Ceramics International 44 (2018) 1227–1239

Contents lists available at ScienceDirect

Ceramics International

journal homepage: www.elsevier.com/locate/ceramint

Review article

Damage formation and suppression in rotary ultrasonic machining of hard and brittle materials: A critical review

Jianjian Wang[a,b], Jianfu Zhang[a], Pingfa Feng[a,c,*], Ping Guo[b]

[a] State Key Laboratory of Tribology, Tsinghua University, Beijing, China
[b] Department of Mechanical and Automation Engineering, The Chinese University of Hong Kong, Hong Kong, China
[c] Division of Advanced Manufacturing, Graduate School at Shenzhen, Tsinghua University, Shenzhen, China

ARTICLE INFO

Keywords:
Rotary ultrasonic machining
Machining induced damages
Subsurface damage
Edge chipping
Brittle materials

ABSTRACT

Rotary ultrasonic machining (RUM) combines diamond grinding with small-amplitude tool vibration, to improve machining processes of hard and brittle materials. It has been successfully applied to the machining of a number of brittle materials from optical glasses to advanced ceramics as well as ceramic matrix composites. The emphasis of this literature review was on formation mechanism and suppression methods of machining induced damages that truly limit RUM machining efficiency improvement of brittle materials. In this review paper, material removal mechanism and cutting force modeling of RUM of brittle materials were presented, as well as all corresponding roles in the damage formation process. The critical processing capacity of RUM machine tools was described, which guarantees the RUM effectiveness and consequently constitutes the boundary condition of processing parameters determination. Formation mechanisms of edge chipping, tearing defects, subsurface damages, and their interactive effects were summarized. Advances in damage suppression methods were also described, including optimization of processing parameters, tool design of low damage, and other methods such as rotary ultrasonic elliptical machining.

1. Introduction

Brittle materials, such as optical glass, advanced ceramics and ceramic matrix composites have been widely applied in the industries of aeronautics, astronautics, automobile, medical devices, defense and military, due to the corresponding superior performances in high hardness, low density, high heat and abrasion resistance, as well as high chemical stability [1]. As an example, due to both excellent optical properties and high chemical stability, the optical glass is an important raw material for the key components manufacturing of optical instruments including prisms, lenses, reflectors and windows. It is also a fundamental material of information technology, consequently widely utilized in the field of optical transmission, storage and display [2]. Furthermore, as a typical advanced ceramic, sapphire has been frequently applied to many high technology fields, such as in infrared night vision equipment, window of high-speed fairings, substrate of microelectronics, due to high strength, good light-admitting quality and high resistance to wind erosion [3]. In addition, ceramic matrix composites, represented by C/SiC and SiC/SiC, have emerged as strategic structural materials for meeting the challenges in tougher and stronger material applications in the fields of nuclear, energy, military, aerospace and transportation industries. The ceramic matrix composites have excellent physical and mechanical properties, combining ceramic characteristics of high strength, hardness and temperature resistance with high toughness owing to fibers reinforcement, resulting in an improved safety factor of products under impact loading [4].

The fast development of high technology places increasingly higher requirements on the machining quality and efficiency of brittle materials. In contrast, due to their high hardness and low toughness as well as the layered characteristics of ceramic matrix composites, the machining of brittle materials is very difficult [5]. Up to now, grinding through diamond abrasives is still the major conventional machining method applied to brittle materials. Simultaneously, the conventional metal cutting methods with cremated tools are not qualified for brittle materials machining due to severe tool wear and machining induced damage. The high efficiency and low damage machining of brittle materials has already become the major obstacle that limits the further application of brittle materials. The machining of brittle materials is still a hotpot in the fields of materials processing technology. Various unconventional machining methods have been introduced or invented by academics and engineers, to improve the machining efficiency and quality of brittle materials, such as ultrasonic vibration assisted

* Correspondence to: Department of Mechanical Engineering, Tsinghua University, 100084 Beijing, China.
E-mail address: fengpf@mail.tsinghua.edu.cn (P. Feng).

http://dx.doi.org/10.1016/j.ceramint.2017.10.050
Received 26 August 2017; Received in revised form 10 October 2017; Accepted 10 October 2017
Available online 12 October 2017

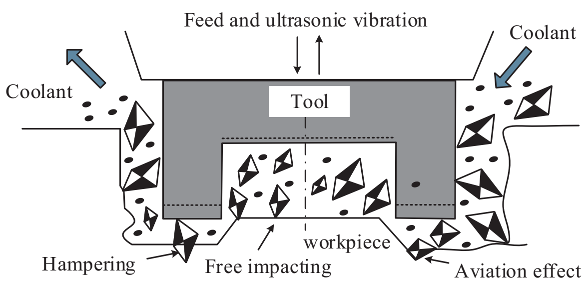

Fig. 1. Illustration of USM [14].

grinding [5], abrasive waterjet machining [6], laser beam machining [7], ultrasonic machining [8] and rotary ultrasonic machining [9].

Among the various unconventional machining methods, the rotary ultrasonic machining has been proved as a suitable method for brittle materials machining. As it is implied by name, rotary ultrasonic machining (RUM) was developed from ultrasonic machining (USM). As presented in Fig. 1, in USM, an ultrasonically vibrated tool feeds towards the workpiece under the driving action of a constant force. The motions of fluidized abrasives are motivated by the tool ultrasonic vibration to remove the workpiece material with hampering, free impact and aviation effects. By utilizing tools of different shapes, the USM can machine both the hole and cavity of different shapes with reduced residual stress and without heat damage [8]. However, the USM also have shortages such as low machining efficiency, poor processing ability of deep holes and severe tool wear. In order to overcome these kinds of shortages of USM, the RUM was developed through the addition of a rotational motion on the USM tool. Compared to USM, the RUM can dramatically improve the machining efficiency and drilling ability for deep holes [10,11]. At the beginning, fluidized abrasives were still utilized and the tool were driven by a constant force in RUM. From the last decades, in RUM a tool with fixed abrasives was utilized gradually. At that time frame, the material removal rate under a certain tool driving force was the focused issue of most studies [12]. Although sometimes, the longitudinal ultrasonic vibration assisted drilling with a twist drill is also called as RUM, due to an ultrasonic vibration utilization on the rotating twist drill [13]. However, with consideration of development history, the RUM usually refers to the machining method that adds a rotational motion on the USM tool.

After many years of development, as presented in Fig. 2(a) and (b), currently in RUM, an electroplated diamond core tool is usually utilized along with a constant tool feedrate instead of a constant driving force. Through the feeding type of constant federate utilization, RUM cannot only drill holes, whereas it also can mill the plain face [15]. As presented in Fig. 2(a), when the tool feeds along the tool axis, RUM is also called rotary ultrasonic drilling (RUD) [16]. As presented in Fig. 2(b), when the tool feeds perpendicularly to the tool axial, RUM is also called rotary ultrasonic face milling (RUFM) [17]. In both RUD and RUFM, the abrasives on the tool end face are dominant in the material removal. For a certain RUM machine tool (RUMT), as presented in Fig. 2(c), the

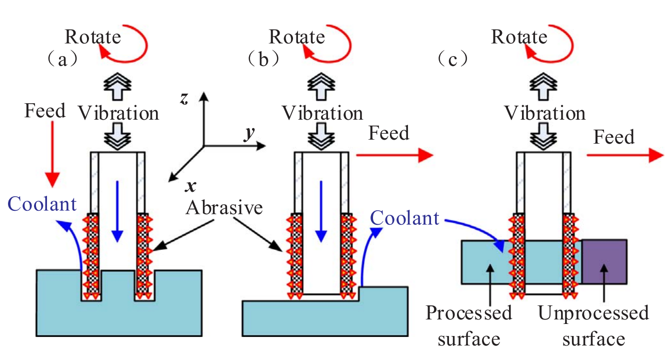

Fig. 2. Illustration of RUM and UVAG. (a) RUD, (b) RUFM, (c) UVAG.

ultrasonic vibration assisted grinding (UVAG) can also be achieved [18]. In UVAG, the abrasives on the tool side face are dominant in the material removal. Although UVAG and RUM can be accomplished using a same machine tool, with consideration to their significant difference in the material removal mechanism and development history, the UVAG is not suitable to be classified as a special type of RUM. Therefore, in this paper, only the literatures regarding both RUD and RUFM were reviewed.

RUM has been sufficiently proved that it can significantly improve the machining efficiency compared to USM, when the feeding type of constant driving force is applied [19]. However, due to the tool rotation, RUM cannot drill irregularly shaped holes similarly to USM. Up to now, when the feeding type of constant feedrate is applied, the processing performance of RUM is usually compared to conventional grinding (CG), which is the major conventional machining method of brittle materials [20]. The CG is generally achieved by the ultrasonic vibration shutdown of a RUMT. It is believed that RUM can improve the machining efficiency by many times compared to CG due to the reduced cutting force [21]. However, this conclusion cannot be drawn without the machining induced damages evaluation. Actually, the machining induced damages rather than the cutting force truly and directly limit the improvement of machining efficiency. Cutting force is only one of the factors that may affect the formation of machining induced damages.

In RUM, the machining induced damages mainly include edge chipping [22], tearing or delamination [23] and subsurface damages [24]. These damages not only affect the products assembly accuracy, but also reduce the component strengths. In addition, these damages are prone to induce catastrophic fracture of brittle materials, consequently reducing the product service life [25]. Furthermore, the low controllability of these damages would harm the designability of all products [26]. In order to truly achieve the high efficiency machining of brittle materials, the studies of machining induced damages should be focused on. This inspired the authors to comprehensively review the publications on machining induced damages of RUM in the last decade. An attempt was made to outline the systematic methods of damage suppression in RUM.

Fig. 3 presents the main logic structure of this review article. The first part of this article was focused on the material removal mechanism and cutting force modeling, followed by the critical processing capacity of RUMT. Following, the damage formation mechanism and modeling were considered. The critical processing capacity of RUMT provides the boundary condition of RUM process planning. Also, the damage formation mechanism and modeling are the theoretical fundamentals of process optimization. Consequently, the damage suppression methods were outlined lastly, according to the previous two parts.

2. Material removal mechanism and cutting force modeling

2.1. Material removal mechanism

All processing outputs of RUM, such as cutting force, machining induced damages and surface roughness are resulted from the corresponding material removal. The material removal has micro and macro effects on the formation of machining induced damages. Some damages are directly induced by the micro material removal process of a single abrasive, whereas some other damages are induced by the macro effect of all abrasives. The material removal mechanism is a fundamental scientific issue for the formation mechanism investigation of machining induced damages.

RUM includes two specific machining methods, namely the RUD and RUFM. In RUFM, only the diamond abrasives on the tool end face remove material from the workpiece surface. In contrast, in RUD, the diamond abrasives on both the tool end face and the side face take part in the material removal as well as the hole wall surface generation. Though, the diamond abrasives on the tool end face are dominant in the

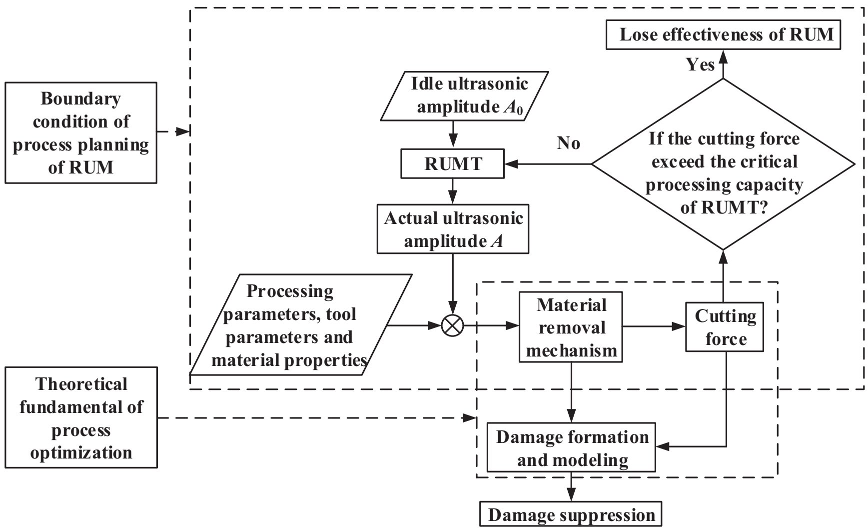

Fig. 3. Illustration of relationship among material removal, RUMT processing capacity, damage formation and suppression.

material removal and cutting force formation, the material removal of diamond abrasives on the tool side face directly leads to the surface generation of the hole wall. Regarding the surface generation mechanism of diamond abrasives on the tool wall face with the effect of ultrasonic vibration in RUD, two proposed viewpoints exist. These include the superposition mechanism of abrasive motion trajectories and alteration mechanism of the abrasive cutting direction. Due to the tool ultrasonic vibration, the motion trajectory of the diamond abrasive is sinusoidal. This is beneficial to the trajectory superposition of diamond abrasives, resulting in the improvement of hole wall quality in RUM [27]. However, some researchers reported that RUM cannot reduce the hole wall surface roughness compared to CG when sapphire is machined. On the other hand, when ceramic matrix composites are machined, the alteration mechanism of the abrasive cutting direction appears. As it is well known, the cutting direction of carbon fiber highly affects the corresponding fracture mechanism hence the machined surface integrity. Wang et al. discovered that the ultrasonic vibration could contribute to the hole surface quality improvement in the RUM of ceramic matrix composites through the fiber cutting direction changing towards 90° [28].

Regarding the material removal mechanism of diamond abrasives on the tool end face, due to the ultrasonic vibration effect, the diamond abrasives on the tool end face are not always in contact with the workpiece material. As presented in Fig. 4, the abrasives indent to and separate from the workpiece material periodically under ultrasonic frequency. During this indentation of diamond abrasives, lateral cracks and radial cracks are generated [29,30]. The lateral cracks propagate and interact with each other, leading to material removal in the brittle fracture mode. Furthermore, the diamond abrasive cutting motion accelerates the propagation of lateral cracks, consequently proving beneficial to the improvement of material removal rate of RUM. Based on this material removal mechanism, Pei et al. developed a model to predict the material removal rate, when the feeding type of constant force was utilized [31]. This model has far-reaching effect to the following theoretical studies of RUM. Based on the model of material removal rate, various models for the processing outputs predictions were developed, such as cutting force for the feeding of constant feedrate, the edge chipping size at the hole exit, as well as the subsurface damage depth.

Though the typical material removal model, presented in Fig. 4, has achieved great success, academics still apply various methods to further discover the material removal mechanism of diamond abrasives on the tool end face in RUM. The effect of ultrasonic vibration on the material removal is the major concern of researchers. The CG material removal characteristic is generally compared to the RUM material removal characteristic. As presented in Fig. 5, four methods mainly exist for the investigation of material removal mechanism of RUM.

a Ultrasonic vibration assisted scratching tests. This method was developed from the scratching method in the investigation of CG material removal mechanism, through the material removal process simplification as the single abrasive scratching the material surface. As presented in Fig. 5(a), in ultrasonic vibration assisted scratching tests, an ultrasonically vibrated single diamond abrasive scratches the oblique and polished material surface with a certain velocity. Through the scratching force and morphology comparison with the conventional scratching tests without ultrasonic vibration, the material removal mechanism of RUM can be discovered. This method has been successfully utilized in the RUM material removal mechanism discovery of sapphire [32], SiC [5], BK7 glass [33], SiC_p/Al composite [34] and KDP crystal [35].
There are two specific ways to conduct ultrasonic vibration assisted scratching experiments. One way is the single diamond abrasive or indenter utilization. The scratch motion is achieved by the machine tool feed motion. In this way, the scratching depth of ultrasonic vibration assisted scratching and conventional scratching can be

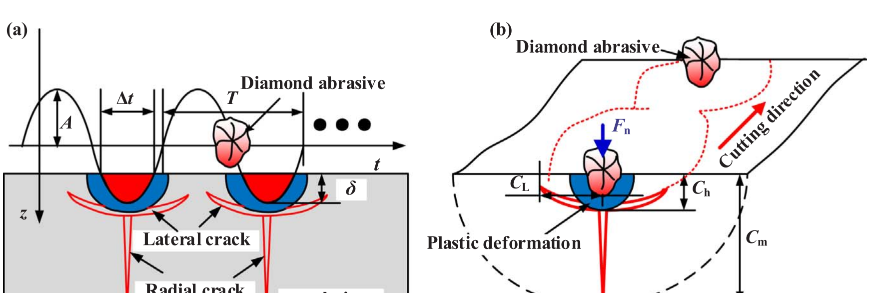

Fig. 4. Material removal model of RUM. (a) periodic contact and separation between abrasive and workpiece, (b) starching of diamond abrasive due to tool rotation.

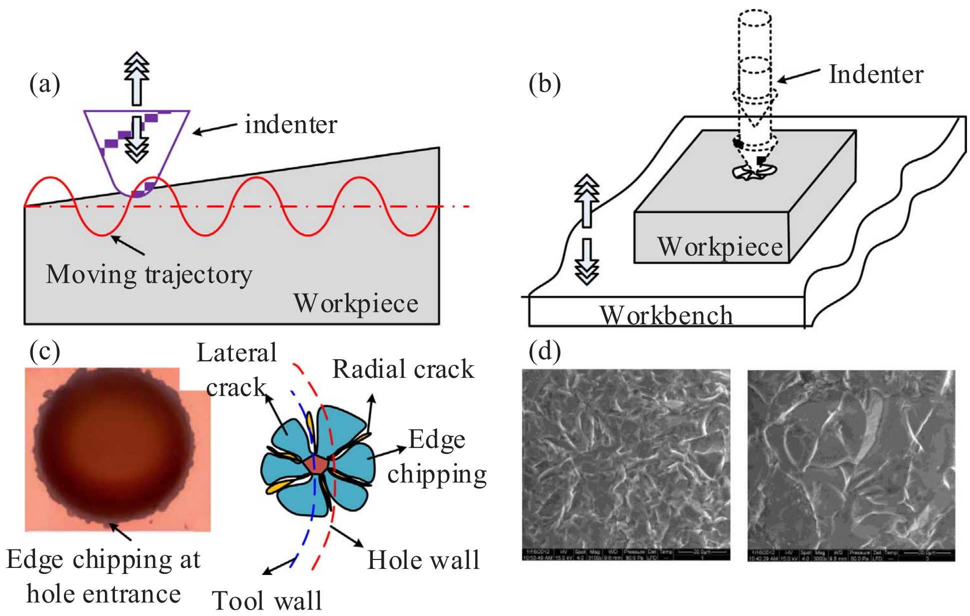

Fig. 5. Research methods for RUM material removal mechanism. (a) ultrasonic vibration assisted scratching, (b) ultrasonic vibration assisted indentation [22], (c) edge chipping at hole entrance [36], (d) surface morphology.

easily controlled identically and comparably. However, the scratching velocity of this way is relatively not sufficiently high compared to the actual cutting velocity in RUM [32]. The other way is through the rotating diamond core tool directly utilization to machine the oblique material surface. In the machined surface boundary, the scratching trace can be identified. This way can ensure the scratching velocity to be identical to the actual cutting velocity in RUM. However, the scratching depth cannot be well controlled and the scratching force cannot be measured [33].

b Ultrasonic vibration assisted indentation tests. The basic principle of this method is presented in Fig. 5(b). As presented in Fig. 5(b), an ultrasonically vibrated diamond indenter is used to conduct indentation tests on the polished material surface. Simultaneously, the indentation force and surface morphology are obtained and compared to conventional indentation tests without ultrasonic vibration [22]. Due to the axial position drift of the diamond indenter resulting from the thermal effect of ultrasonic vibration, the indentation depth cannot be easily controlled to be identical between the two different indentation methods. Therefore, it is significantly difficult to implement this method than the ultrasonic vibration assisted scratching tests.

c Hole entrance characteristics observation. According to Lv et al., the edge chipping at the hole entrance is induced directly by the material removal process of individual abrasives [36]. Consequently, the feature of edge chipping at the hole entrance can be used to assist the material removal characteristics comparison between RUM and CG. More detailed results of this method were discussed in the following section regarding the edge chipping defect at the hole entrance.

d Machined surface morphology observation. The machined surface morphology contains the information regarding the material removal process. Through the morphology characteristics comparison between RUM and CG, the material removal characteristic of the diamond abrasive with the effect of ultrasonic vibration can be identified. Due to the corresponding good feasibility of implementation, this method has been widely utilized [37–39].

2.2. Cutting force modeling

As presented in Fig. 6, due to the ultrasonic vibration of diamond abrasive, the actual cutting force on the workpiece varies with time in ultrasonic frequency. According to the Fourier transformation knowledge, the actual cutting force includes multiple frequency components. One component is the direct current component, namely the average cutting force. Another component is of the first-order ultrasonic frequency, which is identical to the tool vibration frequency. Others are the components of higher orders of frequency. However, because the resonant frequency of processing system and dynamometer is usually

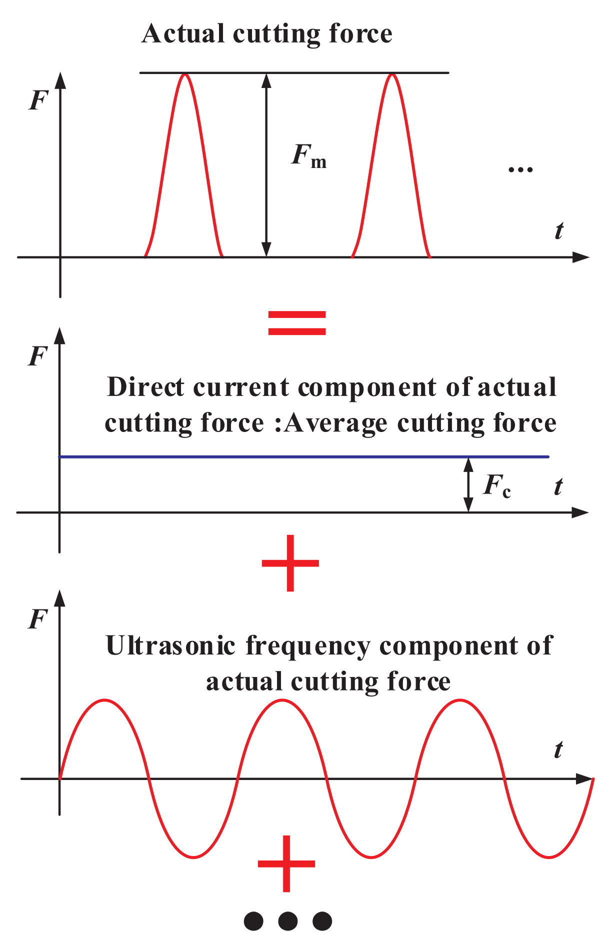

Fig. 6. Components of actual cutting force.

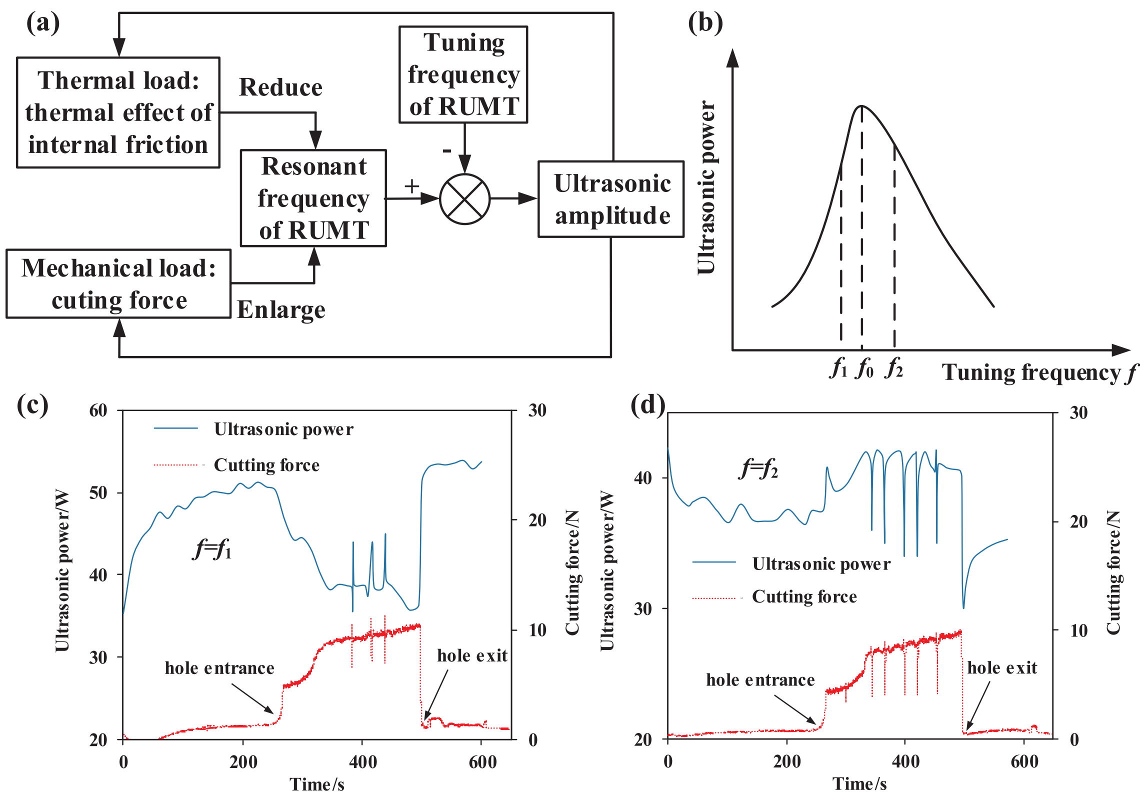

Fig. 7. Effect of thermomechanical load on the ultrasonic amplitude stability [50]. (a) effect mechanism of thermomechanical load, (b) selection of tuning frequency, (c) ultrasonic power and cutting force variation, at tuning frequency lower than resonant frequency, (d) ultrasonic power and cutting force variation at tuning frequency higher than resonant frequency.

quite lower than the ultrasonic frequency, only the direct current component of actual cutting force can be measured accurately [28]. Therefore, academics developed the models of average cutting force in general.

During the cutting force model development, a fundamental relation of equality was usually utilized. This fundamental relation was that the macro material removal rate was equal to the micro material removal rate. The macro material removal rate refers to the material removal rate calculated based on the tool feed. The micro material removal rate refers to the material removal rate calculated by the material removal volume sum of all the individual abrasives in a unit time according to the material removal mechanism. Various cutting force models for RUD and RUFM were developed [17,18,40–46]. These models established the dependency of cutting force on processing parameters, tool parameters and material properties. The developed cutting force models can predict the effect of processing parameters on the cutting force in good accuracy, especially the effect of cutting parameters such as spindle speed, feedrate and cutting depth. However, although most developed cutting force models can capture the variation tendency of cutting force as the ultrasonic amplitude increases, the prediction accuracy of these models is relatively low. Deeper works are required to modify these models, such as including the effect of cutting velocity on the propagation depth of lateral cracks that were produced in the material removal process. Furthermore, in RUM of composites, the material properties of the cutting force models, such as hardness, elastic modules and fracture toughness are usually equivalent values that can be obtained by the experiments or calculation, according to the mixing rule of composites [40–43,47,48].

The dramatic reduction of cutting force is an important processing superiority of RUM compared to CG. The cutting force reduction of RUM can be attributed to multiple aspects. The major aspect is the processing system filtering effect, which can only produce efficient action to the average cutting force. The average cutting force is quite lower than the actual cutting force maximum value, as presented in Fig. 6. Furthermore, the periodic contact and separation between diamond abrasives and workpieces is beneficial to the cooling and lubrication condition improvement of the cutting region, consequently beneficial to the cutting force reduction. In addition, the ultrasonic impact of diamond abrasives on the workpiece material leads to the initiation of vast micro cracks, resulting in the fact that lower cutting force is required to remove the workpiece material [49].

3. Critical processing capacity of RUMT

3.1. Effect of thermomechanical load on stability of ultrasonic amplitude during machining

As it is well known, the tool ultrasonic amplitude is a key processing parameter. Both experimental and theoretical results demonstrated that higher ultrasonic amplitude is usually accompanied with lower cutting force. A stable ultrasonic amplitude with sufficient magnitude is essential to guarantee the superior processing performance of RUM. However, the thermomechanical loads that were produced during the machining process would indeed affect the ultrasonic amplitude stability. Based on the effect mechanism discovery of thermomechanical load, the affecting degree characterization is an important basis to decide the processing parameters of RUM.

Because of the difficult measurement of ultrasonic amplitude during machining process, the experimental investigations on the ultrasonic amplitude stability are quite few. Cong et al. developed a vibration amplitude measurement method through the observation of abrasive moving trajectory left on the ductile material hole wall [51]. Though it cannot be used to monitor the ultrasonic amplitude during machining in real time, this method provides a reliable research method for the discovery of processing parameters effect on the actual ultrasonic amplitude [51]. Wang et al. proposed that the ultrasonic power could be used to assist in monitoring the ultrasonic amplitude variation during machining process, based on the positive dependency of ultrasonic power on the ultrasonic amplitude [50]. As presented in Fig. 7(b),(c) and (d), when the tuning frequency was not set at the resonant frequency of RUMT, the variation tendency of ultrasonic power displays the variation tendency of the RUMT resonant frequency. Through this method, as presented in Fig. 7(a), the authors observed that the thermomechanical loads would affect the ultrasonic amplitude stability by changing the RUMT resonant frequency. The thermal load produced by the thermal effect of ultrasonic vibration would change the elastic modules of the ultrasonic system component material; consequently, reducing the RUMT resonant frequency. In contrast, the mechanical load, namely the cutting force, would increase the RUMT resonant frequency. Ultimately, the deviation variation between the resonant and tuning frequencies of RUMT would induce the ultrasonic amplitude variation. In addition, the effects of thermomechanical load are coupled, due to the reaction effect of ultrasonic amplitude on the intensity of thermomechanical load. The ultrasonic amplitude increase would reduce the cutting force, whereas it would increase the thermal effect of ultrasonic vibration. Simultaneously, all experimental results indicated that the composite characteristics of ceramic matrix composites would not have sufficient effect on the aforementioned coupled effect mechanism of thermomechanical load [52].

3.2. Critical cutting force of RUMT guaranteeing RUM effectiveness

Among the thermal and mechanical loads, the mechanical load is directly related to both the material removal and processing parameters determination. Generally, the tuning frequency of RUMT is set at the idle resonant frequency, to achieve the maximum outputs of ultrasonic amplitude on the tool end face. At this time, the effect of cutting force on the stability of ultrasonic amplitude can be expressed as presented in Fig. 8(a). It could be deduced that the relationship between the cutting force and the ultrasonic amplitude is established as a positive feedback mechanism. In other words, the cutting force increase would induce the ultrasonic amplitude decrease. In turn, the ultrasonic amplitude decrease would further increase the cutting force. This kind of positive feedback relationship would induce the instability of ultrasonic amplitude during machining. As presented in Fig. 8(b), during the drilling process of a brittle material, with the abrupt decrease of ultrasonic power, the cutting force increased abruptly also. Based on experimental and theoretical investigations, Wang et al. observed that a critical cutting force existed guaranteeing the effectiveness of RUM [52]. When the actual cutting force exceeded the critical cutting force, the instability of ultrasonic vibration would occur. In addition, the critical cutting force is an inherent property of RUMT, because it is only dependent on the idle ultrasonic amplitude and energy consumption factor of RUMT, whereas it is independent of both processing parameters and workpiece material properties. Due to the corresponding inherent characteristic of critical cutting force, Wang et al. proposed it as a process-based index for the design and manufacture of RUMT. Simultaneously, ensuring that the actual cutting force is lower than the critical cutting force constitutes the first criterion to guarantee the potential superior performance of RUM. Due to the critical cutting force existence of RUMT, the feedrate that determines the machining efficiency should also be limited by the corresponding critical value [53]. There are two methods for determining the critical cutting force. For a certain already existing RUMT, the simplest method is measuring the cutting force during the machining process as shown in Fig. 8(b). On the other hand, for the design and manufacture of RUMT according to the requirement of material processing, the critical cutting force should be carefully determined by adjusting the structure, dimensions and power input of ultrasonic system [52]. More researches are needed to further verify the determination of critical cutting force on various RUMTs and workpiece materials.

In contrast, the experimental results by Cong et al. demonstrated a cutting force slight effect on the stability of ultrasonic amplitude [54]. This difference between the results of Wang et al. and Cong et al. could also be an evidence for the important role of RUMT parameters on the variation of ultrasonic amplitude during machining, because the used machine tools in their studies were rather different. These machine tools were respectively produced by DMG and Sonic-Mill companies.

4. Damage formation mechanism and modeling

4.1. Subsurface damage

Subsurface damage is a major damage pattern in mechanical face machining of brittle materials. As presented in Fig. 9, the subsurface damage is the radial crack produced in the material removal process. As presented in Fig. 4, when the diamond abrasive indents the material surface, in addition to the lateral crack, the radial crack is also produced. It is left on the workpiece material subsurface forming the subsurface damage. The subsurface damage is quite harmful to the service performance of products made of brittle materials. It not only reduces the light-admitting quality of optical glass, whereas it also reduces the fatigue life of the products. In order to eliminate subsurface damage, ultra precise as well as low efficiency machining methods, such as polishing and lapping are usually applied. In order to improve the entire machining efficiency of a brittle material, the subsurface damage depth is required to be reduced as low as possible.

In RUM, both the RUD and RUFM have the problem of subsurface damage. According to the experimental results of Wang et al. on a K9 glass, compared to CG, the RUFM can reduce the subsurface damage depth by 30–40%. The reduction mechanism of subsurface damage could be attributed to the shielding effect of lateral crack on the radial crack propagation. Qu et al. observed from ultrasonic assisted double scratching tests, that when the lateral crack length was higher than the

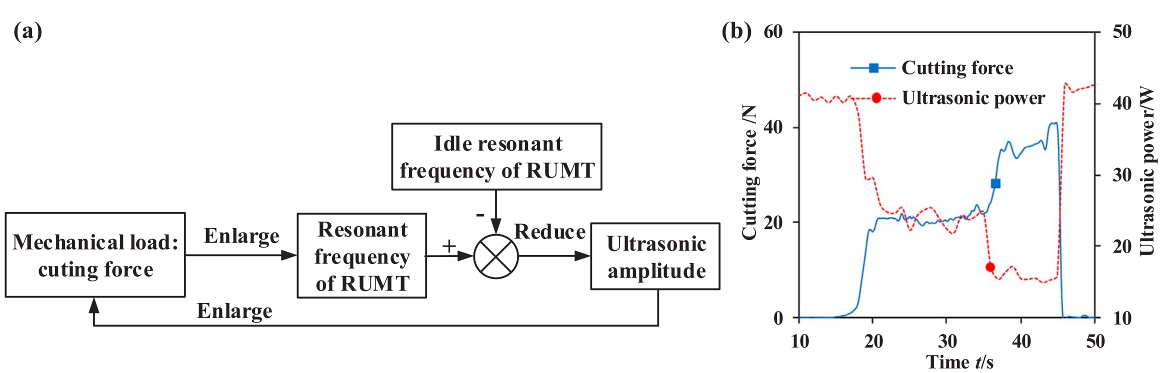

Fig. 8. Existence of critical cutting force guaranteeing RUM effectiveness [52]. (a) positive feedback relationship between cutting force and ultrasonic amplitude. (b) abrupt increase of thrust cutting force during drilling.

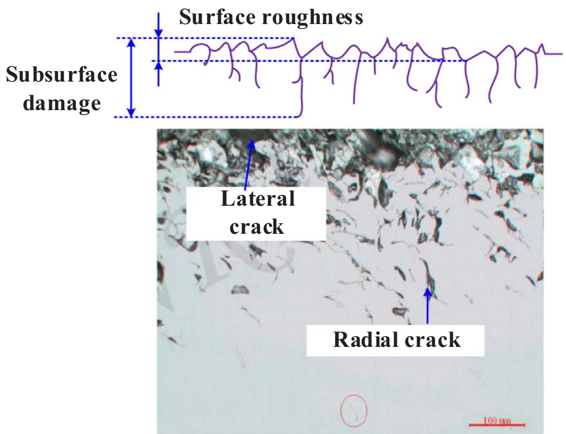

Fig. 9. Subsurface damages of RUFM [24].

diamond abrasive moving distance in one vibration cycle, the lateral crack would suppress the initiation and propagation of the radial crack, consequently resulting in the subsurface damage reduction [55]. In contrast, the experimental results of Lv et al. on a BK7 glass displayed different appearance. The RUFM could increase the subsurface damage depth by 5–10% compared to CG. The major difference of processing parameters between the experiment design of Wang et al. [56] and Lv et al. [57] was the feedrate. The feedrate of the former authors' experiment was 2–24 mm/min, while the feedrate of the latter authors' experiment was 100–600 mm/min. This indicated that the feedrate was a key processing parameter that affected the performance of RUFM in terms of subsurface damage reduction. Only when the feedrate was relatively low, could the RUFM reduce the subsurface damage. More experimental works were required to identify the potential critical feedrate that ensures the superior performance of RUFM in terms of subsurface damage reduction.

As presented in Fig. 4, both the lateral and radial cracks are produced in the material removal process of RUM under the effect of indentation force of the diamond abrasive. As presented in Fig. 9, the lateral crack induces the machined surface generation. Its depth is related to the surface roughness. Also, the length of radial crack, which is left beneath the machined surface, is related to the subsurface damage depth. Therefore, according to the indentation fracture mechanics, as illustrated in Fig. 10, a positive relationship between the subsurface damage depth and the cutting force or surface roughness could be derived theoretically and verified experimentally. Wang et al. and Lv et al. developed models for dependency of subsurface damage depth on the cutting force and surface roughness, respectively [56,57].

In addition, subsurface damage exists in RUD of a brittle material. Cong et al. observed that the subsurface damage in RUD was less severe compared to CG through qualitative observation [58]. Wang et al. developed an experimental method to evaluate the subsurface damage in RUD of brittle materials quantitatively [16]. As presented in Fig. 11(a), the critical driving force that drove the formation of edge chipping at the hole exit was utilized to indirectly compare the subsurface damage degree among different machining methods. A higher critical driving force is accompanied with lower size of subsurface damage [16]. As presented in Fig. 11(b), the experimental results demonstrated that RUD could reduce the subsurface damage compared to the CG.

4.2. Edge chipping or tearing defects at hole exit

Edge chipping or tearing defects at the hole exit is the major type of machining induced damages in RUD of brittle materials. As presented in Fig. 12, when drilling a brittle material of a single substrate, edge chipping is easily to be produced at the hole exit, while when drilling brittle composites, the tearing defect is easily to be produced at the hole exit. The degree of edge chipping is usually defined through edge chipping width or edge chipping thickness. With consideration that the edge chipping width is usually proportional to the edge chipping thickness [16] and the edge chipping width is quite easier to be measured than the edge chipping thickness, the edge chipping width is recommended to be used to evaluate the edge chipping size. Also, the tearing defect degree is usually evaluated by the tearing factor, which is calculated by the tearing defect area. The edge chipping size d_s and tearing factor K_A can be expressed as:

$$\begin{cases} d_s = \frac{D_m - D_h}{2} \\ K_A = \frac{4A_t}{\pi D_h^2} \end{cases} \tag{1}$$

where, D_m is maximum diameter of edge chipping, D_h is the nominal diameter of the machined hole and A_t is the area of tearing defects.

Thrust force and torque are the two major force outputs in hole machining of brittle materials. Generally, the edge chipping or tearing defect at the hole entrance is significantly lower compared to the hole exit. Based on this fact, Wang et al. proposed that the thrust force rather than the torque is the major driving factor that drove the formation of edge chipping and tearing defect at the hole exit in the hole machining of brittle materials and composites [23]. Based on the FEA methods, Pei et al. also confirmed the driving effect of thrust force in the formation of edge chipping at the hole exit [60]. However, the specific crack length was neglected in FEA method, the brittle material strength discussion consequently not following the fundamental fracture mechanics of brittle material. Wang et al. proposed a novel edge chipping formation

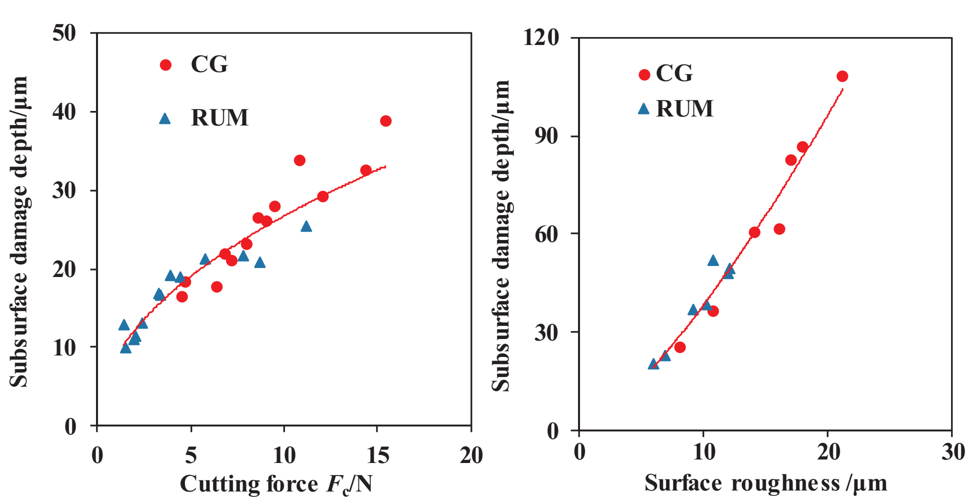

Fig. 10. Relationship between subsurface damage depth and cutting force [56] & surface roughness [57].

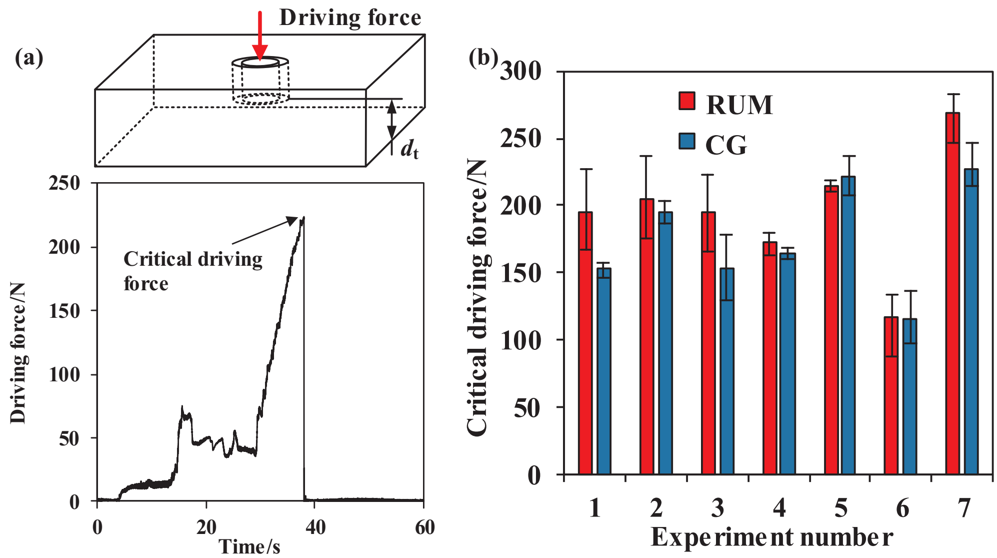

Fig. 11. Evaluation of RUD [16] surface damage degree.

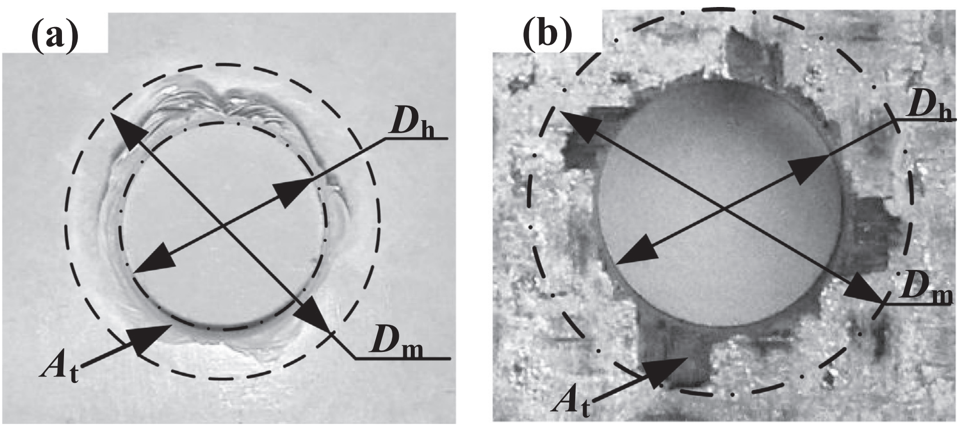

Fig. 12. Defects of hole edge. (a) edge chipping size, (b) tearing.

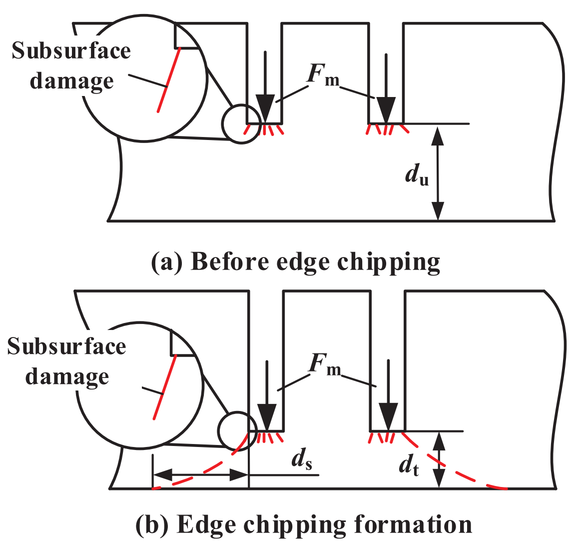

Fig. 13. Formation mechanism of edge chipping at hole exit [59].

mechanism in RUD of a brittle material through the effect consideration of subsurface damage [59]. As presented in Fig. 13, as the undrilled thickness d_u decreases, the drilling induced subsurface crack propagated in the macro scale under the driving effect of thrust force, resulting in edge chipping formation at hole exit. Simultaneously, it was concluded that for a certain hole machining with a certain diamond core tool, the edge chipping size at the hole exit is mainly determined by the undrilled thickness when the edge chipping forms. However, the undrilled thickness for the edge chipping formation is determined by the driving force and the subsurface damages size. Consequently, two types of methods exist to reduce the edge chipping size at the hole exit, namely the reduction of driving force and subsurface damage size. RUD could reduce the edge chipping size at the hole exit compared to CG through the subsurface damage size reduction. According to the proposed edge chipping formation mechanism, Wang et al. developed a model to establish the edge chipping size dependency on the processing parameters and it was verified experimentally.

Regarding the formation mechanism of tearing defect at the hole exit in RUD of ceramic matrix composites, Wang et al. proposed that the thrust force was the major driving factor rather than the torque through the application of comparison research method. As presented in Fig. 14, the tearing defect formed due to the ordinal appearance of interfacial debonding among the matrix and fiber, the fiber bending, as well as the fiber fracture under the driving effect of thrust force. The difference from the edge chipping formation was that thrust force was the dominant factor that affected the tearing defect formation. As presented in Fig. 15, the dependences of the tearing defect degree and edge chipping at the hole exit on the thrust cutting force under different machining methods were markedly different. Due to the important effect of subsurface damage, the curve that described the dependency of edge chipping size on the thrust force in RUD was distinct compared to the CG curve. In Fig. 15(b), when the edge chipping size was identical, the

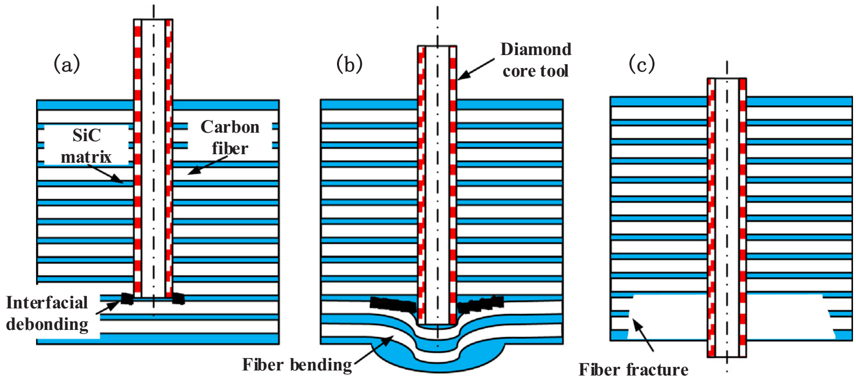

Fig. 14. Formation mechanism of tearing defect at hole exit [23].

thrust force that drove the formation of edge chipping F_{RUM} exceeded F_{CG}, indicating that the subsurface damage in RUD was lower compared to the CG subsurface damage. In contrast, In Fig. 15(a), the RUD and CG shared the same curve that described the dependency of tearing factor on the thrust force. Consequently, it was deduced that the thrust force reduction was the major method to reduce the tearing defect at the hole exit. According to Wang et al. as the effectiveness of ultrasonic vibration was guaranteed, RUD could reduce the tearing defect by 42–89% compared to CG, due to the dramatic reduction of cutting force by 55–72% [23]. The ultrasonic amplitude increase can further improve the hole exit quality in the RUD of ceramic matrix composites through further reduction of thrust cutting force.

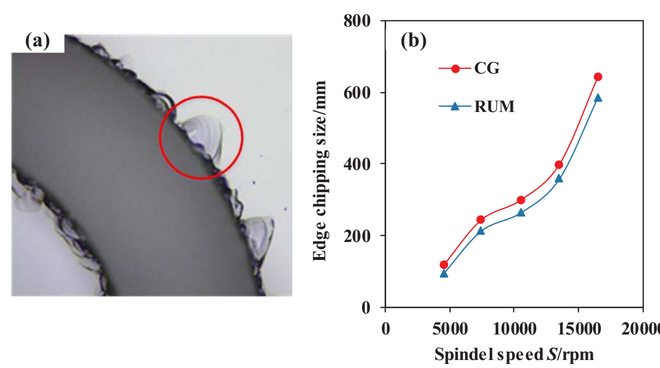

Fig. 16. Edge chipping at hole entrance [36]. (a) morphology, (b) effect of spindle speed.

4.3. Edge chipping or tearing defects at hole entrance

Though the edge chipping defect at the hole entrance was quite lower than the defect at the hole exit, however, sometimes, when the edge chipping at the hole exit is suppressed, the edge chipping at the hole entrance should be also paid attention. As presented in Fig. 16, the edge chipping shape at the hole entrance was serrated, which was rather different compared to that at the hole exit. This occurred because the edge chipping formation mechanism at the hole entrance was significantly different from that at the hole exit. According to Lv. et al., the edge chipping at the hole entrance directly resulted from the material removal of individual diamond abrasives [36]. As it is well known, the propagation and interaction of lateral cracks result in the material removal during hole drilling in brittle materials with a diamond core tool. The lateral cracks that were produced by the outermost diamond abrasives of the tool end face propagated to the material surface, consequently forming the edge chipping defect at the hole entrance. Subsequently, the factors that affected the material removal process, namely the propagation of lateral cracks, would directly affect the edge chipping size at the hole entrance. As presented in Fig. 16, the edge chipping size at the hole entrance increased as the spindle speed increased in both RUD and CG. This indicated that the lengths of lateral cracks increased as the cutting speed increased. This cutting speed effect on the propagation of lateral cracks had not been included in the modeling work of the RUM investigation.

4.4. Edge chipping in RUFM

In addition to subsurface damage, edge chipping is also an important kind of machining induced defect in RUFM of brittle materials. As presented in Fig. 17(a), Gong et al. classified the edge chipping in RUFM as entry edge chipping, exit edge chipping and interior edge chipping [61]. Similarly to edge chipping in RUD, the exit edge chipping is quite larger than entry edge chipping due to the corresponding

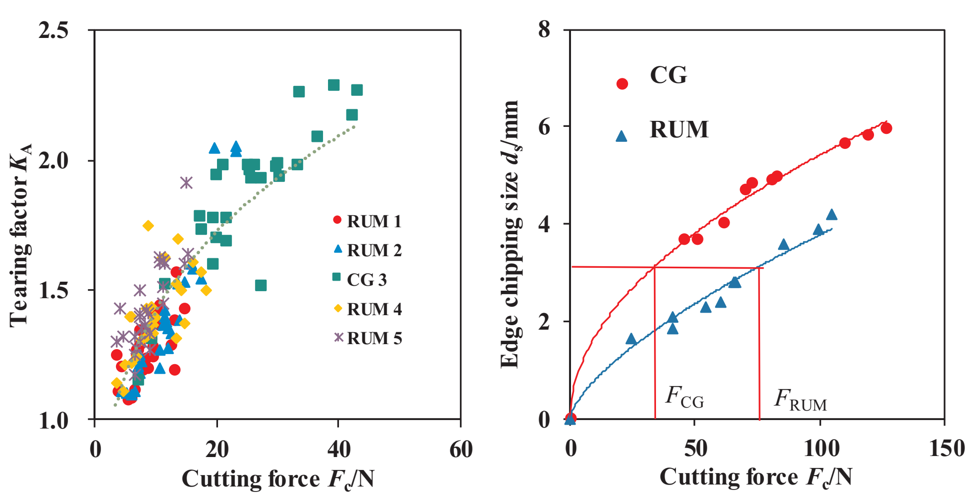

Fig. 15. Relationship between hole exit defects degree and cutting force. (a) tearing factor [23], (b) edge chipping size [59].

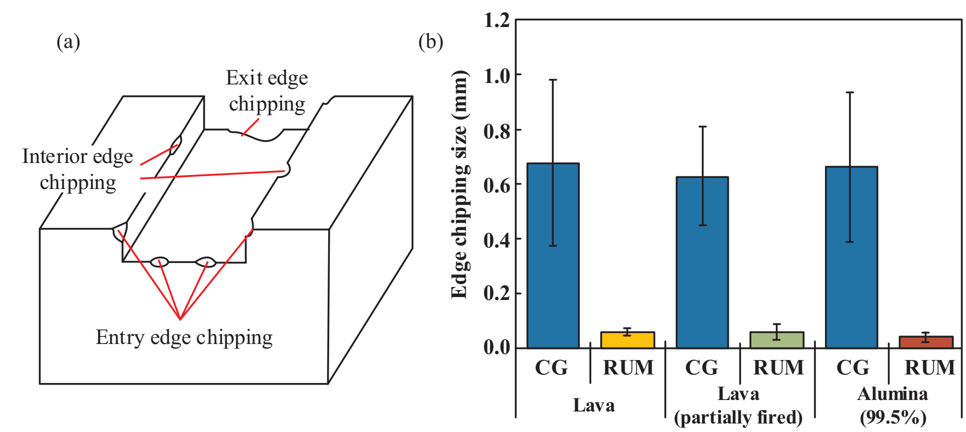

Fig. 17. Edge chipping defects in RUFM. (a) classification [61], (b) comparison with CG [22].

distinct formation mechanism. Similarly to RUD, the exit edge chipping in RUFM results from the macro driving effect of tool cutting force on the workpiece, while the entry edge chipping and interior edge chipping are directly induced by the material removal process of the individual diamond abrasives. As presented in Fig. 17(b), Tesfay et al. discovered experimentally that RUFM could dramatically reduce the interior edge chipping compared to CG [22]. Consequently, the RUFM could be regarded as a promising and reliable method to improve the edge quality of brittle materials.

5. Damage suppression methods

5.1. Optimization of processing parameters

Optimization of processing parameters is the simplest method to suppress the machining induced damages in RUM of brittle materials. Table 1 presents the effect of processing parameters on the degree of every kind of machining induced damage. The up arrow ↑ means that the corresponding processing parameter increase can increase the degree of the corresponding kind of machining induced damage. Similarly, the up arrow ↓ means that the corresponding processing parameter increase can reduce the degree of the corresponding kind of machining induced damage. In addition, × means no reported results and − means no significant effect. A major effect tendency of processing parameters on the degree of machining induced damages was that the spindle speed and ultrasonic amplitude increase, as well as the feedrate and cutting depth decrease contribute to suppress these machining induced damages.

The first principle of processing parameters optimization is the guarantee of efficient ultrasonic vibration, with consideration of the load effect of material removal on the ultrasonic system stability. In order to maximize the drilling efficiency of RUD of brittle materials and composites, as presented in Fig. 18, Wang et al. proposed a determination method of processing parameters based on the research results, in terms of critical processing capacity of RUMT as well as damage formation mechanism and modeling. The feedrate sets were divided into two stages. The former feedrate was higher, the later feedrate was lower. The former feedrate was determined by the critical cutting force, while the later feedrate was determined by the damage tolerance of

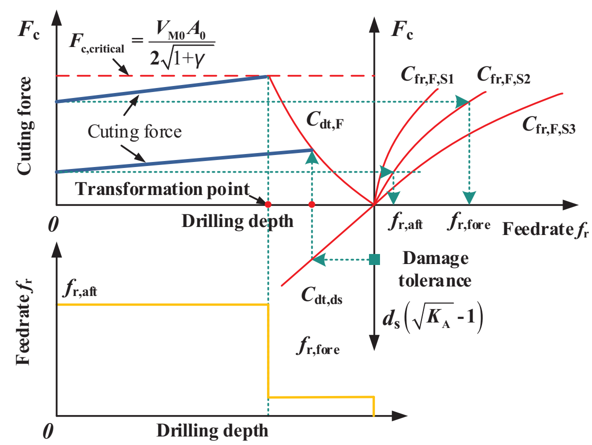

Fig. 18. Optimization strategy of processing parameter for drilling efficiency maximization.

drilled holes. Through this method application, the drilling efficiency would be improved and the hole exit quality would also meet the requirement.

5.2. Tool design of low damage

Regarding the edge chipping and tearing defect at the hole exit, the tool design of low damage is another reliable method in addition to processing parameters optimization. Qin et al. reported that the tool end face shape affects the edge chipping size at the hole exit significantly in RUD of brittle materials [64]. According to the formation mechanism of edge chipping and tearing defect at the hole exit, for a certain cutting force, a critical undrilled thickness that satisfies the damage formation condition always exists. Consequently, when the common tool with a flat end face is used, the edge chipping and tearing defect are certain to be produced at the hole exit theoretically. Aiming at the solution of this inevitability of damage formation at the hole exit when the common tool is utilized, Wang et al. proposed a design concept of low damage tool to suppress the formation of edge chipping and

Table 1
Effect of processing parameters on damage degree in RUM.

Processing parameters	Subsurface damage in RUFM	Edge chipping in RUFM	Edge chipping at hole entrance	Edge chipping at hole exit	Tearing at hole entrance	Tearing at hole exit
Spindle speed	↓[56]	↓[62]	↑[36]	↓[59]	×	↓[23]
Feedrate	↑[56]	↑[62]	×	↑[59]	×	↑[23]
Ultrasonic amplitude	×	↓[62]	×	− [59]	×	↓[23]
Cutting depth	↑[56]	↑[63]	NA	NA	NA	NA

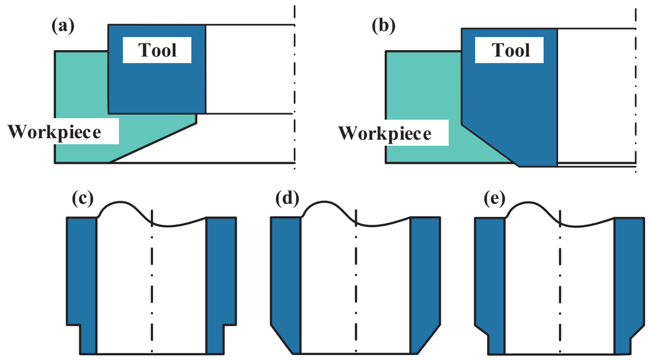

Fig. 19. Design of special-shaped and low-damage tool [65–68].

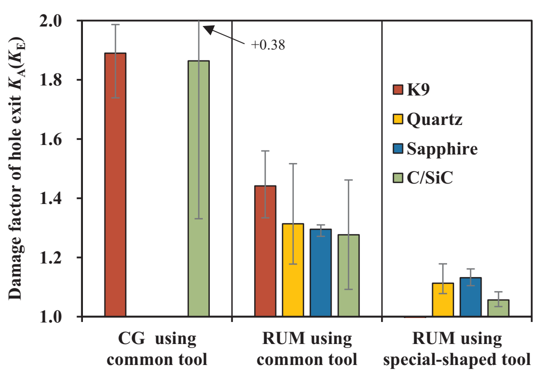

Fig. 20. Comparison of damage degree when common and special-shaped tool are utilized [65–68].

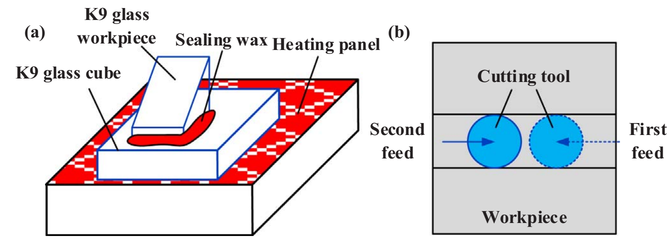

Fig. 22. Other methods for reduction of edge chipping defects [61]. (a) addition of assistant support, (b) tool feeding path.

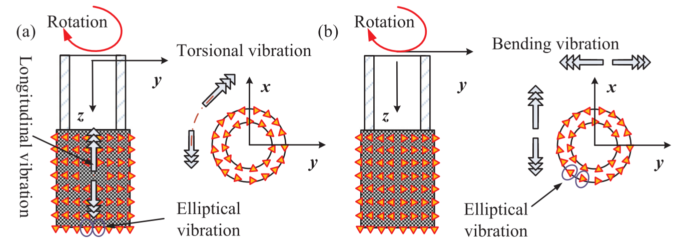

Fig. 23. Illustration of rotary ultrasonic elliptical machining. (a) longitudinal-torsional coupled elliptical vibration, (b) bending coupled elliptical vibration.

tearing defect at the hole exit. As presented in Fig. 19(a) and (b), the wedge-type contact structures between the tool end face and the workpiece material were expected to reduce the cutting force gradually at the hole exit. Accordingly, as presented in Fig. 19(c), (d) and (e), three types of special-shaped tools, namely the step tool, the taper tool and the compound step-taper tool, were designed to build that wedge-type contact structure [65–68].

As presented in Fig. 20, though RUM had already reduced the edge chipping and tearing defect at the hole exit by 50% compared to CG, the edge chipping and tearing defect at the hole exit in RUD of brittle materials and composites are further reduced by 50% by applying these special-shaped tools. In Fig. 20, K_E is the edge chipping factor, which can be calculated by:

$$K_E = \frac{2d_s}{D_h} + 1 \tag{2}$$

In order to guarantee the damage reduction mechanism at the hole exit when these three types of tools are utilized, the tool dimension should be carefully designed. Among these special-shaped tools, the compound tool is a modified taper tool in nature. It utilizes the taper face to build the wedge-type contact structure similarly to the taper tool. The step structure of compound tool is beneficial to decrease the critical characteristic angle of the taper face, guaranteeing the corresponding effectiveness on edge chipping or tearing defect reduction.

When the special-shaped tools are utilized, the edge chipping size at the hole exit can be reduced to the low degree, where the edge chipping size at the hole entrance is located. At this time, the edge chipping size at the hole entrance should also be paid attention. One method is decreasing the spindle speed, as presented in Fig. 16. The other method is to use the tool with a taper face, such as the taper tool and the compound step-taper tool. As presented in Fig. 21(a), through the tool with taper face utilization, the edge chipping size at the hole entrance can be reduced by 30–40%, compared to common tool utilization with a flat face. As presented in Fig. 21(b), the edge chipping reduction at the hole

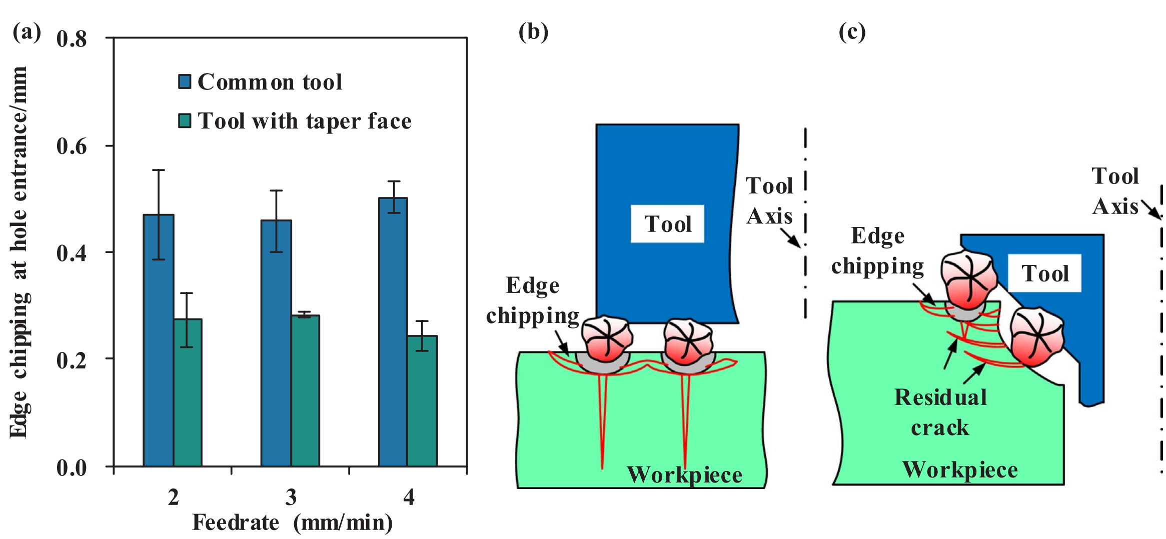

Fig. 21. Edge chipping size at hole entrance [68]. (a) performance of tool with taper face, (b) mechanism of edge chipping reduction at hole entrance.

entrance, during tool with taper face utilization, can be attributed to the shielding effect of residual cracks produced by the second outermost diamond abrasives of taper face on the production of lateral cracks, that would be produced by the outermost diamond abrasives of the taper face.

5.3. Other methods

Apart from the processing parameters optimization and tool design of low damage, certain other reported methods exist to suppress the formation of machining induced damages in RUM of brittle materials. Regarding the suppression of edge chipping or tearing defect at the hole exit, as presented in Fig. 22(a), an addition of support is quite effective [61]. However, the addition of support at the hole exit is not quite easy in most machining situations, especially when the hole exit is located in a cavity of products. Regarding the suppression of exit edge chipping in RUFM of a brittle material, Gong et al. proposed a method through the tool feeding path adjustment, as presented in Fig. 22(b). In this method, the tool feeding is divided into two directions. The two directions of tool feeding encounter with each other in the middle of the workpiece. Through this method application, the exit edge chipping could be reduced as the degree of entrance edge chipping in RUFM of brittle materials [61].

Novel types of RUM technology, such as rotary ultrasonic elliptical machining (RUEM), are also promising methods for machining induced damages suppression, through elliptical vibration application on the tool. Differently from the conventional RUM, which utilizes a 1D longitudinal vibration, the vibration trajectory of diamond abrasives in RUEM is 2D elliptical. As presented in Fig. 23, two types of RUEM exist. The first type is presented in Fig. 23(a); it is accomplished through longitudinal-torsional coupled vibration of the tool [69]. This method is promising in the hole exit quality improvement and thrust cutting force reduction, compared to conventional longitudinal vibration RUM, as the longitudinal torsional vibration has been successfully applied in the USM of brittle materials with improved material removal rate [70]. The second type is presented in Fig. 23(b), it is accomplished through two bending vibrations coupling of the tool. According to Zhang et al. this method is beneficial to the surface damage reduction in composites machining and extending the tool life, due to the corresponding special material removal mechanism [71–74]. With consideration to vibration directions, the longitudinal-torsional coupled elliptical vibration is significantly suitable for hole drilling, while bending coupled elliptical vibration is quite suitable for face milling.

6. Conclusions

Rotary ultrasonic machining (RUM) is one of the most widely utilized unconventional processes especially for the machining of hard and brittle materials, such as optical glasses, advanced ceramics and ceramic matrix composites. The machining induced damages apart from tool wear are the main aspect that limits the further improvement of machining efficiency in RUM of brittle materials, due to low fracture toughness. Following, certain conclusions could be drawn regarding the machining induced damages in RUM of brittle materials:

1. The periodic contact and separation between diamond abrasives and workpiece material are the major characteristics of material removal in RUM of brittle materials, resulting in various advantages of RUM over conventional grinding (CG), such as dramatically reduced average cutting force. The material removal mechanisms of RUM compared to CG are summarized. The modeling principle of cutting force on the basis of material removal mechanism was also described.

2. Due to the load effect of cutting force on the stability of ultrasonic vibration during the machining process, a critical processing capacity of RUM machine tool exists, characterized by a critical cutting force to guarantee the effectiveness of RUM. The determination of processing parameters of RUM should first ensure that the cutting force would not exceed the critical cutting force. Only in this way, RUM application could reduce the machining induced damages, compared to CG.

3. The edge chipping or tearing defect at the hole entrance in rotary ultrasonic drilling (RUD) results directly from the material removal process of individual diamond abrasives. In contrast, the edge chipping or tearing defect at the hole exit results from the macro force effect of all diamond abrasives. Similarly, the edge chipping in rotary ultrasonic face milling (RUFM) also follows the aforementioned formation mechanism.

4. Through the processing parameters optimization, the tool design of low damage, as well as other reported methods, such as support addition at the hole exit, the machining induced damages could be effectively suppressed. Specifically, the novel RUM method, namely rotary ultrasonic elliptical machining with utilization of longitudinal-torsional coupled elliptical vibration or bending coupled elliptical vibration, is promising in the machining quality improvement of brittle materials.

Acknowledgements

We gratefully acknowledge the financial support for this research from the National Natural Science Foundation of China (Grant No. 51475260) and the Beijing Natural Science Foundation (Grant No. 3141001).

Conflict of interest

The authors declare that they have no conflict of interest to report.

References

[1] I. Inasaki, Grinding of hard and brittle materials, CIRP Ann.-Manuf. Techn. 36 (1987) 463–471.
[2] H.N. Li, T.B. Yu, L.D. Zhu, W.S. Wang, Evaluation of grinding-induced subsurface damage in optical glass BK7, J. Mater. Process. Technol. 229 (2016) 785–794.
[3] Q. Wang, Z. Liang, X. Wang, T. Zhou, W. Zhao, Y. Wu, L. Jiao, Investigation on surface formation mechanism in elliptical ultrasonic assisted grinding (EUAG) of monocrystal sapphire based on fractal analysis method, Int. J. Adv. Manuf. Technol. 87 (2016) 2933–2942.
[4] K. Ding, Y. Fu, H. Su, F. Cui, Q. Li, W. Lei, H. Xu, Study on surface/subsurface breakage in ultrasonic assisted grinding of C/SiC composites, Int. J. Adv. Manuf. Technol. (2017).
[5] J. Cao, Y. Wu, J. Li, Q. Zhang, Study on the material removal process in ultrasonic-assisted grinding of SiC ceramics using smooth particle hydrodynamic (SPH) method, Int. J. Adv. Manuf. Technol. 83 (2016) 985–994.
[6] D.K. Shanmugam, T. Nguyen, J. Wang, A study of delamination on graphite/epoxy composites in abrasive waterjet machining, Compos. Part A: Appl. Sci. Manuf. 39 (2008) 923–929.
[7] W. Li, R. Zhang, Y. Liu, C. Wang, J. Wang, X. Yang, L. Cheng, Effect of different parameters on machining of SiC/SiC composites via pico-second laser, Appl. Surf. Sci. 364 (2016) 378–387.
[8] J. Kumar, Ultrasonic machining-a comprehensive review, Mach. Sci. Technol. 17 (2013) 325–379.
[9] R.P. Singh, S. Singhal, Rotary iltrasonic machining: a review, Mater. Manuf. Process. 31 (2016) 1795–1824.
[10] A.K. Jain, P.M. Pandey, Modeling of un-deformed chip thickness in RUM process and study of size effects in μ-RUM, Ultrasonics 77 (2017) 1–16.
[11] A.K. Jain, P.M. Pandey, Experimental studies on tool wear in μ-RUM process, Int. J. Adv. Manuf. Technol. 85 (2016) 2125–2138.
[12] W. Cong, Z. Pei, Process of ultrasonic machining, in: A.Y.C. Nee (Ed.), Handbook of Manufacturing Engineering and Technology, Springer, London, 2014, pp. 1629–1650.
[13] S. Thirumalai Kumaran, T.J. Ko, C. Li, Z. Yu, M. Uthayakumar, Rotary ultrasonic machining of woven CFRP composite in a cryogenic environment, J. Alloy. Compd. 698 (2017) 984–993.
[14] A.B.E. Khairy, Assessment of some dynamic parameters for the ultrasonic machining process, Wear 137 (1990) 187–198.
[15] Z.J. Pei, D. Prabhakar, P.M. Ferreira, M. Haselkorn, Rotary ultrasonic drilling and milling of ceramics, Urbana 51 (1994) 61801.
[16] J. Wang, H. Zha, P. Feng, J. Zhang, On the mechanism of edge chipping reduction in rotary ultrasonic drilling: a novel experimental method, Precis. Eng. 44 (2016) 231–235.
[17] C. Zhang, J. Zhang, P. Feng, Mathematical model for cutting force in rotary ultrasonic face milling of brittle materials, Int. J. Adv. Manuf. Technol. 69 (2013) 161–170.
[18] X. Xiao, K. Zheng, W. Liao, H. Meng, Study on cutting force model in ultrasonic

vibration assisted side grinding of zirconia ceramics, Int. J. Mach. Tools Manuf. 104 (2016) 58–67.

[19] T.B. Thoe, D.K. Aspinwall, M.L.H. Wise, Review on ultrasonic machining, Int. J. Mach. Tools Manuf. 38 (1998) 239–255.

[20] F.D. Ning, W.L. Cong, Z.J. Pei, C. Treadwell, Rotary ultrasonic machining of CFRP: a comparison with grinding, Ultrasonics 66 (2016) 125–132.

[21] V. Gupta, P.M. Pandey, An in-vitro study of cutting force and torque during rotary ultrasonic bone drilling, Proc. Inst. Mech. Eng. Part B: J. Eng. Manuf. (2016).

[22] H.D. Tesfay, Z. Xu, Z.C. Li, Ultrasonic vibration assisted grinding of bio-ceramic materials: an experimental study on edge chippings with Hertzian indentation tests, Int. J. Adv. Manuf. Technol. 86 (2016) 3483–3494.

[23] P. Feng, J. Wang, J. Zhang, J. Zheng, Drilling induced tearing defects in rotary ultrasonic machining of C/SiC composites, Ceram. Int. 43 (2017) 791–799.

[24] D. Lv, Y. Tang, H. Wang, Y. Huang, Experimental investigations on subsurface damage in rotary ultrasonic machining of glass Bk7, Mach. Sci. Technol. 17 (2013) 443–463.

[25] Control of machining induced edge chipping on glass ceramics.

[26] Mizobuchi Akira, Kota Honda, Tohru Ishida, Improved chip discharge in drilling of glass plate using back tapered electroplated diamond tool, Int. J. Precis. Eng. Manuf. 18 (9) (2017) 1197–1204.

[27] H. Gong, F.Z. Fang, X.T. Hu, Kinematic view of tool life in rotary ultrasonic side milling of hard and brittle materials, Int. J. Mach. Tools Manuf. 50 (2010) 303–307.

[28] J. Wang, J. Zhang, P. Feng, Effects of tool vibration on fiber fracture in rotary ultrasonic machining of C/SiC ceramic matrix composites, Compos. Part B: Eng. 129 (2017) 233–242.

[29] D.B. Marshall, H.S. Abdalla, Elastic/plastic indentation damage in ceramics: the lateral crack system, J. Am. Ceram. Soc. 65 (1982) 561–566.

[30] D.B. Marshall, H.S. Abdalla, Elastic/plastic indentation damage in ceramics: the mediad radial crack system, J. Am. Ceram. Soc. (1980).

[31] D. Prabhakar, Z.J. Pei, P.M. Ferreira, A theoretical model for predicting material removal rates in rotary ultrasonic machining of ceramics, Trans. N. Am. Manuf. Res. Inst. SME 21 (1993) 167–172.

[32] C. Zhang, P. Feng, J. Zhang, Ultrasonic vibration-assisted scratch-induced characteristics of C-plane sapphire with a spherical indenter, Int. J. Mach. Tools Manuf. 64 (2013) 38–48.

[33] D. Lv, H. Wang, Y. Tang, Y. Huang, Z. Li, Influences of vibration on surface formation in rotary ultrasonic machining of glass BK7, Precis. Eng. 37 (2013) 839–848.

[34] P. Feng, G. Liang, J. Zhang, Ultrasonic vibration-assisted scratch characteristics of silicon carbide-reinforced aluminum matrix composites, Ceram. Int. 40 (2014) 10817–10823.

[35] J. Zhang, D. Wang, P. Feng, Z. Wu, C. Zhang, Material removal characteristics of KDP crystal in ultrasonic vibration-assisted scratch process, MAter. Manuf. Process. 31 (2016) 1037–1045.

[36] D. Lv, Y. Zhang, Y. Peng, High-frequency vibration effects on hole entrance chipping in rotary ultrasonic drilling of BK7 glass, Ultrasonics 72 (2016) 47–56.

[37] J. Zhang, D. Wang, P. Feng, Z. Wu, D. Yu, Effect of processing parameters of rotary ultrasonic machining on surface integrity of potassium dihydrogen phosphate crystals, Adv. Mech. Eng. 7 (2015) 1–10.

[38] D. Lv, H. Wang, Y. Tang, Y. Huang, H. Zhang, W. Ren, Surface observations and material removal mechanisms in rotary ultrasonic machining of brittle material, Proc. Inst. Mech. Eng. Part B: J. Eng. Manuf. 226 (2012) 1479–1488.

[39] R.P. Singh, S. Singhal, Rotary ultrasonic machining of macor ceramic: an experimental investigation and microstructure analysis, Mater. Manuf. Process. (2016) 1–13.

[40] C. Zhang, S. Yuan, M. Amin, H. Fan, Q. Liu, Development of a cutting force prediction model based on brittle fracture for C/SiC in rotary ultrasonic facing milling, Int. J. Adv. Manuf. Technol. 85 (2016) 573–583.

[41] M. Zhou, W. Zheng, A model for grinding forces prediction in ultrasonic vibration assisted grinding of SiCp/Al composites, Int. J. Adv. Manuf. Technol. 87 (2016) 3211–3224.

[42] S. Yuan, C. Zhang, M. Amin, H. Fan, M. Liu, Development of a cutting force prediction model based on brittle fracture for carbon fiber reinforced polymers for rotary ultrasonic drilling, Int. J. Adv. Manuf. Technol. 81 (2015) 1223–1231.

[43] W.L. Cong, Z.J. Pei, X. Sun, C.L. Zhang, Rotary ultrasonic machining of CFRP: a mechanistic predictive model for cutting force, Ultrasonics 54 (2014) 663–675.

[44] X. Xiao, K. Zheng, W. Liao, Theoretical model for cutting force in rotary ultrasonic milling of dental zirconia ceramics, Int. J. Adv. Manuf. Technol. 75 (2014) 1263–1277.

[45] D. Liu, W.L. Cong, Z.J. Pei, Y. Tang, A cutting force model for rotary ultrasonic machining of brittle materials, Int. J. Mach. Tools Manuf. 52 (2012) 77–84.

[46] C.L. Zhang, P.F. Feng, Z.J. Wu, D.W. Yu, A mathematical model for predicting cutting force in rotary ultrasonic, Drill. Adv. Mater. Res. 433–440 (2012) 2034–2041.

[47] S. Liu, T. Chen, C. Wu, Rotary ultrasonic face grinding of carbon fiber reinforced plastic (CFRP): a study on cutting force model, Int. J. Adv. Manuf. Technol. 89 (2016) 847–856.

[48] S. Yuan, H. Fan, M. Amin, C. Zhang, M. Guo, A cutting force prediction dynamic model for side milling of ceramic matrix composites C/SiC based on rotary ultrasonic machining, Int. J. Adv. Manuf. Technol. 86 (2015) 37–48.

[49] D. Lv, Y. Huang, H. Wang, Y. Tang, X. Wu, Improvement effects of vibration on cutting force in rotary ultrasonic machining of BK7 glass, J. Mater. Process. Technol. 213 (2013) 1548–1557.

[50] J. Wang, P. Feng, J. Zhang, Experimental investigation on the effects of thermo-mechanical loading on the vibrational stability during rotary ultrasonic machining, Mach. Sci. Technol. (2016).

[51] W.L. Cong, Z.J. Pei, Vibration amplitude in rotary ultrasonic machining: a novel measurement method and effects of process variables, J. Manuf. Sci. Eng. 133 (2011) 34501.

[52] J. Wang, J. Zhang, P. Feng, Experimental and theoretical investigation on critical cutting force in rotary ultrasonic drilling of brittle materials and composites, Int. J. Mech. Sci. (2017) (In preparation).

[53] J. Wang, P. Feng, J. Zhang, W. Cai, H. Shen, Investigations on the critical feed rate guaranteeing the effectiveness of rotary ultrasonic machining, Ultrasonics 74 (2017) 81–88.

[54] F. Ning, H. Wang, W. Cong, P.K.S.C. Fernando, A mechanistic ultrasonic vibration amplitude model during rotary ultrasonic machining of CFRP composites, Ultrasonics 76 (2017) 44–51.

[55] W. Qu, K. Wang, M.H. Miller, Y. Huang, A. Chandra, Using vibration-assisted grinding to reduce subsurface damage, Precis. Eng. 24 (2000) 329–337.

[56] J. Wang, C. Zhang, P. Feng, J. Zhang, A model for prediction of subsurface damage in rotary ultrasonic face milling of optical K9 glass, Int. J. Adv. Manuf. Technol. 83 (2016) 347–355.

[57] D. Lv, Y. Huang, Y. Tang, H. Wang, Relationship between subsurface damage and surface roughness of glass BK7 in rotary ultrasonic machining and conventional grinding processes, Int. J. Adv. Manuf. Technol. 67 (2013) 613–622.

[58] Y. Ahmed, W.L. Cong, M.R. Stanco, Z.G. Xu, Z.J. Pei, C. Treadwell, Y.L. Zhu, Z.C. Li, Rotary ultrasonic machining of alumina dental ceramics: a preliminary experimental study on surface and subsurface damages, J. Manuf. Sci. Eng.-Trans. ASME 134 (2012) 67–75.

[59] J. Wang, P. Feng, J. Zhang, C. Zhang, Z. Pei, Modeling the dependency of edge chipping size on the material properties and cutting force for rotary ultrasonic drilling of brittle materials, Int. J. Mach. Tools Manuf. 101 (2016) 18–27.

[60] Y. Jiao, W.J. Liu, Z.J. Pei, X.J. Xin, C. Treadwell, Study on edge chipping in rotary ultrasonic machining of ceramics: an integration of designed experiments and finite element method analysis, J. Manuf. Sci. Eng. 127 (2005) 752–758.

[61] H. Gong, F.Z. Fang, X.F. Zhang, J. Du, X.T. Hu, Study on the reduction strategy of machining-induced edge chipping based on finite element analysis of in-process workpiece structure, J. Manuf. Sci. Eng.-Trans. ASME 135 (2013) 11017.

[62] A. Jain, Fabrication of Glass Serpentine Microchannels using Rotary Ultrasonic Milling, Thapar University, 2017.

[63] H.D. Tesfay, Ultrasonic Vibration Assisted Grinding of Bio-ceramic Materials: Modeling, Simulation, and Experimental Investigations on Edge Chipping, North Carolina A & T State University, Greensboro, North Carolina.

[64] N. Qin, Z.J. Pei, W.L. Cong, D.M. Guo, Effects of tool design on edge chipping in ultrasonic-vibration-assisted Grinding, 2010, pp.147–154.

[65] J. Wang, P. Feng, J. Zhang, Reduction of edge chipping in rotary ultrasonic machining by using step drill: a feasibility study, Int. J. Adv. Manuf. Technol. 87 (2016) 2809–2819.

[66] J. Wang, P. Feng, J. Zheng, J. Zhang, Improving hole exit quality in rotary ultrasonic machining of ceramic matrix composites using a compound step-taper drill, Ceram. Int. 42 (2016) 13387–13394.

[67] J. Wang, P. Feng, J. Zhang, Investigations on the edge-chipping reduction in rotary ultrasonic machining using a conical drill, Proc. Inst. Mech. Eng. Part B: J. Eng. Manuf. (2016).

[68] J. Wang, P. Feng, J. Zhang, Reducing edge chipping defect in rotary ultrasonic machining of optical glass by compound step-taper tool, J. Manuf. Process. (2017) (In preparation).

[69] H. Al-Budairi, M. Lucas, P. Harkness, A design approach for longitudinal–torsional ultrasonic transducers, Sens. Actuators A: Phys. 198 (2013) 99–106.

[70] T. Asami, H. Miura, Study of ultrasonic machining using longitudinal and torsional vibration, In: Proceedings of IEEE International Ultrasonics Symposium (IUS), IEEE, 2015, pp. 1–4.

[71] D. Geng, D. Zhang, Y. Xu, F. He, D. Liu, Z. Duan, Rotary ultrasonic elliptical machining for side milling of CFRP: tool performance and surface integrity, Ultrasonics 59 (2015) 128–137.

[72] D. Geng, D. Zhang, Y. Xu, X. Jiang, Z. Lu, D. Lu, Effect of speed ratio in edge routing of carbon fiber-reinforced plastics by rotary ultrasonic elliptical machining, J. Reinf. Plast. Compos. (2015).

[73] D. Geng, D. Zhang, Y. Xu, F. He, F. Liu, Comparison of drill wear mechanism between rotary ultrasonic elliptical machining and conventional drilling of CFRP, J. Reinf. Plast. Compos. 33 (2014) 797–809.

[74] D. Geng, Z. Lu, G. Yao, J. Liu, Z. Li, D. Zhang, Cutting temperature and resulting influence on machining performance in rotary ultrasonic elliptical machining of thick CFRP, Int. J. Mach. Tools Manuf. 123 (2017) 160–170.