Ultrasonic Assisted Grinding of C/SiC composites

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Abstract. C/SiC composites are widely used in aerospace industry, national defense industry owing to their advantages of high temperature resistance, good mechanical properties, stable physical and chemical properties. In the manufacturing of this material, traditional machining methods have disadvantages of severe tool wear, large cutting force and low production rate, which is caused by their structure and physical properties. In order to solve these problems, a method of ultrasonic assisted grinding of C/SiC composites was proposed, and a test machine was set up. The grinding force and ground surface roughness in ultrasonic assisted grinding and common grinding were discussed. The results indicated that the grinding force increased along with the rise of feed speed or grinding depth , and decrease with the rise of spindle speed. The effect of improving surface roughness in UAG is non-significant.

Introduction

Continuous carbon fiber reinforced silicon carbide ceramic matrix composites (C/SiC) have been widely used in aerospace field, due to these properties of higher anti-impact toughness, bending strength and high temperature resistance[1−4]. However, C/SiC composites possess high hardness and obdurability, and are not allowed to use coolant in the process. Therefore, the C/SiC composites are typical difficult–to-machine materials. The traditional machining methods and tools are difficult to meet the requirements of machining C/SiC composites[5-6].

Ultrasonic assisted grinding(UAG) is considered to be one of the most methods to machine carbon fiber composites with high quality and of the most important methods to efficiency. Compared to conventional grinding(CG), UAG is applied with high frequency vibrations on the end face of the rotating tool, which possess excellent advantages in decreasing the cutting force, improving the surface quality and extending tool life effectively[7-8].

Ding et al. studied the surface/subsurface breakage types and formation mechanism. They concluded that main breakage types of different angle fibers in ground surface were lamellar brittle fracture and pit group originating from fracture and pullout of fibers, while breakage types of different angles fibers in ground surface were brittle fracture[9].

Based on the self-developed ultrasonic assisted grinding system, the influence of processing parameters on grinding force and surface roughness of C/SiC composites is studied.

Experimental setup and conditions

The ultrasonic assisted grinding test equipment used in this paper is based on a three - axis CNC milling machine, which integrated with the self-developed ultrasonic vibration system as Fig. 1 illustrated and the main parameters are shown in Table 1.

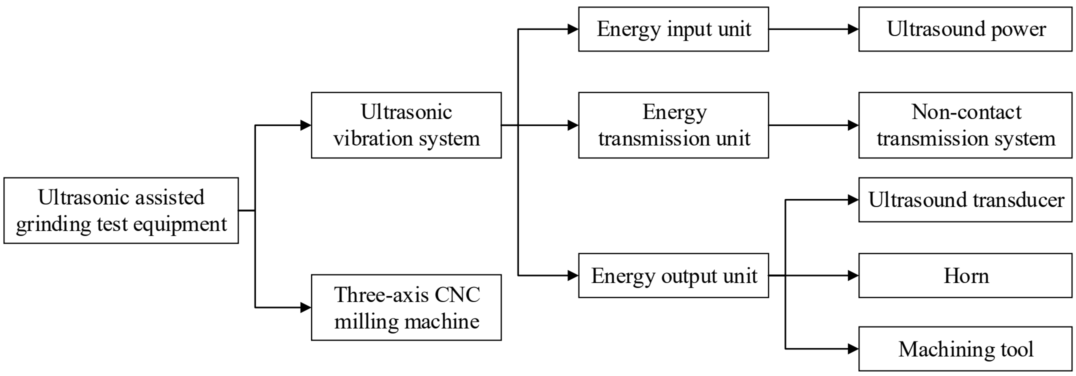


Fig. 1 Schematic diagram of ultrasonic auxiliary grinding test equipment

Tables 1 Main parameters of ultrasonic auxiliary grinding test equipment

Maximum spindle speed	Maximum feed speed	Positional accuracy	Repositioning Accuracy	ultrasonic frequency	ultrasonic amplitude
18000r/min	10m/min	±3μm/300mm	2μm/300mm	15~40kHz	3~20μm

The workpiece material was C/SiC composites. It was fixed to the dynamometer by a workbench. The YDCB-Ⅲ05 dynamometer was designed and manufactured by institute of sensing measurement control and precision machining technology of Dalian university of technology. The sizes of the workpiece were 120mm×30mm×10mm. The grinding tools were diamond grinding wheels. The outer diameter was 8mm, and the average grain size was about 200μm. The diamond grinding wheel was grooved on the workpiece surface. The dynamometer measured the axial force and tangential force. the photograph of the experimental setup is shown in Fig. 2. The surface roughness of the material was measured by a surface profiler (Talysurf PGI 840).

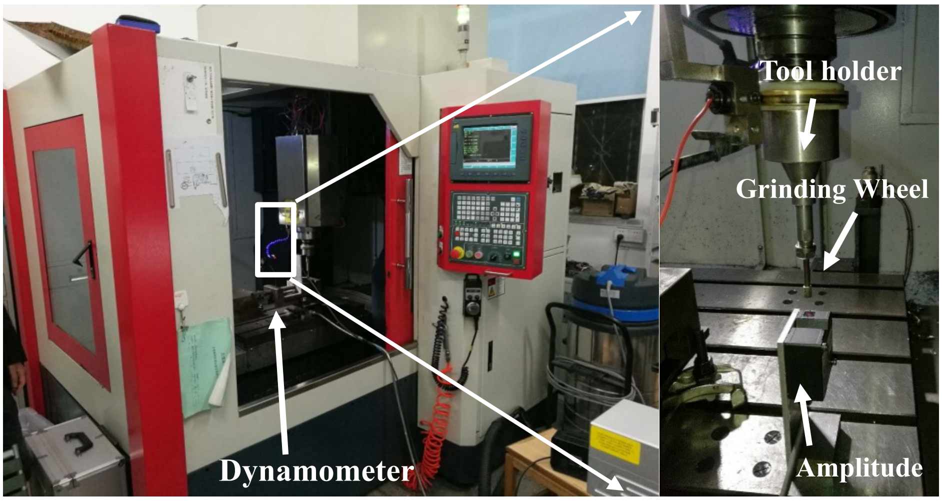


Fig. 2 Photograph of the experimental setup

In order to explore the relations between process parameters and grinding forces, the methodology of single factor experiments were adopted for the grinding experiments of C/SiC material. One of the three process parameters, namely spindle speed, feedrate and cutting depth, were varied while the other two remained unchanged. In order to improve the effect of ultrasonic vibration and the visibility of ultrasonic vibration effect, the ratio of frequency to spindle speed should be as large as possible [10]. The selected values of the process parameters are shown in Table 2.

Both UAG and CG experiments were conducted to investigate the discrepancy of UAG and CG when processing C/SiC materials, especially regarding grinding force and surface roughness. The UAG process were carried out with the vibration frequency of 21.08 kHz and the vibration amplitude of 10 μm.

Table 2 The selected process parameters

Spindle speed/r·min^{-1}	Feedrate/mm·min^{-1}	Grinding depth/mm
2000, 3000, 4000, 5000	100,200, 300, 400	0.1, 0.2, 0.3, 0.4

Experimental results and discussion

Grinding force. In order to facilitate analysis, the grinding force was divided into three components perpendicular to each other, namely, tangential grinding force F_t, normal grinding force F_n and axial grinding force F_a. Since F_n was too small, no discussion was made.

Figures 3,4,5 present the effects of process parameters, i.e., spindle speed, feedrate, and grinding depth, on grinding force.

From figure 3, it is seen that Fa and Ft increase with increasing grinding depth in both UAG and CG, when the spindle speed and feedrate was 3000r/min, 200mm/min, respectively. At the same grinding depth, the Ft and Fa in UAG are smaller than those in CG. Compared to CG, UAG can reduce the tangential grinding force by 47%~76%, and axial grinding force by 49%~65%.

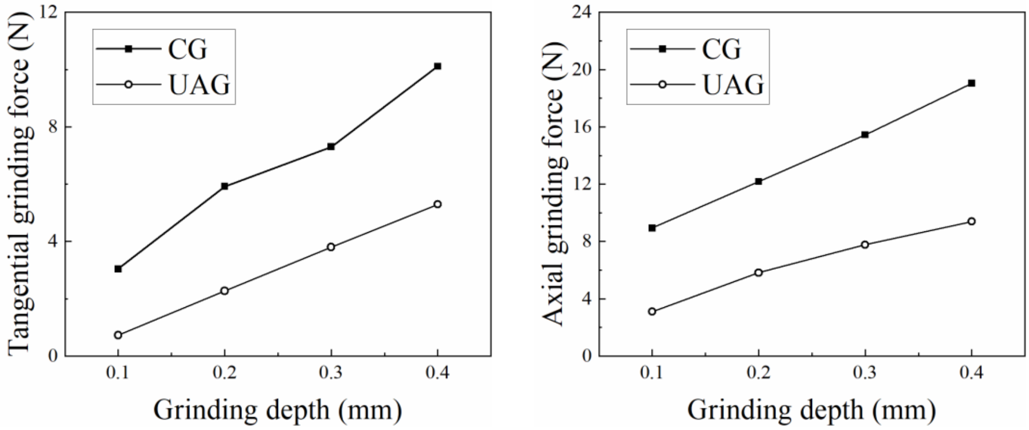


Fig. 3 Grinding force vs grinding depth

In UAG, the introduction of ultrasonic vibration causes the cutting speed of diamond abrasive particles on the grinding wheel to be higher than that in CG, and the grinding ability of the grinding wheel is enhanced. Due to the effect of high frequency *micro impact on the material, micro-crack and micro-fracture formed on the processed surface, which change the material removal mechanism in CG, the cutting force in grinding process is significantly reduced. Therefore, UAG can effectively reduce the grinding force in the case of the same grinding depth.

Feedrate is directly related to machining efficiency in grinding. It is of great significance to study the effect of feedrate on grinding force. From figure 4, it is seen that Fa and Ft increase with increasing feedrate in both UAG and CG, when the spindle speed and grinding depth was 3000r/min, 0.2mm, respectively. At the same parameter, the Ft and Fa in UAG are smaller than those in CG. Compared to CG, UAG can reduce the tangential grinding force by 50%~55%, and axial grinding force by 18%~37%. UAG has obvious advantages in reducing grinding force.

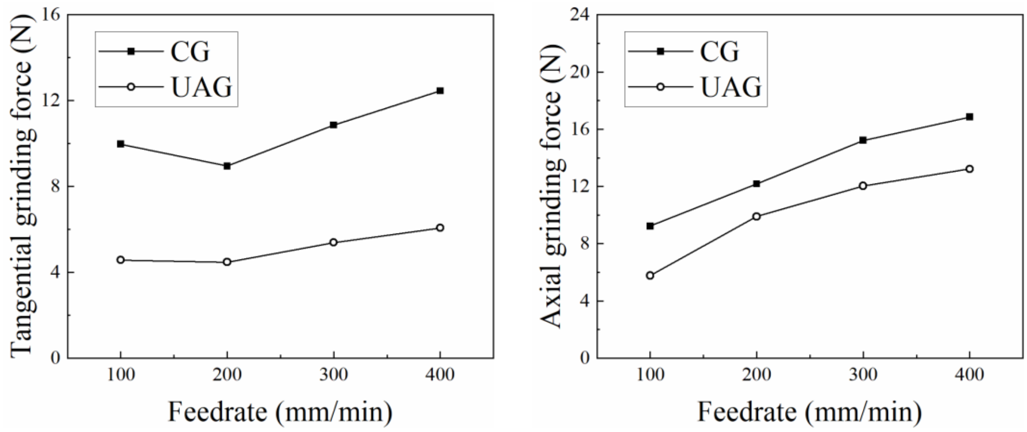


Fig. 4 Grinding force vs feedrate

From figure 5, it is seen that Fa and Ft decrease with increasing spindle speed in both UAG and CG, when the feedrate and grinding depth was 200mm, 0.2mm, respectively. The main reason is that with the increase of spindle speed, the cutting speed of abrasive particles on grinding wheel increases, which leads to the decrease of F_t and F_a. At the same spindle speed, both F_t and F_a are relatively smaller in UAG, with F_t reduced by about 19%~48%, and F_a reduced by about 7%~18%. In UAG, the high frequency vibration perpendicular to the machining surface is compounded on the grinding trajectory, which increases the cutting speed of the grinding particle relative to the workpiece and enhances the grinding performance of the grinding wheel.

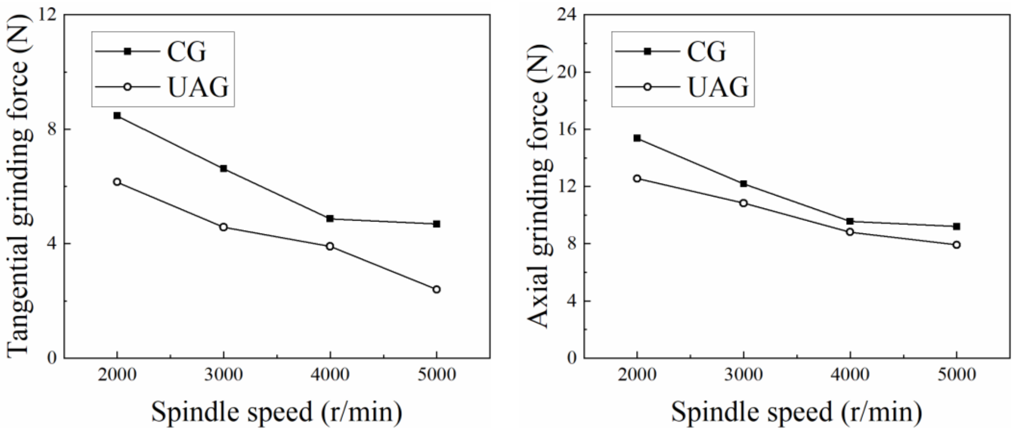
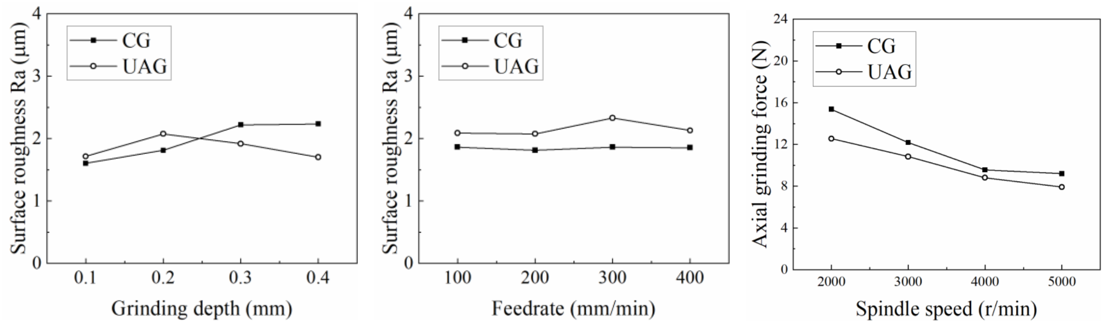


Fig. 5 Grinding force vs spindle speed

Ground surface roughness. Figures 6 present the effects of process parameters, i.e., spindle speed, feedrate, and grinding depth, on ground surface roughness. Unlike on grinding force, the effects of process parameters on surface roughness are non-significant. As can be seen from the figure 6(a), when the other processing parameters remain unchanged, the surface roughness gradually increases from 1.6μm to 2.2μm as the grinding depth increases from 0.1mm to 0.4mm in CG. The surface roughness first increases and then decreases in UAG. In the grinding depth of 0.2mm, it reaches the maximum value of 2.07μm. In the grinding depth of 0.4mm, it reaches the minimum value of 1.7μm. The results show that, with the increase of grinding depth, the surface roughness becomes larger and the processing environment deteriorates, which leads to the deterioration of processing quality in CG. But in UAG, when the grinding depth is smaller than the grinding grain size, the surface roughness is similar to that in CG. When the grinding depth is near the grinding grain size, the processing quality is the worst. And when the grinding depth is greater than the grinding grain size, the surface roughness is obviously better and better. This is an interesting phenomenon. A hypothesis was obtained after preliminary analysis, when the grinding depth increases to the size of the abrasive particles, the material removal rate of the abrasive particles on the end surface increases, and the roughness value increases. When the grinding depth is greater than the abrasive particle scale, because of the rounded corner of grinding wheel, the diameter of grinding grain on the side of grinding wheel is larger than that on the corner, and the grinding depth is also smaller. The material is removed and processed by side grinding firstly. In the action of ultrasonic vibration, processed material surface produced micro-cracks and micro-fractures, and the residual machining allowance will be reduced. Instead of removing the material directly by "ploughing" , the grinding particle on the end surface clear the micro-crack and micro-fracture structure left by the side grinding particle, which is more conducive to the removal of the material and the reduction of the surface roughness. This hypothesis will be tested in subsequent experiments.

From figure 6(b), the effect of feedrate on ground surface roughness is non-significant. The surface roughness of the material in UAG fluctuates from 2.07μm to 2.32μm, and that in CG fluctuates from 1.81μm to 1.86μm. The effect is the same as that shown in figure 6(a). And from figure 6(c), the surface roughness decreases with increasing spindle speed in CG, but it has no significant change in UAG.



(a) Grinding depth (b) Feedrate (c) Spindle speed

Fig.6 The effects of process parameters on surface roughness

Discussion. Though the above experiments, it can be observed that the grinding forces of UAG process were much smaller than that of CG process under the same processing parameters. In CG process, there are only rotating feeding movements of the grinding wheel, in which case the trajectories of the grains were straight lines on the cutting direction. Hence, the cutting velocity of the grains were the sum of linear velocity of the wheel and the feeding velocity. Since the fibers are supposed to be removed by the compressional faulting cause by shearing actions on the tangential orientation of the grains, they would easily bend when the cutting velocity is insufficient, when the fibers are unable to be cut off entirely. The uncut fibers would be pulled out, leading to the deteriorate of processed C/SiC surface. Moreover, only one of the grains' cutting edge participate in the cutting process. Hence, the grinding forces would increase rapidly due to the wear of the grinding wheel, and furtherly boosting the wear of the grinding wheel in return. Finally, the grains were constantly in touch with the workpiece at the cutting zone, which accelerated the accumulation of thermal energy, and bring down the grinding abilities of the grinding wheel.

Compared to CG process, in UAG process the grinding wheel would be in periodical movement of high frequency, despite of the original rotating movement and feeding movement. The distances that grains travelled per unit time were enhanced, and the cutting velocities of the grains were improved. The maximum accelerated velocities of the grains can exceed 80km/s2 on the vertical orientation, causing massive impact on the C/SiC material while enforcing “chopping” effects. The “chopping” effects can cut off the hard carbon fiber and reduce the grinding force of the wheel. Meanwhile, the cutting angle of the grains are changed due to the vibration, and there are more cutting edge for each grain instead of merely single cutting edge under CG process. Hence, the cutting ability of the grains are enhanced, which help the wheel’s performance. Under multiple circumstance, the wheel was separated from the workpiece. The contacting time of the wheel and the workpiece were decreased, causing the decrease of average grinding forces. In the meanwhile, the performance of the wheel was enhanced due to the heat dispersion.

The surface roughness of the C/SiC after UAG process were measured via Talysurf PGI 840 surface profiler. The comparison were conducted regarding cutting depth, feedrate and spindle speed as variations. Results showed that the process parameters influenced surface roughness differently under CG and UAG process. In CG, the surface toughness increased upon the increase of cutting depth, decreased upon the increase of spindle speed, and failed to show relevance with feedrate. In UAG, the surface toughness firstly increased and then decreased upon the increase of cutting depth, and failed to show relevance with both spindle speed and feedrate. The surface toughness after UAG was slightly greater than that of CG. Further analysis showed that the vibration parameters were not ideal, which caused the deteriorate of surface quality. The coupling of vibration parameters and process parameters is planned in future work.

Conclusions

In this study, both UAG and CG experiments were conducted on C/SiC material via single factor tests. The following conclusions were drawn:

(1) The grinding forces of UAG process were obviously lower than that of CG process under same process parameters. Meanwhile, the surface roughness of UAG were slightly greater than that of CG.

(2) For both UAG and CG processes, the effects were observed that the grinding forces would decrease upon the increase of spindle speed while increase upon the increase of federate and cutting depth. The changing trend of grinding forces were similar for all three groups of experiments.

(3) For CG process, the surface roughness would decrease upon the increase of cutting depth; and decrease upon the increase of spindle speed; the influence of feedrate on surface roughness was insignificant. For UAG process, the surface roughness would firstly increase and then decrease upon the increase of cutting depth; and the influences of both spindle speed feedrate on surface roughness were insignificant.

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