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Machinability study of ultrasonic assisted machining (UAM) of carbon fibre reinforced plastic (CFRP) with multifaceted tool

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Abstract

This paper discusses the conventional machining (CM) and ultrasonic assisted machining (UAM) of end milling carbon fibre reinforced plastic (CFRP). Tool condition, cutting forces and surface integrity of machined surface were evaluated. A commercially available tool with a diameter of 10mm and a nickel bonded, 420 µm diamond grit coating was used with a constant speed of 565 m/min, feed rate of 1500 mm/min and radial depth of cut of 3 mm. For UAM, a frequency of 43 kHz and amplitude of 6.9 µm were employed. UAM showed a reduction in cutting force, better tool condition and improved of surface roughness as compared to CM.

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Keywords: End milling, Machinability, Composite, Ultrasonic Assisted Machining.

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1. Introduction

Carbon fibre reinforced plastic (CFRP) offers unique mechanical and physical properties making them increasingly popular in replacing metal in various industries such as aerospace and automotive. The low volume to weight ratio and high strength to weight ratio of CFRP makes them increasingly desirable in aerospace applications for cost reduction and fuel saving. CFRP components are made near to net-shape; however, secondary machining processes, such as milling, edge trimming and drilling are still required. Milling/edge trimming of CFRP components is essential for part dimensional accuracy, removing excess materials and finishing operation [1, 2]. Machining of CFRP composites is a challenging task as the anisotropic and non-homogenous nature of CFRP makes it difficult to machine. The highly abrasive nature of carbon fibres leads to rapid tool wear and reduced tool life. Delamination, fibre and matrix pull-out, matrix cracking and smearing, and rapid tool wear are the most commonly problems reported when machining CFRP [2-4]. Careful selection of machining parameters, cutting tool and machining conditions are essential and critical in machining CFRP since this will affect the workpiece quality and component performance. Machining of CFRP with a diamond abrasive cutter is recommended by several researchers [5-7] when employing high cutting speed and feed rate. High material removal rate and the improved quality of the machined surface can be achieved by employing diamond abrasive cutters compared to a conventional milling cutter [6]. Longer tool life, lower surface roughness and lower machining force are achieved when employing a diamond abrasive cutter as compared to a CBN tool when routing CFRP [5]. The high wear rate of CBN tools increases the machining temperature, resulting in smearing of the matrix resin on the cutting tool. Some authors [8, 9] have suggested that the application of chilled air during milling CFRP can prolong the sharpness of the cutting tool and yield lower surface roughness together with tool life. They found that fibre pull-out and matrix degraded due to the high cutting temperatures resulted when machining CFRP in dry conditions. Chilled air coolant can prevent the matrix from burning [9, 10] and aid in chip evacuation during machining CFRP [8], since application of a water-based coolant is not recommended when machining CFRP [4].

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Several authors suggest that fibre orientation is critical when machining CFRP[4, 9, 11]. Theory suggests that machining should be done parallel to fibre direction in order to attain low surface roughness and cutting force. There are three principle types of chip formation: delamination, fibre buckling and fibre bending [4]. In terms of machining parameters, low feed and high speed results in lower surface roughness and low cutting force [5, 8, 10]. The effect of feed rate is more dominant compared to speed and depth of cut when machining composite because feed rate influences the mechanism of chip formation [4]. Ahmad et al. [3, 12] recommended low feed rate, high cutting speed and small effective chip thickness when edge trimming CFRP composite to achieve the best machined surface quality in terms of surface roughness and delamination depth.

In order to overcome problems associated with machining CFRP composites, several non-conventional machining methods have been explored. Combinations of both workpiece and cutting tool vibrations have been shown to improve the machinability of CFRP in terms of tool life, forces and workpiece surface integrity [13-16]. The general principal of ultrasonic assisted machining (UAM) is applying high frequency (20-40 kHz) and low peak-to-peak amplitude (up to 10µm) to the tool or workpiece [13-15]. Authors [14, 16] have suggested that the lower force recorded in UAM can be attributed to less tool-workpiece engagement where the tool and workpiece have no contact over a certain period. There is no consensus, however, with respect to surface roughness, where both improvement and degradation of Ra has been reported. Where lower Ra is reported, it is attributed to prolonged tool edge sharpness when employing ultrasonic assistance [16]. Increases in Ra occur when ultrasonic vibration is perpendicular to the feed direction [13]. The purpose of this study is to investigate the effectiveness of ultrasonic assisted machining in terms of tool condition, cutting forces and surface integrity in comparison with conventional machining of CFRP.

2. Methodology and Experimental Set-Up

The experiments conducted in this work involved end milling of CFRP panels using multifaceted cutting tools. In this study, experimental work was carried out on an Ultrasonic DMU 65 machine with maximum spindle speed of 18000 RPM. End milling of CFRP for both UAM and CM was carried out employing a 10 mm nickel layer electroplated cutting tool with an average of 420 µm diamond grit (Fig.1). The workpiece material employed in this study was 10mm thick CFRP, comprising 76 layers of multidirectional fibre and 5250-4 BMI resin. The workpiece was cut into 50x100x10 mm strips for force measurement. Another CFRP panel with a dimension of 300x300x10 mm was attached on a special fixture for progression of tool wear (Fig. 2a.). The Dynamometer Kistler type 9257b was employed for force measurement. It was connected to a charge amplifier and linked to a personal computer running Dynoware software for the force analysis. Ultrasonic amplitude was measured using a Keyence LKH-008 before the ultrasonic assisted machining was performed (Fig. 2b.).

Fig. 1. 10mm diameter of nickel layer electroplated cutting tool with average of 420µm diamond grit.

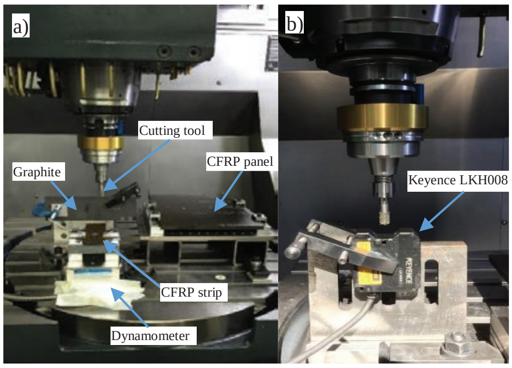

Fig. 2. (a) Experimental set-up (b) Amplitude measurement

To quantify the tool wear, a graphite plate of 3 mm thick was employed for tool diameter reduction measurement after every 1 metre machining length [5]. The slot area on the graphite made by the cutting tool was measured using a Vernier calliper at three different heights and the average of the diameter was calculated. Surface roughness was measured using an ALICONA surface profiler in longitudinal direction with 0.8 mm cut-off and 4 mm evaluation length. An optical microscope equipped with ZEISS Axiocam digital camera was employed to capture the tool condition every 1 metre cut length. Scanning Electron Microscopy (SEM) was employed for machined surface evaluation and cutting tool inspection at the end of the test. For both tests, a constant speed of 565 m/min, feed rate of 1500 mm/min and 3 mm of radial depth of cut were employed to machine a 10 metre length of CFRP. For UAM, a frequency of 43 kHz and amplitude of 6.9 µm were employed. All machining tests were carried out in dry condition.

3. Results and Discussion

3.1 Cutting tool condition

Cutting tool variations over 10 metre machining length for both UAM and CM have been plotted, Fig. 3. For the first 3 metres of machining length, both UAM and CM cutting tools experienced rapid tool wear, representing the initial conditioning of the sharp abrasive peaks of the diamond. As the machining length increased, the tool diameter for the conventional machining started to increase, while the tool diameter for UAM decreased. Examination under the microscope showed that the cutting tool of CM was covered with the broken fibre and the CFRP material's resin that had degraded in between the diamond grit (Fig. 4). It was suspected that the machining temperature at this stage started to increase and degraded the material, whereby smoke was observed when machining was performed.

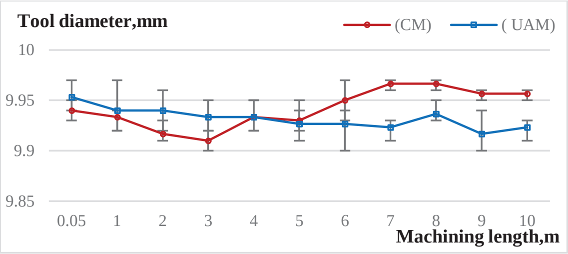

Fig. 3. Cutting tool diameter variation.

The motion of the cutting tool in UAM, which vibrates and rotates at the same time, improved the circulation of the chip when machining CFRP. Constant separation between the cutting tool and workpiece during machining created the mechanism for the chips to evacuate during the machining process. However, for CM, the CFRP chips did not have sufficient space to evacuate from the cutting tool and machine surface. As a result, broken fibre and resin were found on the cutting tool and machined surface. At the end of the machining test, both cutting tools were cleaned using ultrasonic cleaning in acetone; however, the materials still adhered to the CM's cutting tool suggesting that the matrix resin had degraded and plastically deformed during the machining. Further investigation under SEM (Fig. 5) after 10 metre machining length indicated that the cutting tool for CM experienced grain pull-out, minor cracking between diamond grit and nickel bond, and the diamond grit was completely covered by the deformed resin and broken fibre. For UAM, ultrasonic oscillation during machining generated micro cracks on the diamond grit, which created more sharp cutting edges on the cutting tool.

Fig. 4. Cutting tool condition after 10 metre machining length

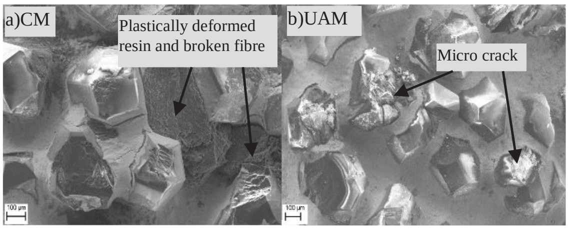

Fig. 5. Tools condition under SEM after 10 metre machining length with voltage and aperture size of 15 kV and 30 µm respectively

3.2 Cutting force

Fig. 6 shows that the machining forces recorded in y-direction for UAM and CM are comparable. The feed force (Fx) recorded by UAM showed up to 20% of force reduction as compared to the CM. Both, in CM and UAM, forces increased as the machining length increased and the cutting tool started to wear. However, higher machining forces were recorded in CM than those in UAM. This took places due to larger plastically deformed matrix transferred to the tool in CM than that in UAM causing higher obstruction in machining in CM, as shown in Fig. 4. The resin that covered the diamond grit in CM reduced the active cutting edges, creating more friction, and increased the energy for the cutting tool to remove the materials. Due to the increasing number of wear flats and diamond cracks in CM, it initiated greater frictional interaction between the cutting tool and the workpiece. Material loaded on the cutting tool created the rubbing effect between the loaded materials and workpiece, hence increasing the cutting force.

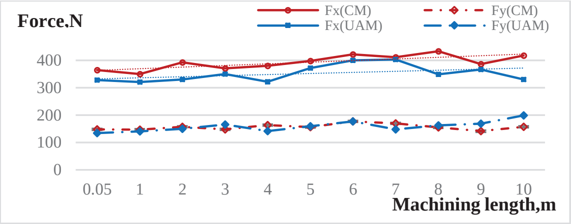

Fig. 6. Maximum machining force for conventional machining (CM) and ultrasonic assisted machining (UAM).

3.3 Surface integrity

Fig. 7 shows surface roughness of the machined surface for UAM and CM over the 10 metre machining length. Surface roughness of the UAM machined surface was 20% improved compared to the CM. As the machining length increased, the surface roughness increased for both UAM and CM. Progression of surface roughness can be related to the cutting tool condition and machining force for both processes. The CM cutting tool was loaded with the workpiece materials and experienced wear flat as the cutting length increased; hence, the cutting action was in the form of friction instead of fracturing the workpiece materials. In UAM, the periodic separation of cutting tool and workpiece, due to the ultrasonic motion of the diamond grit, aided to fracture the fibre.

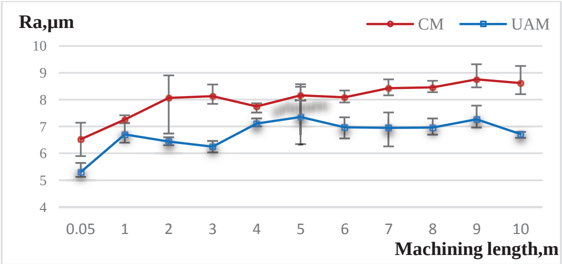

Fig. 7. Surface roughness by Alicona surface profilometer.

Inspection of the surface condition after 10 metre length showed that the surface for the CM cutting condition experienced matrix smearing, fibre pull-out and fibre-matrix cracking, Fig. 8(a). At this length, the CM cutting tool was loaded by matrix materials covering the diamond grit. Instead of cutting the fibre and matrix by fracturing them, the cutting tool tended to remove the material by pushing and increased friction between the tool and workpiece. As a result, it was observed that the polymer matrix had smeared on the machined surface and fibres had been pulled out from the workpiece (Fig. 8a). For UAM, Fig. 8b shows that there is a void and hole on the surface and fibres have been pulled out from the surface. However, on the machined surface of UAM there is less evidence of matric smearing and broken fibre.

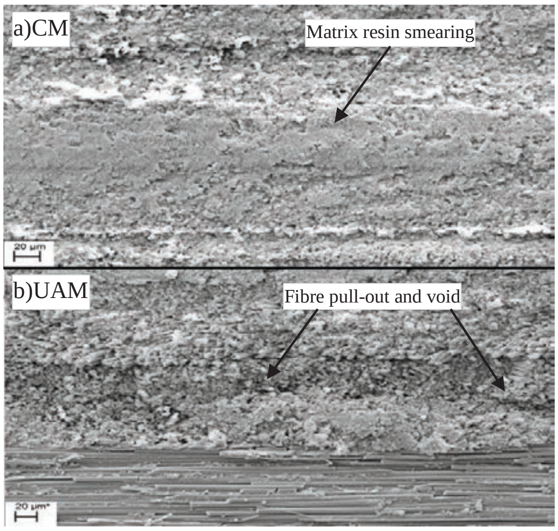

Fig. 8. Surface condition under SEM after 10 metre machining length for a) CM and b) UAM with voltage and aperture size of 15 kV and 30 µm respectively.

4. Conclusion

The effect of ultrasonic assisted machining (UAM) and conventional machining (CM) of CFRP has been discussed in this paper. Experimental work is presented comparing UAM with CM in terms of tool life and workpiece quality. The following conclusions can be drawn:

- The presence of ultrasonic assistance when machining CFRP yielded better tool condition when compared to conventional machining. UAM creates more active cutting edges because less materials stuck on the tool compared to CM. During CM, however, the chips adhered and covered the diamond grit. Hence, there were less active cutting edges in CM of CFRP as compared to the UAM.
- Major wear occurring in CM was grain pull-out and wear flats of the diamond grit. In contrast to UAM, micro cracks in the diamond grits were observed after 10 metre machining length, suggesting that UAM can prolong tool life.
- Cutting forces and surface roughness recorded by UAM showed 20% improvement as compared to CM.
- Thus, application of ultrasonic amplitude has been shown to increase tool life, provide improved surface roughness and lower machining forces when machining CFRP.

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