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Effect of chisel edge in ultrasonic assisted drilling of carbon fibre reinforced plastics (CFRP)

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Abstract

Ultrasonic assisted drilling (UAD) has been reported effective for thrust force reduction during drilling of CFRP resulting in lower exit delamination. However, this process is not fully understood in relation to machining theory. This work focused on understanding the separate effects of chisel and cutting edges during UAD in comparison with conventional drilling (CD). Experiments were performed at 100 m/min cutting speed and 0.05 mm/rev feed rate. UAD produced 36% lower thrust force with a chisel edge, similar torque and 35% lower wear on chisel edge compared to CD, suggesting forces from chisel edge specifically, being reduced in UAD.

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Keywords: Composite materials; Drilling; thrust force; tool wear; pilot holes

1. Introduction

Carbon fibre reinforced plastics (CFRP) have been increasingly useful in aircraft and aerospace industries due to their superior properties of lighter weight and higher strength-to-weight ratio in comparison to metals [1-3]. In spite of being cured to the final shape, mechanical drilling is required at several stages of production in CFRP in order to fasten the components through bolts and rivets in the assembly [1]. Unfortunately, CFRP material gets damaged during drilling which includes fibre pull-out, matrix cracking, thermal damage and entrance/exit delamination. Exit delamination has been reported to be the most detrimental [3, 4]. Reduction of thrust force during drilling has been found to cause reduction in exit delamination. Therefore, several attempts have been made to reduce the thrust force during drilling in order to reduce exit delamination [5]. In a recent research, ultrasonic assisted drilling (UAD) has been reported to cause reduction in thrust force in drilling of CFRP however this process has not been explored in relation to machining theory [6]. According to authors [6], thrust force has been found to reduce due to specific 'intermittent cutting action' of drill during UAD. However, no conclusive evidence has been produced in order to support this argument during drilling. The present research focused on developing an understanding on UAD process by studying the effects of cutting and chisel edges of a twist drill separately on damage during drilling by using pilot holes [7].

2. Experimental setup and procedure

Experiments were performed in Ultrasonic 65 machine from DMG/MORI SEIKI at WMG High Value Manufacturing Catapult centre. In this machine, the ultrasonic actuator is embedded in the tool holder which works on the concept of reverse piezo-electric effect. The ultrasonic oscillations are superimposed on drill in the axial feed direction during drilling. The ultrasonic oscillation parameters (frequency and amplitude) depend upon the tool – tool holder combination. Once the drilling tool is located within the tool holder, the optimum oscillation frequency is determined by the machine and the maximum oscillation amplitude is fixed. The amplitude can be varied from 0 to 100% of the maximum oscillation amplitude of tool – tool holder combination [8].

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The workpiece used in the present research was quasi-isotropic carbon fibre composite material having bismaleimide matrix. In order to examine the effects of chisel edge, pilot-hole drilling was utilized. Pilot-hole is a pre-drilled hole having equivalent diameter of chisel edge of drill used for drilling concentric main-hole. As 40 to 60% of thrust force in CD comes from chisel edge [9], therefore, pilot holes have been proposed by authors in order to reduce the thrust force during drilling of concentric main-hole. [7]. In the present research, pilot-holes were used in order to investigate the effect of chisel edge in CD and UAD. The specifications of two-flute twist drills used in the present research are summarized in Table 1. The diameter of the chisel edge of the concentric main-hole drill was 1.5 mm. Therefore, drilling of pilot holes was performed with a 1.5 mm diameter drill. Drilling of concentric main-hole was performed at 100 m/min cutting speed and 0.05 mm/rev feed rate in both CD and UAD processes. Maximum 10 holes could be drilled in each case of CD, UAD, with and without pilot-hole with a single drill due to excessive tool wear on HSS drills and matrix burnout by 10^{th} hole. After drilling of 10^{th} hole, the drills were replaced with a new drill and the experiment was repeated. The entire experiment was repeated two times in each condition and the average values were considered for analysis. The details of the ultrasonic frequencies and peak-to-peak amplitudes for the two repetitions in UAD for all the holes are presented in Table 2 and the entire experimental setup is shown in Figure 1.

Table 1. Details of two-flute twist drills used in the present research

Drill	Material/Coating/Diameter
Pilot hole drill	Tungsten carbide/ TiAlN/ 1.5 mm
Drill for concentric main-hole	High speed steel (HSS)/ TiN/ 6 mm

Table 2: Data for ultrasonic frequencies and peak-to-peak amplitude for UAD with and without pilot hole drilling repetitions for all the holes

Ultrasonic parameters	UAD without pilot1	UAD without pilot 2	UAD with pilot 1	UAD with pilot 2
Frequency (Hz)	40350	40020	40120	39970
Peak-to-peak amplitude (μm)	5.3	4.7	5.2	4.3

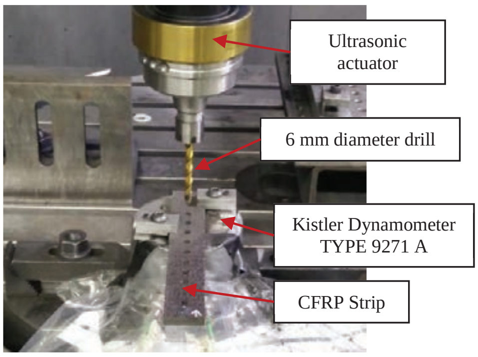

Figure 1: Experimental setup for the present research

3. Results

The parameters of thrust force, torque, tool wear and exit delamination were considered for the analysis.

3.1. Thrust force and torque

Thrust force and torque were recorded through a Kistler Dynamometer, Figure 1. Average values of thrust force and torque during drilling of a hole were considered as a reading for a particular hole. Average values of thrust force and torque are plotted in the Figures 2 and 3 respectively. It is further discussed in Section 4.

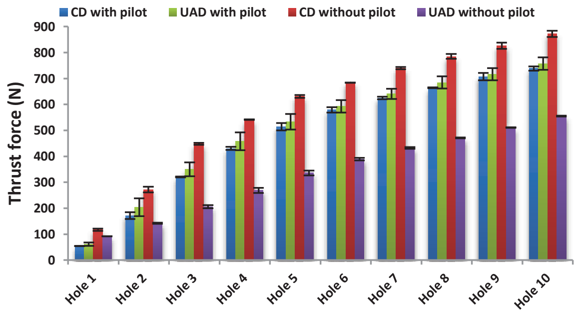

Figure 2: Variation of thrust force with respect to number of drilled holes for CD and UAD in with and without pilot hole drilling cases

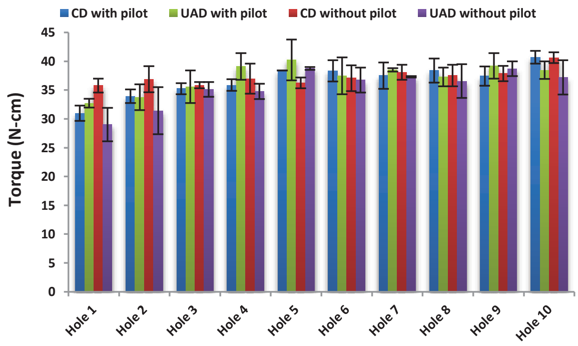

Figure 3: Variation of torque for with respect to number of drilled holes CD and UAD in with and without pilot hole drilling cases

3.2. Tool wear

The tool wear was recorded with the help of *'ZEISS AxioCam ERc 5s'* microscope camera. Due to excessive tool wear and its irregular profile, the wear area was selected as tool wear criteria in the present research. The tool wear area was quantified by calculating the difference between the measured area of flank surface of a new tool and unworn area of flank surface in a worn tool as shown in Figure 4.

The wear area on the flank surface was plotted against the number of drilled holes in CD, UAD with and without pilot holes as shown in Figure 5. From Figure 5, it is clear that the flank wear increased after drilling of every hole in all the cases. This is in agreement with the findings of other authors

[10-12]. The tool wear increased after drilling of every hole because of abrasive nature of carbon fibres [13]. When comparing CD and UAD (with and without pilot hole), the minimum flank surface wear was found in the case of 'UAD without pilot hole'.

In addition to wear on flank surface, the wear on chisel edge was also recorded and quantified. The variation of wear on chisel edge with respect to number of drilled holes is plotted in Figure 6 for CD and UAD (without pilot hole) drilling cases. It can be seen in Figure 6 that wear area in the chisel edge was lower in UAD than that in CD after drilling of every hole. After 10[th] hole, the average wear on chisel edge was 46% less in UAD without pilot than that in CD without pilot.

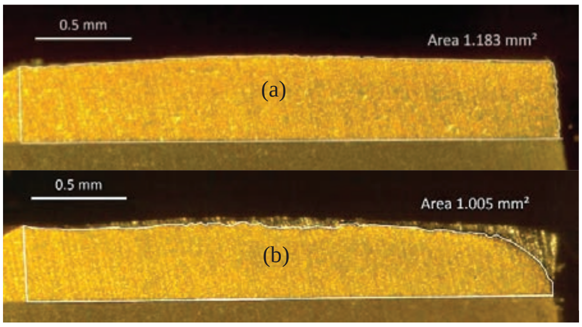

Figure 4: (a) Measurement of flank surface area in a new tool (b) Measurement of unworn area in flank surface in worn tool

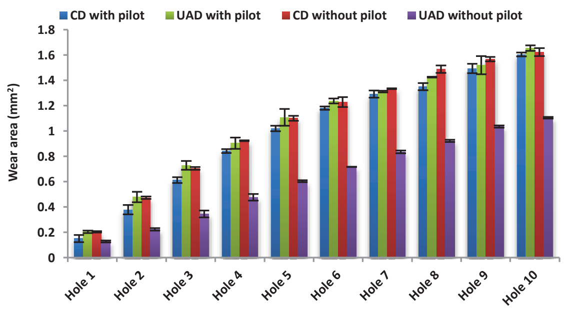

Figure 5: Flank surface wear area in the cases of CD, UAD, with and without pilot hole drilling cases in the present research

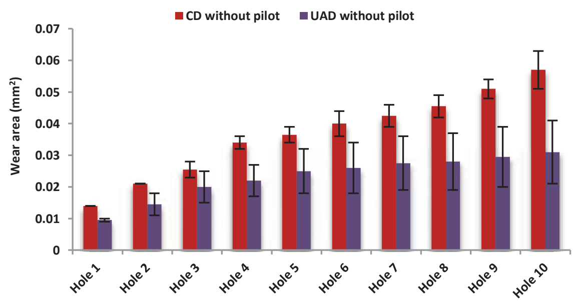

Figure 6: Variation of wear area on chisel edge in 'CD without pilot hole' and 'UAD without pilot hole' drilling cases

In addition, the condition of the chisel edge after drilling of 10 holes was also recorded through scanning electron micrography (SEM) for CD and UAD (without pilot hole), Figures 7 and 8. The SEM images of chisel edge display lower wear on chisel edge in UAD than that in CD.

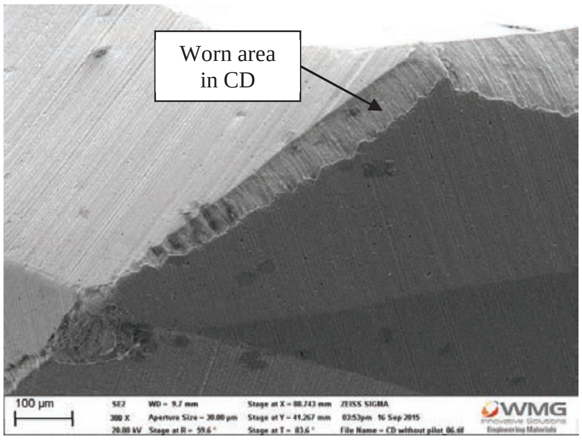

Figure 7: SEM image of chisel edge displaying chisel edge condition in the case of 'CD without pilot hole' drilling after drilling of 10 holes

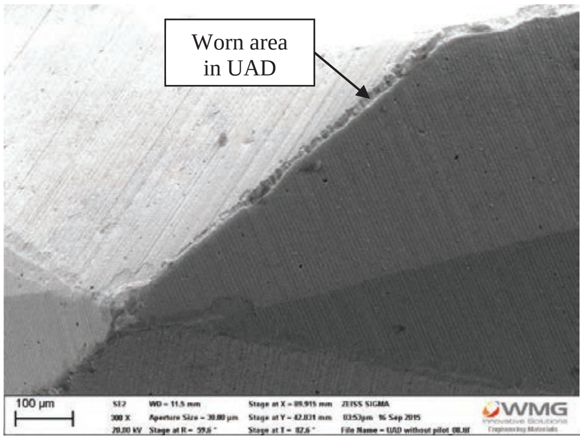

Figure 8: SEM image of chisel edge displaying chisel edge condition in the case of UAD without pilot hole drilling after drilling of 10 holes

3.3. Exit Delamination

The holes were sectioned diametrically, mounted and polished. The delamination depth at the diametrical plane in a hole was measured through optical microscopy. The maximum extent of delamination depth at exit in a hole was considered as the exit delamination criterion.

Hole-numbers 1, 5 and 10 were selected for damage quantification which is plotted in Figure 9 for all the cases in CD and UAD. It can be seen in Figure 9 that delamination damage depth at exit increases with increasing number of drilled holes. In addition, when comparing individual cases of CD and UAD (with and without pilot) in a particular hole, the lowest delamination depth is obtained in the case of 'UAD without pilot'.

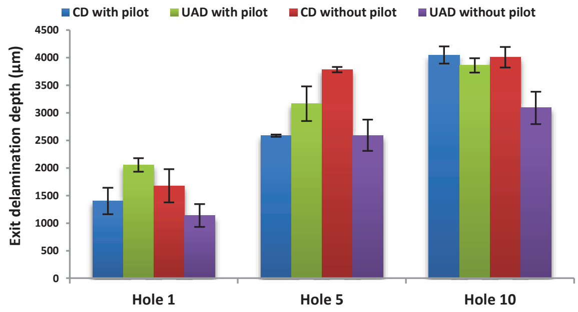

Figure 9: Maximum damage depth at exit in CD and UAD for with and without pilot hole drilling.

4. Discussion

Thrust force variation in Figure 2 and flank surface wear in Figure 5 show that thrust force and tool wear increase with respect to number of drilled holes in each drilling case. This can be explained from the fact that after drilling of every hole, tool-wear increased in each case. Increase in tool-wear caused increase in cutting and thrust forces during drilling of next hole which further caused increase in exit delamination, Figure 9. Similar findings have also been reported by Chen et al. [13]. It can also be observed from thrust force data in Figure 2 that in any specific hole, thrust force in ‘CD with pilot’ and ‘UAD with pilot’ cases are similar and in ‘UAD without pilot’ is the lowest of four drilling tests. In order to understand and explain this result, thrust force (Figure 2), torque (Figure 3) and tool flank surface wear (Figure 5) would have to be considered simultaneously. Since, chisel edge is not involved in the cases of ‘CD with pilot’ and ‘UAD with pilot’, for these cases, thrust force and torque are generated by cutting edges. Tool flank surface wear data is similar for the cases of ‘CD with pilot’ and ‘UAD with pilot’ in a particular hole. Therefore, similar level of tool flank surface wear caused similar cutting and thrust forces in a particular hole. This is also evident from similar torque values for the cases of ‘CD with pilot’ and ‘UAD with pilot’ in Figure 3. These results indicate that the behavior of CD and UAD was similar when chisel edge was not involved in drilling.

When comparing ‘CD without pilot’ and ‘UAD without pilot’ cases, thrust force (Figure 2) and tool flank wear (Figure 5) were found to be lower in ‘UAD without pilot’ in every hole as compared to those in ‘CD without pilot’ whereas torque values (Figure 3) were similar. Also, lower chisel edge wear in ‘UAD without pilot’ compared to ‘CD without pilot’ in Figure 6, indicates that forces on chisel edge were lower in ‘UAD without pilot’ as compared to those in ‘CD without pilot’. Thus, lower thrust force, lower chisel edge and flank wear and similar torque values (cutting forces) suggest that lower forces on chisel edge in ‘UAD without pilot’ led to lower overall thrust force required for drilling which in turn caused lower exit delamination (Figure 9) and lower flank wear in the case of ‘UAD without pilot’ as compared to that in ‘CD without pilot’. Therefore, the evidence suggests that due to reduction in the forces from chisel edge in UAD, the overall thrust force was reduced causing reduction in exit delamination in UAD, in comparison to those in CD. Hence, it can be stated that the machining mechanism at chisel edge in UAD is different from that in CD which requires to be determined in further investigation.

5. Conclusions

Based upon the evidence and results from this research, it can be concluded that the specific forces from chisel edge during drilling are reduced in UAD in comparison to those in CD. However, the specific mechanism causing this reduction in thrust force from chisel edge in UAD is required to be investigated further.

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