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Helical Milling of Carbon Fiber Reinforced Plastics Using Ultrasonic Vibration and Liquid Nitrogen

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Abstract

Carbon fiber reinforced plastics (CFRP) have been used for various applications such as aerospace, automobiles, and sporting goods due to their superior properties, and the demand for through-hole drilling of CFRP is increasing. A novel hybrid helical milling technique applying ultrasonic vibration and cryogenic tool cooling method is proposed in this paper, as an effective machining method for CFRP. To investigate the effects of ultrasonic-vibration-assisted machining and cryogenic tool cooling method, cutting performance evaluations based on thrust force, machining accuracy, and tool wear were conducted in this study. The results of the cutting tests clearly indicated that the proposed cutting method provides reductions in thrust force, and suppresses delamination at the machined surface.

Selection and peer-review under responsibility of the International Scientific Committee of the “New Production Technologies in Aerospace Industry” conference in the person of the Conference Chairs: Prof. Berend Denkena, Prof. Yusuf Altintas, Prof. Pedro J. Arrazola, Prof. Tojiro Aoyama and Prof. Dragos Axinte

Keywords: Helical milling; CFRP; Ultrasonic vibration; Liquid nitrogen

1. Introduction

Recently, composite materials have been used for various applications such as aerospace, automobiles, and sporting goods owing to their superior properties: lightweight, high strength, and high heat resistance. In the aerospace industry, carbon fiber reinforced plastics (CFRP) are primarily used in structural components as a replacement for metal alloys, allowing for weight reduction. As structural materials, these materials must be drilled in order to connect them with other material components, and the bolt joining efficiency and quality depend critically on the accuracy of the machined holes [1]. Therefore, high-precision and high-efficiency drilling of composite materials is required. However, in the drilling of carbon fiber composite materials, delamination at the edge of machined hole occurs easily because of the material properties, such as anisotropy and inhomogeneity. Besides these problems, the tool wear caused by the high hardness of carbon fibers must be considered. Ultrasonic-vibration-assisted drilling has been proposed as an effective cutting method for difficult-to-machine materials. The use of axial ultrasonic vibration is expected to reduce thrust force, increase tool life, and provide lubrication and cooling effects at the cutting point. In fact, these positive effects have been obtained in the machining of inconel superalloy and stainless steel [2, 3]. Generally, dry machining has been used for CFRP machining, because post-cleaning is unnecessary when not using soluble cutting oil. However, lubrication and cooling effects are not obtained in dry machining, and the cutting heat can easily cause tool wear and delamination damage at the machined surface. In order to overcome these problems, cryogenic machining has been studied in the past research [4]. To machine CFRP with high accuracy, a novel hybrid helical milling technique that applies ultrasonic vibration and cryogenic tool cooling is proposed in this paper.

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2. Principles of helical milling applying ultrasonic vibration and cryogenic tool cooling

2.1. Axial ultrasonic-vibration-assisted machining

The axial ultrasonic vibration was applied to the cutting tool using a specially designed spindle and an ultrasonic device. To apply ultrasonic vibration to the cutting tool, a piezoelectric crystal oscillator was fitted in and mounted properly between the chuck and collet. In conventional machining, it is difficult to directly supply cutting fluid to the cutting point because the contact between the cutting tool and workpiece is continuous. On the other hand, when axial ultrasonic vibration is applied to the cutting tool, the intermittent cutting improves the flow of the cutting fluid, which is expected to provide lubrication and cooling effects at the cutting point. As a consequence, the reduced friction between the cutting tool and workpiece decreases the thrust force and results in a longer tool life.

2.2. Cryogenic cooling of tool with liquid nitrogen

In this study, the supply of liquid nitrogen was limited to the cutting tool. If both the cutting tool and the CFRP are cooled, the thrust force generated in the machining process is increased, because of an increase in the hardness of CFRP due to its being frozen [4]. The increase in the thrust force causes progression of tool wear and delamination at the machined holes. Therefore, the cooling target was limited to the cutting tool just before cutting process starts. At the beginning of the machining process, the previously cooled cutting tool is expected to prevent the increase of cutting temperature and it results in the suppression of tool wear and temperature rise of workpiece. From the middle to the final stages of the machining process, the cutting tool temperature will gradually increase, and the thrust force will reduce due to softening of the epoxy resin by the slightly increased cutting temperature. But the softening of epoxy resin will be small comparing with the case of dry cutting, so that the influence of the temperature rise on the delamination at the outlet of machined hole will be suppressed.

2.3. Kinematics of helical milling

The principal difference between drilling and helical milling processes is the kinematic conditions. In the helical milling process, the cutting tool moves in a spiral and mills holes that are larger than the tool diameter, as shown in Fig. 1. A space is generated between the cutting tool and the workpiece so that the cutting fluid can be easily supplied to the cutting point [5]. In addition, in a helical milling process, the cutting forces generated in the X and Y directions are higher than those in a drilling process. Therefore, in the helical milling process, the thrust force is comparatively small because of dispersion of the cutting forces. As a consequence, helical milling is expected to improve the surface quality by decreasing the thrust force and improving the chip evacuation.

3. Experimental setup and procedure

Fig. 2 shows the experimental setup. A three-axis vertical machining center (V33, Makino Milling Machine Co., Ltd.) with a maximum ultrasonic vibration spindle rotation speed of 8000 min^{-1} was used for the cutting tests. A specially designed spindle was controlled by an ultrasonic vibration controller (Sonic Impulse SD-100, Taga Electric Co., Ltd.) that was used to supply the axial ultrasonic vibration to the cutting tool. The frequency and amplitude were 70.2 kHz and 9.1 μm, respectively. A three-component dynamometer (9257B, KISTLER Co., Ltd.) was set on the machine table in order to measure the cutting forces. The CFRP was fixed by a jig.

In proposed cryogenic tool cooling, the cutting tool was cooled in a LN_2 chamber for one minute before machining, as shown in Fig. 3. Then, a hole was machined by the cooled cutting tool. These two steps were repeated. The cutting tests were carried out using a ball endmill with a 2.0 mm diameter. The thickness of the CFRP was 3.5 mm. As shown in Fig. 4, the CFRP consisted of 5 layers: bidirectional layers were arranged on the top and bottom, and three uni-direction layers were sandwiched between the bidirectional layers.

The effects of the ultrasonic-vibration-assisted machining, cryogenic tool cooling, and hybrid machining applying ultrasonic vibration and cryogenic tool cooling were investigated by evaluating the thrust forces, machining accuracy, and tool wear.

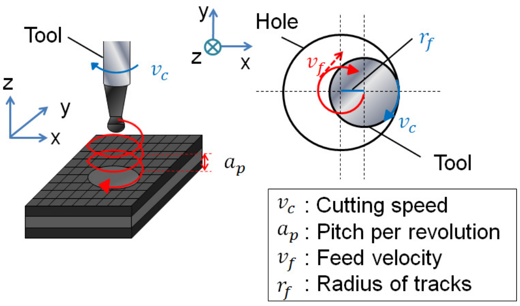


Fig. 1. Kinematics of helical milling

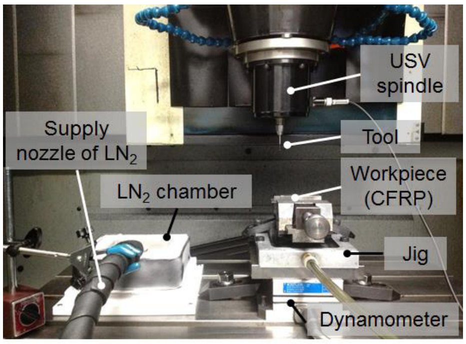
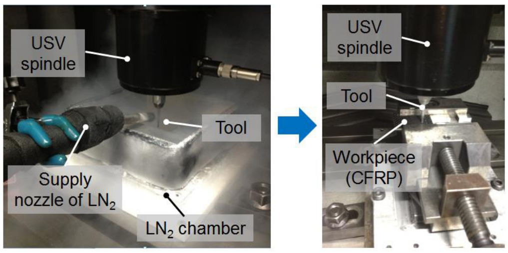


Fig. 2. Experimental setup for cryogenic tool cooling and ultrasonic vibration (USV)



(a) Step1: Cooling for the cutting tool (b) Step2: Machining process

Fig. 3. Procedure of cryogenic tool cooling

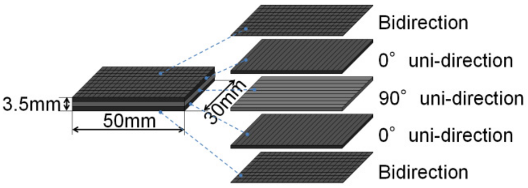


Fig. 4. Model of laminate structure

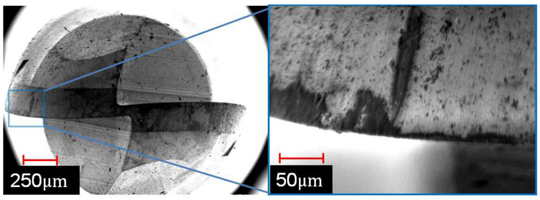
4. Evaluation of tool wear

The experiment was carried out with five different cutting processes: ① conventional helical milling, ② ultrasonic-vibration-assisted helical milling, ③ helical milling with cryogenic tool cooling, ④ultrasonic-vibration-assisted and helical milling with cryogenic tool cooling, and ⑤ dry helical milling.

Table 1 shows the cutting conditions for helical milling. The flank wear of the cutting edge was measured using a scanning electron microscope. Scanning electron microscopy images of the cutting edge of tool before machining is shown in Fig. 5. Flank wear was measured after each of the five holes were machined. Fig. 6 is the image of the end cutting edge zone after machining 40 holes using conventional helical milling. The outside flank wear, which is shown on the left side of the image, is comparatively wide. It is thought that the tool wear on the outside edge progresses due to the high cutting speed and long cutting distance. Therefore, the average widths of the outside flank wear with ten points measurement were plotted in Fig. 7, according to the number of machined holes.

Table 1. Cutting conditions

Cutting condition type	Cutting condition
Tool	Carbide ball endmill
Hole depth	3.5 mm
Cutting fluid	Soluble cutting oil, Liquid nitrogen
Rotation speed	8000 min^{-1}
Feed velocity	270 mm/min
Pitch per revolution	1.0 mm
Radius of tracks	0.5 mm
Axial ultrasonic vibration (Frequency/Amplitude)	70.2 kHz / 9.1 μm



(a) Bottom view (b) Magnified view at cutting edge

Fig. 5. Scanning electron microscopy image of the tool before machining

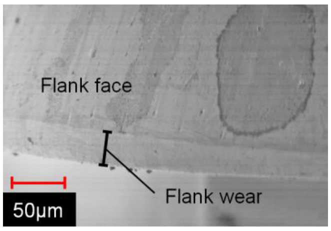


Fig. 6. Scanning electron microscopy image of the end cutting edge after machining 40 holes in conventional helical milling

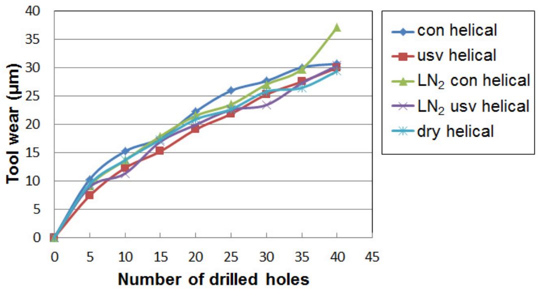


Fig. 7. Comparison of tool wear in each cutting process

As shown in this figure, no significant differences were obtained between the five different cutting processes. It is supposed that, in machining of CFRP, the tool wear is significantly caused by the hardness of carbon fibers which is hardly depends on the cutting temperature.

5. Evaluation of thrust force

Fig. 8 shows the behavior of the cutting force at the 40th hole in conventional helical milling. As shown in Fig. 8, in a helical milling process, the cutting forces are distributed in the X and Y directions, in contrast to a drilling process. In this paper, the thrust force in each cutting process was evaluated.

Fig. 9 shows a comparison of the maximum thrust force in each cutting process. As the number of machined holes increased, the thrust force increased according to the progression of tool wear. By applying ultrasonic vibration, the thrust force was reduced compared with conventional helical milling because of the reduction in friction between the cutting tool and the workpiece. The thrust force in dry machining was the smallest. This was because the epoxy resin of the CFRP was softened by the cutting heat. The thrust force was also reduced by applying the proposed cryogenic tool cooling. It is supposed that the cooling effect for the cutting tool was lost during the machining process, because liquid nitrogen was not supplied during the machining process. As shown in Fig.10, when using the proposed cryogenic tool cooling, the thrust force gradually reduces as the machining time proceeds. This phenomenon will be caused by the softening of the epoxy resin by the cutting heat generated from the middle to the final stages of the machining process. It is expected to implement the cutting process since the epoxy resin in the proposed method does not get softer than the one in dry machining.

6. Evaluation of machined hole accuracy

To evaluate the accuracy of the machined holes, the delamination size at the machined holes was measured using a digital microscope (VHX-600, KEYENCE Co., Ltd.). In this study, a two dimensional delamination factor F_a was introduced in order to evaluate the accuracies of the machined holes. As shown in Fig. 11, F_a was defined by the following equation:

$$F_a = A_d/A_0 \tag{1}$$

where A_d is the delamination area, and A_0 is the hole area.

Fig.12 shows the two dimensional delamination factor F_a at the inlet of the machined holes in each cutting process. The average and variation of F_a show the highest values in dry helical milling. This was because the cutting process was not applied for epoxy material of CFRP due to softening of epoxy resin in dry machining. On the other hand, in the helical milling with cutting oil, machining accuracy was improved at the inlet of the machined holes because of suppression of cutting heat. From the comparison result of thrust force, the largest thrust force indicated that cutting process could be implemented to solid epoxy resin with sufficient cooling and chip evacuation. The delamination was successfully suppressed in the proposed cryogenic tool cooling. As shown in Fig. 13, the delamination size at the inlet of the 40th machined hole, was small in each cutting process.

Fig. 14 shows the two dimensional delamination factor F_a at the outlet of the machined holes in each cutting process. The experimental results clearly showed that F_a was reduced by applying ultrasonic vibration and proposed tool cooling method. According to past studies, it is clear that the delamination size at the outlet of the machined holes depends critically on the thrust force acting on the uncut plies. Fig. 15 shows a model of the delamination mechanism. Delamination at the outlet of the composite materials is caused when the thrust force exceeds the interlaminar bonding strength [6, 7]. That is to say, the reduction in thrust force by applying ultrasonic vibration and proposed tool cooling method improved the accuracy of the machined holes. Although the

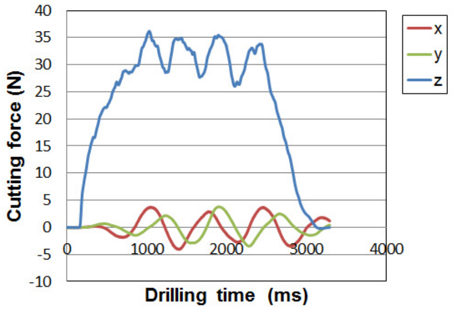


Fig. 8. Waveform of the cutting force (Conventional 40th hole)

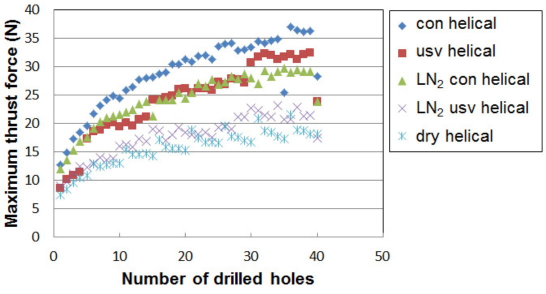


Fig. 9. Comparison of thrust force in each cutting process

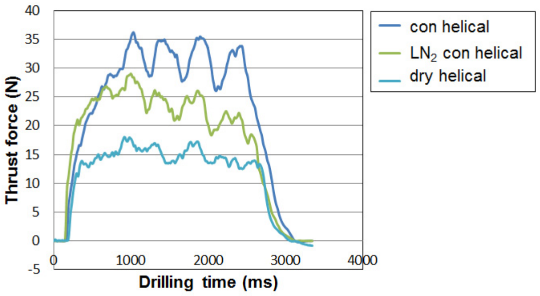


Fig. 10 Waveform of the thrust force (Conventional, LN_2 conventional and dry 40th holes)

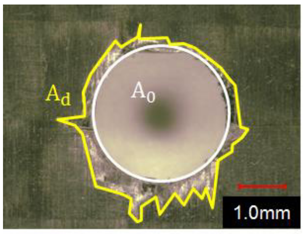


Fig. 11. Model of two dimensional delamination factor F_a

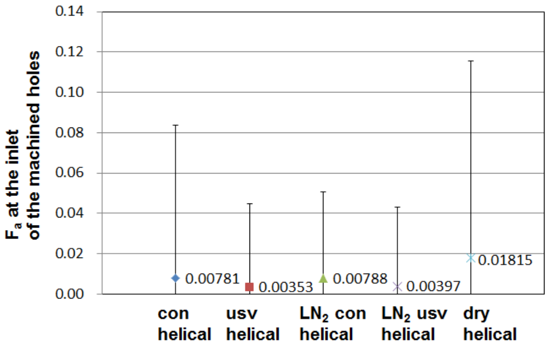
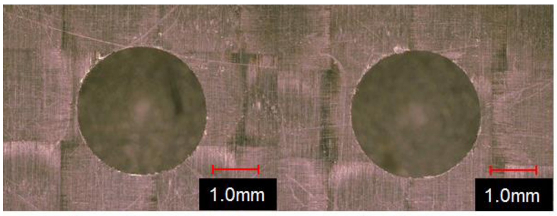
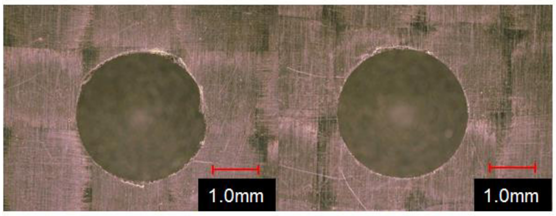


Fig. 12. Two dimensional delamination factor F_a at the inlet of machined holes in each cutting process

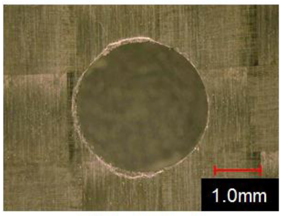
thrust force was the smallest in the dry helical milling, the accuracy at the outlet of machined holes was low. This was due to the large softening of epoxy resin occurred by the cutting heat at the outlet of the machined hole. As a consequence, the average and variation values of F_a were the smallest for hybrid helical milling. As shown in Fig. 16, the delamination size was small in each of the cutting processes, because the helical milling method with a ball endmill was effective in reducing the thrust force.



(a) Conventional helical (b) USV helical



(c) LN_2 conventional helical (d) LN_2 USV helical



(e) Dry helical

Fig. 13. Digital microscope image of delamination at the inlet of the 40th machined holes

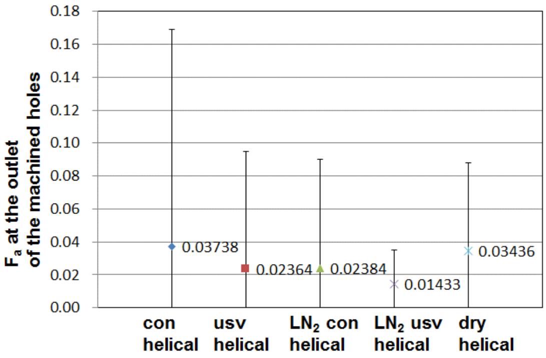


Fig. 14. Two dimensional delamination factor F_a at the outlet of machined holes in each cutting process

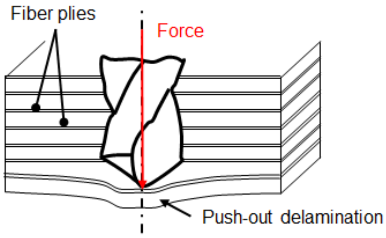
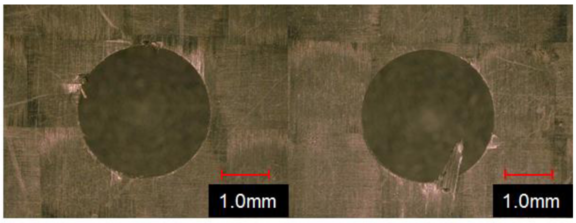
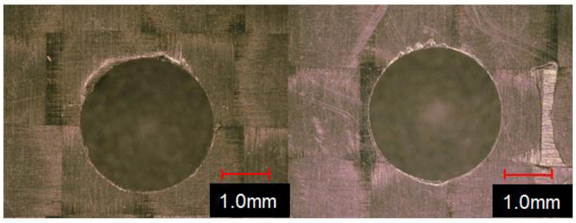


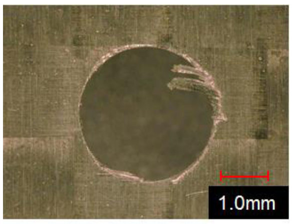
Fig. 15. Model of delamination mechanism



(a) Conventional helical (b) USV helical



(c) LN_2 conventional helical (d) LN_2 USV helical



(e) Dry helical

Fig. 16. Digital microscope image of delamination at the outlet of the 40th machined holes

7. Conclusion

Helical milling of CFRP applying axial ultrasonic vibration and cryogenic tool cooling was proposed in this paper. The tool wear, thrust force, and accuracy of the machined holes were evaluated. The results are summarized as follows.

1) When comparing tool wear, there were no significant differences between the five different cutting processes.
2) Thrust force was clearly reduced by ultrasonic-vibration-assisted helical milling and proposed helical milling with cryogenic tool cooling.
3) In particular, high-precision holes were obtained at the inlet of the machined holes by the proposed helical milling with cryogenic tool cooling.

4) The delamination size at the outlet of the machined holes was reduced by ultrasonic-vibration-assisted machining and proposed cryogenic tool cooling, because of the reduction in the thrust force.
5) Synergistic effects with regard to thrust force and delamination size were obtained by combining ultrasonic-vibration-assisted helical milling and proposed helical milling with cryogenic tool cooling.

Acknowledgements

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