An Experimental Investigation on Drilling of CFRP/Ti stacks using Minimal Flow Lubricating- (MFL) technique using coated (TiAlN) and uncoated drills

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Abstract

Carbon Fibre Reinforce Plastics (CFRP) and Titanium alloy (Ti6Al4V) were stacked together in aircraft frames and structure for its high strength to weight ratio and the honey comb structure were replaced by the stacked material, since the honey comb structure observes moisture which is been used for the wing frame for the defence aircraft. Most of the aircraft structure and frames were manufactured to near net shape but still few machining process like drilling were done to help in assembling various parts. Majority of the drilling process were done under dry condition which cause rapid cutting tool wear and increases friction between the tool and workpiece. The cutting tool manufacturer introduced various drilling to address these issue with through coolant hole in the drill bit under near dry condition which can be classified into two types minimal flow lubrication and minimal quantity lubrication. Less research outcome were available in the study of machining under minimal quantity lubrication condition. The outcome of the researchers in the area of drilling states that palm oil out performed synthetic oil with respect to reducing the flank wear and corner wear. In this paper an experimental investigation has been presented on drilling of stacks using palm oil as lubricant under MFL condition. Two types of drill bit of ø 5 mm was used for the study. Temperature was also measured during the exit of Ti alloy with the help of K type thermocouple. Maximum Thrust forces of 960N was observed at higher feed rates (0.15 mm/rev). Maximum Delamination factor (DF) was observed as 2.31 for higher feed rate (0.15 mm/rev); temperature at the exits of Ti alloy increased to 214°C at higher feed rate (0.15 mm/rev); Maximum burr height of 1.9 mm was formed at higher feed rate (0.15 mm/rev).

Keywords: Drilling, CFRP/Ti6Al4V stacks, minimal flow lubrication, palm oil

1. INTRODUCTION

In many cases the driving force behind the introduction of dry machining is the recognition that today workpiece-related costs for cooling lubricants can be several times higher than tool costs. Moreover, the handling of coolant is increasingly causing problems, including the burden they place on employers and the environment.

Experience shows that productivity is significantly improved at the same time: production times are cut by as much as 50% regardless of the production job and choice of tools. Since there is no need to clean workpieces, the process chain is shortened and further costs saved as a result. Internally, a conversion of production processes from wet to dry machining helps to motivate personnel; externally it contributes to a better corporate image. In addition, lawmakers and statutory accident insurance associations are enacting stricter laws and regulations in reaction to the hazards posed by cooling lubricants. For a company that means not only more responsibility and new obligations vis-a-vis the personnel but also, and above all, higher costs. Wide-scale introduction of dry machining in the production sector makes it possible to avoid the economic and ecological problems entailed by wet machining. The use of minimal lubrication significantly reduces process costs and protects the environment. Investigations of various literature outcomes have shown that dry machining of CFRP/Ti stacks under flood lubrication condition will result in loss in strength of CFRP because of chemical reaction between the lubricant and CFRP and high velocity of lubrication flow can cause delamination on CFRP. Near dry machining was introduced to tackle these issues by finding different types of lubrication which can be generally classified based on the flow rate in which the lubricant is supplied to the cutting region. The general standards of lubrication is stated in Table 1 [5]
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### Table 1 Standards of lubrication [1]

<table>
<thead>
<tr>
<th>Sl no</th>
<th>Flow rate (ml/hr)</th>
<th>Type of lubrication</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>Dry</td>
</tr>
<tr>
<td>2</td>
<td>&lt; 80</td>
<td>Minimum quantity lubrication</td>
</tr>
<tr>
<td>3</td>
<td>80 – 2000</td>
<td>Minimal flow lubrication</td>
</tr>
<tr>
<td>4</td>
<td>&gt;2000</td>
<td>Wet</td>
</tr>
</tbody>
</table>

2. Literature Review

Carbon fibre reinforced plastics (CFRP) are characterized by a combination of high properties (specific strength and stiffness, light weight, etc.) which make their use especially attractive for aircraft and aerospace applications. Machining of CFRP is difficult due to their material discontinuity, inhomogeneity and anisotropic nature. The delamination is a major problem associated with the drilling of CFRP apart from reducing the structural integrity of the materials. The combination of CFRP with titanium to form multi-layered material stacks has also gained prominence in recent years especially for applications involving aerospace structures subject to extreme mechanical loads in service. The joining of these materials typically requires the production of fastener holes. At present, such holes for wing and tail plane components are manufactured via a multi-shot routine which necessitates pre-drilling of each individual layer followed by a deburring cycle. However, drilling of dissimilar materials is a challenging task to manufacturing engineers because of the different machining properties for each material [1, 6-8, 11-13]. Park et al [9] stated that the spindle speed has no significant influence on CFRP drilling forces. Results showed that initial thrust forces in Ti drilling are similar for high and low spindle speeds; but as hole number increases, thrust force at the high spindle speed condition grows to be higher than those for low spindle speed drilled holes. Durval.U.Braga et al [3] conveyed that a lot has been done to minimize, or even completely avoid, the use of cutting fluid in machining processes. The reasons for this is the high percentage of fluid costs in the overall manufacturing costs (reaching 17% in some cases), ecological and legal demands and human health among others. Near dry machining is classified into minimal quantity lubrication (MQL) and minimal flow lubrication (MFL). The MFL and MQL techniques involve the application of a small quantity of lubricant dispersed to the tool–workpiece interface by compressed air flow. Rahim et al [14] did his research in the area of drilling of Ti6Al4V under MQL condition using palm oil as lubricant and observed that palm oil produced lower tool wear rate in comparison to synthetic ester. Palm oil exhibits the lowest tool wear rate than the synthetic ester and air blow conditions, and comparable with flood condition. Zeilmann et al [13] carried out thermal analysis using K type thermocouple during drilling of Ti6Al4V. Three thermoelements (T1–T3) were placed at a distance of 0.2mm from the wall of the hole. Experimentation were done under MQL condition with an external nozzle and dry drilling and range of temperature measured were 500°C for dry condition and 450°C for wet condition [12]. Prabukarthi et al [10] optimized the machining parameter on drilling of Ti6Al4V alloy and stated that spindle speed of 1000 rpm and feed rate of 0.13mm/rev produce acceptable hole diameter deviation. The current study is to implement a MFL system for the drilling of CFRP/Ti stacks to overcome the disadvantages of dry, wet drilling using palm oil as the Lubricant. To study the effect of machining parameters (spindle speed and feed rate), delamination (in CFRP), burr height (in Titanium alloy) while drilling of the composite/metal stack under MFL conditions. In addition to that temperatures at the exit of the Ti alloy was measured using K type thermocouple.

3. Experimentation

The CFRP and titanium plates were held together by means of mechanical fasteners. The thickness of each plate was 3mm. Drilling was carried out on the VMC (DECKEL MAHO DMC 835V) with palm oil as the lubricant. A solid carbide twist drill of 5 mm diameter was used and details of the cutting tool are given in Table 2.

Table 2 Tool specification

<table>
<thead>
<tr>
<th>Point angles (degree)</th>
<th>118°-130°</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coatings used</td>
<td>TiAlN coated/ uncoated</td>
</tr>
<tr>
<td>Helix angle (degree)</td>
<td>20°</td>
</tr>
</tbody>
</table>

Thrust force and torque were measured using a two component tube type strain gauge drilling dynamometer. A minimal flow lubrication apparatus (DOML-1500) with a reservoir capacity 1.5 ltr was used to supply palm oil at a near dry condition. The experimental setup shows [Fig 1] the workpiece held by the fixture and MFL nozzle focusing the cutting region, a K-type thermocouple inserted into a hole of 2mm diameter drilled at the side of Ti6Al4V plate to a depth of 4 mm for temperature measurement and drill tool dynamometer for recording the thrust force.
Taguchi approach L4 array was chosen for designing experiments. Two factors each with two levels were considered. The factors considered were A – Spindle Speed, B – Feed. Table 3 shows the summary of experimental conditions.

Table 3 Experimental conditions

| Spindle speeds (rpm) | 612, 1836 |
| Feed rates (mm/rev) | 0.05, 0.15 |

Delamination in CFRP was measured using 'ImageJ' software package. Images of the hole were captured using a stereo microscope as shown in Fig 2 and imported into the image processing software 'Image J'. First the hole area is marked by oval option (A), then the delamination zone area \( A_{\text{max}} \) is marked and the edge detection option enables the perfect edges. The ratio of the two areas gives the delamination factor \( F_d \). [13]

\[
F_d = \frac{A_{\text{max}}}{A}, \quad (1)
\]

A dial indicator gauge (Least count of 0.01 mm) and a surface plate were used to measure the height of the burr at the end of the holes. The stylus was first referenced to the surface next to the holes. Then, the stylus was swept slowly towards the periphery of the hole by moving the base of the dial indicator gauge on the surface plate. The largest value registered on the dial was taken as the burr height at that point. Four points were taken on the border of the hole at 90\(^\circ\) angles. [14]

4. Result and Discussion

4.1 Effect of cutting variable on thrust force

During drilling of CFRP/Ti stacks, thrust force varied based on the material being cut by the drill. Figures 3–6 show the typical thrust force variation with various spindle speeds and feed rates for coated (TiAlN) and uncoated tools.
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During drilling, it was noted that thrust force in titanium and CFRP increases with feed rate for both spindle speeds while using 118°&130° point angled coated and uncoated tools. A maximum thrust force of 960 N in titanium was found to occur at a spindle speed of 612 rpm and 0.15 feed rate while using 118° point angle coated tool. A maximum thrust force of 210 N in CFRP was found to occur at a spindle speed of 1836 rpm and 0.15 feed rate while using 118° point angle uncoated tool.

4.2 Effect of Cutting variables on delamination in CFRP

Delamination occurs at the entrance and exit of the drilling of CFRP composite laminate. The first phase was concerned with the delamination at the entrance (peel up delamination) and the second at the exit (push out delamination). It was found that feed rate has significant influence on the peel-up and push-out delamination. Both peel up and push out was found to increase as feed increases as depicted in Figure 7 and 8. Maximum push out (1.64) was found to occur at 1836 rpm and 0.15 mm/rev feed rate while using 118° coated tool. Minimum push out (1.05) was found to occur at 612 rpm and 0.05 mm/rev feed rate while using 118° uncoated tool. Maximum peel up (1.25) was found to occur at 1836 rpm and 0.15 mm/rev feed rate while using 118° coated tool. Minimum peel up (0.43) was found to occur at 1836 rpm and 0.05 mm/rev feed rate while using 130° uncoated tool. During dry drilling the amount of push out delamination factor is less at higher feed rate because of Ti layer below but it was observed that under MFL conditions push out was found to be higher at high feed rates. The top surface of CFRP is not having any support; moreover the hot titanium chip flow through the hole may also influence the peel up delamination [13]. It was found that 118° coated tool produced maximum peel up and push out while 130° uncoated tool produced minimum push out and peel up.

4.3 Effect of cutting variables on temperature

Temperatures were measured for each spindle speed and feed combinations using a K-Type Thermocouple and LABVIEW interface using a NI9219 DAQ card. A 2mm hole was drilled on the side of the titanium plate with a depth of 3.5mm - 4mm and the thermocouple inserted into the hole. It was found that temperature increases with increase in feed rate. Temperature generated was found to be higher than dry drilling conditions which were carried out at the same machining conditions. But temperature generated was found to be lower than MQL-PO conditions which were carried done for similar speed and feed rates. The detail effects of temperature over the different point angle were presented in figure 9.
Figure 9 Thermal effects during drill using uncoated and coated drill

Temperature generated was found to be a maximum of 214 °C for a speed of 612 rpm and 0.15 mm/rev feed rate while using a 118° coated drill bit. Burning of chip occurred whenever the temperature was above 135 °C. This was because of the fact that the flash point of palm oil is 135°C. For dry drilling and with MQL applied by an external nozzle (MQL ext), the temperatures recorded are over 450°C, for a cutting speed of 900 rpm, and exceed 500°C for 1800 rpm.

For temperatures over 500°C, the mechanical resistance of the titanium alloy Ti6Al4V diminished sensibly and the material presents more facility to be deformed plastically, favourable to the flow between the lateral guides of the drill and the wall of the hole, resulting in the formation of a micro-welding on the surface of the hole (similar to adhesion). [2]

The oil mist decreases the friction between the cutting tool and chip/workpiece, which decrease the cutting temperature, but higher outlet pressure should be given to increase the velocity of air flow during transport, which may decrease the adhesion of oil mist and carry oil mist to the closer position of the cutting point may be otherwise this may leading to increase in temperatures.

4.4 Effect of Cutting variables on Burr height

It is noted that exit burr decreases with the increase in feed rate. Maximum burr height was found to occur at a spindle speed of 612 rpm with a feed rate of 0.05 mm/rev while using 118° coated tool. Maximum burr height was found to occur at a spindle speed of 612 rpm with a feed rate of 0.05 mm/rev while using 118° coated tool which is understood from figure 10.

5. CONCLUSIONS

Minimal flow lubrication system was implemented for drilling of CFRP/Ti stacks. A thrust force under MFL-palm oil conditions was found to increase linearly with feed. A maximum thrust force of 960 N in titanium was found to occur at a spindle speed of 612 rpm and 0.15 mm/rev feed rate while using 118° point angle coated tool. A maximum thrust force of 210 N in CFRP was found to occur at a spindle speed of 1836 rpm and 0.15 mm/rev feed rate while using 118° point angle uncoated tool. Temperature generated was found to be higher in MFL-palm oil conditions. Temperature generated was found to be a maximum of 214 °C for a speed of 612 rpm and 0.15 mm/rev feed rate while using a 118° coated drill bit. Delamination was found to be less under MFL – palm oil conditions than in dry drilling and 118° coated tool produced maximum peel up and push out and 130° uncoated tool produced minimum push out and peel up. Exit Burr height in Ti alloy was found to be less under MFL-palm oil conditions. Maximum burr height was found to occur at a spindle speed of 612 rpm with a feed rate of 0.05 mm/rev while using 118° coated tool.

REFERENCES

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