# The influence of tool geometry, feed rate and machining strategy on hole surface integrity following single-shot drilling of 3 layer metallic-composite stacks

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# THE INFLUENCE OF TOOL GEOMETRY, FEED RATE AND MACHINING STRATEGY ON HOLE SURFACE INTEGRITY FOLLOWING SINGLE-SHOT DRILLING OF 3 LAYER METALLIC-COMPOSITE STACKS

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## ABSTRACT

A full factorial experimental design involving single-shot drilling of 3 layer Ti-6Al-4V/CFRP/Al7050 stack workpieces was performed to evaluate the effect of drill geometry (single and triple margin), feed rate (0.05 and 0.08mm/rev) and operating strategy (with and without pecking) on burr formation and hole surface integrity. All tests were carried out wet using twin-fluted, coated tungsten carbide drills having a diameter of 6.35mm. When employing triple margin drills, average hole surface roughness ($R_a$) values were 2.20, 9.66 and 0.83µm in the Ti, CFRP and Al sections respectively at test cessation (90 holes). These were 4 times higher for the Ti and Al layers compared to those produced with the single margin geometry. Similarly, an increase in Al entrance and exit burr heights of ~100 and ~430% respectively was observed when employing triple margin drills due to the greater contact area between the tool and workpiece. However no delamination of the CFRP layer was detected in any of the holes machined with the triple margin tools. Cross-sectional microstructures of Ti and Al layers showed plastically deformed regions of up to 184 and 75µm respectively beneath the machined surface. Corresponding microhardness evaluation of the Ti section showed an increase of up to $60HK_{0.025}$ above the bulk value, to a depth of ~200µm.

**KEYWORDS: Ti/CFRP/Al stacks, drilling, surface integrity**

## 1. INTRODUCTION

Up to 50% of structural components in modern commercial passenger aircraft such as the Boeing 787 Dreamliner and Airbus 380 are made from advanced carbon fibre reinforced plastic (CFRP) composites, the move from traditional metallic materials providing superior strength to weight ratios and improved fatigue performance [1, 2]. In tandem, multilayer metallic-composite stacks involving titanium, aluminium and CFRP are also increasingly being employed in aerospace applications to meet design requirements for greater load bearing capability/stiffness without incurring significant weight penalties. Applications include aircraft wing sections and fuselage with typical configurations involving two (Ti/CFRP and Al/CFRP) or three layers (Ti/CFRP/Al) [3]. Such assemblies normally rely on mechanical joining and consequently, conventional hole drilling is a key processing technology.

Current production strategies involve the drilling of each material layer separately prior to stacking, due to the requirement for hole de-burring. While hole accuracy (diameter, out of roundness, parallelism, cylindricity etc.) is a primary consideration to meet part tolerance and assembly specifications, surface integrity following drilling is an equally important factor which must be controlled in order to avoid premature failure from fracture, fatigue or stress corrosion [4]. Workpiece integrity is influenced by changes to surface and sub-surface conditions such as surface roughness, microstructure, microhardness and residual stress. In the case of drilling operations, burr formation on hole entry and exit locations can also lead to assembly and safety issues, with the average expense of de-burring estimated to be up to 9% of total manufacturing costs [5]. The relatively poor machinability of titanium alloys is due in part to low thermal conductivity and high chemical reactivity [6] and the abrasive nature and inhomogeneity/anisotropy of CFRP [7], introduces further difficulties in single shot drilling of Ti/ACFRP/Al stacks. Commonly induced defects following machining of Ti alloys include microstructural deformation/drag, white layer formation and adhered/re-deposited material, whereas fibre pullout, matrix cracking, delamination and thermal degradation are characteristic of cut CFRP workpieces [8]. The paper details experimental work to investigate the effect of feed rate, pecking strategy and margin design on cutting forces and hole surface integrity when drilling 3 layer metallic-composite stack materials.

## 2. EXPERIMENTAL WORK

The workpieces used in all tests were 3 layer metallic-composite stacks comprising annealed Ti-6Al-4V titanium alloy, unidirectional CFRP composite and age-strengthened Al7050-T7651 aluminium alloy. The CFRP was laid up with 36 unidirectional pre-pregs (ply thickness of 0.3mm) according to an orientation of $[45^{\circ}/0^{\circ}/135^{\circ}/90^{\circ}/45^{\circ}/0^{\circ}]_{6s}$ and comprised 56% volume fraction of high tensile strength (HTS) carbon fibre (6–8μm diameter) within an epoxy matrix. Table 1 details the respective mechanical/physical properties and heat treatment/lay-up configuration of each material in the stack. Workpieces employed in mainstream testing were provided in the form of square plates measuring 120×120×30mm, which were bonded in the order Ti/CFRP/Al using an epoxy-based film adhesive (3M AF163). A separate batch of mechanically joined (with two M6 screws) 17mm wide strips was also produced and utilised for cutting force evaluation. The latter allowed for easy disassembly to enable subsequent burr formation analysis as well as hole surface integrity evaluation of the individual material layers. In order to avoid air gaps between material elements, strips were securely clamped using a bespoke fixture.

Table 1: Mechanical/physical properties and condition/configuration of stack materials [9-11]

| Material specification | Ti-6Al-4V | CFRP | Al7050-T7651 |
|---|---|---|---|
| **Treatment/ configuration** | Annealed | [45°/0°/135°/90°/45°/0°]$_{6S}$, | Duplex aged/ stabilised/stress-relieved |
| **Density (g/ cm$^3$)** | 4.43 | 1.6 | 2.83 |
| **Hardness** | 350 HV | 60-65 Barcol | 171 HV |
| **Thermal conductivity (W/mK)** | 7 | 1 ⊥ and 70 // to fibre direction | 153 |
| **Ultimate tensile strength (MPa)** | 950 | 2000 | 515 |
| **Modulus of elasticity (GPa)** | 115 | 150 | 72 |

The drills were K30-K40 grade (0.6μm average grain size) solid tungsten carbide (WC) with 10% cobalt binder and a multilayer TiAlN/TiN coating. The combination of high traverse rupture strength (> 3600MPa) and stiffness (590GPa) of the solid carbide substrate together with the increased hardness of the TiAlN/TiN coating (~35GPa) was recommended for the drilling of stacks involving Ti and CFRP, see Table 2 for mechanical and physical properties of the WC and coatings [12].

Table 2: Mechanical/physical properties of the tool material and coatings [12]

| | WC-6Co | TiN | TiAlN/TiN |
|---|---|---|---|
| **Crystal system** | N/A | fcc | fcc |
| **Density (g/cm$^3$)** | 14.9 | 5.44 | 4.81 |
| **Microhardness** | 1580 HV$_{30}$ | ~20GPa | 30-35GPa |
| **Young's modulus (kN/mm$^2$)** | 590 | 424 - 570 | 359 - 515 |
| **Coefficient of thermal expansion ($10^{-6}$/K)** | 5.5 | 9.4 | 6.5 |
| **Thermal conductivity (W/mK)** | 80 | 11.9 – 29.0 | 4.63 |

All drills had a diameter of 6.35mm with point and helix angles of 140° and 30° respectively together with internal coolant delivery channels. Two different geometries involving single and triple margin designs were evaluated, see Figure 1. Testing was performed on a Matsuura FX-5 CNC machining centre retrofitted with a spindle adaptor (maximum rotational speed of 6000rpm) to enable through tool coolant operation, see Figure 2. The stack workpieces were mounted on a fixture with an array of pre-drilled holes to provide drill clearance on exit. The cutting fluid was a water-miscible emulsion with a 7-8% volume solution of mineral oil which was delivered at a fixed pressure of 70 bar and flow rate of ~30 litres/min.

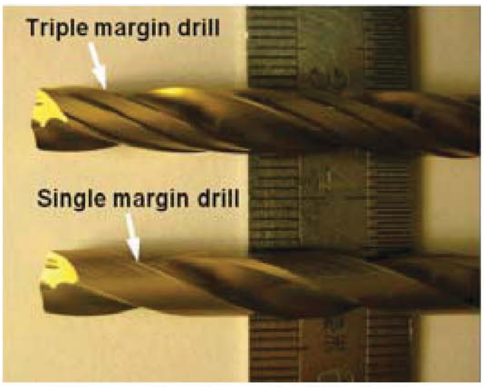


Figure 1: Coated WC drills

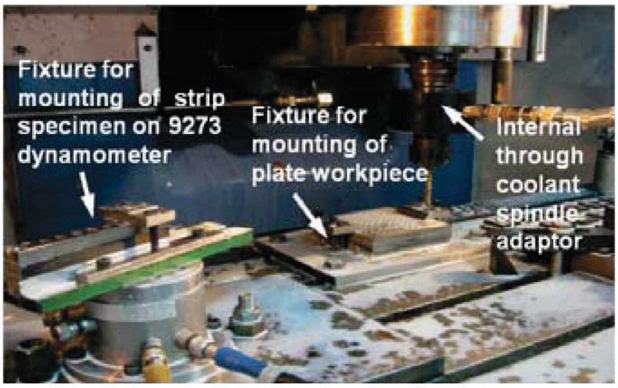


Figure 2: Experimental setup

A full factorial experimental design was employed involving 3 variable factors (margin design, feed rate and feed strategy) each at 2 levels, see Table 3. A peck cycle was employed to facilitate material and cutting changes as the drill progressed through the stack. This gave a total of 8 tests as shown by the array in Table 4. No replications were performed due to limitations in tooling and workpiece material. A dual level cutting speed regime was employed when drilling through the stack, which was 30m/min for the Ti-6Al-4V and 120m/min for both the CFRP and Al7050 layers. Analysis of variance (ANOVA) was performed to determine the significance of individual variable factors on selected response measures. The end of test criterion was either a maximum drill flank wear of 300µm or 90 holes drilled.

Table 3: Variable parameters and associated levels

| Factor | Level 1 | Level 2 |
|---|---|---|
| Margin design | Single margin | Triple margin |
| Feed (mm/rev) | 0.05 | 0.08 |
| Feed peck cycle | No pecking | 2mm peck at entry into different stack layers |

Table 4: Full factorial experimental array

| Test no. | Margin design | Feed (mm/rev) | Feed peck cycle |
|---|---|---|---|
| 1 | Triple margin | 0.05 | No pecking |
| 2 | Single margin | 0.05 | No pecking |
| 3 | Triple margin | 0.08 | No pecking |
| 4 | Single margin | 0.08 | No pecking |
| 5 | Triple margin | 0.05 | Pecking |
| 6 | Single margin | 0.05 | Pecking |
| 7 | Triple margin | 0.08 | Pecking |
| 8 | Single margin | 0.08 | Pecking |

Thrust force and torque were measured at the first hole and at subsequent 20 hole intervals with a Kistler 9273 piezoelectric dynamometer connected to Kistler 5011A charge amplifiers. The data signals were sent to a PC and analysed using Dynoware software. The height of entry and exit burrs was measured using a dial gauge with a precision of 1µm. Workpiece surface roughness was assessed using a Talysurf 120L with a diamond tipped stylus over a cut-off and evaluation length of 0.8 and 4.0mm respectively. Sub-surface microstructural analysis of cross sectioned holes involved use of a Leica optical microscope (maximum magnification of 500X) as well as a JEOL 6060 scanning electron microscope (SEM) for higher resolution images. Microhardness depth profile measurements of the hole surface in the Ti and Al sections (at the middle location) were taken using a Mitutoyo HM-124 equipped with a Knoop indenter (25g load for 15s). Each measurement was replicated twice and an average calculated.

## 3. RESULTS AND DISCUSSION

### 3.1 Cutting forces

All of the drills tested produced 90 holes without reaching the flank wear criterion of 0.3mm. Figure 3 details the measured thrust force and torque for each material section at test cessation (hole 90). The use of a peck cycle and variation in feed appeared to have limited influence on either thrust forces or torque. In contrast, thrust forces recorded in the Ti, CFRP and Al layer increased by up to 36%, 28% and 67% respectively when utilising the triple margin drill over the single margin variant. This was caused by the increase in contact/rubbing between the tool and hole surface when employing the former geometry. The trend in torque results was similar to the thrust force responses but with even greater ratios of escalation, particularly in the titanium section of the stack (up to 153%). Although not shown here, this was attributed to the formation of a tri-lobbed hole profile as the drill entered the stack (most likely due to inherent process vibration), which exacerbated the interaction of tool margins with the workpiece material.

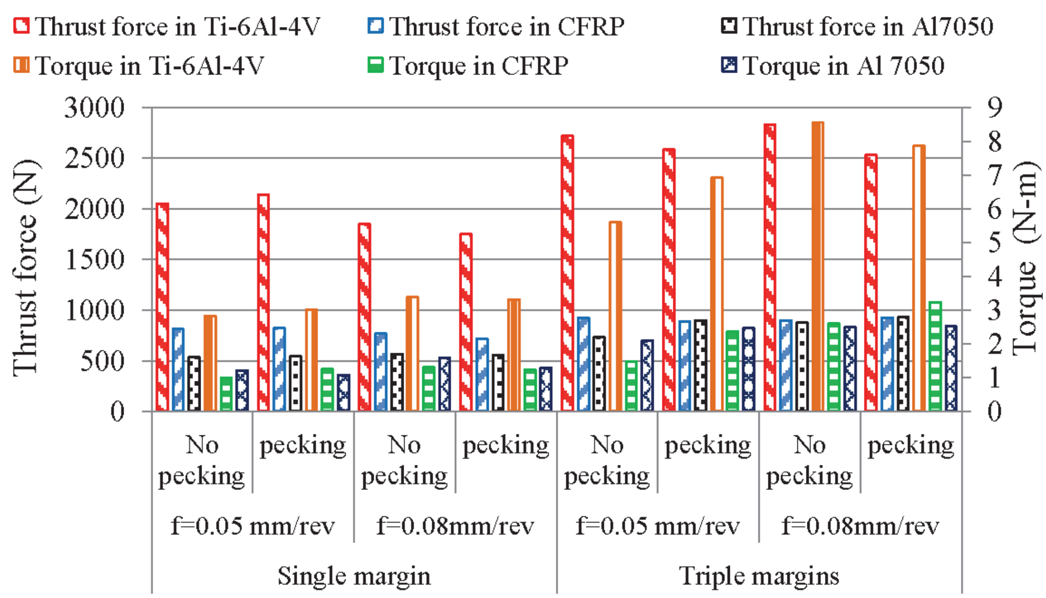


Figure 3: Thrust force and torque in each individual material section at hole 90

The results were supported by ANOVA calculations which confirmed that drill margin design was the only statistically significant factor affecting both thrust force and torque. Corresponding percentage contribution ratios (PCR's) of margin design on thrust force were 85.4%, 79.6% and 85.9% for the titanium, CFRP, and aluminium sections respectively. Similarly for torque, high PCR's of 85.5% (Ti), 50.9% (CFRP) and 89.5% (Al) were attributed to drill margin design while the PCR levels for feed rate and pecking cycle with respect to both thrust force and torque were negligible.

### 3.2 Burr formation

Figure 4 shows the burrs generated at the entry and exit of the last hole drilled in the titanium and aluminium layers from Test 7. In general, transient type burrs occurred at the entry location of both metallic layers while those at the exit were uniform. The action of the drill when entering the workpiece is analogous to an impact extrusion process, where material at the periphery of the hole is forced to flow opposite to the feed direction by the reaction against thrust forces. Conversely, material at the hole exit is pushed outwards following plastic deformation as the drill breaks through the bottom of the individual stack layers [13].

Tool geometry was found to be the dominant factor as burr size generally increased by 50 to 430% when machining with the triple margin drills. Burr height at test cessation was typically larger at the exit position with a maximum of 0.43 and 0.77mm compared to 0.32 and 0.28mm at hole entry in the titanium and aluminium sections respectively. The smaller exit and entry burrs on the Ti and Al layers respectively were due to the presence of the CFRP laminate which acted to suppress/resist material flow at the interface. For the adhesive bonded stacks, it is likely that burrs at these locations would be smaller.

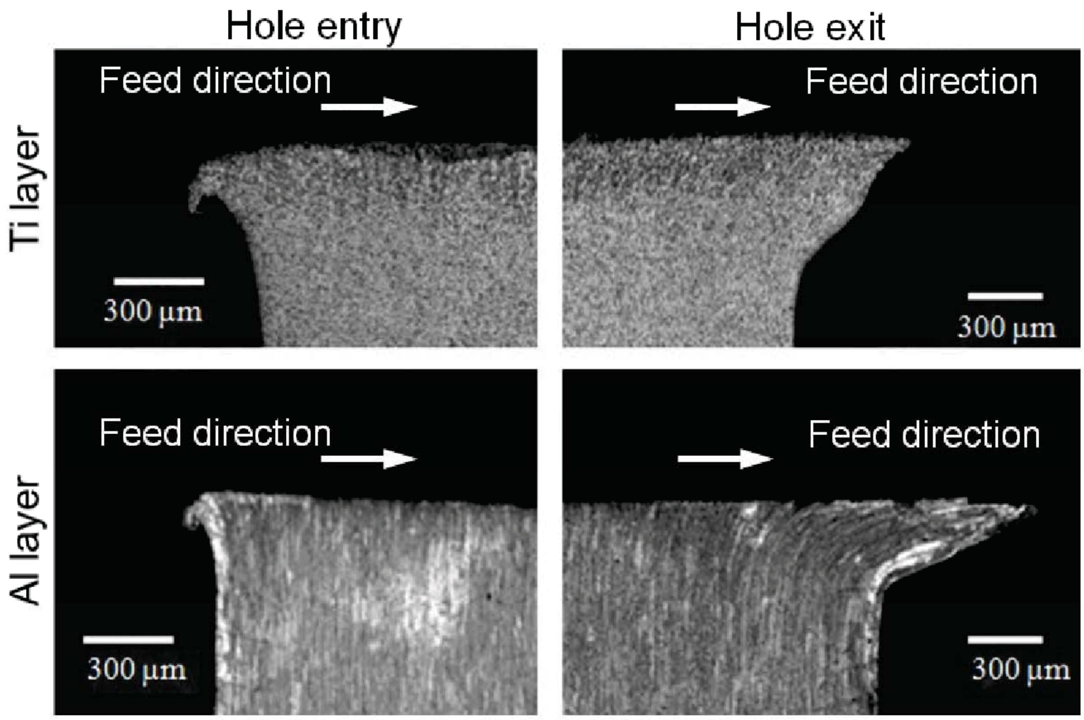


Figure 4: Burr formation at hole entry and exit in the Ti and Al layers of the last hole drilled in Test 7

According to results from the ANOVA, margin design was the sole factor having a significant influence on hole entry burrs in the Ti section with a PCR of

90.12%. None of the variables were statistically significant with respect to entrance burr size in the aluminium sections. In terms of exit burr heights however, margin design was significant at the 5% level in both the Ti and Al layers with PCR's of 49.9% and 80.5% respectively.

### 3.3 Workpiece surface roughness

Hole surface roughness in the metallic layers of the stack was found to deteriorate when employing the triple margin geometry over the single margin drills, although this trend was reversed on the CFRP section. Figure 5 shows the evolution of workpiece surface roughness ($R_a$) against number of holes drilled in each material element for Test 5 (triple margin) and Test 6 (single margin) when operating under a feed rate of 0.05mm/rev with a pecking cycle. The maximum hole surface roughness on the Ti section produced in Test 5 was 1.35μm Ra, which was approximately double that obtained when utilising the single margin drill. Similarly for the aluminium layer, $R_a$ was up to 3 times greater when using the triple margin drills. Additionally, visual inspection of the hole surfaces in Test 5 revealed extensive rubbing marks in the radial direction particularly on the metallic segments, which suggests excessive contact between the tool margins and stack material.

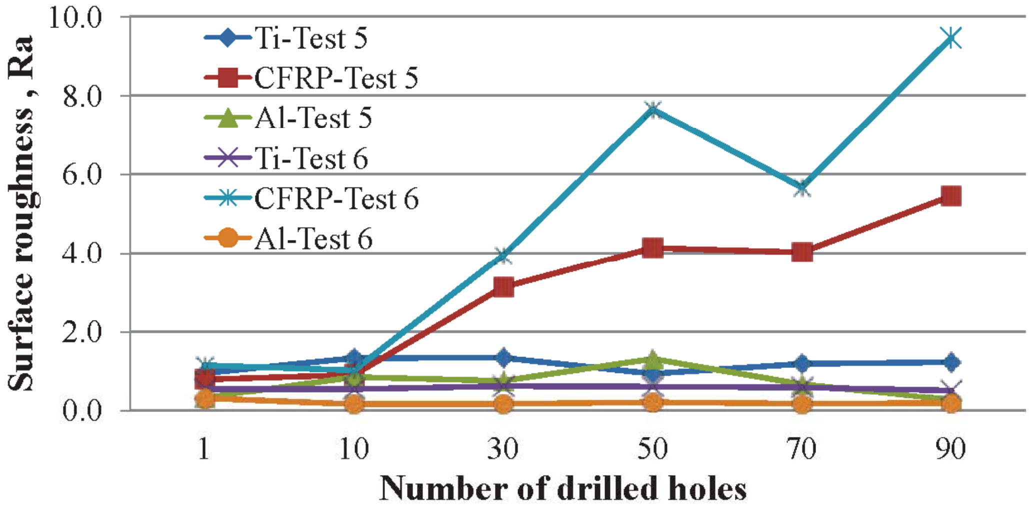


Figure 5: Workpiece surface roughness for each material layer in Tests 5 and 6.

Workpiece surface roughness in the CFRP layer was generally observed to increase rapidly after ~10 holes, irrespective of the experimental parameters although there was some variability (with respect to trend), especially for tests involving single margin drills, see Figure 5. This was due to the nature of damage/flaws typically generated on CFRP surfaces following machining, which include material pull out, uncut fibres, resin melt, matrix cracking etc. [13]. In contrast to results seen in the Ti and Al sections, surface roughness was found to be lower in holes machined with the triple margin drills. This was thought to be due to the lower incidence of uncut fibres and 'smearing' of the matrix material; see Figure 6(a), as a result of the increased rubbing/contact between the drill and workpiece surface. However, defects in the form of matrix cracking and fibre loss on the CFRP hole surfaces were evident and more widespread on all plies when using single margin drills, see Figure 6(b).

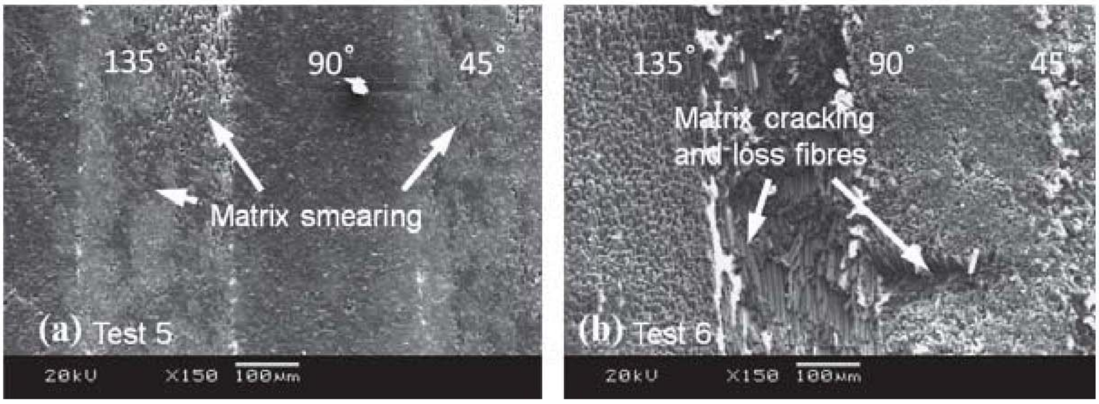


Figure 6: SEM micrograph of CFRP surface in (a) Test 5, (b) Test 6

## 3.4 Workpiece microstructural alterations

Figures 7(a) and (b) show cross-sectional microstructures of the Ti and Al layers respectively for the last hole drilled in Test 5, which produced the highest levels of sub-surface alterations. Severe plastic deformation extending to a depth of ~184µm beneath the machined surface was recorded in the titanium section while a ~75µm layer of elongated grains was similarly visible in the aluminium segment of the stack. This contrasted significantly with the depth of deformation obtained when using the single margin drill in Test 6, which was only ~40 and 30µm in the Ti and Al layers respectively.

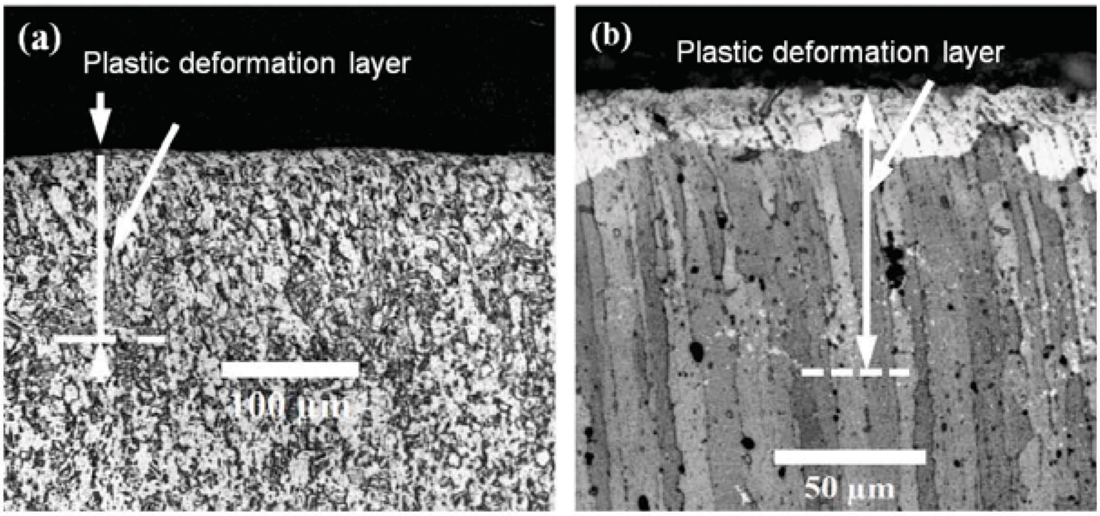


Figure 7: Microstructure in (a) Ti and (b) Al sections of hole 90 in Test 5.

## 3.5 Microhardness evaluation in metallic sections

Sub-surface microhardness alterations commonly occur after machining due to thermal softening or strain hardening, depending on the process conditions and metallurgical nature of the workpiece material. Figure 8 shows microhardness depth profile plots for the last hole drilled in the titanium and aluminium plates for all tests. When drilling with triple-margin tools, the hole surfaces in the Ti section typically exhibited a strain hardened layer extending to a depth of

~200µm, with a maximum level of 440$HK_{0.025}$ (15% above bulk material hardness) observed in Test 5. This corresponded with the increased thrust forces and torque recorded for the triple margin drills as shown previously in Figure 3. Conversely, the use of single margin drills generally resulted in softened sub-surface regions down to a minimum hardness of 330$HK_{0.025}$ (~13% below bulk hardness value), which was seen in Test 8. No significant variation in workpiece microhardness was evident in the aluminium section of stacks machined with triple margin drills, despite the presence of heavily deformed sub-surface microstructure similar to that detailed in Figure 7(b). An increase of up to 10% (~ 190$HK_{0.025}$) however was obtained in all trials employing the single margin tools.

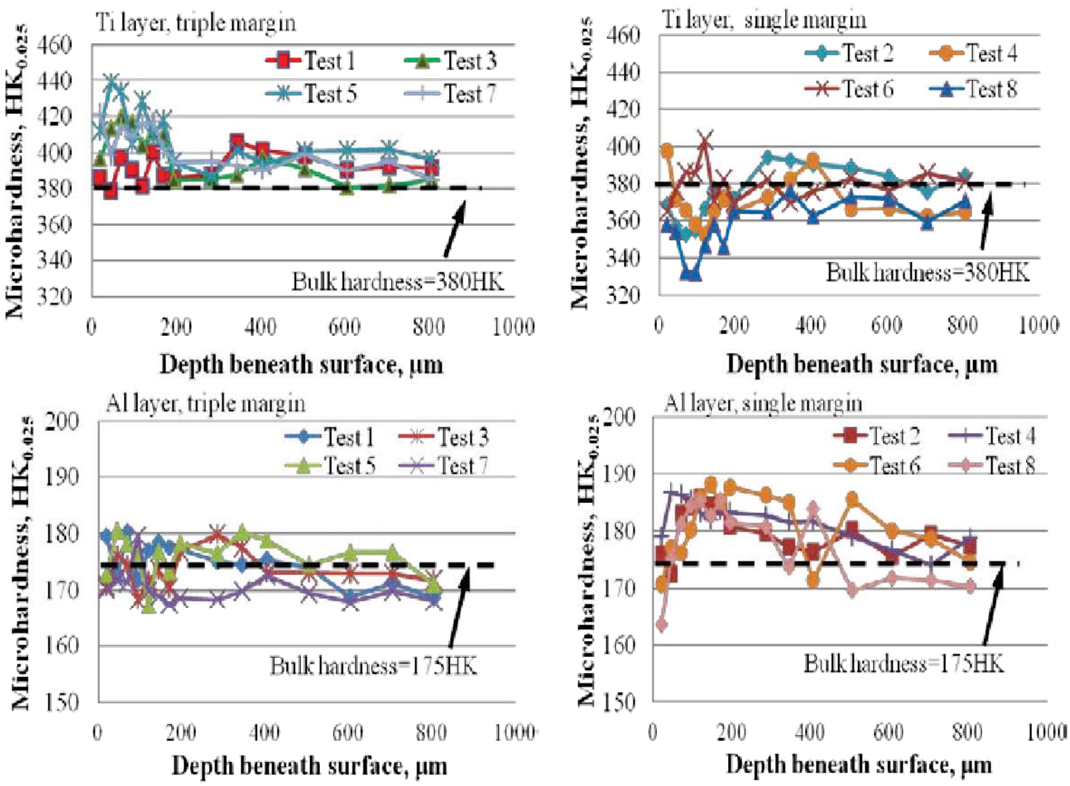


Figure 8: Microhardness depth profile measurements of Ti and Al sections in hole 90 for all tests

## 4. CONCLUSIONS

- Drill margin design had the strongest impact on the response measures evaluated, which typically superseded the effects due to variations in feed rate and peck cycle.
- Thrust force and torque typically increased by a maximum of 67% and ~160% respectively when drilling Ti-6Al-4V/CFRP/Al-7050 stacks with triple margin tools. This was mainly due to the increased frictional contact between the tool and workpiece surface.
- Burr height at the hole entry (titanium) and exit (aluminium) of the stack workpieces increased by up to ~430% when utilising triple margin drills due to the greater contact between tool and machined surface.
- Hole surface roughness in the metallic layers of the stack were typically 2 to 3 times higher when utilising triple margin drills in comparison to the

conventional single margin geometry. This trend however was reversed in the CFRP section due to the greater levels of matrix smearing and lower incidence of uncut fibres when employing the former drill design.

- Subsurface microhardness in the titanium sections typically increased by up to ~15% (maximum of $440HK_{0.025}$) due to severe strain hardening when using triple margin drills, while holes produced with single margin tools exhibited a softened layer up to ~$50HK_{0.025}$ below the bulk material hardness. However, virtually no change in aluminium microhardness was recorded when employing triple margin drill geometry, irrespective of the feed rate and pecking strategy.

## 5. ACKNOWLEDGEMENTS

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