well at various process parameters. The measured MRR values for ductile removal mode were found to have a considerable increase at vibration amplitudes of 2 μm and 2.4 μm for silicon and quartz, respectively, which is in favor of increasing the accuracy of the model prediction. The rise in measured MRR values at above amplitudes could be attributed to the transition from purely ductile removal mode to partially ductile mode. This transition introduces radial cracks to intended zone of the workpiece, causing strength degradation in the material impacted by subsequent particles and thus an increased removal rate.

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