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Procedia CIRP 13 (2014) 405 – 410

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2nd CIRP Conference on Surface Integrity (CSI)

The effect of cutting speed and feed rate on hole surface integrity in single-shot drilling of metallic-composite stacks

C.L. Kuo[a], S.L. Soo[a,*], D.K. Aspinwall[a], W. Thomas[b], S. Bradley[b], D. Pearson[c], R. M'Saoubi[d], W. Leahy[e]

[a]*Machining Research Group, School of Mechanical Engineering, University of Birmingham, Edgbaston, Birmingham, B15 2TT, UK.*
[b]*GKN Aerospace Services Ltd., Composites Research Centre, Whippingham Road, East Cowes, Isle of Wight, PO32 6LR, UK.*
[c]*Seco Tools (UK) Ltd, Springfield Business Park, Alcester, B49 6PU, UK.*
[d]*Seco Tools AB, SE-737 82, Fagersta, Sweden.*
[e]*Element Six Ltd., Global Innovation Centre, Harwell, Oxford, OX11 0QR, UK.*

* Corresponding author. Tel.: +44-121-414-4196; fax: +44-121-414-4201. *E-mail address*: s.l.soo@bham.ac.uk.

Abstract

Experimental work was carried out to evaluate the influence of cutting speed (Ti/CFRP/Al: 30/120/120 and 36/144/144m/min) and feed rate (0.05, 0.08, 0.12 and 0.15mm/rev) on workpiece surface integrity following single-shot drilling of multilayer metallic-composite stacks (Ti-6Al-4V/CFRP/Al-7050) using CVD diamond coated tooling. When operating with the lower cutting speed set of 30/120/120m/min and a feed rate of 0.08mm/rev, average hole surface roughness (Ra) was ~ 0.60, 0.87 and 0.27μm in the Ti, CFRP and Al layers respectively after 30 holes. Roughness values in the stack increased to 0.84, 1.6 and 0.43μm Ra when employing the higher cutting speed of 36/144/144m/min, with the drill lasting only 20 holes. Microhardness depth profile evaluation of the machined surfaces showed no appreciable variation in both the Ti and Al material, irrespective of cutting conditions. Matrix cracking and burn were apparent in the CFRP layer as feed rate increased due to greater wear of the drill corner.

Selection and peer-review under responsibility of The International Scientific Committee of the "2nd Conference on Surface Integrity" in the person of the Conference Chair Prof Dragos Axinte dragos.axinte@nottingham.ac.uk

Keywords: Drilling; Composite; Diamond coating; Damage

1. Introduction

Multilayer metallic-composite stacks comprising two (Ti/CFRP, Al/CFRP) [1, 2] or three layer (Ti/CFRP/Al) configurations [3, 4], are increasingly being employed in aircraft structural components including wing joints and fuselage sections. Such stack assemblies however normally require mechanical joining (bolting or riveting) and hence hole drilling is a key processing technology. Due to critical tolerance requirements, current industrial practice relies on a multi-step operation where each material layer is drilled before being de-burred and assembled into stacks. This is followed by finish reaming of the assembly to ensure appropriate hole accuracy and surface roughness. Single-shot drilling of stacks (without the need for prior drilling, de-burring and reaming) has become the subject of extensive research in recent years because of increasing demand for higher manufacturing productivity and efficiency. Although limited, previously published work involving the drilling of 3-layer stacks highlighted the Ti layer as being the limiting factor in terms of tool life due to the high thrust forces and cutting temperatures generated during machining [3, 5]. Wear is typically characterised by workpiece adhesion, attrition and fracture when drilling Ti-6Al-4V with tungsten carbide (WC) tools under internal cutting fluid supply [6], while diffusion and crater wear are prevalent under dry conditions [7] due to the high cutting temperatures generated (~900˚C). Subsurface hardening of up to ~30% above the workpiece bulk value is also reported when utilising a cutting speed of 50m/min and a feed rate of 0.07mm/rev.

Apart from being highly abrasive, the anisotropic

Selection and peer-review under responsibility of The International Scientific Committee of the "2nd Conference on Surface Integrity" in the person of the Conference Chair Prof Dragos Axinte dragos.axinte@nottingham.ac.uk
doi:10.1016/j.procir.2014.04.069

nature of carbon fibre reinforced plastic (CFRP) composites (due to the different properties of the matrix and reinforcement phase as well as varying fibre orientation), make them extremely difficult to cut without inducing surface/subsurface defects. Abrao et al. [8] commented that drills employed for machining CFRP in industry were principally made from WC and accounted for up to 49% of total tool utilisation, whilst the use of polycrystalline diamond (PCD) was only ~ 3%, partly due to higher capital costs and the lack of performance data. However, the relatively high wear rates associated with WC tools can produce severe workpiece damage including fuzzing, spalling/delamination and matrix cracking together with loss of fibres at the interface between plies [9].

Polycrystalline diamond is generally recommended for machining advanced aluminium alloys and has been shown to provide superior productivity and wear resistance compared to WC tools [10], although CVD diamond coatings can be a cost effective alternative. Sánchez et al. [11] carried out a microstructural evaluation of built-up layer (BUL) and built-up edge (BUE) formation on cutting tools when machining Al alloys. They reported that a BUL was initiated by the diffusion of the tool material into the aluminium workpiece whilst BUE was the result of mechanical action, which subsequently degraded the machined surface quality and tool life. In experimental trials involving dry drilling of aluminium alloys, Nouari et al. [12] showed that diamond coated tools increased tool life up to 3-fold in comparison to uncoated WC. The present paper details experimental work to evaluate the effect of operating parameters and tool wear on hole surface integrity (surface roughness, microstructure and microhardness) when single-shot drilling 3 layer metallic-composite stacks.

2. Description of experimental work

The workpieces were three layer metallic-composite stacks comprising Ti-6Al-4V titanium alloy, CFRP and Al-7050-T7651 aluminium alloy. The Ti workpieces were supplied in the annealed condition with yield strength and Young's modulus of 880MPa and 114GPa respectively [13]. The CFRP laminates were composed of 36 unidirectional plies (each 0.18mm thick) involving high tensile strength (HTS-268-12K) carbon fibres pre-impregnated (pre-pregs) within an epoxy based matrix laid up according to an orientation of $[45°/0°/135°/90°/45°/0°]_{3S}$. This resulted in a fibre volume fraction of 56% giving a tensile strength of 1200MPa and Young's modulus of 145GPa [14]. In contrast, the Al alloy was age strengthened to provide a yield strength and Young's modulus of 550MPa and 72GPa respectively [15]. The individual workpiece materials had dimensions of 120×120mm and were bonded together (in the order of Ti/CFRP/Al) using a thermosetting modified epoxy film adhesive. The overall stack thickness was 27mm. Thin strip workpiece samples (120×17×27mm) joined using two M6 screws were also employed at intervals for force measurement and subsequently cross-sectioned for surface integrity investigation, see Fig. 1(a). The drills evaluated (recommended by tool supplier) were 6.38mm diameter CVD diamond coated WC with a two-stage point angle of 120°×180°, helix angle of 30° and relief angle of 14°; see Fig. 1(b). Table 1 details the mechanical/physical properties of the CVD diamond coating.

All experiments were undertaken on a Matsuura FX-5 CNC machining centre with a maximum spindle rotational speed of 20000rpm rated at 15kW, see Fig. 1(c) for the test setup. Preliminary tests (Tests 1 and 2) involving feed rates of 0.08 and 0.15mm/rev were initially performed with a cutting speed set of 30/120/120m/min (Ti/CFRP/Al). These values were subsequently increased by 20% to 36/144/144m/min with further trials undertaken at 3 different feed rate levels of 0.05, 0.08 and 0.12mm/rev, see Table 2 for test array. A water-miscible emulsion with a 7-8% volume solution of mineral oil was utilised in all tests, which was delivered via external coolant nozzles at a fixed pressure of 70 bar and flow rate of ~ 47 l/min.

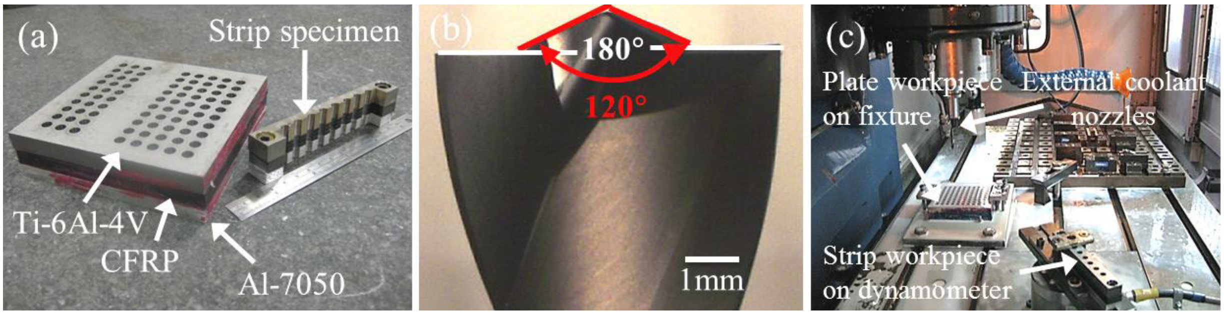

Fig. 1. (a) Ti/CFRP/Al stacks; (b) CVD diamond coated drill; (c) experimental setup

Table 1. Properties of CVD diamond coating

Property	Value
Chemical composition	C(SP^3)
Coating thickness	5-6μm
Stiffness modulus	1000GPa
Hardness	~10000HV$_{0.05}$
Coefficient of friction	0.4-0.6
Thermal conductivity	560W/mK
Oxidation temperature	650°C

Table 2. Experimental array with variable factor levels

Test no.	Cutting speed in Ti/CFRP/Al (m/min)	Feed rate (mm/rev)
1	30/120/120	0.08
2	30/120/120	0.15
3	36/144/144	0.05
4	36/144/144	0.08
5	36/144/144	0.12

A peck strategy incorporating 2mm tool retraction after every 5mm of travel was applied during drilling in order to alleviate swarf packing. The end of test criteria were either a maximum flank wear of 600µm or tool catastrophic fracture. Thrust force and torque were recorded using a Kistler 9273 two-component drilling dynamometer connected to Kistler 5011A charge amplifiers. The force signals were transmitted to a PC and analysed using Dynoware software. Tool flank wear was measured using a toolmaker's microscope equipped with a micrometre stage (0.001mm resolution) and digital camera for capture of wear scar micrographs. Workpiece surface roughness was evaluated using a Mitutoyo Surftest 201 portable contact stylus unit with a 0.8mm cut-off and 4mm evaluation length. Both an optical and scanning electron microscope (SEM) were used to obtain hole surface/subsurface micrographs while corresponding 3D surface topographic maps were generated using an Alicona InfiniteFocus G4 system at 20X magnification (resolutions of 39.3µm and 1.97nm in the lateral and vertical hole directions respectively). Microhardness measurement was performed with a Mitutoyo HM-124 employing a Knoop indenter with a 25g load over a 15s duration.

3. Results and discussion

With the exception of Test 2 (which involved the highest feed rate of 0.15mm/rev) where the drill suffered catastrophic fracture after the first hole, all of the other trials produced 20 – 30 holes before reaching the maximum flank wear criterion. Fig. 2 details surface roughness results measured at the last hole drilled for all tests. Under the low speed/intermediate feed rate regime (Test 1), average hole roughness in the Ti, CFRP and Al sections at test cessation was 0.60, 0.87 and 0.27 µm Ra respectively. Equivalent values for the Ti and CFRP layers were obtained in Test 3 after 20 holes, when operating at the higher cutting speed of 36/144/144 m/min and lower feed rate of 0.05mm/rev. The Ra in the Al section however was ~ 59% higher.

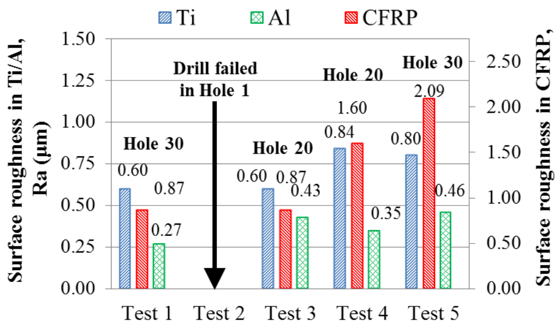

Fig. 2. Hole surface roughness in each material at last hole drilled

Increasing feed rate from 0.05 to 0.12mm/rev (at 36/144/144 m/min cutting speed) led to a ~ 140% rise in average hole surface roughness within the CFRP section, which was ~ 2.09µm Ra in Test 5 at hole 30. In terms of the Ti layer, roughness was 40% higher when operating at 0.08mm/rev compared to 0.05mm/rev, but remained approximately stable despite a further increase in feed rate to 0.12mm/rev. In contrast, no clear trend was apparent in the Al sections due to changes in feed rate, with the surface roughness varying between 0.35 and 0.46µm Ra.

The principal wear mode of the drills was flaking/delamination of the CVD diamond coating, irrespective of operating parameters. This was observed primarily on the tool flank face near the peripheral corners as well as at the chisel point. Micrographs of the worn CVD diamond coated drills for trials undertaken at the higher cutting speed level (Tests 3, 4, 5) together with corresponding hole surfaces in the CFRP section of the stack are shown in Fig. 3. Rapid abrasion of the exposed WC substrate was also prevalent in all tests, which increased cutting edge rounding and the corner radius of the drill. Wear was generally more severe at higher feed rates, with gross fracture of the chisel point occurring in Test 4 (0.08mm/rev) and chipping/fracture of the peripheral corner in Test 5 (0.12mm/rev). No significant wear/damage however was seen at the chisel section of the drill employed in Test 5 even after 30 holes, see Fig. 4, which was possibly due to the shorter tool-workpiece interaction time. Evidence of workpiece adhesion on the cutting edges was however visible.

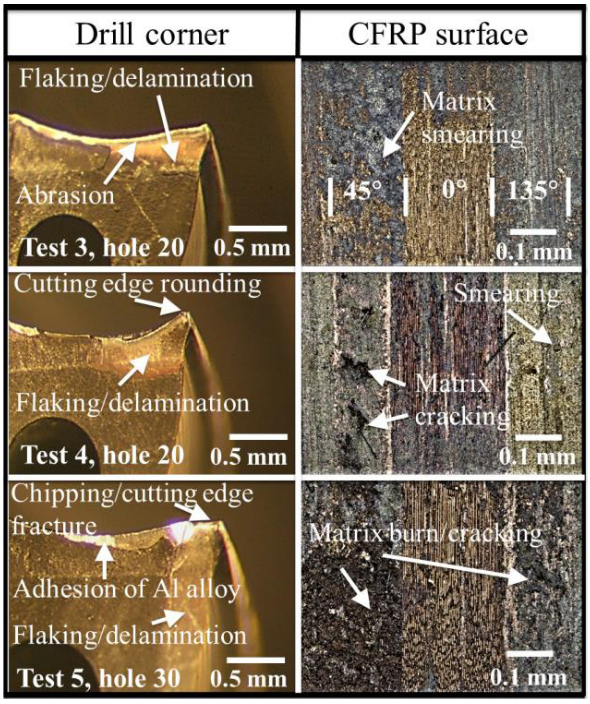

Fig. 3. Wear micrographs of drill corner and corresponding CFRP surface at last hole drilled in Tests 3, 4 and 5

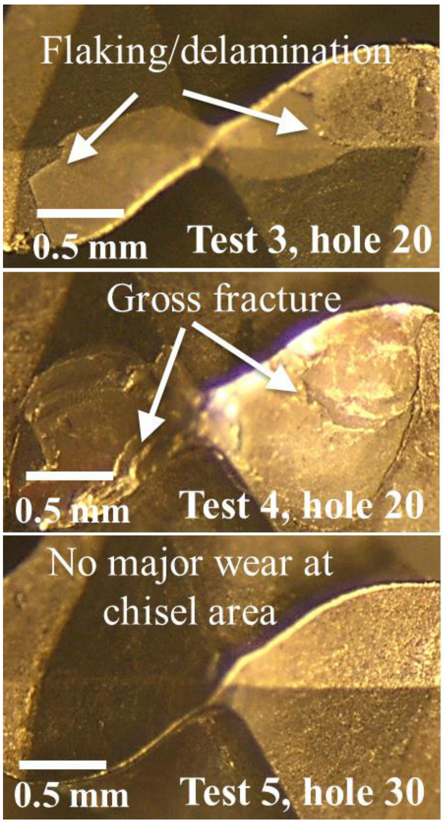

Fig. 4. Micrographs of worn drill chisel section in Tests 3, 4 and 5

Smearing of melted epoxy resin was the primary damage mode observed on the surface of the CFRP layer after 20 holes when drilling with the lowest feed rate of 0.05mm/rev, see Fig. 3. Greater deterioration of the workpiece surface occurred as feed rate increased, with matrix cracking and burning evident in the last holes drilled for Tests 4 and 5 respectively, which explains the surface roughness results detailed previously in Fig. 2. This was possibly due to the higher cutting temperatures generated from the increased feed rate and tool wear levels. No signs of grooves or significant material loss however were detected in any of the samples evaluated. In addition, defects were generally most severe in the 135° ply positions, as shown in the high resolution SEM micrograph and corresponding 3D topographic map (1.25 x 0.5mm scan area near the centre of the hole) of the machined surface (hole 30, Test 5) in Fig. 5.

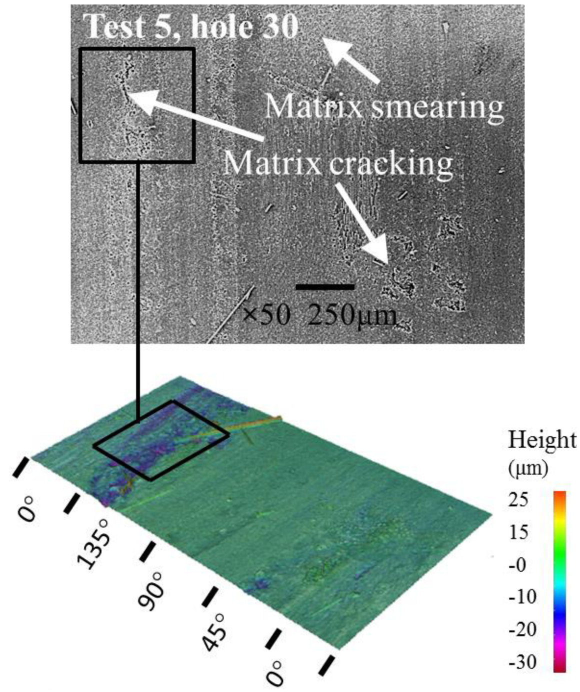

Fig. 5. SEM micrograph and 3D topographic map of CFRP hole surface in Test 5

Test 1 was subsequently extended to 70 holes in order to investigate drill wear progression and its consequent influence on workpiece integrity. Fig 6 shows a micrograph of the drill after hole 70 together with associated SEM images of the machined surfaces in each material layer. Flank wear increased to ~ 1mm with near complete delamination of the coating from the cutting edge. Evidence of sporadic re-deposited chips was seen on the surface of the Ti layer while the Al section appeared to be relatively free of major flaws. In contrast, the highly worn drill caused substantial degradation of the CFRP surface, with gross fibre loss and matrix pullout particularly at the 45°, 90° and 135° orientated plies.

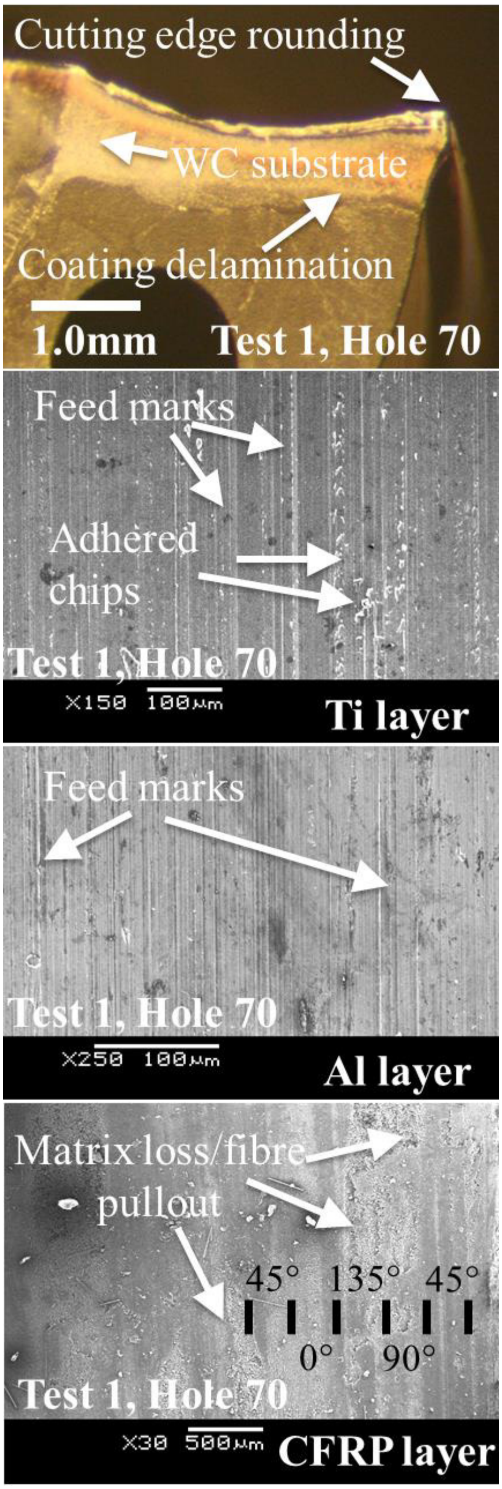

Fig. 6. Wear micrograph of the drill used in Test 1 and SEM images of the machined surfaces in each layer of the stack in hole 70

Fig. 7(a) and 7(b) detail cross-sectional micrographs of the machined Ti and Al subsurface respectively from the last hole drilled in Test 5. No appreciable change in material microstructure was visible in both workpiece samples, despite chipping of the peripheral drill corner (Fig. 3). This was representative of results seen in the other trials.

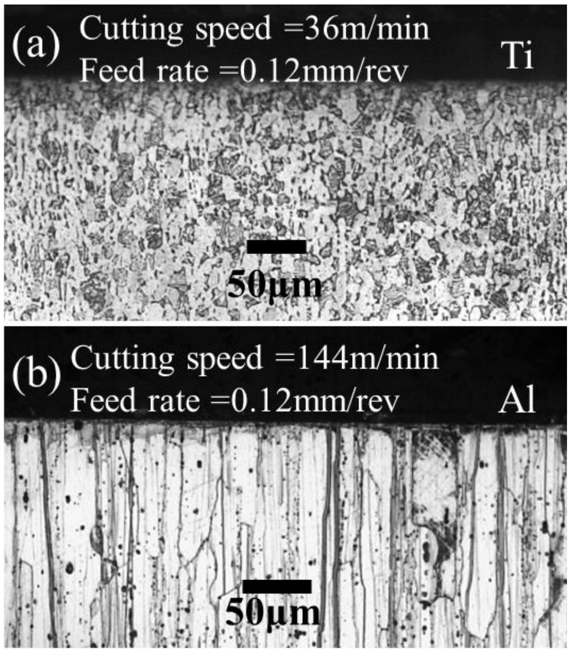

Fig. 7. Cross-sectional micrographs of the machined (a) Ti; (b) Al layers for last hole drilled in Test 5

Fig. 8 details microhardness depth profiles of both the Ti and Al layers at the last hole drilled for Tests 3, 4 and 5 (cutting speed of 36/144/144m/min). No significant variation in microhardness was observed for the Ti layer in any of the trials evaluated; see Fig 8(a). This was despite measured thrust forces showing a rise of ~ 41% (~690 vs. 980N) as feed rate was increased from 0.05 to 0.12 mm/rev. Corresponding torque values ranged between ~2.3 and 3.6Nm at test cessation. Similarly, an analysis of the Al sections revealed no substantial changes in subsurface microhardness due to changes in feed rate; see Fig. 8(b). Here, thrust forces and torque for the last hole drilled varied from ~278 to 410N and ~0.75 to 1.3Nm respectively, as feed rate increased from 0.05 to 0.12mm/rev. The results suggest that neither strain hardening nor thermal softening played a major role.

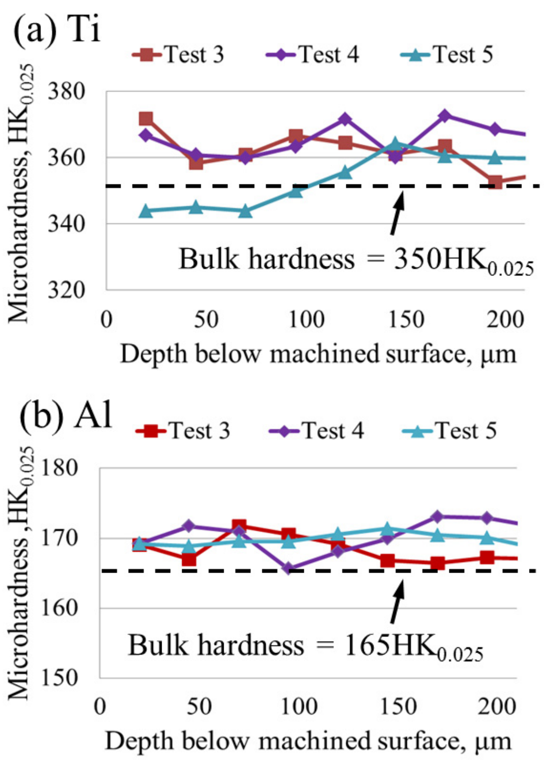

Fig. 8. Microhardness depth profile at test cessation when drilling at 36/144/144m/min cutting speed in (a) Ti; (b) Al layers

4. Conclusions

- Tool life did not exceed 30 holes over the range of operating parameters employed. This was mainly due to severe flaking/delamination of the CVD diamond coating, which suggests the tool was not suitable for single-shot drilling of the stack material.
- Hole surface roughness in the CFRP section at test cessation deteriorated (by ~140%) with increasing feed rate (0.05 to 0.12mm/rev) when operating at a cutting speed of 36/144/144m/min. This was attributed to the greater rounding and chipping of the drill peripheral corners at the higher feed rate levels following flaking/delamination of the CVD coating layer.
- When machining at the lower cutting speed and intermediate feed rate of 30/120/120m/min and 0.8mm/rev respectively, no signs of tool chipping or edge fracture were observed even after 70 holes, although flank wear increased to ~1mm. This led to minor workpiece adhesion on the surface of the Ti layer while no appreciable defects were seen on the Al section.
- No significant changes in workpiece microhardness were recorded at test cessation for both the Ti and Al layers, irrespective of the feed rate employed. Similarly, there was no apparent subsurface microstructural modification or damage in any of the metallic samples evaluated.
- Surface defects in the form of matrix cracking and burn were prevalent on the CFRP layer when drilling with worn tools at feed rates of 0.08 and 0.12mm/rev. The damage was particularly evident in the 45° and 135° plies.

Acknowledgements

The authors would like to thank GKN Aerospace, Seco Tools and Element Six for the supply of workpiece material and tooling together with the provision of financial support.

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