

Analysis of Tool Wear, Cutting Force, Surface Roughness and Machining Temperature During Finishing Operation of Ultrasonic Assisted Milling (UAM) of Carbon Fibre Reinforced Plastic (CFRP)

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Abstract

Carbon fibre reinforced plastic (CFRP) is typically manufactured near to net-shape. However, secondary machining processes such as milling are often required before final assembly operation. Conventional milling is often associated with challenges such as rapid tool wear, poor surface roughness, fibre pull-out, delamination and high cutting forces. The present work compares ultrasonic assisted milling (UAM) with conventional milling (CM) of CFRP in term of tool wear, cutting force, surface roughness, and machining temperature. Experiments for UAM and CM were conducted using three fluted polycrystalline-diamond (PCD) tools employing constant speed (500m/min) and feed rate (0.8m/min). For UAM, the amplitude and frequency were fixed at 5µm and 39000 Hz, respectively. Application of UAM resulted in reduced forces (up to 20 %) and temperatures (up to 15 %), however, it was observed that surface roughness increased (up to 5 %). In addition, UAM produced higher tool wear (106 µm) when compared to CM (80 µm) after 10m machining length. Analysis of thermal damage of machined surface using Differential Scanning Calorimetry (DSC) is also presented. The glass transition temperature (T_g) of CFRP shifted from 272 °C to ≈70 °C for both UAM and CM suggesting that machining temperature resulted in significant material property changes.

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1. Introduction

Due to high demand in high strength and stiffness to weight ratio materials, especially in aerospace and automotive industries, application of composite materials in this area has been increasing significantly. For instance, the use of carbon fibre reinforced plastic (CFRP) can reduce 40 % of the mass of products in some aerospace applications for example by replacing aluminium yet keeping the same material properties [1]. Moreover, weight reduction in aerospace application gives benefits to the product performances and better fuel consumption. CFRP can also be modified to suit particular engineering applications. CFRP composites have much freedom in shape design and are usually moulded near to net shape. A secondary machining operation, however, such as milling of CFRP is typically required in order to remove excess material, to produce complex contours and to meet product dimensional tolerances as well as for quality requirements [2-4]. Milling of CFRP is crucial since the machining operation usually takes place at the end of the manufacturing process. Properties of CFRP which are isotropic and heterogeneous, create problems in machining such as rapid tool wear, fibre delamination, high cutting force, fibre pull-out and fibre-matrix debonding [5-7]. Poor surface roughness and high internal damage of CFRP decrease the strength of the CFRP structure [5-7].

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Selection of machining parameters, tool geometry and materials are crucial in machining of CFRP to reduce the damage on the machined surface and increase tool life. Polycrystalline Diamond (PCD) has typically been selected as cutting tools when the surface roughness requirement and tool life expectation are the major concerns in machining. PCD tools provide longer tool life due to their superior abrasion resistance [5]. Machining forces present during milling are dependent on machining parameters such as cutting speed, feed rate, tool geometry, ply orientation and tool condition. Many researchers agree that with an increase in feed rate and a decrease in cutting velocity [6, 7], forces exerted on the composite laminates will be increased. Increasing volume of uncut chip thickness generally resulted in an increase in machining force [8, 9]. In terms of depth of cut, higher depth of cut will require more force to remove the material. Machining quality of CFRP is described by surface finish and surface integrity including the mechanical, and thermal damage of the machined surface [10]. The mechanism of chip formation is determined by feed rate and therefore largely influence the value of average surface roughness (Ra). Azmi et al. [11] suggest that higher feed rate leads to an increase in strain rate on the composite, which promotes excessive fracture of the fibre leading to deterioration of the surface roughness.

In addition, machining temperature is an important factor that needs to be considered when machining CFRP. Machining temperature that is higher than the glass transition temperature (T_g) of the resin will degrade the strength and properties of the CFRP [5,6]. Several methods have been implemented to measure temperature while milling CFRP such as thermal camera [12], K-type thermocouple and tool-work thermocouple [13]. However, there is no consensus that the temperature recorded using any of these proposed methods is the actual machining temperature. The application of water based coolant in machining CFRP is not recommended [14] since it can affect the strength and properties of the CFRP. Meanwhile, it has been proven that the implementation of chilled air coolant during machining, will reduce the measured machining temperature [12, 15]. To overcome deficiencies in conventional machining (CM), ultrasonic assisted machining (UAM) is one of the prominent techniques being investigated in machining CFRP. The general principle of UAM is to apply high frequency (10-40 kHz), and low peak-to-peak vibration amplitude to the tool or workpiece [16-18]. Ultrasonic vibration can be implemented by either vibrating the workpiece [19, 20] or oscillated the cutting tool. The ultrasonic vibration can be superimposed either in x, y or z- direction for both tool and the workpieces. Research on UAM of CFRP is still ongoing and limited literature can be found. However, UAM of metal has been reported widely by many researchers. Razfar et al. [16] investigated the effect of ultrasonic assisted milling of AISI 1020 steel in term of depth of cut, cutting speed and feed rate. The surface roughness is improved by up to 12.9 % when implementing UAM. Throughout UAM, the cutting tool cooled more quickly, and they attributed this to the periodic separation between the cutting tool and the workpiece. Lower cutting parameters are recommended for UAM to achieve lower forces and improvements in surface roughness, since the tool and the workpiece were separated during ultrasonic vibration [16, 18, 19]. In terms of tool life, however, Janghorbanian et al. [20] suggest employing higher cutting speed in order to improve tool life while milling AISI 304 steel. Phadnis et al. [21] reported that average thrust force was reduced by 30 % when applying ultrasonic vibration when drilling CFRP. Zarchi et al. [17] and Shen et al. [22] agree that forces while milling AISI 420 steel are reduced during UAM compared to CM. Reduction of cutting forces is attributed to the vibration amplitude influencing the gap between the cutting tool and the workpiece material resulting in improved chip-breaking conditions.

The aim of the present work is to investigate the influence of UAM and to compare with CM of CFRP using a finishing tool recommended by the aerospace industry in terms of tool wear, machining force, surface roughness and machining temperature. The effect of machining temperature on the materials property changes will be discussed as well in this paper.

2.0 EXPERIMENTAL METHODOLOGY

End milling of Carbon Fibre Reinforced Plastic (CFRP) was performed on an Ultrasonic DMU 65 machine using a 10 mm diameter Polycrystalline Diamond (PCD) tool with three straight cutting flutes supplied by Exactaform, Figure 1. The workpiece materials employed in this study comprised of 36 layers unidirectional fibre layered up to achieve quasi-isotropic materials with 5250-4 BMI type of resin. The BMI resin has a glass transition temperature of 272 °C. CFRP workpiece materials were cut into two different dimensions of 50x100x5 mm and 165x100x5 mm, for force measurement and tool wear measurement, respectively. The CFRP strip for force measurement was attached to a special fixture on a Kistler Dynamometer Type 9257 B while for the progression of tool wear the CFRP panel was clamped on the machine table using a special fixture. The dynamometer was connected to a personal computer running Dynoware software that recorded cutting forces during the end milling process. Figure 2 illustrates the overall set up for the end milling experiment. The temperature during end milling of CFRP was recorded using FLIR T425 thermal camera with capabilities of recording maximum 2000 °C temperature. The thermal camera was located 50 cm from the machining area, and it was covered using plastic to avoid the carbon dust from affecting the camera lens. Progression of tool wear during milling was measured for every 1-metre of machining length using an optical microscope equipped with ZEISS Axiocam digital camera. The tool wear was measured at all three flutes. Variation of surface roughness was measured using an Alicona optical 3D micro coordinate system in the longitudinal direction with 0.8 m cut off and 4 mm evaluation length. The surface roughness was measured at six different locations on the machined surface. In addition, machined surface and tool condition after milling were examined using a Scanning Electron Microscope (SEM) for detailed analysis. Figure 3(a-b) show the method for measuring the ultrasonic amplitude using Keyence LK-H008 laser device before the UAM test was performed. The ultrasonic amplitude was measured three times to ensure the validity of the data. Ultrasonic amplitude and frequency were kept constant at 5 μ m peak-to-peak and 39000 Hz, respectively for UAM. The ultrasonic oscillation was imposed on the cutting tool and in the z-direction. A constant machining parameter was employed in this speed (500 m/min),

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