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Experimental study on vibration stability in rotary ultrasonic machining of ceramic matrix composites: Cutting force variation at hole entrance

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ABSTRACT

Rotary ultrasonic machining (RUM) is a superior hole-manufacturing method for ceramic matrix composites (CMC) with reduced cutting force and improved hole quality. Among various processing parameters, sufficient and stable ultrasonic vibration is crucial to guaranteeing RUM effectiveness in terms of cutting force reduction. This study was devoted to investigating the effect of material characteristics on vibration stability in RUM of CMC. The variations of cutting force and ultrasonic power at hole entrance in RUM of C/SiC CMC, quartz glass and sapphire were evaluated. Experimental results on these three materials were all in good consistency with the predicted results of theoretical model, which describes the cutting force effect on ultrasonic power variation without considering whether the machined material was composite or not. Ultrasonic power variation was also used to help identify the effect of thermo-mechanical loading on resonant frequency during RUM of C/SiC CMC. It was revealed that the composite characteristic of CMC didn't affect the effect mechanism of thermo-mechanical load on the stability of ultrasonic vibration. By pre-adjustment of tuning frequency, the indispensable effect of tool wear on cutting force increase in RUM of CMC can be weakened.

1. Introduction

The hard and brittle materials represented by optical glass, advanced ceramics and ceramic matrix composites (CMC) are the most difficult-to-cut materials, due to severe tool wear and low resistance to machining induced damages. Rotary ultrasonic machining (RUM) has been proved as a superior hole-manufacturing method for brittle materials with reduced cutting force and improved hole quality. As presented in Fig. 1, in RUM, an electroplated diamond core tool vibrates in ultrasonic frequency with micrometre scale amplitude, while feeding towards the workpiece to remove materials. The inner coolant flows into and out of the diamond core tool to cool down the cutting zone and discharge chips. A plenty of typical and widely utilized brittle materials have been successfully machined by RUM, such as optical glass [1–3], sapphire [4], silicon carbide [5], C/SiC [6,7], CFRP [8,9], glass ceramics [10] and zirconia [11].

Among the various processing parameters of RUM, ultrasonic amplitude that characterizes the intensity of ultrasonic vibration is crucial to guaranteeing RUM effectiveness in terms of cutting force reduction. According to the experimental and theoretical results by Cong et al., the cutting force of RUM decreases with increasing ultrasonic amplitude [12]. As a typical application of power ultrasonic, RUM ought to be sensitive to the load produced by material removal process [13]. In other words, cutting force would affect the actual ultrasonic amplitude during the machining process. The possible decrease of ultrasonic amplitude is dangerous to the performance guarantee of RUM. However, up to now, the invariant ultrasonic amplitude was assumed in most reported studies neglecting the effects of material removal [14].

There are only a few studies that examined the effect of material removal on the stability of ultrasonic amplitude, due to the difficult measurement of actual ultrasonic amplitude during RUM. Ning et al. developed a measurement method for actual ultrasonic amplitude by observing the moving trajectory of diamond particle, which was left on the hole surface of metallic material [15]. It was discovered that the actual ultrasonic amplitude is relevant to the feedrate and spindle speed. Wang et al. used the variation of ultrasonic power to monitor the variation of actual ultrasonic amplitude during machining process [16]. Through this method, the effect mechanism of thermo-mechanical load on the vibration stability during RUM of quartz glass was investigated. It was concluded that thermo-mechanical load affects the vibration stability by changing the resonant frequency of RUM machine tool (RUMT) [16]. Furthermore, the actual ultrasonic amplitude decreases

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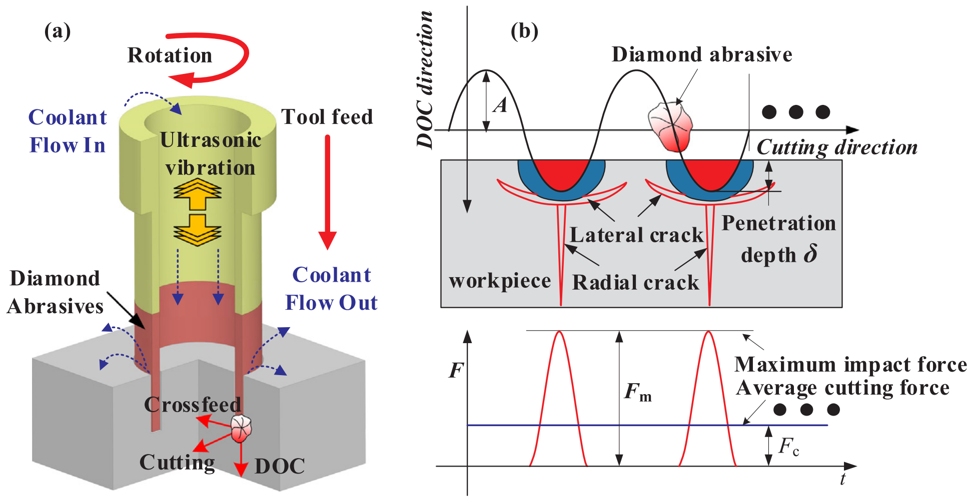

Fig. 1. Illutration of RUD. (a) Basic configuration. (b) Machining mechanism.

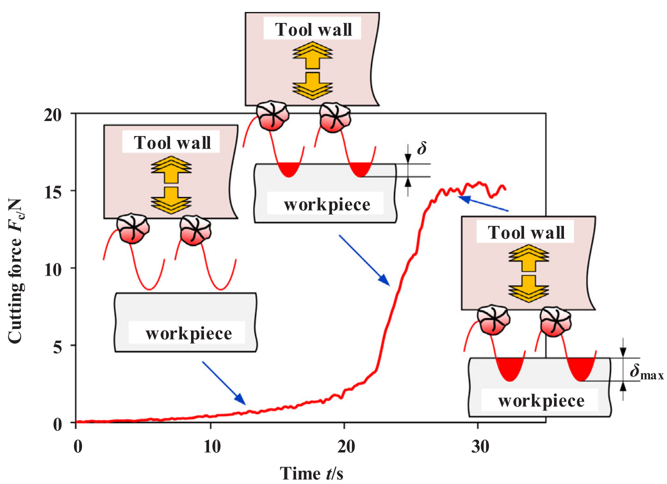

Fig. 2. cutting force variation with varying penetration depth at hole entrance.

with increasing cutting force when the RUMT is tuned at its corresponding idle resonant frequency [17].

All aforementioned conclusions regarding vibration stability were drawn from experiments on single-substrate brittle materials. CMC such as C/SiC are also important machining objects of RUM. Even though the reinforcement and matrix of CMC are both brittle, the role of composite characteristic in the material removal effect on vibration stability is not explicit. The question whether the conclusions established on single-substrate material could also be valid in RUM of CMC is also not well answered. In this study, the aforementioned question was answered both qualitatively and quantitatively. The vibration stability in RUM of C/SiC CMC was investigated by analysing the ultrasonic power and cutting force variations at hole entrance, when RUMT was tuned at different frequencies. The experimental results on quartz glass and sapphire were used as comparison benchmarks.

2. Materials and methods

2.1. Cutting force model at hole entrance

In order to investigate the effect of CMC material characteristic on the stability of ultrasonic vibration, various levels of processing parameters are supposed to be selected for experimental design to obtain sufficient data. However, this way not only requires numerous experiments, but also enhances the effect of thermal load due to the relatively longer machining duration. In this study, the cutting force variation at hole entrance was used for data collection to help reduce experimental workload and suppress the effect of thermal load.

As presented in Fig. 1(b), the diamond abrasives in RUM are not always in contact with workpiece material. The abrasives are in contact with and separated from workpiece material periodically with a penetration depth δ in an ultrasonic frequency. During the periodical penetration process, lateral and radial cracks are produced beneath the material surface. The lateral cracks propagates and interact with each other resulting in material removal. According to our previous study [18], cutting force F_c in RUM can be expressed as a function of penetration depth δ:

$$F_c = \frac{\sqrt{2}\, m\xi \tan^2\psi H_V}{4\pi\sqrt{A}}\delta^{\frac{5}{2}} \tag{1}$$

where ξ and ψ are the geometrical factor and semi-vertical angle of abrasive indenter respectively, H_V is the micro hardness of workpiece material, m is the quantity of effective abrasives that participate in material removal, A is the ultrasonic amplitude of tool.

Eq. (1) indicates that penetration depth δ greatly affects cutting force F_c in RUM of brittle materials. As presented in Fig. 2, the increase of cutting force at hole entrance results from the penetration depth δ increase from zero to δ_{max}, which is the stable and maximum value of δ. The δ_{max} is dependent of processing parameters, such as ultrasonic amplitude, spindle speed, feedrate and abrasive geometries [12]. Therefore, under certain processing condition, the cutting force increase at hole entrance reflects a continuous increase of penetration depth δ. This kind of continuous increase of penetration depth provides sufficient information of machining process, which can only be obtained by changing processing parameters in conventional experimental design method.

2.2. Experiment design

The RUM experiments in this study were performed on Ultrasonic 50 (DMG, Germany). Its tuning frequency range was 16.5–30 kHz. As presented in Fig. 3, the key components of Ultrasonic 50 were a power supply and ultrasonic spindle. The power supply had a maximum output power of 300 W and converted a 50 Hz electrical current into ultrasonic frequency output for the ultrasonic spindle. The ultrasonic spindle had a maximum rotation speed of 6000 rpm. It consisted of a piezoelectric transducer, an ultrasonic concentrator and a diamond core tool. The piezoelectric transducer converted the current of ultrasonic frequency into mechanical vibration. The ultrasonic concentrator and the diamond core tool were synergistically designed to amplify the

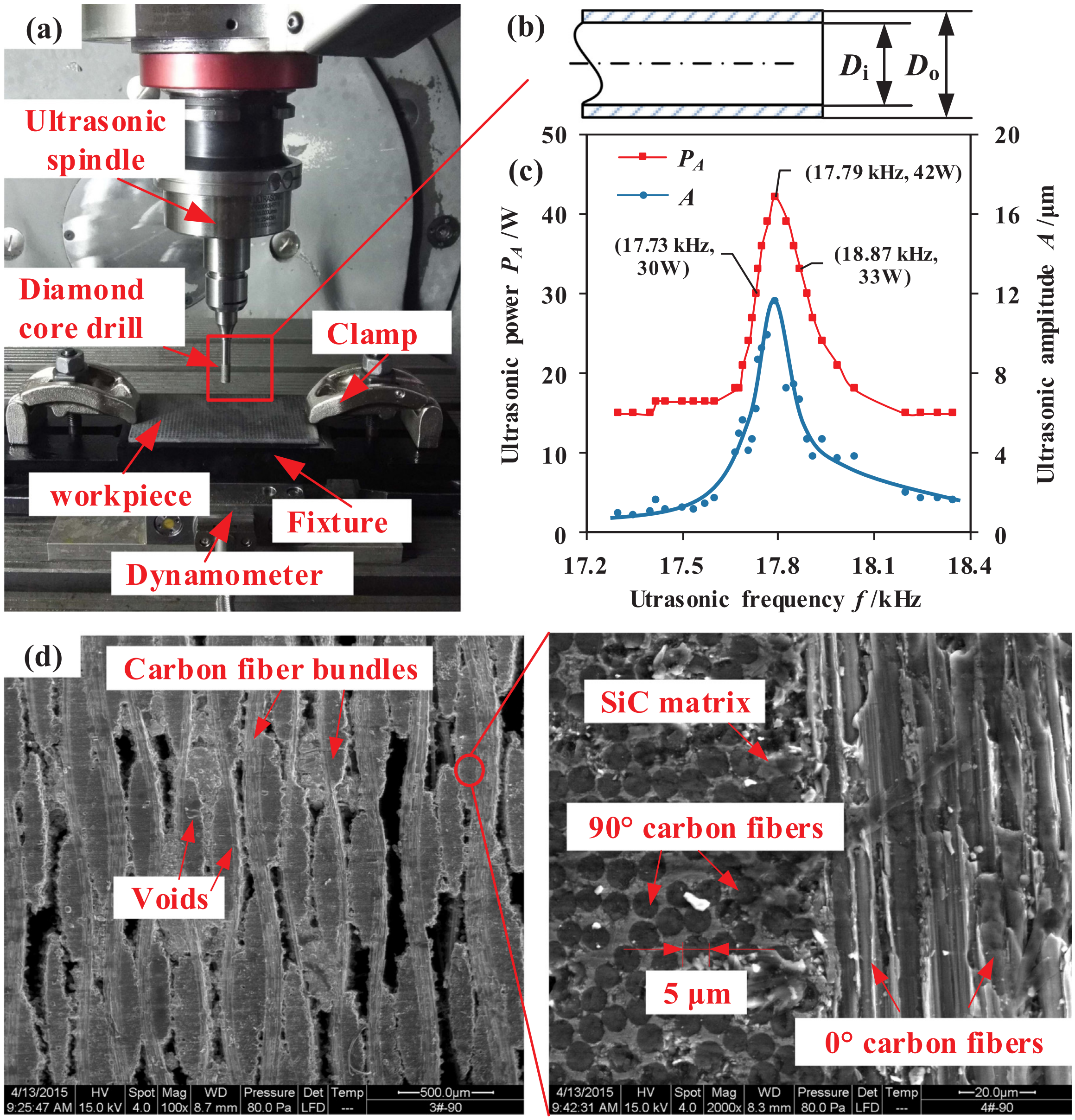

Fig. 3. Experiment setup. (1) Ultrasonic machine tools arrangement. (2) Dimensions of diamond core tool. (3) Ultrasonic power/amplitude vs frequency characteristic of ultrasonic machine tools. (d) Micro structures of 2D C/SiC lamenates.

mechanical vibration into applicable magnitude for machining. As presented in Fig. 3(b), the tool utilized in this study was electroplated diamond abrasives of D76 in grit size. Its outer diameter D_o was 8 mm and inner diameter was D_i 5.6 mm. Fig. 3(c) shows the ultrasonic power/amplitude vs frequency characteristic of Ultrasonic 50 when it was mounted with the aforementioned tool [16]. As presented in Fig. 3(c), when tuning frequency was 17.73 kHz or 18.87 kHz, the ultrasonic power/amplitude was smaller than that when tuning frequency was 17.79 kHz. The idle resonant frequency f_{r0} was 17.79 kHz, the idle ultrasonic amplitude A_0 was 11.2 μm, the peak ultrasonic power P_{A_0} was 42 W.

The RUM experiments were performed on quartz glass, sapphire crystal and C/SiC CMC. A fixture with two clamps was utilized to hold workpiece. The quartz glass and sapphire crystal are typical single-substrate brittle materials, their mechanical properties are listed in Table 1. The C/SiC, namely the carbon fibers reinforced SiC matrix composite, is a typical brittle composite material. The C/SiC workpiece utilized in this study was fabricated by the precursor infiltration and pyrolysis. Its density was 1.8 g/cm^3. As presented in Fig. 3(d), the C/SiC was composed of carbon fibers, SiC matrix and voids. The diameter of carbon fibers was about 5 μm. The carbon fiber bundles oriented in 0° and 90°. The processing parameters utilized for RUM experiments are listed in Table 2. The processing coolant (Blaser, Switzerland) was utilized both internally and externally. A piezoelectric dynamometer (9256C2, Kistler Instrument Corp., Switzerland) was used to measure cutting force. The variation of ultrasonic power was recorded from the operation panel of Ultrasonic 50.

Table 1
Material properties.

Property	Unit	Quartz glass	Sapphire
Young's modulus	GPa	76.7	478
Vickers hardness	GPa	9.5	27.6
Fracture toughness	MPa m$^{1/2}$	0.71	2.0
Density	g/cm^3	2.2	3.9
Poisson ration	/	0.17	0.28

Table 2
Processing parameters.

Experiment	Spindle speed	Feedrate	Material	Tuning frequency f_t
Group 1	2000 rpm	0.3 mm/min	C/SiC	17.73 kHz
Group 2	2000 rpm	0.3 mm/min	C/SiC	17.87 kHz
Group 3	1000 rpm	0.8, 1 mm/min	C/SiC, Quartz glass, Sapphire	17.79 kHz
Group 4	3000 rpm	5 mm/min	C/SiC	17.79 kHz or 17.85 kHz

3. Results and discussion

3.1. Cutting force vs ultrasonic power variation at hole entrance when RUMT is not tuned at its resonant frequency

As presented in Fig. 3(c), when the tuning frequency of RUMT was lower than its resonant frequency, the ultrasonic power/amplitude increased with the increasing tuning frequency. In contrast, when the tuning frequency of RUMT exceeded its resonant frequency, the ultrasonic power/amplitude decreased with the increasing tuning frequency. Therefore, the deviation between the resonant and tuning frequencies of RUMT significantly affected the intensity of ultrasonic vibration. A higher deviation between resonant and tuning frequencies was followed by larger decrease of ultrasonic power/amplitude.

The experimental results of Groups 1 and 2 were used to qualitatively compare the effect mechanism of cutting force on vibration stability when workpiece materials were different. Cutting force is always coupled with the thermal effect of ultrasonic vibration. Fig. 4 presents the effects of thermo-mechanical loads on the stability of ultrasonic vibration, which was concluded in our previous study when single-substrate materials were machined. [16]. The thermo-mechanical loads affect the stability of ultrasonic vibration by changing the resonant frequency of RUMT. The variation of deviation between the resonant and tuning frequencies results in the variation of ultrasonic amplitude. In this study, the validity of abovementioned loads effect mechanism when machining C/SiC was evaluated by comparison with machining quartz glass.

As presented in Fig. 3(a), the tuning frequency of 17.73 kHz in the experiments of Group 1 was lower than the idle resonant frequency of 17.79 kHz. The corresponding ultrasonic power at the tuning frequency of 17.73 kHz was 30 W. Fig. 5(a) and (b) present the experimental results on C/SiC and quartz glass respectively, when the tuning frequency of RUMT was lower than its idle resonant frequency.

As demonstrated in Fig. 5, the variation tendencies of ultrasonic power in the vicinity of hole entrance were identical when machining different materials, as well as cutting force. Before the tool machined workpiece, the ultrasonic power increased due to thermal effect of ultrasonic vibration, which reduced the resonant frequency of RUMT. Since the tuning frequency was lower than the idle resonant frequency, the resonant frequency reduction narrowed the deviation between the tuning and resonant frequencies. Therefore, the ultrasonic power increased before the tool machined the workpiece. However, when the tool started machining the workpiece, the ultrasonic power decreased as cutting force increased, verifying that the cutting force increased the resonant frequency of RUMT. Since the tuning frequency was lower than the idle resonant frequency, the resonant frequency increase widened the deviation between the tuning and resonant frequencies.

As presented in Fig. 3(a), the utilized tuning frequency of 17.87 kHz in the experiments of Group 2 was higher than the idle resonant frequency of 17.79 kHz. The ultrasonic power at the tuning frequency of 17.87 kHz was 33 W. Fig. 6(a) and (b) presents the experimental results on the C/SiC and quartz glass respectively, when the tuning frequency of RUMT exceeded its idle resonant frequency.

As demonstrated in Fig. 6, the variation tendencies of ultrasonic power in the vicinity of the hole entrance when machining C/SiC and quartz glass were identical, as well as cutting force. Before the tool machined workpiece, the ultrasonic power decreased due to the thermal effect of ultrasonic vibration. Since the tuning frequency was higher than the idle resonant frequency, the resonant frequency reduction induced by thermal effect widened the deviation between the tuning and resonant frequencies. Therefore, the ultrasonic power decreased before the workpiece machining. However, when the tool started machining the workpiece, the ultrasonic power increased as the cutting force increased, indicating that the cutting force increased the resonant frequency of the RUMT. Since the tuning frequency was higher than the idle resonant frequency, the resonant frequency increase narrowed the deviation between the tuning and resonant frequencies.

Therefore, it can be concluded from the experimental results presented in Figs. 5 and 6 that, the composite characteristic of CMC did not qualitatively affect the effect mechanism of thermos-mechanical loads on the stability of ultrasonic vibration.

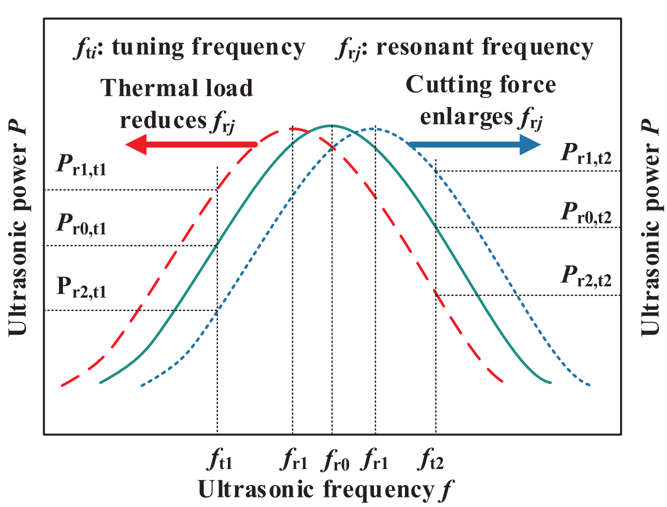

Fig. 4. Schematic diagram of ultrasonic power variation when the ultrasonic system is not tuned at its resonant frequency.

3.2. Cutting force vs ultrasonic power variation at hole entrance when RUMT is tuned at its resonant frequency

When RUMT is tuned at its idle resonant frequency f_{r0}, the effect of cutting force F_c on ultrasonic power variation ΔP can be expressed as [17]:

$$\Delta P = \frac{4\pi f_{r0}}{V_{M0}} F_c^2 \tag{2}$$

where $\Delta P = P_{A_0} - P_A$, P_{A_0} and P_A are ultrasonic powers that RUMT consumes when ultrasonic amplitude are A_0 and A respectively. V_{M0} is the energy consumption factor of RUMT. For Ultrasonic 50, the V_{M0} has been obtained as 4.25 N/μm by experiments [17]. The detailed acquisition cutting force F_c and ultrasonic power variation ΔP is illustrated in Fig. 7. In the modeling process of Eq. (2), only the material hardness H_V was involved. The difference of composites and non-composites in material characteristic was not distinguished. Eq. (2) indicates that the

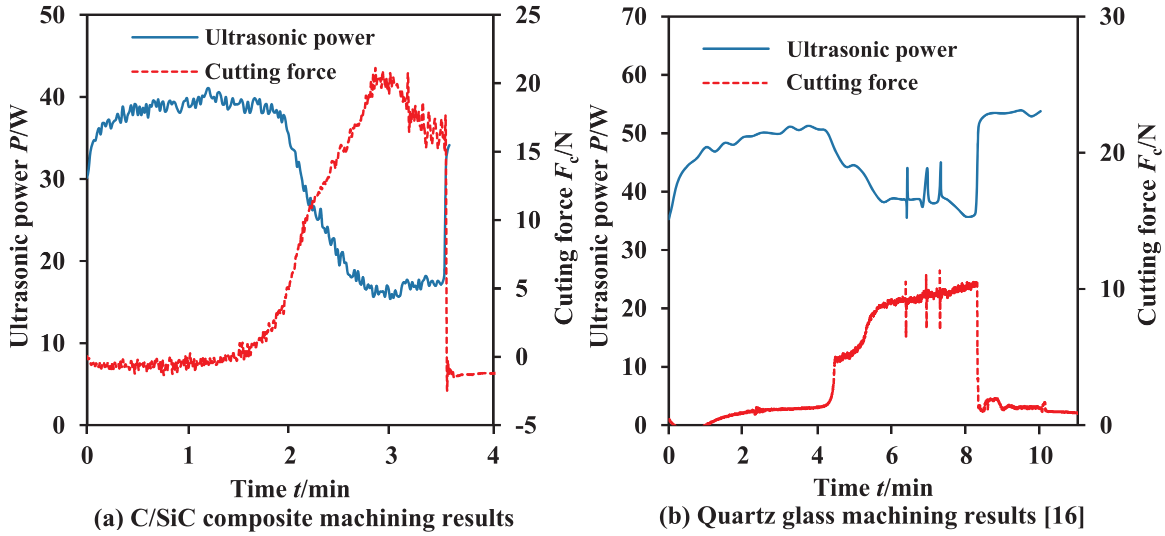

Fig. 5. Cutting force vs ultrasonic power when tuning frequency was smaller than idle resonant frequency.

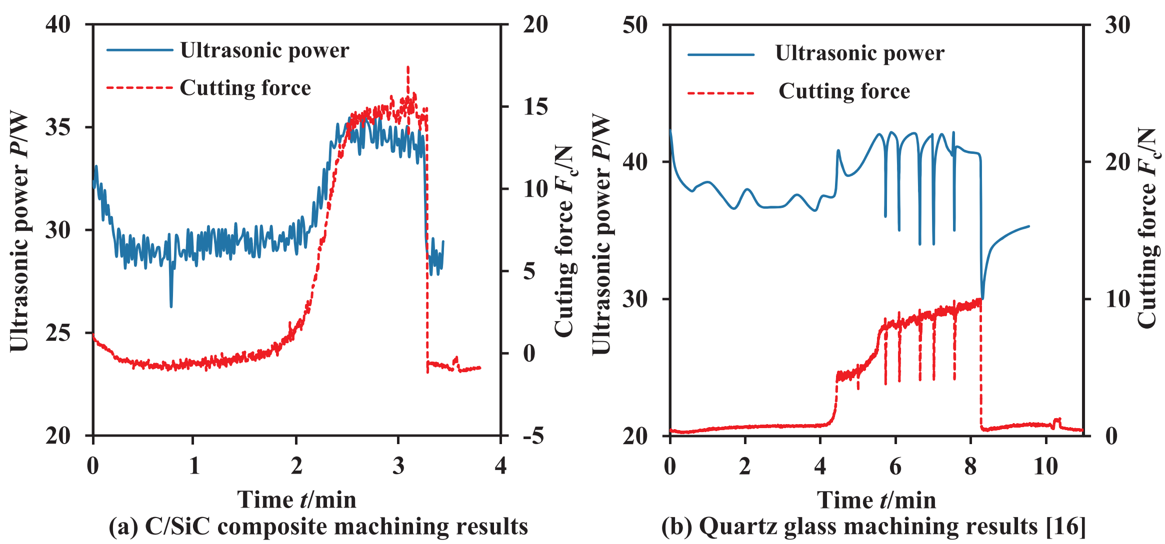

Fig. 6. Cutting force vs ultrasonic power when tuning frequency was larger than idle resonant frequency.

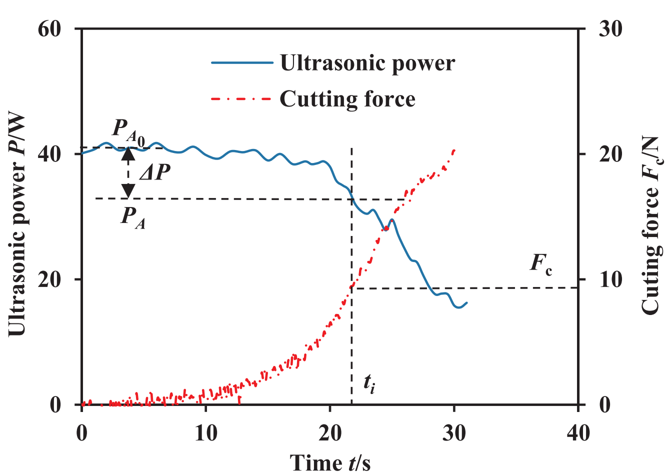

Fig. 7. Calculation of cutting force and ultrasonic power variation.

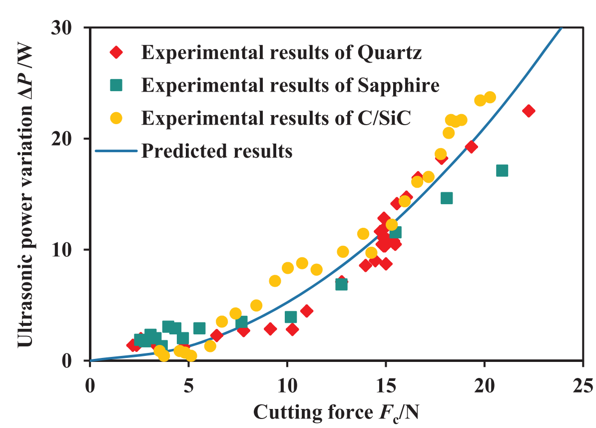

Fig. 8. Effect of cutting force on ultrasonic power variation at hole entrance when RUMT tuning frequency was at its idle resonant frequency.

effect of material characteristic on vibration stability can be attributed to the differences of cutting force.

The experimental results of Group 3 were used to quantitatively compare the effect mechanism of cutting force on vibration stability, when workpiece materials were different. Fig. 8 presents the predicted results of Eq. (2) as well as experimental results in terms of ΔP versus F_c, when the RUMT was tuned its idle resonant frequency. As presented in

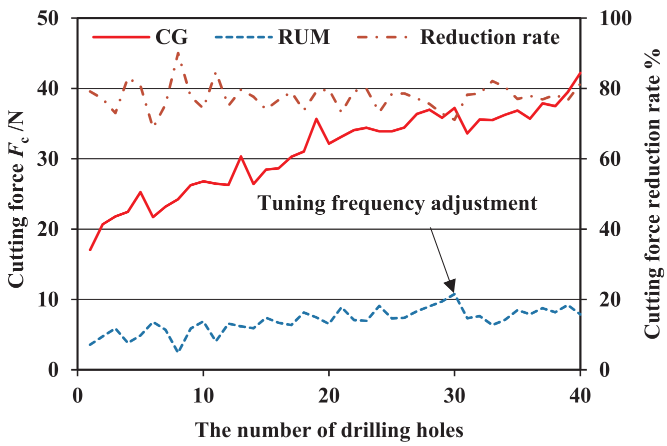

Fig. 9. Effect of tool wear on cutting force variation.

Fig. 8, the ultrasonic power variation ΔP increased with increasing cutting force. The predicted results of Eq. (2) were in good agreement with the experimental results on quartz, sapphire and C/SiC materials. The differences in ultrasonic power versus cutting force curves among C/SiC, quartz glass and sapphire were acceptable. They came from several sources, including measurement error and the unbalanced effects of thermal load. As presented in Fig. 8, the effect of relative measurement error was larger when the cutting force was small. Eq. (2) was derived with assuming that the RUMT was tuned at its idle resonant frequency after the thermal balance was reached. However, the thermal balance couldn't be strictly reached due to the coupling effects of thermo-mechanical loads on ultrasonic vibration. The increasing cutting force made the ultrasonic amplitude decrease. The decrease of ultrasonic amplitude weakened the intensity of heat generation, resulting in the break of thermal balance.

According the modeling process of Eqs. (1) and (2), the composites characteristic of C/SiC material was not taken into consideration. Therefore, the good agreement between the experimental and theoretical results quantitatively indicates that the composite characteristic of CMC can be neglected in the cutting force effect on the vibration stability. The insignificant effect of composite characteristic of CMC was beneficial for the universal design of RUMT. In actual engineering application, the RUMT is generally tuned at its idle resonant frequency to obtain the maximum value of ultrasonic amplitude [13]. The RUMT designer is recommended to consider the unavoidable effect of cutting force on the stability of ultrasonic vibration. According to Eq. (2), the V_{M0} improvement can contribute in the effect suppression of cutting force on the ultrasonic power variation. Regardless of brittle materials, only one equation exists describing the effect of cutting force on the ultrasonic power variation. Therefore, the RUMT can be designed to own more stable ultrasonic vibration under the guidance of Eq. (2), without considering whether the workpiece material is composite or not.

3.3. *Tuning frequency adjustment to suppress the effect of tool wear on cutting force increase*

Fig. 9 shows the experimental results of Group 4. Both the cutting force variations of RUM and conventional grinding (CG) of C/SiC were illustrated. The first 30 holes of RUM were drilled when RUMT was tuned at its idle resonant frequency. The last 10 holes of RUM were drilled when RUMT was tuned at a larger frequency than the idle resonant frequency. As presented in Fig. 9, the cutting forces of RUM were always smaller than that of CG. With the help of ultrasonic vibration, RUM can reduce cutting force by about 80% compared with CG. Cutting force reduction is one of the most important superiority of RUM, which directly induces the improvement of hole exit quality. Tool wear can greatly affect the cutting force of RUM and CG. As shown in Fig. 9, the cutting force increased with the number increase of drilling holes in RUM or CG of C/SiC. However, the cutting force reduction rates did not vary a lot with the drilling progress. Generally for both RUM and CG, the effect of tool wear on cutting force is related the variation of abrasive geometries and quantity, which are important parameters in the cutting force model of Eq. (1). The tool wear is a dynamic process which results in the dynamic variation of cutting force in Fig. 9.

However, the effect of tool wear on cutting force in RUM also has its unique characteristic. The tool wear in RUM makes cutting force increase by interactive ways. Firstly, as illustrated by Eq. (1), the bad variations of abrasive geometries and quantity have an enlargement effect on cutting force. The increase of cutting force would further reduce the ultrasonic amplitude due to the change of resonant frequency of RUMT. The cutting force tends to be larger due to the reduction of ultrasonic amplitude. Hence, in order to suppress the positive effect of tool wear on cutting force, the tuning frequency is recommended to be larger than the idle resonant frequency for compensating the resonant frequency increase due to cutting force. In this study, when the tool started drilling the 31 hole, the tuning frequency of RUMT was adjusted based on the above discussion. As shown in Fig. 9, the cutting force in RUM decreased after the tuning frequency adjustment. To a certain extent, this result also indicates that if the tuning frequency can be adjusted automatically in real-time during the machining process, the processing performance of RUM would be more promising and reliable.

4. Conclusions

This study was devoted to the investigation of vibration stability in rotary ultrasonic machining (RUM) of ceramic matrix composites (CMC). The experimental results on C/SiC and quartz glass were compared in terms of ultrasonic power variation versus cutting force, when the tuning frequency of RUMT was different from its idle resonant frequency. The variation tendencies of ultrasonic power were identical when machining C/SiC and quartz glass. This qualitatively indicates that the composite characteristic of CMC did not influence the effect mechanism of cutting force on vibration stability. In addition, the ultrasonic power variation versus cutting force at hole entrance were obtained, when the RUMT was tuned at its idle resonant frequency. The experimental results on quartz glass, sapphire and C/SiC were all in good agreement with the predicted results of theoretical model, which described the effect of cutting force on ultrasonic power variation without consideration to the machined material nature. The good consistency of experimental and theoretical results quantitatively indicates that the composite characteristic of CMC did not influence the cutting force effect degree on vibration stability. The RUMT with more stable ultrasonic vibration can be designed under the guidance of relationship between cutting force and ultrasonic power variation, without consideration whether the workpiece material is a composite or not. By pre-adjustment of tuning frequency, the bad effects of tool wear on cutting force increase can be suppressed to some extent.

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