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Onawumi, P.Y. orcid.org/0000-0001-6677-5018, Roy, A., Silberschmidt, V.V. et al. (1 more author) (2018) Ultrasonically assisted drilling of aerospace CFRP/Ti stacks. Procedia CIRP, 77. pp. 383-386. ISSN 2212-8271

https://doi.org/10.1016/j.procir.2018.09.041

Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 77 (2018) 383–386

www.elsevier.com/locate/procedia

8th CIRP Conference on High Performance Cutting (HPC 2018)

Ultrasonically assisted drilling of aerospace CFRP/Ti stacks

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Abstract

Structural application involving aerospace stacks consisting of carbon-fiber-reinforced plastics (CFRP) and metals (such as aluminium and titanium) are characterized by their superior mechanical properties and relative ease of design. In many of such applications, drilling is required for hole making to facilitate fasteners for assembly. However, drilling with conventional methods pose several well-documented challenges including a requirement of an additional step for de-burring, increased tool wear, damage in the composite phase etc. Ultrasonically assisted drilling (UAD) is a hybrid machining technique, which has proven to enhance drilling quality in hard-to-machine materials. In this paper, UAD of stacks is implemented demonstrating significant improvement in hole quality produced in aerospace CFRP/Ti study with reduced drilling forces and energy spent.

Keywords: Drilling; Ultrasonically assisted drilling; Conventional drilling; CFRP/Ti stack; Hole quality; Thrust force and torque

1. Introduction

The evolution of composite/metals stacks has rapidly increased in their application of in the aerospace, automotive, naval and space industries bringing about a major transformation in the way modern structural components are manufactured [1]. Economic need for lightweight structures and more fuel-efficient vehicles led to the utilization of stacks for supporting and reinforcing components exposed to extreme loadings such as wing spars, skin segments, fuselage and tail components [2]. Drilling operation is an essential machining process, used extensively to facilitate assembly processes since mechanical fastening such as with bolts and rivets is a preferred method for attaching composites to metals. Drilling of composite/metal stacks in a single operation is often required to accommodate an efficient assembly process [3]. However, conventional drilling of CFRP/Ti stacks poses well-documented challenges due to the difference in machinability properties of components of the stacks; in particular, an abrasive nature of CFRP leads to rapid tool wear and low thermal conductivity and chemical affinity of titanium to the tool material causes thermo-chemical wear [4]. Several studies were performed to obtain high-quality holes in such composite/metal stacks. Entry and exit burrs produced in the titanium phase the during drilling process can be reduced by applying a combination of a low cutting speed with a low feed rate [5], while in the CFRP phase a high cutting speed with a low feed rate is required to reduce delamination [6]. Prior studies show that lower cutting forces with favourable machining conditions promoted better hole quality produced in CFRP/Ti stacks [8-9].

To overcome the known limitation of the existing drilling technologies, new techniques are sought. Ultrasonically assisted drilling (UAD) is a hybrid machining process that combines conventional drilling (CD) with high-frequency vibration at low amplitude superimposed at the tooltip to enhance the cutting process and improve hole quality in difficult-to-machine materials. Previous studies on application of UAD in drilling of CFRP demonstrated a significant reduction in drilling forces and improvement in hole quality as

10.1016/j.procir.2018.09.041

well as reduction in delamination [10] when compared to CD. In titanium alloys, UAD has the capability of reducing burrs with improved hole quality [11], in both materials, CFRP and Ti when compared to conventional drilling, UAD has also produced a low error in circularity.

In this paper, effect of feed rate on hole quality and to study and focus on the benefits and improvements when UAD is implemented in comparison with CD. UAD is applied to enhance machining process in a CFRP/Ti stack. This paper is sectioned as follows: Section 2 gives detailed descriptions of an experimental methodology, a workpiece, instrumentation and a drilling tool. Section 3 provides details on measurements, analysis and discussion of the results obtained. The paper concludes with Section 4.

2. Material and experimental methodology

A studied aerospace stack consists of M21/T700 quasi-isotropic CFRP with the stacking sequence $[(0°/45°/90°/-45°)_{4s}/0°]_s$ with a tensile strength and the Young's modulus of 14 GPa and 115 GPa, respectively [12] and Ti6Al4V with yield strength of 950 MPa and modulus of 113.8 GPa [13]; each phase has thickness of 10mm. Overall dimensions of the stack are 300 mm (length) × 150 mm (width) × 20 mm (thickness). A standard two-flute solid carbide twist drill WC-10% Co CoroDrill 460 with a diameter of 6 mm having a point and helix angles of 140° and 28°, respectively, was used for all experimental studies.

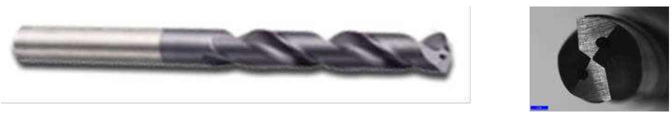

Fig. 1. Drilling tool

2.1. Machining setup and methodology

All drilling trials were carried out on a modified universal Harrison M-300 lathe machine to incorporate a Langevin-style piezoelectric transducer, with the capability of interchanging between conventional drilling and ultrasonically assisted drilling by appropriately switching. The transducer was mounted in a three-jaw chuck, with a horn attached to the front mass to amplify vibration in the axial direction, using appropriate fixtures to attach the drilling tool to the horn as shown in Fig. 2. Workpiece materials were placed in front of a two-channel Kistler™ dynamometer mounted on a cross slide of the lathe to measure level of thrust force and torque of every drilling regime.

The force data measured with the dynamometer were obtained using a charge amplifier, converting and transmitting the data through an analog-digital converter (digital oscilloscope Picoscope) connected to the computer. A thermal camera was mounted on the lathe and connected to the computer to monitor the temperature of the tool tip in the process of drilling the material. The cooling system consisting of a cold-air gun vortex tube, a pressure and a regulator gauge meter was used to supply compressed air as a coolant to the tool tip and the workpiece surface.

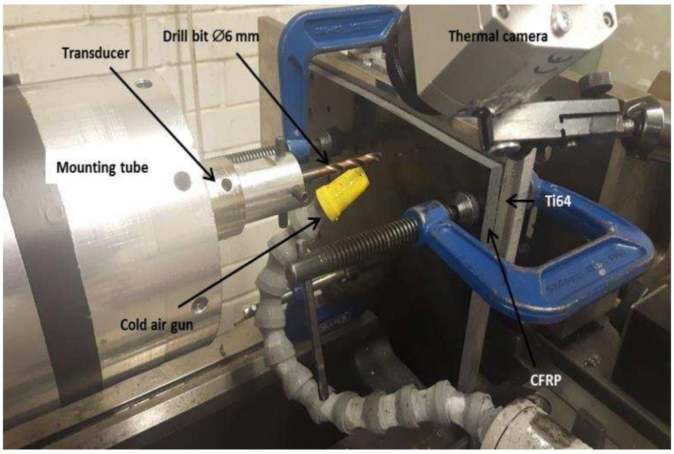

Fig. 2. Drilling setup

Comprehensive drilling experimentation was performed on CFRP/Ti stacks using both the CD and UAD procedures. Each drilling study was repeated three times for each cutting parameter for repeatability and accuracy. Parameters employed in the drilling tests are shown in Table 1. In UAD the frequency and amplitude are important parameters that affect the overall drill quality. The choice of 21 kHz and 30.2 peak-to-peak amplitude was based on the optimum working capacity of the Langevin transducer. The imposed frequency was sustained throughout the drilling process without any damping.

Table 1. Drilling parameters for drilling CFRP/Ti stack

Parameter	Magnitude
Feed rate (mm/rev)	0.03; 0.05;0.1
Spindle speed (rpm)	370
Vibration frequency (kHz)	21
Peak-to-peak vibration amplitude (μm)	30.2

3. Experimental result

In this section, a detailed discussion and analysis of results obtained in the experimental drilling processes - both CD and UAD - for CFRP/Ti stack are presented.

3.1. Effect of drilling parameter on thrust force and torque

Drilling parameters play a vital role in determining quality of holes produced. Fig. 3(a) and (b) demonstrates a comparison of the nominal machining forces in each material phase for all the experiments. In general, the thrust force and the torque in the titanium alloy increased with higher feed rate in both conventional and ultrasonically assisted drilling, which is associated with tool wear and adhesion of titanium to the machining tool. It is found that at the lowest feed rate of 0.03 mm/rev, the thrust-force reduction produced by UAD in comparison to CD was ~49%. This is a result of high forces required to plastically deform the titanium alloy in order to remove material, while intermittent cutting action in UAD promoted lower forces due to micro-chipping of the material, inducing local damage and deformation. At the highest feed rate, this force reduction vanished, generating a higher by 6% torque in UAD in comparison to CD due to titanium adhesion to the drill tool and wear. In contrast, in the CFRP phase, it was observed that with the increased feed rate, lower levels of thrust force and torque were generated in both CD and UAD experimentation. In general, UAD resulted in lower cutting forces in all experiments, compared to CD. Previous research indicated that a thrust force played a vital role in formation of delamination damage in CFRP [14]; this confirms that UAD generates lower delamination damage than CD thanks to significant reduction in the thrust force. At the highest feed, the torque in UAD for both materials showed an increase confirming the coiling and uncoiling action of the drill tool as a result of coupled torsional and longitudinal vibration [10]. In summary, UAD demonstrated that, as feed rate increased, the extent of reduction in forces decreased. This indicates that for UAD to be most effective, low feed rates between 0.01 – 0.1 min/rev should be employed.

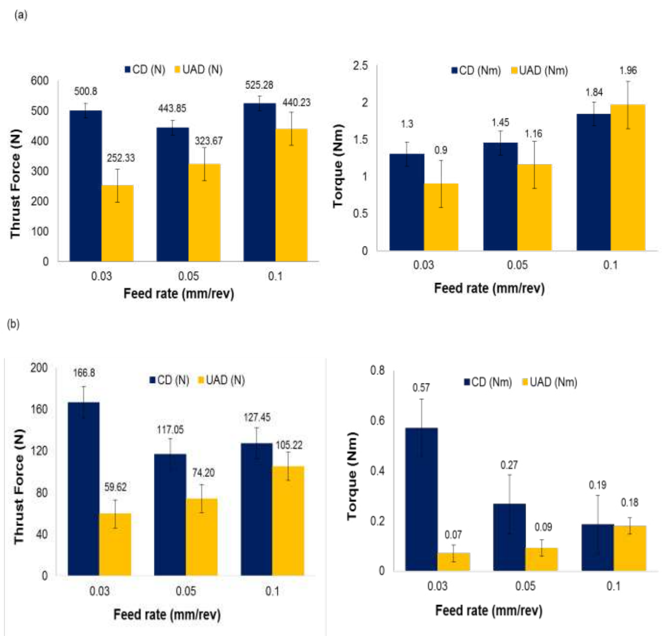

Fig. 3. Comparison of forces during CD and UAD of titanium (a) and CFRP (b) (spindle speed 370 rpm)

3.2. Hole quality

An average hole diameter and an error in circularity were measured with an analog scanning probe of ∅2 mm stylus of a Coordinate Measuring Machine at three different depths of 1 mm, 5 mm and 8 mm from the entry surface of each material of the CFRP/Ti stack. Fig. 4 and 5 show the obtained. The hole diameter was larger than the drill size (6 mm) for both drilling methods. As the feed rate increased, the holes in CD became more oversized with the largest hole of 6.14 mm created at a feed rate of 0.1 mm/rev, while holes obtained with UAD decreased with an increase in feed rate, leading to the hole diameter closer to the drill size. The obtained results confirmed the previous findings that carbide drills created holes larger than the drill size [15].

UAD demonstrated some improvements in circularity in both materials producing the lowest value in the titanium alloy at a feed rate of 0.05 mm/rev while having a higher value of 0.027 mm than its counterpart in CFRP. The error in circularity for CD in titanium was larger; this was found in all holes drilled at this feed rate. In summary, UAD was able to improve circularity in both materials and should be employed in drilling hybrid stacks to enhance drilling outcomes.

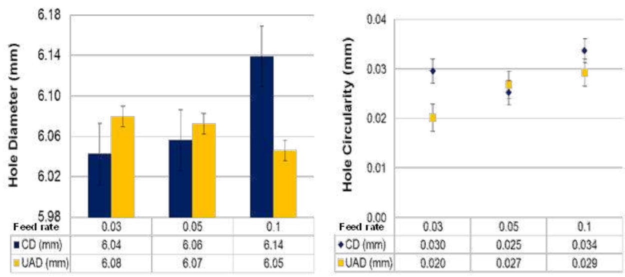

Fig. 4. Effect of feed rate on drilled hole diameter and circularity in CFRP

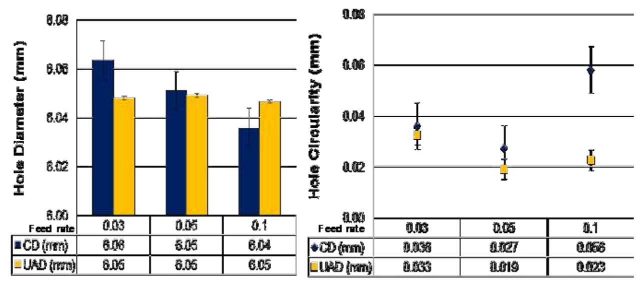

Fig. 5. Effect of feed rate on drilled hole diameter and circularity in titanium

3.3. Exit burr formation in titanium alloy

Ti burrs produced at the exit plates were found to pose a major challenge in the industry, resulting in an additional cost due to a need for a deburring process. Fig. 6 exhibits the average of four measurements of burrs along the hole's circumference of titanium alloy. It shows that the increased feed rate resulted in lower burr formation supporting results of [6]. As feed rate increased, the contact time of the drill corner with the titanium alloy decreased, thus, stimulating higher fracture of chips and lower heat generation in titanium alloy during the drilling process. UAD globally displayed a higher performance when compared to CD, with 50% reduction in burrs at the lowest feed rate and 47% at the highest. At the lowest speed, heat was generated rapidly and the exit side of the titanium plate became more ductile; therefore, lower fracture/shear was observed. In UAD, the process of separation of the tool from the material, generated higher shearing of chips.

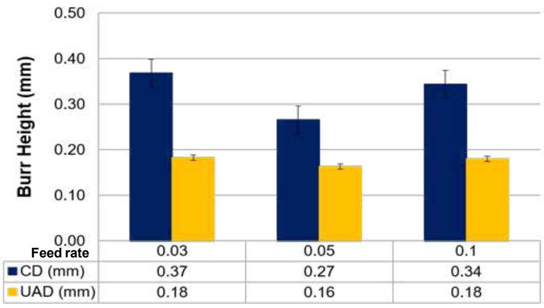

Fig. 6. Burr formation at the exit of titanium alloy.

3.4. Temperature

High temperatures during the drilling process of CFRP/Ti stacks play an important role as it can have a detrimental effect on the CFRP phase. In the test, temperature was monitored to ensure that it did not surpass the glass-transition temperature of the composite, which corresponds to ~170ºC. Compressed air was used to cool the drilling zone during the machining process. A thermal camera was used to monitor the surface temperature in both CD and UAD. In all experiments, the temperature did not exceed 110ºC. Fig. 7 illustrates the nominal maximum temperature of the workpiece surface during the machining process. The maximum temperature was observed in UAD at a feed rate of 0.1 mm/rev - 108.9ºC, while in CD it was 93.4ºC.

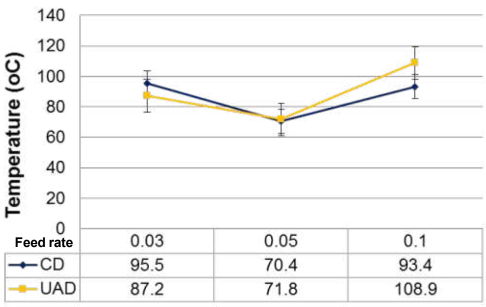

Fig. 7. Thermographic reading of maximum temperatures at varied feed rate

4. Conclusions

This paper presents initial results of drilling in CFRP/Ti stacks, assessing cutting forces and hole quality under dry machining conditions. The comparative study employing conventional drilling and ultrasonically assisted drilling of CFRP/Ti was performed to study the effect of feed rate on hole quality. The experimental investigation resulted in the following conclusions.

- The force analysis revealed a significant force reduction when UAD was utilized both in CFRP and the titanium alloy, in comparison to CD.
- The effect of producing lower forces in UAD resulted in lower energy required for drilling of stacks. As the feed rate increased, the extent of reduction decreased; this demonstrates that at higher feed, the intermittent interaction of the drill bit with the workpiece material in UAD was no longer effective.
- Both CD and UAD produced larger hole diameters than the drill nominal size of 6 mm, with UAD resulting in the improved error in hole circularity.
- The burr height was reduced in UAD in comparison with CD, creating burrs smaller by some 50%.

References

[1] P. Cirillo, A. Marino, C. Natale, E. Di Marino, P. Chiacchio, and G. De Maria, “A low-cost and flexible solution for one-shot cooperative robotic drilling of aeronautic stack materials,” *IFAC-PapersOnLine*, vol. 50, no. 1, pp. 4602–4609, 2017

[2] O. Pecat and E. Brinksmeier, “Low damage drilling of CFRP/titanium compound materials for fastening,” *Procedia CIRP*, vol. 13, pp. 1-7, 2014

[3] B. Wang, W. Yin, M. Wang, Y. Zheng, X. Li, and Z. Ma, “Edge chipping mechanism and failure time prediction on carbide cemented tool during drilling of CFRP/Ti stack,” *Int. J. Adv. Manuf. Technol.*, vol. 91, no. 9–12, pp. 3015–3024, 2017

[4] J. Xu, A. Mkaddem, and M. El Mansori, “Recent advances in drilling hybrid FRP/Ti composite: A state-of-the-art review,” *Compo Struct.*, vol 135, pp. 316-338, 2016

[5] M. Eynian, K. Das, and A. Wretland, “Effect of tool wear on quality in drilling of titanium alloy Ti6Al4V, Part I: Cutting Forces, Burr Formation, Surface Quality and Defects,” *High Speed Mach*, vol. 3, pp. 1–10, 2017

[6] M. Ramulu, T. Branson, and D. Kim, “A study on the drilling of composite and titanium stacks,” *Compos. Struct.*, vol. 54, no. 1, pp. 67–77, 2001

[7] K.-H. Park, A. Beal, D. Kim, P. Kwon, and J. Lantrip, “A Comparative Study of Carbide Tools in Drilling of CFRP and CFRP-Ti Stacks,” *J. Manuf. Sci. Eng.*, vol. 136, no. 1, pp. 14501, 2013

[8] W. L. Cong, Z. J. Pei, and C. Treadwell, “Preliminary study on rotary ultrasonic machining of CFRP/Ti stacks,” *Ultrasonics*, vol 54, pp. 1594-1602, 2014

[9] O. Pecat, T. Paulsen, P. Katthöfer, E. Brinksmeier, and S. Fangmann, “Vibration Assisted Drilling of Aerospace Materials,” 2016

[10] F. Makhdum, V. A. Phadnis, A. Roy, and V. V. Silberschmidt, “Effect of ultrasonically-assisted drilling on carbon-fibre-reinforced plastics,” *J. Sound Vib.*, vol 333, pp. 5939-5952, 2014

[11] J. Pujana, A. Rivero, A. Celaya, and L. N. López de Lacalle, “Analysis of ultrasonic-assisted drilling of Ti6Al4V,” *Int. J. Mach. Tools Manuf.*, Vol 49, pp. 500-508, 2009

[12] V. A. Phadnis, F. Makhdum, A. Roy, and V. V. Silberschmidt, “Drilling in carbon/epoxy composites: Experimental investigations and finite element implementation,” *Compos. Part A Appl. Sci. Manuf.*, vol 47, pp. 41-51, 2013

[13] Z. Zhu, S. Sui, J. Sun, J. Li, and Y. Li, “Investigation on performance characteristics in drilling of Ti6Al4V alloy.” *Int. J. Adv. Manuf. Technol.*, vol 93, pp 651-600, 2017

[14] H. Hocheng and C. C. Tsao, “The path towards delamination-free drilling of composite materials,” *J. Mater. Process. Technol.*, vol 167, pp. 251-264, 2005

[15] D. R. M. Kim, “Drilling process optimization for graphite/bismaleimide–titanium alloy stacks,” *Compos. Struct.*, vol. 63, no. 1, pp. 101–114, 2004