ULTRASONIC ASSISTED MACHINING

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ABSTRACT

A commercially available DMG MORI ULTRASONIC 65 monoBLOCK machining centre was installed in WMG in 2013 and has been primarily used to machine aerospace grade materials such as carbon fibre reinforced plastic (CFRP) and titanium alloy Ti 6Al-4V (individually and stacked) and 2000 / 6000 series aluminium alloys. Rather than discuss a single set of experimental work in detail, this paper discusses some of the issues that have been encountered when applying the technique of ultrasonic assisted machining (UAM) and some of the effects that have been observed using examples from the research conducted so far to illustrate some of the more important findings.

Keywords: Ultrasonic assisted machining, carbon fibre reinforced plastic, titanium alloys

1. INTRODUCTION TO ULTRASONIC ASSISTED MACHINING

Ultrasonic ***assisted*** machining (UAM) should not be confused with ultrasonic machining (USM) which is a well-established technique for machining hard and brittle materials with a history stretching back to 1927 (Thoe et al. 1998). Traditionally, in USM the tool has no cutting edges and abrasive slurry is pumped around the cutting zone where the ultrasonic vibration causes abrasive particles between the tool and workpiece to impact the workpiece and remove material by a process of micro-chipping (Nath et al. 2012). However, in recent years, diamond impregnated cutting tools have been increasingly used with a non-abrasive slurry (Lv et al. 2013, Cong et al. 2014). Ultrasonic assisted machining differs in that it uses conventional cutting tools, with traditional cutting edges to remove workpiece material. However, in addition to the normal machining parameters of cutting speed and feed, ultrasonic vibrations (typically >20 kHz) are applied.

Ultrasonic assisted machining is not a new concept and there has been a significant amount of interest in the technique in recent years. Researchers have used drilling and turning operations to investigating the UAM of a range of workpiece materials (metal matrix composites (Kadivar et al. 2014), titanium alloys (Pujana et al. 2009), Inconel (Baghlani et al. 2013), aluminium alloys (Chang and Bone 2010) and carbon fibre composites (Phadnis et al. 2012, Wang et al. 2004). UAM can be performed by vibrating the workpiece, actuated work system (AWS) or the cutting tool, the actuated tool system (ATS) (Kadivar et al. 2014) and they do exhibit some differences in behaviour. The cutting force in ATS was found to be 50% lower than that in AWS at 22 m/min cutting speed and 0.08 mm/rev feed rate. However, the practicality of actuating the workpiece can obviously be a problem for large components. There is general agreement in the literature that ultrasonic oscillations in the order of 3 to 20 μm in amplitude at frequencies of 17 to 46 kHz have a beneficial effect with the thrust and torque forces reportedly reduced along with the tool wear (Babitsky et al. 2007, Pujana et al. 2009, Wang et al. 2004) and burr formation when drilling (Kadivar et al. 2014). Reductions in thrust force from ~550 N to ~150 N as a result of ultrasonic assistance have been reported (Babitsky et al. 2007). Surface finish is also reported to improve with the addition of ultrasonic vibration although a temperature rise has been noted which increased with increasing amplitude of oscillation (Pujana et al. 2009).

However, such research has generally been invariably performed on laboratory scale implementations of the UAM technique. Work reported here used a commercially available, purpose built, ultrasonic assisted machine tool and production quality aerospace materials.

2. PRACTICAL ISSUES ASSOCIATED WITH ULTRASONIC ASSISTED MACHINING

Securing the cutting tool to the tool holder (ultrasonic actuator): The beneficial effect of UAM is dependent on the ultrasonic frequency and amplitude generated at the tool tip which in turn has been found to be dependent on cutting tool used (dimensions, density and density distribution) and how the tool is held within the too holder / actuator. At present, the optimum resonant frequency for use with each cutting tool which is inserted into the tool holder / actuator is identified automatically by the machine tool which scans the range of available frequencies. However, as the resultant oscillation amplitude is not reported to the operator, a Keyence laser displacement sensor, Figure 1(a), has been utilised to develop an on-machine measuring capability which provides accurate data on the amplitude of ultrasonic oscillation being achieved with each individual cutting tool.

In this method, the laser is directed at the flank surface of the tool, Figure 1(b), and the measurements made converted to the amplitude at 90° to the workpiece using Equation 1. An evaluation of the technique demonstrated that it was repeatable with an uncertainty of 0.19 µm.

The method was further used to examine the factors which could affect the oscillation amplitude during a normal machining process. To determine if any variation in amplitude were introduced repeated measurements were taken after a) the machine had automatically transferred the tool holder between the spindle and tool magazine, b) after manually removing the tool holder from the machine tool and c) after removing the tool from the holder and replacing it at the same location. Cycling the tool holder between the spindle and magazine introduced 0.22µm uncertainty while manually removing the tool holder from the machine introduced an uncertainty of 0.47 µm. Although a height gauge was used in order to return the tool to the collet in the same positions after it had been removed, this action was found to introduce an uncertainty of 0.76 µm. Therefore, removing the tool from the tool holder was found to introduce maximum uncertainty making re-measurement necessary.
The ongoing work is an investigation on the effect of the actual holding mechanism used to retain the tool in the holder. Early results indicate a significant difference in amplitude when comparing shrink-fit to collet systems.

$$\text{Real amplitude} = \frac{\text{Measured amplitude}}{\cos\theta} \qquad \text{...Equation (1)}$$

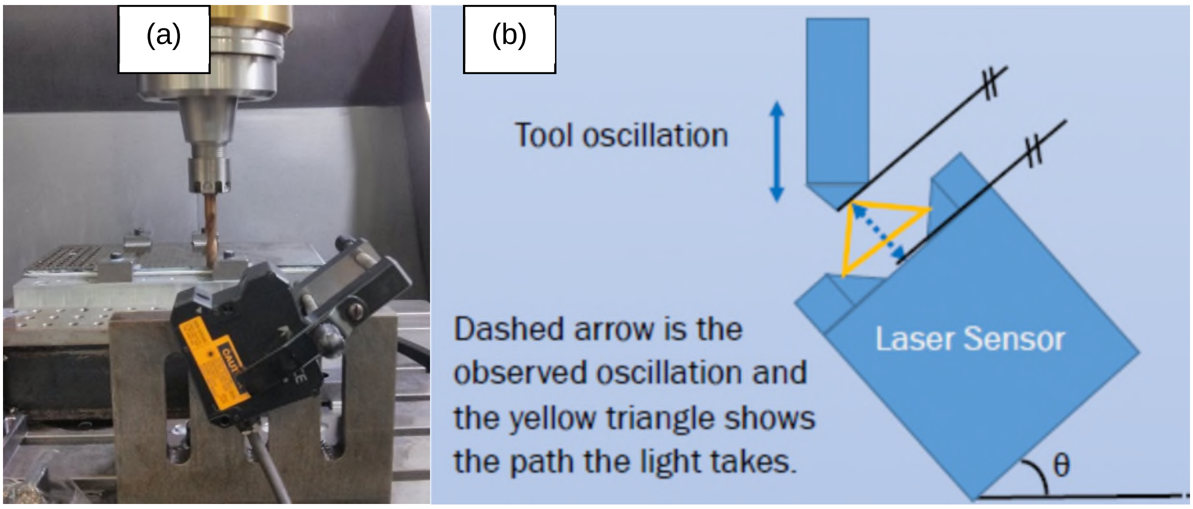


Figure 1. (a) Keyence laser setup for amplitude measurement for a 6 mm. diameter drill, (b) schematic representation showing the angular relationships.

3. POTENTIAL BENEFITS OF ULTRASONIC ASSISTED MACHINING

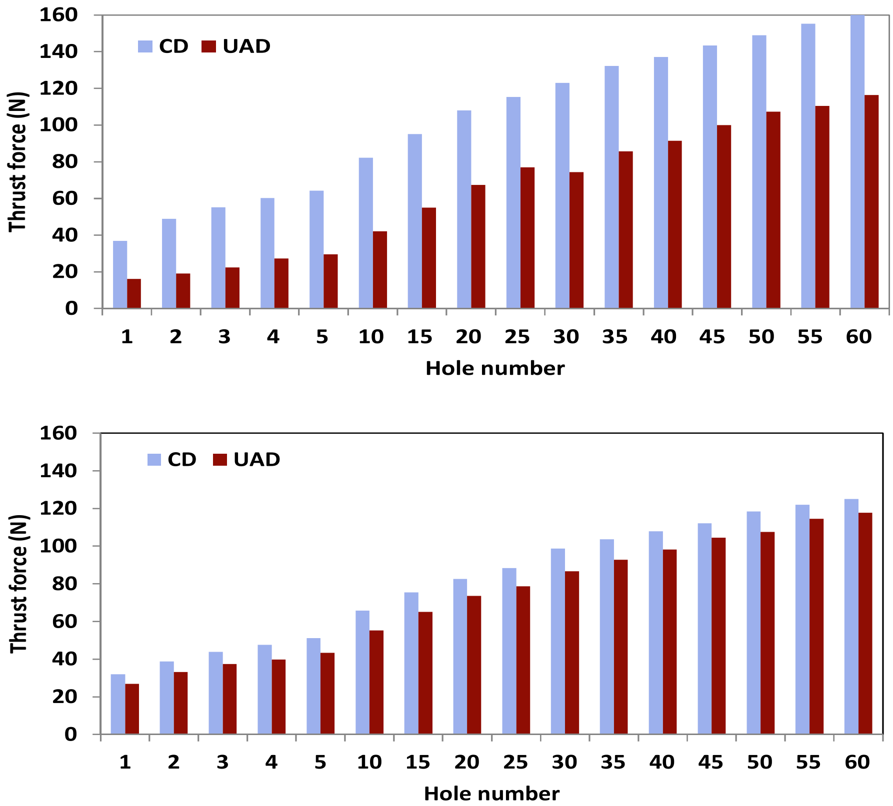
Force Reduction during Drilling of CFRP: The research is still in its initial phase for the drilling of CFRP materials using ultrasonic assistance. In the recent years, Makhdum et al. (Makhdum et al. 2014) and Gupta et al. (Gupta et al. 2014) have conducted studies on ultrasonic assisted drilling (UAD) of CFRP. In the work of Makhdum et al. (Makhdum et al. 2014), the feed rate was varied from 4 to 20 mm/min at a constant cutting speed of 0.38 m/min at 27.8 kHz frequency and 6 µm oscillation amplitude in order to study any reduction in thrust force due to ultrasonic assistance when compared conventional drilling (CD). The reduction in the thrust force due to ultrasonic oscillation was reported to increase from 229 N to 356 N as feed rate was increased from 4 to 16 mm/min. However, at 20 mm/min feed rate the thrust force in the CD and UAD were reported to be similar (511 N and 508 N respectively). The reason for this was speculated to be the absence of an intermittent cutting action at the higher feed rate of 20 mm/min. A 15% lower tool wear was also reported for UAD in their work after drilling of 50 holes. In contrast to the finding of Makhdum et al. (Makhdum et al. 2014), the work of Alam et al. (Alam et al. 2011) does indicate a reduction in thrust force at 20 mm/min feed rate. Alam et al. (Alam et al. 2011) argued that the maximum speed of ultrasonic assistance (1256 mm/min) is “very high” as compared to 20 mm/min feed rate and therefore, the intermittent cutting action must take place resulting in the lower thrust force. Following the argument of Alam et al. (Alam et al. 2011), the maximum speed of ultrasonic assistance in the work of Makhdum et al. (Makhdum et al. 2014) was 1048 mm/min which is also “very high” as compared to the feed rate of 20 mm/min. Therefore, it becomes unclear whether the absence of intermittent cutting action was the actual reason for no reduction in thrust force at 20 mm/min feed rate. In addition no evidence was produced to supporting absence of intermittent cutting action in the work of Makhdum et al. (Makhdum et al. 2014).

Earlier work at WMG, reported in (Gupta et al. 2014) attempted to correlate effective rake angles and thrust force in CD and UAD with cutting speed with the focus in this work being to quantify and analyze the damage produced during drilling using X-ray CT scanning.

In subsequent work outlined in this paper, CD and UAD trials were performed on the Ultrasonic65 in order to investigate the effect of ultrasonic oscillations on the drilling of CFRP at two cutting speeds of 10 and 100 m/min keeping the feed rate constant at 0.05 mm/rev. The ultrasonic frequency was 40 kHz and the peak-to-peak amplitude was 7.4 µm. Force measurements indicated that there was a reduction in thrust force due to ultrasonic assistance compared to CD and that this reduction was more significant at the slower cutting speed, Figure 2. Similarly, Figure 3 shows a larger reduction in torque at 10 m/min than at 100 m/min when CD and UAD are compared. This finding is supported by the theory explained in the previous work at WMG reported in (Gupta et al. 2014). Due to larger effective rake angles generated at lower cutting speeds, larger reduction in thrust force and torque is obtained at lower cutting speed.

It can also be observed in Figure 2 that the reduction in thrust force due to ultrasonic assistance decreased as the number of holes increased, i.e., the reduction in thrust force decreased from 56 to 27% at 10 m/min and from 16 to 6% at 100 m/min when the number of drilled holes increased from 1 to 60. Similarly, the reduction in torque due to ultrasonic assistance diminished from 49 to 33% at 10 m/min and 14 to 6% at 100 m/min.

Therefore, unlike the case of Makhdum et al. (Makhdum et al. 2014), the present research indicates that the effectiveness of ultrasonic assistance is diminished as the number of drilled holes increased, i.e., as tool wear increased. Such finding has not been reported anywhere in the existing literature. The reason that ultrasonic assistance produces less benefit as the tool becomes worn is the subject of ongoing research. However, results so far indicate that it is related to the complex interaction between the ultrasonic oscillations and the effective rake angles which these oscillations generate.



(a)

(b)

Figure 2. Average thrust force in CD and UAD at a fed rate of 0.05 mm/rev and cutting speeds of a) 10 m/min and b) 100 m/min.

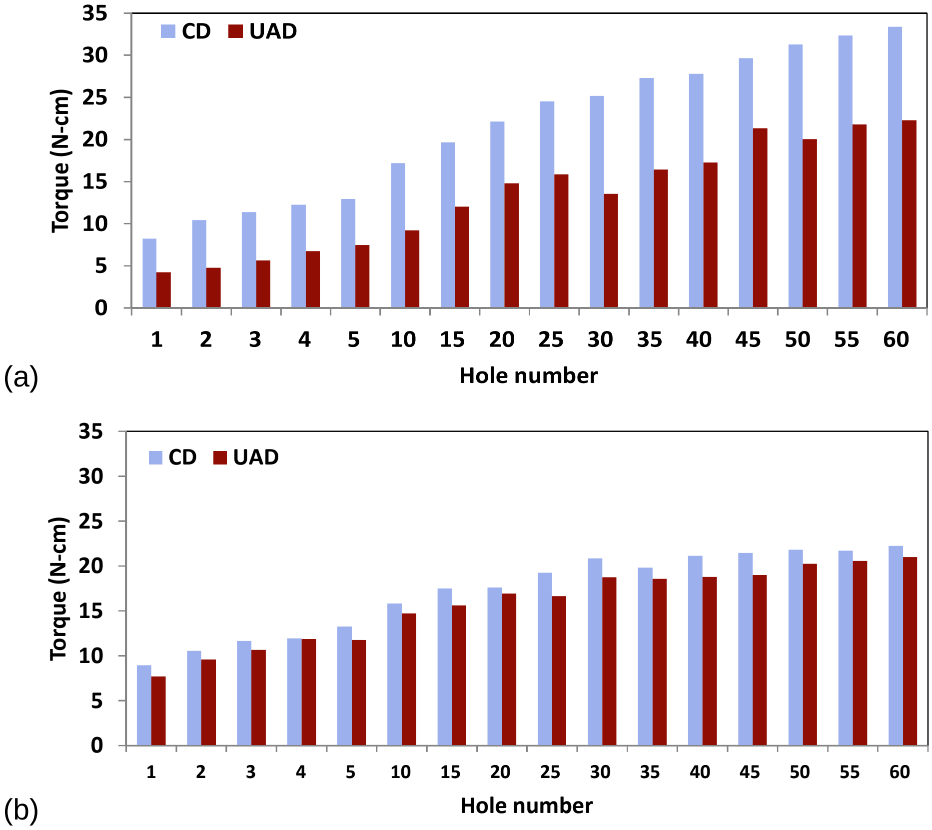


Figure 3. Average torque in CD and UAD at a feed rate of 0.05 mm/rev and cutting speeds of (a) 10 m/min and (b) 100 m/min.

Drilling of "Stack" Materials: In the aerospace sector there is a requirement to drill through two, or sometimes several materials, which have been joined together to form a "stack" (e.g. for assembly by mechanical means). CFRP and titanium alloys are typical materials, stacked and drilled together during the manufacture and assembly of aircraft. Drilling these materials individually has been widely recognized as a challenging and costly process due to rapid tool wear and failure, which also contributes to difficulty in achieving damage-free holes (Faraz et al. 2009, Feldshtein 2011, Hale 2006, Davim 2014a). When drilling titanium alloys, tool failure is mostly due to chip adhesion to the cutting edges which results in significant edge chipping and fracture (Isbilir and Ghassemieh 2013, Sharif and Rahim 2007). This occurs due to the fact that titanium has a strong affinity with cutting tool materials, particularly at high cutting temperatures (Stephenson and Agapiou 2005, Davim 2014b). In contrast, the main reason for rapid tool failure when drilling CFRP is abrasive wear of the cutting edges by the hard and abrasive carbon fibres (Sheikh-Ahmad 2009, Faraz et al. 2009).

With regard to hole quality, the titanium burrs which form at the exit of the cut and the delamination, fibre breakage and fiber-matrix debonding which occurred in the CFRP due to its heterogeneous structure, are critical issues which need to be managed (Feldshtein 2011, Davim and Reis 2003). Hole quality is known to be influenced by thrust forces in conventional machining and this is governed by the choice of cutting parameters and the amount of tool wear. The use of UAD has been reported to improve the quality of the machined surface of CFRP and titanium (Dahnel et al. 2015, Makhdum et al. 2014, Pujana et al. 2009). The work of Makhdum *et al*. (2014) involving UAD of CFRP using 3 mm diameter TiN coated tungsten carbide drills demonstrated that UAD resulted in a 90% reduction in thrust forces combined with a 30-47% reduction in surface roughness and 35-50% less delamination in comparison to conventional drilling. There is little published work regarding UAD of CFRP and titanium alloys individually and an early work regarding the UAD of these materials in the form of CFRP/Ti stacks was reported to be promising for improving drilling performance (Dahnel et al. 2015).

Work to compare CD and UAD has been performed on the DMG Ultrasonic65 machine tool using 6.1 mm diameter tungsten carbide drills to produce through holes in CFRP/Ti stacks with a constant cutting speed and feed rate of 50 m/min and 0.05 mm/rev respectively. The CFRP material was drilled first (i.e., it was the top layer of the stack) and the total thickness of both CFRP and titanium alloy materials was 8 mm; with each material has 4 mm thickness. An externally applied cutting fluid flooded the cutting zone throughout the drilling trials. During UAD, ultrasonic amplitude and frequency were fixed at 5.5 μm and 39 kHz, respectively. The main objective of the work was to prolong the tool life as well as improve hole quality by mean of reducing thrust force. In this work, end of tool life was considered to be when flank wear reached 300 μm, in line with recommendations in ISO 3685: 1993.

From the point of view of assessing the performance of the drilling operations, the adhesion of titanium to the cutting edges was a major issue (when drilling titanium) and this caused difficulty in measuring tool wear. CFRP, in contrast wore out the tool by abrasive action as expected, thus proved beneficial in removing some of the adhering titanium from the cutting edges. This is in agreement with (Wang et al. 2014) who reported a similar phenomenon. Therefore, in this work, after 30 holes (where titanium started to build up on cutting edges), in order to see a clear cutting edge, the wear was measured after drilling the CFRP plate, before drilling titanium plate. Figure 4 and 5 show a summary of tool wear and thrust forces during CD and UAD of the CFRP/Ti stacks. It can be seen that UAD resulted in longer tool life which was 80 holes compared to conventional drilling which was 60 holes; Figure 4. Consequently, as cutting forces are strongly affected by tool wear, the UAD generated 11% lower thrust forces (for both CFRP and titanium alloy) than conventional drilling; Figure 5.

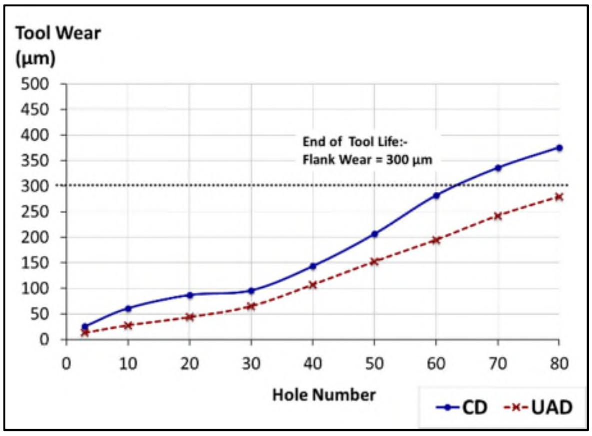


Figure 4. Tool wear during conventional and UAD of CFRP/Ti stacks.

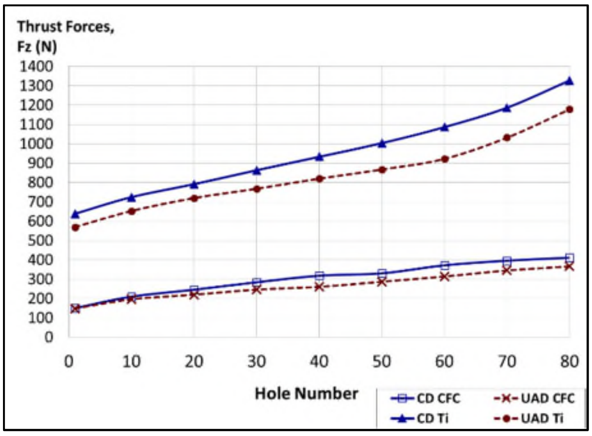


Figure 5. Thrust forces during conventional and UAD of CFRP/Ti stacks.

Figure 6 shows cutting edges of the drills after producing 30 holes in stack material (CD and UAD). It is evident that there was less titanium adhesion on the cutting edges during UAD compared to CD. Since the adhesion is strongly influenced by cutting temperature, this suggests that UAD generated lower cutting temperature than conventional drilling. In this aspect of machining, lower cutting temperature is favorable because it would help maintaining the strength of the material being machined (especially CFRP) as well as the cutting tool, thus resulting in less machining defects and tool wear. Further work to determine and quantify and compare the cutting temperatures during CD and UAD is ongoing.

During CD, it has been reported that a high tool wear and cutting temperature causes an increase in titanium burr height (Shyha et al. 2011, Kim et al. 2013). Figure 7 shows that UAD resulted in lower burr height (10% reduction on average) up to 80 holes than CD. This is considered to result from lower tool wear and cutting temperature in UAD in comparison to CD. However, in terms of CFRP entry delamination, it can be seen that more delamination occurred with UAD than CD, Figure 8 (although it has to be acknowledged that there is considerable scatter in these results). It is suggested that this is due to the effect of tool vibration during UAD which results in the application of more upward being applied to the CFRP layers (as the tool oscillated along its axis during drilling) hence increasing separation and fibre pull out. In addition, CFRP materials were removed by a brittle fracture mode, thus having tool vibration may not be helpful as it could also potentially lead to more crack propagation. This was not the case for the titanium alloy because it had a structure, typical of a wrought metal, which was homogenous, consistent and uniform throughout. Chip formation in titanium alloys is a result of plastic deformation and vibration of the tool during UAD is thought to assist this process. Therefore, in terms of hole quality, this work suggested that UAD is more beneficial and effective for homogenous and ductile materials like titanium compared to more brittle and heterogeneous materials like CFRP. More extensive analysis of hole quality is ongoing to evaluate the effect of ultrasonic vibration during drilling on hole quality in CFRP/Ti stacks.

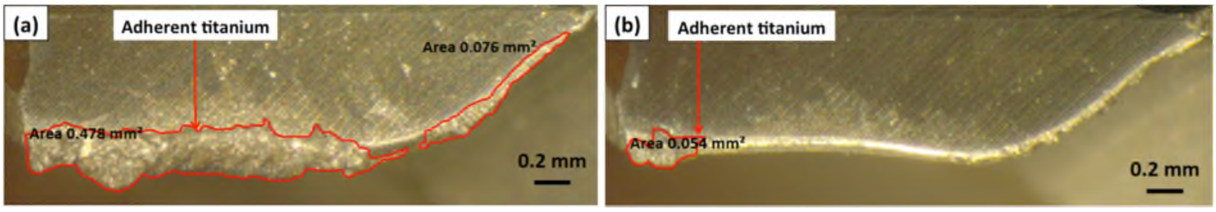


Figure 6. Cutting edge conditions when (a) conventional drilling and (b) UAD after 30 holes in CFRP/Ti stacks.

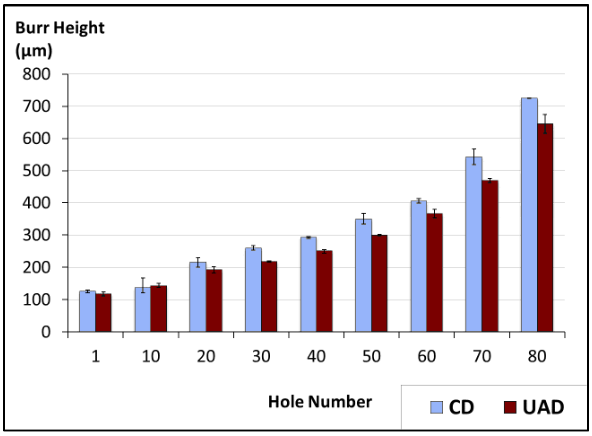


Figure 7. Titanium burr height at the exit of the holes produced by CD and UAD.

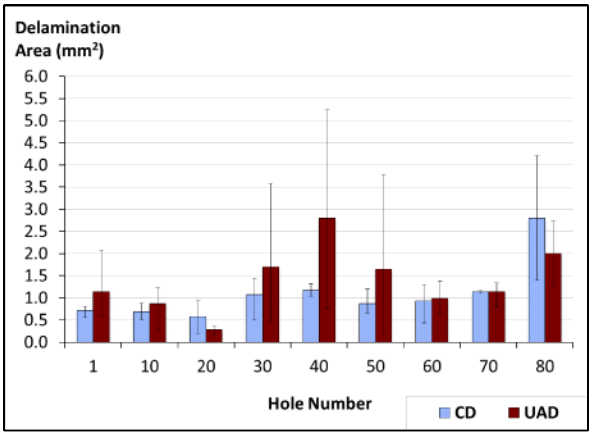


Figure 8. CFRP delamination of the holes produced by CD and UAD.

Milling of CFRP: Apart from drilling CFRP and CFRP/Titanium stacks, milling of CFRP is important during the manufacture of aircraft panels to remove excess materials after autoclaving and to achieve the final dimensional accuracy of the part with a surface integrity which is not detrimental to mechanical properties. However, several problem have been reported in conventional milling of CFRP. The main problems being; delamination, fibre and matrix pull out, rapid tool wear and poor surface finish (Sheikh-Ahmad 2009, Teti 2002). Since machining of CFRP always occurs at the end of the manufacturing cycle, it is important that the machining process is capable of consistently producing high quality results in order to avoid rejection of what at this stage could be extremely expensive components.

Although the application of ultrasonic assisted milling (UAM) to composite materials has the potential to give an improvement in tool life, a reduction in cutting forces and improves surface roughness with reduced damage, and damage, there has not been much research published on UAM of CFRP.

Milling of CFRP in aerospace application is often in two stages (roughing and finishing). This work introduces some initial work examining the roughing process and investigating the potential for UAM to improves this process. Conventional milling (CM) and ultrasonic assisted milling (UAM) was performed with a 10 mm diameter bonded diamond end mill (electroplated nickel bonded diamond with an average grit size of 420 µm), Figure 9. Both milling operation were performed along a 10 m machining length at constant parameters of 565 m/min cutting speed, 1500 mm/min feed rate and 2 mm radial depth of cut. During UAM, the ultrasonic frequency and amplitude was fixed at 43 kHz and 6.9 µm, respectively.

The diameter of the cutting tools were measured after every 1 m of machining to monitor the progression of tool wear, Figure 10. Both cutting tools experienced rapid tool wear during the first 3 m of machining, however, for CM the tool diameter started to increase after machining 3 m until machining was stopped after 10 m. This was explained by looking at the optical microscope images taken at the corresponding cutting intervals. It was evident that workpiece material was adhering to the cutting tool and hence increasing the tools apparent diameter.

Moreover, inspection in the SEM confirmed that some of the CFRP material had been degraded and bonded onto the tool. This was a consequence of the high temperature produced when machining the CFRP conventionally. For UAM, the diameter of the cutting tool reduced as the machining length increased. Vibration and rotation of the cutting tool in UAM creates the opportunity for products of the machining process, dust as opposed to chips, to evacuate the machining zone. Hence, there was less chances to this material to attach and bond to the tool as was the case with CM. Figure 12 shows images of cutting tools after machining a distance of 10 m using CM and UAM where less adhered material can be seen after UAM.

Figure 9. Unused diamond bonded 10 mm diameter end mill.

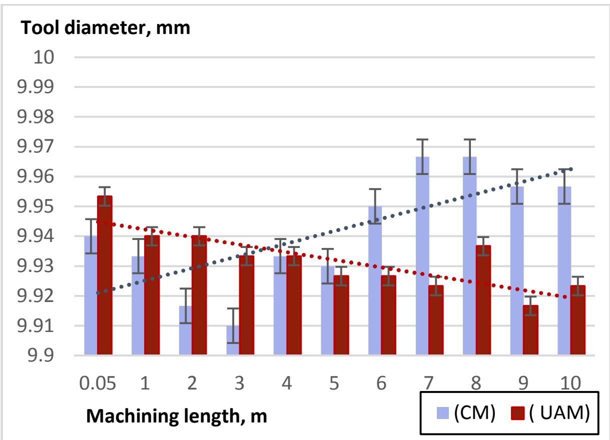


Figure 10. Reduction of cutting tool diameter.

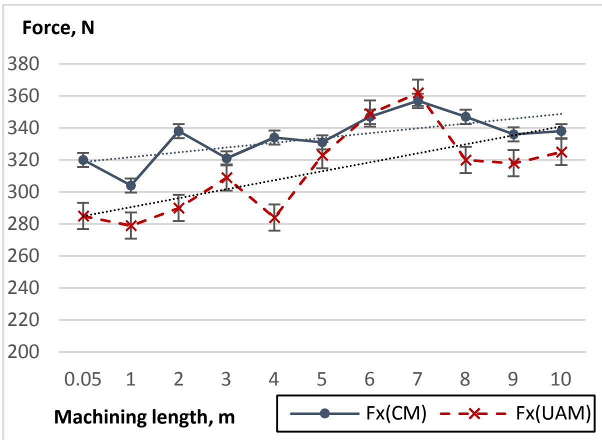


Figure 11. Average machining force for conventional machining and UAM.

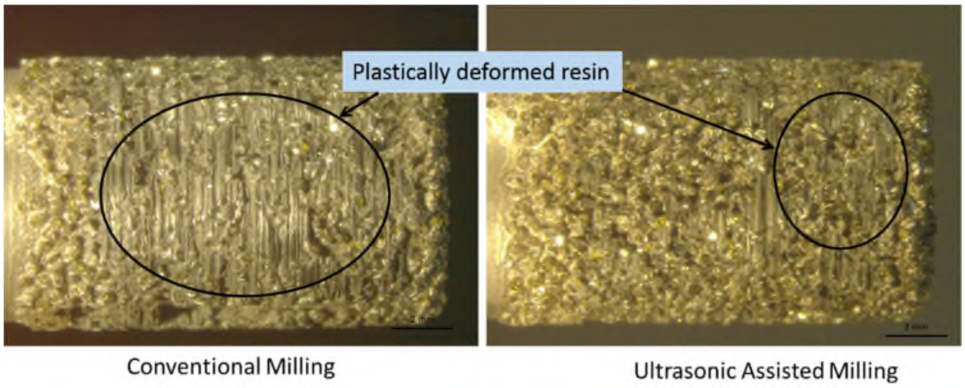


Figure 12. Condition of CM and UAM cutting tools after machining for 10 m

The cutting force data obtained was consistent with the observations regarding adherent material on the cutting tools. Cutting forces recorded during the UAM of CFRP were reduced by 15 to 20%, Figure 11, with the higher average force in CM being associated with the increased adherent material. CFRP material that covered the diamond grit reduced the active cutting edges of the tool. Consequently, the CM cutting tool used more energy and generated more shearing force during the removal of materials during machining as compare to UAM. Furthermore, the higher cutting force generated by CM eventually produced micro cracking of the diamond grit resulting in some of the diamond grit splinting, fracturing and being lost from the coating again reducing the cutting efficiency. This was not observed in UAM.

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Poor tool condition and high cutting force in CM affected the surface roughness and damage to the point that the trial was stopped. Figure 13 shows the surface roughness profile for CM and UAM after 10 m machining length. It was found that UAM improved surface finish after 10 m of UAM the surface roughness was 6.7 μm Ra while for CM the value was 8.6 μm Ra, a 22% reduction. While it could be thought that surface roughness is unimportant as this is designed to be a roughing operation, the fact that there will be an increase in the associated sub-surface damage could be an important consideration.

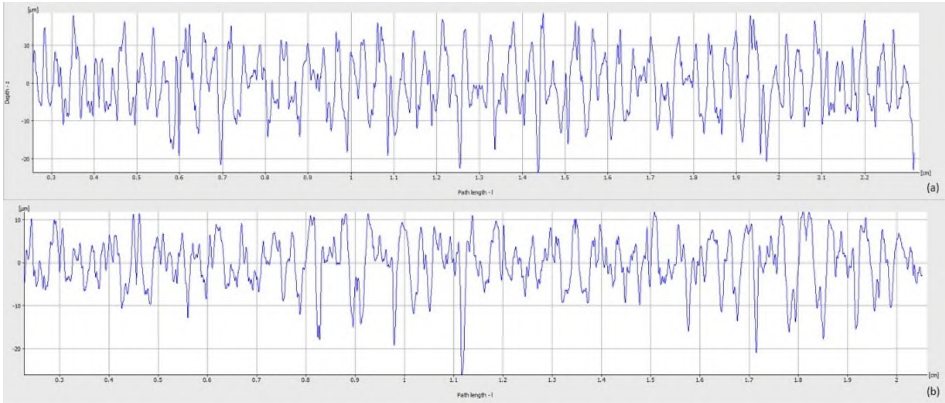

Figure 13. Surface roughness profile of a) CM and b) UAM machined surface

Combination of UAM and cryogenic machining: Although the work is very much in its initial stages, a limited amount of work has been carried out to assess the potential benefits of combining UAM with the technique of cryogenic machining; another technique which is receiving considerable interest recently. Indications are that the combination of these two techniques is capable of providing further benefits in terms of tool wear and workpiece damage reduction.

4. CONCLUSIONS

Ultrasonic assisted machining is certainly proving to be an interesting and complex field for machining research. As noted in the section on practical issues associated with UAM, some variables that need to be considered in UAM such as how to hold the cutting tool, how much to protrude the tool from the holder, the mass of the tool etc., are far more important than they would be in a conventional machining operation. Wear on the cutting tool has also been found to reduce the advantages associated with UAM and therefore this is an additional factor to consider with regard to the life of the tool. In order to get the best out of UAM, it is clear that there is a significant amount of work which needs to be done in order to understand how to operate the process from a practical point of view followed by the development of procedures to ensure optimum and consistent operation.

From the point of view of developing a more scientific understanding of the process, there is also much research that needs to be conducted. The effect of ultrasonic oscillation on the mechanisms which take place in the cutting zone are complex and not easy to study directly. This is especially the case with CFRP due to the heterogeneous nature of the material and the fact that machining generates dust as opposed to chips. However, the machining of metals such as titanium will allow a greater opportunity to study the machining mechanisms in relation to accepted metal cutting theory and develop a modification of that theory specifically for UAM.

A combination of the unusual practical machining considerations, the lack of detailed scientific understanding of the cutting mechanisms and the complex nature of many of the workpiece materials is no doubt partly responsible for some of the variability in results that are reported in the literature, and indeed have been experienced within WMG. The challenge is to develop a more fundamental understanding of the process and its application so that it can be applied appropriately and generate consistent results.

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