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The effect of varying cutting speeds on tool wear during conventional and Ultrasonic Assisted Drilling (UAD) of Carbon Fibre Composite (CFC) and titanium alloy stacks.

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Abstract

The application of Carbon Fibre Composite (CFC) and titanium alloys are becoming more prevalent in aerospace industry due to their high-strength-to-weight ratio. However, the drawback of these materials is poor machinability. This paper presents the potential of Ultrasonic Assisted Drilling (UAD) of CFC and titanium Ti6Al4V stacks in delaying tool wear progression. Experiments comparing conventional and UAD were conducted using 6.1 mm diameter tungsten carbide drills, employing constant feed rate of 0.05 mm/rev and cutting speeds of 25, 50 and 75 m/min, demonstrated that the drills used in UAD underwent lower tool wear rate and thrust forces than conventional drilling.

Keywords: Drilling, Ultrasonic, Wear, Carbon Fibre Composite, Titanium Alloy.

1. Introduction

Increasing demands for lightweight, high performance materials has put Carbon Fibre Composite (CFC) and titanium alloys at the forefront in many industries. CFC which comprises carbon fibre reinforcement in lightweight polymer was originally developed, particularly for making aircrafts due to concerns over fuel and energy saving [1]. Titanium alloy is typically employed in the area where metallic structure and high temperature strength is required such as the airframe and engine parts. Drilling is normally performed on both CFC and titanium alloy for joining by mechanical fasteners. Drilling these materials however, can result in delamination (CFC), burr formation (titanium) and rapid tool failure [2, 3]. CFCs were preferably drilled using cutting speeds of 100 to 200 m/min and feed rates within the range of 0.01 to 0.05 mm/rev; with tungsten carbide cutting tools [4]. Diamond coated and PCD cutting tools though can tolerate higher cutting speeds, which also resulted in longer tool life and improved surface quality [5]. Considering that drilling titanium alloys can result in extremely high cutting temperatures [6], titanium in contrast is preferably drilled with much lower cutting speeds in the range of 10 to 60 m/min and higher feed rates than CFC in the range of 0.05 to 0.1 mm/rev.

The work of Kuo *et al*. [7] involving drilling of titanium, CFC and aluminium stacks demonstrated that the use of higher cutting speeds resulted in higher surface roughness values for all materials and shorter tool life. The use of higher cutting speeds and lower feed rates can result in a significant increase in cutting temperature up to 1000 °C, hence weakening the cutting tool and shortening tool life [8]. In the case of drilling multi-materials stacks, a compromise between the ideal parameters for individual materials in the stacks is recommended, although some literature [2, 3] reported changing and varying the parameters accordingly when drilling respective materials in the stacks was feasible. The work of Makhdum *et al*. [9] and Pujana *et al*. [10]

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demonstrated that Ultrasonic Assisted Drilling (UAD) on CFC and titanium alloy individually has potential to improve drilling performance in terms of lower cutting forces, less CFC delamination and smaller titanium burr compared to conventional drilling. This paper presents the performance of UAD on CFC/Ti6Al4V stacks in terms of tool wear/life when using three different cutting speeds with a constant feed rate in comparison to conventional drilling. UAD is a hybrid machining process in which the cutting motion of a conventional drill is superimposed with high frequency ultrasonic vibration in axial direction [11].

2. Experimental Procedure

The stacks materials used in this work comprise 4 mm thick CFC (multidirectional (0˚, 45˚, 90˚, 135˚) carbon fibres with Bismaleimide (BMI) resin) and 4 mm thick titanium alloy Ti6Al4V. Adhesive Loctite 9492 epoxy (0.3 mm thick) was used to join CFC and Ti6Al4V in the stacks. Experiments comparing conventional drilling and UAD of CFC/Ti6Al4V stacks were conducted using DMG Ultrasonic 65 Monoblock machine tool and 6.1 mm diameter tungsten carbide 2-flutes twist drills. Figure 1 shows the experimental setup for drilling CFC/Ti6Al4V stacks conventionally and with ultrasonic.

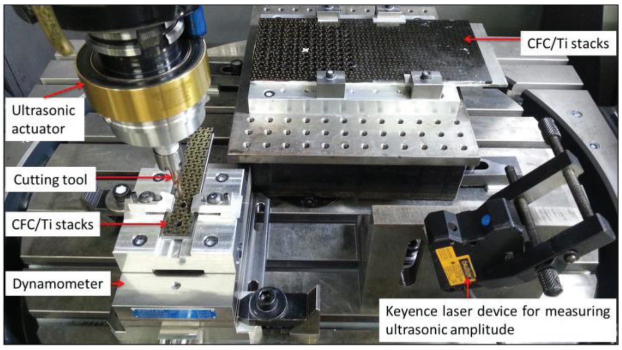

Figure 1: Experimental setup.

Although CFC is sometimes recommended to be machined dry considering the hydrophilic nature of its polymer resin, some researchers demonstrated that machining CFC with water-based cutting fluid resulted in improved surface finish due to suppression of the heat which is favourable in retaining the strength of the resin, hence minimizing thermal damage [3, 12]. Titanium alloys are always preferable to be machined with cutting fluid due to the fact that they are poor heat conductors [8]. Therefore, all drilling operations were performed with cutting fluid, supplied through external nozzles. Drilling was performed from CFC plate through to the Ti6Al4V plate. The ultrasonic actuator was turned on during UAD work with fixed ultrasonic amplitude and frequency of 5.7 µm and 39 kHz, respectively. The cutting parameters are shown in Table 1. The first hole and every subsequent 10^{th} holes were drilled in the CFC/Ti6Al4V stack mounted on Kistler Dynamometer Type 9257B connected to Dynoware software for measuring cutting forces. Tool wear was photographed and measured after drilling every 10^{th} subsequent holes using a Nikon optical microscope connected to a computer equipped with Carl Zeiss ZEN imaging software and further investigation was performed using Scanning Electron Microscope (SEM).

Table 1: Cutting parameters during conventional drilling and UAD of CFC/Ti6Al4V stacks.

Drilling Experiment #		Feed Rate (mm/rev)	Cutting Speed (m/min)	Total Number of Holes
1	Conventional	0.05	25	40
	UAD			
2	Conventional		50	80
	UAD			
3	Conventional		75	80
	UAD			

3. Analysis of Tool Wear and Thrust Forces

Figure 2 compares flank wear rate of the drills used in conventional drilling and UAD with cutting speeds of 25, 50 and 75 m/min. The graph shows that UAD resulted in lower tool wear rate and longer tool life at all cutting speeds used. Based on ISO 3685 standard, tool life ended when the flank wear reached 300 µm [13]. It was observed that titanium adhesion, edge chipping and dull cutting edges were the tool wear features when drilling CFC/Ti6Al4V stacks. With cutting speed of 75 m/min, cutting tool failed after drilling 28 holes conventionally and in UAD, the tool failed after 34 holes since the edge chipping and wear had reached 300 µm. The use of lower cutting speed of 50 m/min resulted in longer tool life which were up to 62 holes in conventional drilling and 80 holes in UAD. With respect to tool life, cutting speed of 25 m/min were seen as the optimum since it resulted in the lowest tool wear rate; with UAD providing longer tool life than conventional drilling; Figure 2.

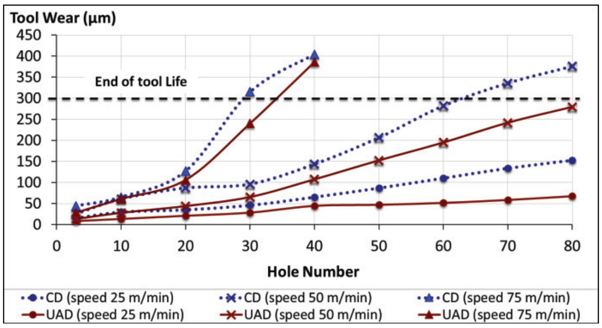

Figure 2: Graph comparing tool wear during conventional drilling (CD) and UAD of CFC/Ti6Al4V stacks using cutting speeds of 25, 50 and 75 m/min (constant feed rate = 0.05 mm/rev).

The lower tool wear in UAD resulted in reduction of thrust forces (for both CFC and titanium) which is favorable for improving hole quality, compared to conventional drilling. As shown in Figure 3 and 4, UAD with cutting speed of 25 m/min resulted in 10 to 42 N lower thrust forces for CFC and 36 to 78 N lower thrust forces for titanium alloy, compared to conventional drilling. UAD with cutting speed of 50 m/min resulted in lower thrust force than conventional drilling by 3 to 58 N for CFC and 70 to 164 N for titanium alloy. Increasing cutting speed to 75 m/min also resulted in lower thrust forces in UAD (by 15 to 40 N for CFC; by 13 to 66 N for titanium) than conventional drilling.

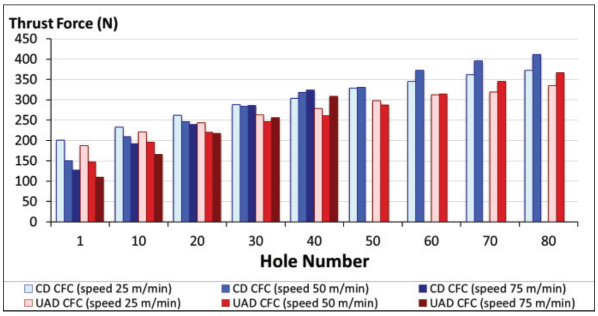

Figure 3: Graph showing comparison of average thrust forces during conventional drilling (CD) and UAD of CFC in the stacks using cutting speeds of 25, 50 and 75 m/min (constant feed rate = 0.05 mm/rev).

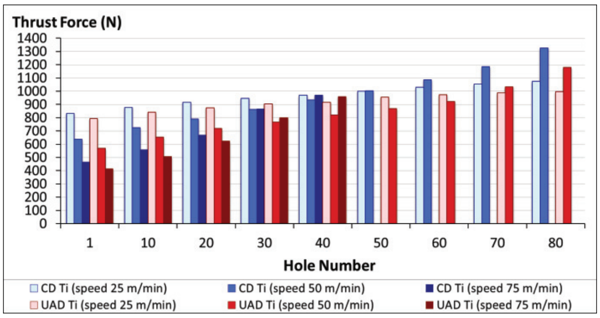

Figure 4: Graph showing comparison of average thrust forces during conventional drilling (CD) and UAD of Ti6Al4V in the stacks using cutting speeds of 25, 50 and 75 m/min (constant feed rate = 0.05 mm/rev).

Figure 5 shows the condition of the cutting edges after drilling 40 holes in CFC/Ti6Al4V stacks using cutting speeds of 25, 50 and 75 m/min. It can be seen in Figure 5, the use of higher cutting speeds resulted in more titanium adhesion, most likely occured due to higher cutting temperatures. Even though cutting temperatures were not measured in this work, the work of Li & Shih [6] involving drilling of titanium-only demonstrated that increase in cutting speed from 24 to 73 m/min caused cutting temperature to increase from 480°C to 1060°C.

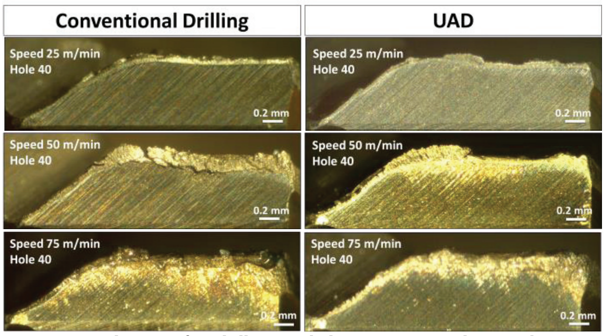

Figure 5: Tool wear after drilling 40 holes in CFC/Ti6Al4V stacks using cutting speed of 25, 50 and 75 m/min conventionally and with ultrasonic.

Titanium is a reactive material and an increase in temperature during drilling stimulated its chemical reaction with the cutting tool material [14]. Rather than sliding along the cutting edges during drilling, part of the titanium chip which was in contact with the tool separated and adhered on the cutting edges. Chipping of the cutting edges occurred when the adherent titanium were removed in which it also took away a part of the tool material. With respect to hole quality, the adhered material on the cutting edges was highly undesirable since its uneven surface and instability caused dimension inaccuracy and poor surface finish of the machined part as discussed in the previous work [15]. Less titanium adhesion on cutting edges during UAD were observed compared to conventional drilling as in Figure 5; as a result of tool vibration which partly resisted the titanium chip from obtaining constant attachment to the cutting edge. Figure 6 shows the condition of the new cutting edge and Figure 7 shows the condition of the cutting edge being chipped, which revealed uneven and rough tungsten carbide grains. This condition made the cutting edges more susceptible to larger tool fracture as drilling progressed, consequently resulted in rapid tool failure.

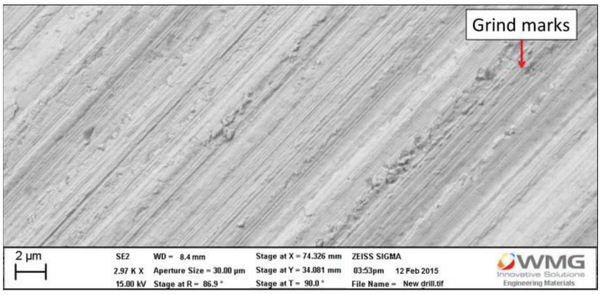

Figure 6: SEM image of new cutting edge (the grind marks are the result of tool sharpening)

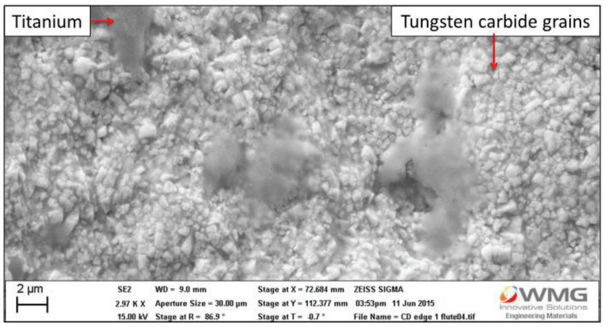

Figure 7: SEM image of the condition of cutting edge after chipping.

In the case of drilling with cutting speed of 75 m/min, edge chipping due to adhered titanium removal was observed as the primary tool wear mechanism, with UAD resulted in less edge chipping than conventional drilling. In contrast, there was no edge chipping observed when drilling using lower cutting speed of 25 m/min up to 80 holes, conventionally and with ultrasonic, and the drills wore mainly by abrasive mechanism. The fact that UAD resulted in slower tool wear progression was attributed to the intermittent cutting. Determining the wear was challenging after drilling 40 holes in the stacks using cutting speeds of 50 and 75 m/min due to the signifiant amount of titanium covering most of the cutting edges. The images of the cutting edges (Figure 5) were taken after the drills exited titanium layer in the stacks. Thus, after 40 holes, in order to see the clear cutting edges and plot the graph of the tool wear rate (Figure 2), the wear was measured after drilling CFC plate and before drilling titanium plate as in Figure 8. Figure 9 shows that the tungsten carbide grains were ground and smoothen by the abrasive carbon fibres. Edge rounding was observed, which was an evidence of abrasive tool wear feature, due to rubbing of the abrasive carbon fibres against the cutting edges.

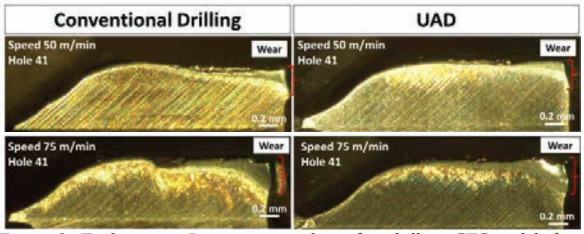

Figure 8: Tool wear – Images were taken after drilling CFC and before drilling titanium.

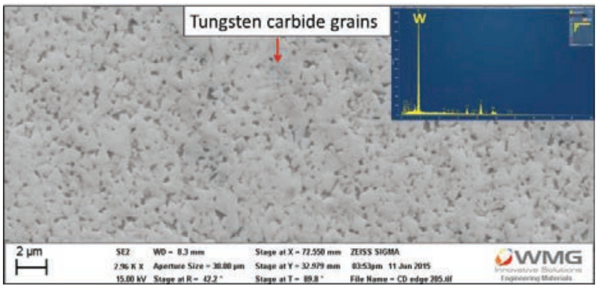

Figure 9: SEM image of abrasive tool wear feature.

4. Conclusions

With regard to drilling of CFC/Ti6Al4V stack using cutting speeds of 25, 50 and 75 m/min and constant feed rate of 0.05 mm/rev, the following conclusions are drawn:

1. Higher cutting speeds resulted in more tool wear in both conventional drilling and UAD.
2. UAD resulted in lower tool wear and thrust forces than conventional drilling at all cutting speeds due to tool vibration which provided intermittent cutting and was beneficial in reducing titanium adhesion.
3. The use of higher cutting speeds particularly in conventional drilling resulted in more titanium adhesion hence more cutting edge chipping.
4. Edge rounding or abrasive tool wear was more dominant when drilling (both conventional and UAD) using lower cutting speeds of 25 m/min compared to 50 and 75 m/min.

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