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Procedia CIRP 24 (2014) 13 – 18
www.elsevier.com/locate/procedia

New Production Technologies in Aerospace Industry - 5th Machining Innovations Conference (MIC 2014)

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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doi:10.1016/j.procir.2014.07.139

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.

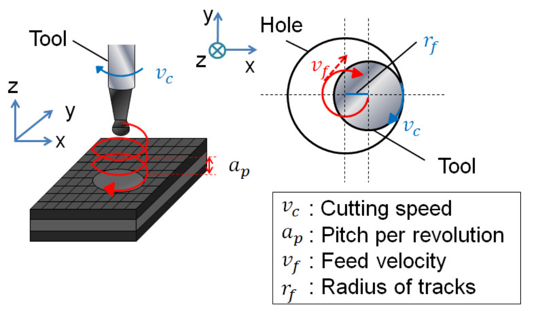

Fig. 1. Kinematics of helical milling

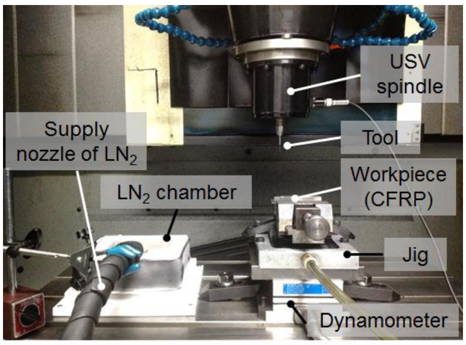

Fig. 2. Experimental setup for cryogenic tool cooling and ultrasonic vibration (USV)