A mechanistic ultrasonic vibration amplitude model during rotary ultrasonic machining of CFRP composites

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Abstract

Rotary ultrasonic machining (RUM) has been investigated in machining of brittle, ductile, as well as composite materials. Ultrasonic vibration amplitude, as one of the most important input variables, affects almost all the output variables in RUM. Numerous investigations on measuring ultrasonic vibration amplitude without RUM machining have been reported. In recent years, ultrasonic vibration amplitude measurement with RUM of ductile materials has been investigated. It is found that the ultrasonic vibration amplitude with RUM was different from that without RUM under the same input variables. RUM is primarily used in machining of brittle materials through brittle fracture removal. With this reason, the method for measuring ultrasonic vibration amplitude in RUM of ductile materials is not feasible for measuring that in RUM of brittle materials. However, there are no reported methods for measuring ultrasonic vibration amplitude in RUM of brittle materials. In this study, ultrasonic vibration amplitude in RUM of brittle

materials is investigated by establishing a mechanistic amplitude model through cutting force. Pilot experiments are conducted to validate the calculation model. The results show that there are no significant differences between amplitude values calculated by model and those obtained from experimental investigations. The model can provide a relationship between ultrasonic vibration amplitude and input variables, which is a foundation for building models to predict other output variables in RUM.

Keywords: Ultrasonic vibration amplitude; Rotary ultrasonic machining (RUM); Brittle material; Cutting force.

1. Introduction

Rotary ultrasonic machining (RUM) has been successfully used in drilling brittle materials (such as alumina, zirconia, silicon, silicon carbide, etc.), ductile materials (titanium and stainless steel alloys), and composite materials (ceramic matrix composites and carbon fiber reinforced plastic composites), and has been proved to be an efficient and effective hole making process [1-21]. RUM is a hybrid nontraditional machining process that combines ultrasonic machining and abrasive grinding, as illustrated in Figure 1. In RUM, the metal-bonded diamond core drill performs as a cutting tool. The cutting tool rotates and axially feeds toward the workpiece at a constant feedrate (or a constant pressure) under an ultrasonic vibration frequency (typically 20

kHz). Coolant is pumped through the core of the drill, washing away the swarf and remaining the workpiece at a relatively low cutting temperature.

Ultrasonic vibration amplitude, one of the most important input variables in RUM, is controlled by ultrasonic power supply. Numerous studies have found that ultrasonic vibration amplitude has direct influences on almost all output variables in RUM [7, 8, 13, 14, 22, 23]. Ultrasonic vibration amplitude measurement would be thus beneficial for exploring the explanations for some experimentally observed phenomena and predicting the results of output responses in RUM. Currently, there are three reported methods for measuring ultrasonic vibration amplitude in RUM: optical vibration sensor method, dial indicator method, and microscope observation method [22, 24]. However, the first two methods can only be used to measure ultrasonic vibration amplitude without RUM machining of materials. It was reported that with the increase of ultrasonic power from 20% to 40%, the ultrasonic vibration amplitude measured by the dial indicator method had similar trends but different values compared with that measured by the microscope observation method in RUM machining of stainless steel [22]. The major limitation of the microscope observation method is that the machining marks, indicating diamond grains trajectories, can only be observed on the RUM-machined surface of ductile materials (The details of the microscope observation method will be reviewed in Section 2 of this paper.). In addition, some methods have been reported for measuring ultrasonic vibration amplitude in other applications [25-34], which can be potentially utilized in RUM without machining of materials. The investigations on all of

these reported methods indicate that there is a lack of methods to measure ultrasonic vibration amplitude in RUM machining of brittle materials.

In this paper, a mechanistic calculation model is developed to investigate ultrasonic vibration amplitude through cutting force in RUM of brittle materials. Carbon fiber reinforced plastic (CFRP) composites have been selected as the workpiece in this investigation based on two major reasons. (1) The material removal mechanism in RUM of CFRP has been identified as brittle fracture; and (2) the mechanistic calculation model can be simplified for RUM of other homogeneous brittle materials [35]. With this model, the relationships between ultrasonic vibration amplitude and different combinations of input variables in RUM of CFRP are established. The ultrasonic vibration amplitude in RUM of brittle materials can be calculated by the model, which will be verified by the microscope observation method using a specially designed aluminum-CFRP stack as the workpiece.

2. Microscope observation method

The microscope observation method is similar to the quick-stop method [36-38] for metal-cutting research where the cutting process is “frozen” for observations. The principle of this method is chasing and then measuring the trajectories of diamond grains relative to the machined surfaces.

A machined hole and a machined rod are generated by the cutting tool in RUM, as illustrated in

Figure 2. The diamond grain trajectories remain on the machined surfaces of both hole and rod, because the diamond grains exist on both outer and inner sides of the tool. Hence, the trajectories can be observed from the micrograph taken on the machined rod surfaces. The measurement methodology and amplitude reading mechanism are shown in Figure 3.

The microscope observation method to measure the ultrasonic vibration amplitude is only applicable to the ductile materials since the machining marks (trajectories of diamond grains) on the machined surfaces are visible on the ductile materials (including stainless steel, titanium, aluminum), but not visible on the brittle materials as well as some composite materials (alumina ceramics, ceramic matrix composites (CMC), and CFRP), as shown in Figure 4. It is still unknown what the ultrasonic vibration amplitude is during RUM of brittle materials. Therefore, a method to measure the ultrasonic vibration amplitude in RUM of brittle materials is needed. Such method will be presented in Section 5 of this paper.

3. Development of mechanistic amplitude calculation model

3.1. Approach to amplitude calculation model development and notations

RUM can be treated as a combination of the ultrasonic machining process and abrasive grinding process. The approach of considering ultrasonic machining as the predominant process has been

successfully used for RUM model development [5, 35, 39-42]. This approach can also be employed in this amplitude model development.

Figure 5 shows the major model development procedures which can be summarized as the following steps.

- (1) Measure cutting force using a dynamometer;
- (2) Establish a relationship between cutting force and abrasive particle indentation depth;
- (3) Estimate the actual volume of material removed by one abrasive particle indentation in a single ultrasonic vibration cycle;
- (4) Calculate material removal rate (MRR) by aggregating the effects of all active abrasive particles;
- (5) Build a relationship between input variables (including feedrate and both inner and outer diameters of the tool) and MRR.
- (6) Finally find out the relationship between ultrasonic amplitude and cutting force.

RUM, a complex process, involves many input variables, including workpiece properties, tool variables, and machining variables. These input variables used in model development are listed in Table 1.

3.2. Major assumptions in model development

The major assumptions for the RUM cutting tools are that all the diamond abrasive particles on the end face of a cutting tool are rigid spheres with the same size and embedded depth, all participating in cutting during each ultrasonic cycle. The major assumptions for workpiece material are that workpiece material is ideally brittle and it is removed in a brittle fracture mode. While using CFRP as the workpiece in model development, a heterogeneous material is allowed to be represented as an equivalent homogeneous material through micromechanics process [35, 43, 44]. Other assumptions for the CFRP composites include uniform and continuous fibers, a perfect bonding between matrix and fibers, and the voids-free structures. Similar assumptions could be found in other investigations on the force model development for grinding (core drill) of CFRP [45-49]. Additional assumptions and simplifications will be discussed at which necessary.

3.3. The relationship between cutting force and indentation depth

In RUM, the cutting force can be calculated by [5, 35, 40-42]

$$F = \Delta t f F_i = n \Delta t f F_1 \quad (1)$$

where, Δt is the effective contact time when an abrasive particle penetrates into the workpiece, s; f is the ultrasonic vibration frequency, Hz; F_i is the maximum impact force between tool and

workpiece, N; F_1 is the maximum impact force between a single abrasive particle and workpiece, N; and n is the quantity of active abrasive grains on the end face of cutting tool.

The effective contact time can be calculated by

$$\Delta t = \frac{1}{\pi f} \left[\frac{\pi}{2} - \arcsin \left(1 - \frac{\delta}{A} \right) \right] \quad (2)$$

where, δ is the indentation depth of an abrasive grain into the workpiece, mm; and A is the ultrasonic vibration amplitude, mm.

The relationship between the maximum impact force and indentation depth could be established as [40, 50]

$$F_i = \frac{8^{1/2} n E d^{1/2} \delta^{3/2}}{3(1-\nu^2)} \quad (3)$$

where, E is the elastic modulus of the workpiece material, MPa; d is the diameter of abrasive grains, mm; and ν is the Poisson's ratio of the workpiece material.

After substituting Eq. (2) and Eq. (3) into Eq. (1), the following equation can be obtained

$$F = \Delta t f F_i = \left[\frac{1}{2} - \frac{1}{\pi} \arcsin \left(1 - \frac{\delta}{A} \right) \right] \frac{8^{1/2} n E d^{1/2} \delta^{3/2}}{3(1-\nu^2)} \quad (4)$$

Eq. (4) can also be expressed to obtain amplitude

$$A = \delta \left\{ 1 - \sin \left[\frac{\pi}{2} - \frac{1.06\pi F(1-\nu^2)}{nEd^{1/2}\delta^{3/2}} \right] \right\}^{-1} \quad (5)$$

3.4. The relationship between indentation depth and material removal rate

In RUM, the material volume removed by one abrasive particle can be calculated by [35]

$$V_1 = \frac{1}{3} K_v \pi \left(\frac{F_1}{K_C} \right)^{3/4} (d\delta - \delta^2)^{1/2} \left\{ \frac{DS}{60f} \left[\frac{\pi}{2} - \arcsin \left(1 - \frac{\delta}{A} \right) \right] \right\} \quad (6)$$

where, K_v is the fracture volume factor that is a proportionality parameter assumed to be constant regardless of input variables; K_C is the fracture toughness represented by stress intensity factor, $\text{MPa} \cdot \sqrt{\text{mm}}$; S is the tool rotation speed, rpm; and D is the cutting tool diameter, mm; The cutting tool has an outer diameter D_o and an inner diameter D_i due to the thickness of the core drill. Thus, D can be calculated by $D = \frac{D_o + D_i}{2}$.

Then, the material removal rate can be theoretically calculated by summing material removal rates of all the abrasive particles on the end face of the cutting tool. The material removal rate can be expressed by

$$MRR = \eta f V_1 = K_v \frac{n\pi S}{180} (D_o + D_i) \left(\frac{8^{1/2} E d^{1/2} \delta^{3/2}}{3K_C(1-\nu^2)} \right)^{3/4} (d\delta - \delta^2)^{1/2} \left[\frac{\pi}{2} - \arcsin \left(1 - \frac{\delta}{A} \right) \right] \quad (7)$$

In addition, it can be expressed in terms of the feedrate (F_r) and area of the cutting tool end face (A_0) based on the definition:

$$MRR = F_r A_0 = \frac{\pi(D_o^2 - D_i^2)}{4} F_r \quad (8)$$

By equating Eq. (7) and Eq. (8), the relationship between A and δ can be obtained

$$A = \delta \left\{ 1 - \sin \left[\frac{\pi}{2} - \frac{47F_r K_C^{3/4} (D_o - D_i)(1 - \nu^2)^{3/4}}{nSK_V (Ed^{1/2} \delta^{3/2})^{3/4} (d\delta - \delta^2)^{1/2}} \right] \right\}^{-1} \quad (9)$$

3.5. Ultrasonic vibration amplitude calculation model

By combining Eq. (5) and Eq. (9), the amplitude calculation model can be expressed as

$$\begin{cases} A = \delta \left\{ 1 - \sin \left[\frac{\pi}{2} - \frac{47F_r K_C^{3/4} (D_o - D_i)(1 - \nu^2)^{3/4}}{nSK_V (Ed^{1/2} \delta^{3/2})^{3/4} (d\delta - \delta^2)^{1/2}} \right] \right\}^{-1} \\ A = \delta \left\{ 1 - \sin \left[\frac{\pi}{2} - \frac{1.06\pi F (1 - \nu^2)}{nEd^{1/2} \delta^{3/2}} \right] \right\}^{-1} \end{cases} \quad (10)$$

The obtaining process of fracture volume factor (K_V) for brittle materials was reported by Cong et al. [35] and Liu et al. [5]. Elastic modulus (E_f, E_m), Poisson's ratio (ν_f, ν_m), and fracture toughness represented by energy (G_{cf}, G_{cm}) of each CFRP component (carbon fiber and epoxy, respectively) are listed in Table 2. E , ν , and K_C of CFRP can be calculated through micromechanics process [35, 43, 44, 51]. Number of active abrasive grains on the end face of cutting tool can be determined by $n = 6.561 \times 10^{-4} \left(\frac{C_a}{d^3 \rho} \right)^{\frac{2}{3}} A_0$ [5], where, C_a is the abrasive concentration and ρ is the density of abrasive material, g/mm³. In the simultaneous Eq. (10), only

indentation depth δ and ultrasonic vibration amplitude A are unknowns. Hence, A can be obtained from this mechanistic amplitude calculation model. δ also can be obtained by substituting A in either Eq. (5) or Eq. (9).

4. Experimental set-up and conditions

4.1. Workpiece properties

The CFRP composite workpiece used in this investigation had a dimension of 200 mm $\times$ 150 mm $\times$ 16 mm and it was composed of carbon fibers and epoxy resin matrix. Plain woven fabric of carbon fibers had an orientation of 0/90 degrees, where the carbon fiber yarn had a thickness of 0.2 mm and a width of 2.5 mm. The CFRP contained 21 layers of fabric with 2 layers of carbon fiber for each. The workpiece properties are listed in Table 2.

In RUM of CFRP, the elastic modulus used in this model is

$$E = \frac{E_f E_m}{V_f E_m + V_m E_f} \quad (11)$$

The Poisson's ratio in transverse direction can be calculated by

$$\nu = \frac{\nu_f V_f + \nu_m V_m}{E_f V_f + E_m V_m} \cdot E \quad (12)$$

The fracture toughness K_c can be calculated by

$$K_c \cong [2E (G_{cf} V_f + G_{cm} V_m)]^{1/2} \quad (13)$$

In Eqs. 11–13, V_f and V_m are the volume fractions of the fiber and the matrix, respectively.

4.2. Experimental set-up and cutting force measurement

The experiments were carried out on a rotary ultrasonic machine (Series 10, Sonicmill, Albuquerque, NM, USA) that was mainly comprised of three subsystems, including an ultrasonic spindle system, a coolant system, and a data acquisition system, as illustrated in Figure 6. The major components of the ultrasonic spindle system were an ultrasonic spindle integrated with an electric motor, an ultrasonic power supply, a control panel, and a hydraulic feeding device. The power supply output the high-frequency (20 kHz) electrical energy converted from the conventional line electricity. Such high-frequency electrical energy enabled a high-frequency mechanical vibration (namely ultrasonic vibration) with the help of a piezoelectric converter. Ultrasonic vibration was then amplified and transmitted to the cutting tool by an acoustic horn inside the ultrasonic spindle, leading to the cutting tool vibration at the frequency of 20 kHz. The ultrasonic vibration amplitude was adjustable due to the variations of the power supply output level. The motor atop the ultrasonic spindle provided the cutting tool rotations and the motor speed controller on the control panel could be adjusted for different tool rotation speeds. The coolant system consisted of a pressure regulator, flow rate gauges, valves, a pump, and a coolant tank, providing coolant to the spindle and the machining interface. The data acquisition system consisted of a dynamometer, a charge amplifier, an A/D convertor, and a computer with software. The dynamometer (9272, Kistler Inc., Winterthur, Switzerland) was utilized to measure the axial

cutting force F_z . Electrical signals (electric charges) from the dynamometer were amplified by the charge amplifier (5070A, Kistler Inc., Winterthur, Switzerland) and then transformed into digital signals by the A/D converter. A data acquisition card (PC-CARD-DAS16/16, Measurement Computing Corp., Norton, MA, USA) on a computer collected the digital signals with the help of a Dynoware software (2815A, Kistler Inc., Winterthur, Switzerland). Configured with the sensitivity values of the dynamometer, the cutting force values could be obtained. Figure 7 shows typical cutting force F_z fluctuating with time in RUM process. There are three major sections in this curve. Section (a) was the period when the cutting tool began to contact with the workpiece and the cutting force kept increasing until the abrasive portion on the tool end was fully involved in the workpiece. Section (b) was the stable cutting zone where all the abrasive grains on the tool participated in the machining process. Once the abrasive portion started leaving the workpiece, the cutting force was gradually decreased to zero, as shown in Section (c). The cutting force used to represent the cutting force F in Eq. (10) was the average value in Section (b).

4.3. Cutting tool variables and machining variables

The cutting tool, as illustrated in Figure 8, was a metal-bonded diamond core drill (N.B.R. Diamond Tool Corp., LaGrangeville, NY, USA). The details of cutting tool used in this study are listed in Table 3.

Considering the limitations of the experimental set-up (for example, ultrasonic vibration frequency was fixed at 20 kHz on the machine), only tool rotation speed, feedrate, and ultrasonic power were changed in the experiments. The ranges of these machining variables were selected based on the experience from the authors' preliminary experiments [16, 17] as well as the guidance from the RUM machine manufacturer, Sonic-Mill Inc. The detailed experimental conditions are listed in Table 4.

5. Pilot experimental verification

As the machining trajectories on the RUM machined surfaces of CFRP composite were invisible, a special workpiece by stacking CFRP composite and ductile aluminum (Al) alloy was designed and manufactured for ultrasonic vibration amplitude measurement in RUM of CFRP, as shown in Figure 9a. The contacting surfaces of CFRP and Al were ground and polished to ensure them to be perfectly joined by bolts and nuts. During the RUM machining, cutting tool primarily cut the CFRP composite at the joining interface, and the material removal mainly occurred within the CFRP composite. Only a small amount of Al was machined simultaneously to catch the abrasive trajectories without changing the dominated brittle fracture mode, as shown in Figure 9b. After the RUM machining, the CFRP and Al workpiece stack was disassembled. The grain trajectory could be observed from the morphology of the machined Al surface using an optical microscope,

as shown in Figure 9c. Thus, the ultrasonic vibration amplitude could be experimentally measured.

Experiments were conducted by varying each machining variable and keeping other variables constant. Figure 10 show comparisons between amplitudes calculated from the mechanistic calculation model and those measured by the microscope observation measurement method. It can be seen that the trends of ultrasonic vibration amplitude with respect to the machining variables (ultrasonic power, tool rotation speed, and feedrate) obtained by model agreed well with those obtained by the experiments. At the highest level of ultrasonic power, the lowest level of tool rotation speed, or the highest level of feedrate, calculation model caused a slightly larger ultrasonic vibration amplitude than the experimental investigations. This was due to the fact that these levels of the input variables were the extreme machining conditions in RUM process, which resulted in a more fluctuated cutting force generating less accurate cutting force than that as predicted. On the other hand, RUM was a complex machining process that combined both ultrasonic assisted machining and abrasive grinding. In order to simplify the machining conditions, several major assumptions for both cutting tool and workpiece material were involved in the development of the mechanistic model, making the theoretical cutting conditions different with the actual ones. In addition, a small amount of Al materials were removed in the actual experimental conditions to facilitate the amplitude measurement. The existence of such non-CFRP materials would cause the errors between the predicted values and the measured

results.

It can be seen from Figure 10a that the ultrasonic vibration amplitude increased remarkably with increase of ultrasonic power for both theoretical and experimental investigations in RUM of CFRP. The ultrasonic vibration amplitude was significantly affected by ultrasonic power. This trend was the same as the reported result in RUM of Ti [22]. Figures 10b and 10c show that ultrasonic vibration amplitude slightly decreased in RUM of CFRP with the increase of tool rotation speed and decrease of feedrate for both model and experimental results. These trends were different from those in RUM of Ti. In RUM of Ti, ultrasonic vibration amplitude showed no significant variations with changes in tool rotation speed and feedrate. The major possible reason is that material removal mechanisms in RUM of CFRP (brittle fracture) and in RUM of Ti (ductile removal) are different.

6. Conclusions

This paper developed a novel modeling method for ultrasonic vibration amplitude measurement through cutting force in RUM of brittle materials. To the best knowledge of the authors, this is the only reported method with the capability of calculating theoretical ultrasonic vibration amplitude from the measured cutting force. In this investigation, ultrasonic vibration amplitudes calculated by the theoretical model had similar trends with those measured by experimental

investigation. The ultrasonic vibration amplitude increased with ultrasonic power increasing, tool rotation speed decreasing, and feedrate increasing.

Ultrasonic vibration amplitude, one of the most important input variables in RUM, has remarkable influences on cutting force, cutting temperature, tool wear, and edge chipping in RUM of brittle materials. Additionally, the mechanistic calculation model reported in this paper can provide a relationship between ultrasonic vibration amplitude and different combinations of input variables, which is a foundation for building models to predict other output variables in RUM.

7. Acknowledgements

This work is supported by the National Science Foundation in United States through award CMMI-1538381.

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Figure 1. Illustration of RUM.

Figure 2. Illustrations of machined rod and hole.

Figure 3. Measurement of ultrasonic vibration amplitude on a microscopic picture in RUM of Ti.

Figure 4. Machined rod surfaces of different materials.

Figure 5. Amplitude calculation model development procedures.

Figure 6. RUM system set-up.

Figure 7. Typical curve of cutting force F_z versus cutting time in RUM process.
(a. The tool was feeding into the workpiece; b. The tool fully fed into the workpiece; and c.
The tool was leaving the workpiece.)

Figure 8. Illustration of cutting tool.

Figure 9. Ultrasonic vibration amplitude measurement. (a. Illustration of the designed CFRP/Al stack; b. The manufactured stack after RUM process; and c. The morphology of the machined Al surface)

a. Effects of ultrasonic power.

b. Effects of tool rotation speed.

c. Effects of feedrate.

Figure 10. Comparisons between calculated model results and experimental results of ultrasonic vibration amplitude.

Table 1. Input variables in model development.

Category	Input variable	Unit
Workpiece properties	Elastic modulus E	MPa
	Poisson's ratio ν	
	Fracture toughness K_c	MPa $\cdot\sqrt{\text{mm}}$
Tool variables	Outer diameter D_o	mm
	Inner diameter D_i	mm
	Abrasive concentration C_a	
	Abrasive size d	mm
Machining variables	Amplitude A	mm
	Frequency f	Hz
	Feedrate F_r	mm/s
	Tool rotation speed S	rpm

Table 2. Properties of CFRP workpiece material.

Property	Unit	Value
Density of CFRP	kg/m ³	1550
Hardness (Rockwell)	HRB	70–75
Poisson's Ratio (ν_{12})	-	0.34
Poisson's Ratio (ν_{13})	-	0.34
Poisson's Ratio (ν_{23})	-	0.42
Longitudinal Young's modulus (E_1)	GPa	136
Transverse Young's modulus (E_t)	GPa	10.5
In-plane shear modulus (G_{12})	GPa	3.76
Density of carbon fiber	kg/m ³	1800
Poisson's ratio of carbon fiber (ν_f)	-	0.3
Young's modulus of carbon fiber (E_f)	GPa	230
Fracture toughness of carbon (Energy/ G_{cf})	J/m ²	2
Density of epoxy matrix	kg/m ³	1200
Poisson's ratio of epoxy matrix (ν_m)	-	0.4
Young's modulus of epoxy matrix (E_m)	GPa	4.5
Fracture toughness of epoxy matrix (Energy/ G_{cm})	J/m ²	500

Table 3. Cutting tool parameters.

Parameter	Unit	Value
Outer diameter (D_o)	mm	9.54
Inner diameter (D_i)	mm	7.82
Tuning length	mm	44.5
Abrasive material		Diamond
Grit size	mesh #	60/80
Abrasive concentration		100
Number of slots		0
Bond		B (metal)

Table 4. Experimental conditions.

Input variable	Unit	Value
Tool rotation speed, S	rpm	2000; 3000; 4000; 5000
Feedrate, F_r	mm/s	0.2; 0.35; 0.5; 0.65; 0.8
Ultrasonic power	%	30; 40; 50; 60