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DOI:

[10.1016/j.jmapro.2017.11.026](https://doi.org/10.1016/j.jmapro.2017.11.026)

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Document Version

Peer reviewed version

Citation for published version (Harvard):

Kuo, CL, Soo, SL, Aspinwall, DK, Carr, C, Bradley, S, M'Saoubi, R & Leahy, W 2018, 'Development of single step drilling technology for multilayer metallic-composite stacks using uncoated and PVD coated carbide tools', *Journal of Manufacturing Processes*, vol. 31, pp. 286-300. <https://doi.org/10.1016/j.jmapro.2017.11.026>

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Checked for eligibility: 15/01/2018

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Development of single step drilling technology for multilayer metallic-composite stacks using uncoated and PVD coated carbide tools

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Abstract

The paper details experimental trials to evaluate the performance of uncoated and PVD coated tungsten carbide twist drills, for single shot drilling of 3-layer metallic-composite stack workpieces. A full factorial experiment was undertaken involving variations in feed rate (0.05 and 0.08 mm/rev) and drilling strategy (with and without pecking cycle), in addition to the tool coating (TiAlN/TiN). All of the uncoated drills machined 180 holes without exceeding the flank wear criterion of 0.3 mm, regardless of feed rate level or drilling strategy. In contrast, tool life for the coated drills was ~20-50% lower (90 to 148 holes). Thrust force decreased by ~12% when operating at the higher feed rate while use of coated drills led to an increase of up to 18% due to the larger cutting edge radius. Conversely, the hard/ceramic coating provided greater wear resistance at the peripheral corner of the drill resulting in lower torque (up to ~10%) compared to the uncoated tool. Furthermore, holes produced utilising the TiAlN/TiN coated drills typically exhibited superior geometrical accuracy in terms of diameter, out of roundness and cylindricity. Drilling at the lower feed rate of 0.05 mm/rev however generated larger exit burrs by up to ~90%.

Keywords: Drilling, hole quality, surface integrity

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1. Introduction

The composition of materials utilised in the design and construction of modern civil aeroplane structures has changed dramatically over the past 20 years. In particular, there has been a significant escalation in the use of carbon fibre reinforced plastic (CFRP) composites, which now accounts for over 50% of the weight in the Airbus A350 and Boeing B787 compared with $\leq 20\%$ in aircraft manufactured prior to 2000 [1]. This is largely attributed to the superior strength to weight ratio of CFRP, which is typically ~ 750 kN.m/kg [2] compared to metallic materials such as titanium and aluminium alloys of $\sim 200\text{--}250$ kN.m/kg, enabling lighter airframes and hence enhanced fuel efficiency. However, in highly loaded sections of the fuselage and wings, the use of two or three layer metallic-composite stack arrangements are essential to provide the necessary structural integrity in service without imposing a significant penalty on overall weight. The linking of these hybrid assemblies is primarily achieved via mechanical joining techniques, with interference fit fasteners having replaced conventional rivets in many areas, providing a reduction in the number of joints required and increased tensile load capability of the structure [3]. Unfortunately, such fasteners require the production of more accurate holes with tighter tolerances, which are generally only attainable using multi-step operations including pre-drilling of individual layers followed by de-burring prior to assembly of the stacks and final reaming [4].

The development of single-shot drilling technology for multilayer CFRP-metallic stacks has been the focus of considerable research in recent years not only as a solution to improve productivity, but also to reduce/avoid the misalignment of holes during assembly of the sandwich configuration [5]. A large majority of published research on this topic has involved twin layer arrangements comprising CFRP/Al or CFRP/Ti alloys. Use of high hardness/wear resistant tooling employing chemical vapour deposited (CVD) diamond coatings or polycrystalline diamond (PCD) blanks on tungsten carbide (WC) tools are generally recommended for drilling CFRP, due to the extremely abrasive and inhomogeneous nature of the workpiece material [6]. However, despite relatively low wear rates, the CVD-diamond coating can be prone to peeling/chipping and delamination, particularly when cutting at high feed rates, due to insufficient adhesion strength between the thin film and substrate or inadequate preparation of the tool surface prior to coating [7]. In contrast, PCD tooling is the preferred option for the machining of high volume aluminium-silicon alloy components

typically employed in the automotive industry as well as other non-ferrous/non-metallic materials including composites [8].

Montoya et al. [9] investigated the performance of different coatings (diamond, TiAlCrN, AlTiSiN-G) against uncoated WC tools when drilling 6 mm diameter holes in 21 mm thick CFRP/AA7010 stacks, at a cutting speed and feed of 55 m/min and 0.04 mm/rev respectively. The diamond coated drill exhibited the lowest wear rate with a flank wear of $\sim 120\text{ }\mu\text{m}$ compared to almost $250\text{ }\mu\text{m}$ for the uncoated tool after 250 holes, with peeling of the diamond coating only commencing after 150 holes. This was despite average thrust forces generated by the former being $\sim 30\text{-}100\%$ higher than the other tools due to the larger cutting edge radius of the diamond coating ($15\text{ }\mu\text{m}$ as opposed to $9\text{ }\mu\text{m}$ for the uncoated tool). Both the TiAlCrN and AlTiSiN-G coatings began to delaminate after only 5 holes, with complete removal from the tool substrate observed after machining 75 holes. The superior wear resistance of the diamond coating led to consistent hole diameter and surface roughness (below $1.6\text{ }\mu\text{m Ra}$ in Al and $3.2\text{ }\mu\text{m Ra}$ in CFRP layers) over the test duration. A twin cutting edge design (similar to a Brad point drill) was evaluated against a conventional twist drill when machining 5 mm diameter holes in thin CFRP/AA7075 stacks (overall thickness of 6.17 mm) by Zhang et al. [10]. All of the drills were CVD-diamond coated with a full factorial experiment performed involving varying cutting speed ($42.5 - 92.5\text{ m/min}$) and feed ($0.03 - 0.07\text{ mm/rev}$), each at 5 levels. Results indicated that tool geometry played a more significant role than operating parameters, with the twin cutting edge drill providing greater hole accuracy (average diameter deviation of $5\text{ }\mu\text{m}$ from nominal value), reduced thrust forces ($\sim 20\%$ lower) and better surface roughness in the CFRP layer ($1\text{-}2\text{ }\mu\text{m Ra}$ as opposed to $2\text{-}4\text{ }\mu\text{m Ra}$). Associated tool life trials undertaken at a cutting speed and feed rate of 63 m/min and 0.04 mm/rev respectively, showed a gradual progression of drill flank wear ($\sim 0.08\text{ mm}$) and thrust force up to ~ 400 holes, following which both factors increased dramatically with peeling of the diamond coating being the main wear mode. An innovative drill design for improving the one-shot drilling of CFRP/Al stacks was developed by Segawa et al. [11], incorporating a smaller diameter multi-angle point edge and a larger chamfered finishing section (similar to a step drill) together with a high helix angle. The arrangement of the pilot section functioned to reduce thrust force by deflecting a larger proportion of the cutting forces in the radial direction thereby minimising delamination while also enhancing breakage of the Al swarf and aiding evacuation. Hole sizing was then achieved by the trailing finishing section, which also removed any initial exit burrs. Experimental benchmarking trials involving CFRP/Al stacks

showed that the new drill design (CVD-diamond coated WC) decreased peak thrust forces by ~70% in the Al layer (~650 to ~200 N) compared to a traditional twist drill, while diameter variation in the CFRP section after machining 500 holes did not exceed ~25 μm .

Zitoune et al. [12] studied the effects of tool diameter (4, 6, 8 mm), rotational speed (1050, 2020, 2750 rpm) and feed rate (0.05, 0.10, 0.15 mm/rev) when drilling CFRP/AA2024 stacks (4.2/3.0 mm thick) with uncoated WC drills. Variation in tool diameter and feed rate had a more prominent influence on thrust force, torque and chip breaking than cutting speed, while only feed rate was seen to affect hole surface roughness in the CFRP layer (~2-4 μm Ra at low feed rate and ~6-8 μm Ra at high feed rate). Additionally, thrust forces were stable with no apparent signs of workpiece delamination or damage up to ~60 holes, however hole quality deteriorated beyond this point, with uncut fibres and edge chipping prevalent. Subsequently, trials were carried out to investigate the performance of 6 mm diameter, nano-composite coated (nanocrystalline-CrAlN/amorphous-Si₃N₄) WC tools at similar operating parameters (1050 – 2750 rpm and 0.05 – 0.15 mm/rev) when drilling CFRP/AA2024 stacks [13]. Thrust forces in the Al and CFRP sections were up to ~47% and 20-25% lower respectively, while average hole surface roughness in the CFRP layer decreased by ~40% when machining with the coated as opposed to uncoated drill. A recent industrial based assessment involving one-shot drilling of CFRP/Al stacks in a robotic manufacturing cell using veined PCD drills (4.1 and 7.9 mm diameter) was reported by Sahin et al. [14]. Variation in diameter after drilling 30 holes was within 5 μm for the 4.1 mm sized drills operating at 25 m/min cutting speed and a feed rate of 0.08 mm/rev. The deviation was somewhat higher at 10 μm for the 7.9 mm diameter holes machined at a cutting speed and feed rate of 40 m/min and 0.06 mm/rev respectively, however this was still well within the tolerance specification of 22 μm .

Work was carried out by Wang et al. [15] to determine the wear characteristics of uncoated, AlTiN and nanocomposite coated WC tools (9.525 mm diameter) when drilling CFRP/Ti-6Al-4V stacks. Cutting speed and feed rate levels corresponding to the individual material layers in the stack were fixed at 180/15 m/min and 0.0762/0.0508 mm/rev respectively for all tests. The principal wear mode observed was a combination of conventional degradation at the flank face and cutting edge rounding caused by brushing of the carbon fibres. This also had the effect of minimising adhered Ti material and chipping defects. Somewhat surprisingly, measured flank wear of the uncoated drill after 120 holes (~105 μm) was found to be ~25-30% lower than with either of the coated tools. This was attributed to the higher

sliding wear rate of the AlTiN and nanocomposite coated surfaces compared to the uncoated WC substrate, which was the dominant wear form rather than solely that associated with abrasion [16]. Similarly, uncoated drills were shown to outperform TiAlN coated tools in terms of lower thrust forces and reduced hole damage when drilling 8 mm thick CFRP/Ti-6Al-4V stacks, although this was also strongly influenced by the smaller point angle (135° vs. 140°) and shorter chisel edge length (0.11 vs. 0.22 mm) of the uncoated drill [17]. In addition, stack sequence had a substantial impact on hole quality, with the Ti/CFRP arrangement producing better surface roughness and diametrical consistency/accuracy than the CFRP/Ti configuration, as abrasion of the drilled CFRP surface by Ti-6Al-4V chips was avoided.

Differences in the wear mechanism of uncoated WC and brazed PCD tools (9.525 mm diameter) when used for drilling CFRP/Ti-6Al-4V stacks were assessed by Park et al. [18]. While the former exhibited 40-60% lower thrust force and torque values at test commencement due to its marginally smaller web thickness ($\sim 10\%$), the rate of increase of both measures with respect to the number of holes machined was significantly lower for the PCD drill. This was due to the slower wear rate of PCD compared to WC. The primary wear mechanisms of the WC tool were attrition caused by adhesion of Ti on the flank face, major cutting edge and margin as well as abrasion from the hard inclusions in the Ti-6Al-4V workpiece. Adhesion was noticeably less pronounced on the PCD drill as diamond has a lower affinity to chemically bond with metallic alloys [19], although micro-cracks/chipping was evident on the cutting edges due to the relatively brittle nature of the tool material. This eventually led to fracture based failure of the PCD tool after 73 holes. Subsequent inspection of the holes revealed reduced entry delamination, smaller Ti exit burrs (by $\sim 100\%$) and lower average surface roughness (up to $\sim 20\%$) when utilising the PCD drill [20]. Similar damage was observed by Wu et al. [21] following drilling of CFRP/Ti-6Al-4V stacks with 3D brazed PCD drills (11.113 mm diameter), however exit burr size did not exceed 0.2 mm even after ~ 120 holes with hole diameters achieving H10 tolerance.

As highlighted previously, literature concerning the drilling of three-layer metallic-composite stacks is comparatively limited. Early work by Brinkmeier and Janssen [22] involving drilling of AlCuMg₂/CFRP/Ti-6Al-4V stacks using 3-flute step drills (to produce 16 mm diameter holes) under an oil mist environment, suggested that the tool coatings evaluated (TiB₂ and diamond) had no appreciable effect on tool wear. Raising the cutting speed from 10 to 20 m/min however improved tool life by 50% (from 20 to 30 holes), albeit triggering increased adhesion of Ti material on the drill edges due to the higher temperatures generated.

Additionally, hole surface quality particularly in the CFRP layer was compromised by the harder titanium swarf/chips during transport up the helical drill flutes. When drilling Ti-6Al-4V/CFRP/AA7050 stacks, Shyha et al. [23] emphasised that application of internal high pressure cutting fluid (70 bar) was vital for realising acceptable tool life and hole quality (diameter accuracy, roundness, cylindricity, surface roughness and burr size), as extremely poor results were obtained when operating with spray mist conditions. The use of low operating parameters (cutting speed of 20/40/40 m/min and feed rate of 0.05 mm/rev) was also recommended in order to maximise tool life (up to 310 holes drilled). In an effort to boost productivity, Kuo et al. [24] investigated the effect of higher cutting speeds (30/120/120 and 36/144/144 m/min) and feed rates (0.05 – 0.15 mm/rev) when one-shot drilling Ti-6Al-4V/CFRP/AA7050 stacks with CVD-diamond coated WC tools. Drill life did not exceed 30 holes over the range of parameters tested, with peeling/flaking of the CVD-diamond coating (at the flank face, chisel and corner edge) identified as the primary failure mode. The greater cutting edge rounding and wear associated with elevated operating parameters caused significant deterioration of hole surface roughness (by ~140%) in the CFRP section of the stack. Major surface flaws such as smearing of melted epoxy material, matrix cracking and burning were evident, especially at test cessation.

The purchase price of CVD-diamond coated WC drills is reported as around 4 times higher than uncoated equivalent products with fabricated PCD tools up to 10 times higher [25]. The current paper aims to assess the feasibility of drilling 3-layer Ti/CFRP/Al stacks in a single operation using uncoated and TiAlN/TiN coated WC drills as an alternative to more costly diamond coated carbide and PCD tooling. Response measures include tool wear/life, thrust force/torque and hole accuracy together with workpiece surface integrity.

2. Experimental work

2.1. Workpiece material, drills and machine tool

The workpiece material comprised a 3-layer metallic-composite stack arranged in the order of Ti-6Al-4V/CFRP/AA7050. The titanium alloy (Ti-6Al-4V) was annealed giving a yield strength and modulus of 880 MPa and 114 GPa respectively, while the aluminium alloy (AA7050) was solution treated, stress relieved via stretching and overaged to provide similar properties of 455 MPa and 72 GPa respectively. The CFRP composites were made up of 36 unidirectional preregs composed of 56.5% volume fraction high tensile strength carbon fibres (HTS-268-12K) within an epoxy based matrix. These were laid up according to a

laminate structure of $[45^\circ/0^\circ/135^\circ/90^\circ/45^\circ/0^\circ]_{3s}$, resulting in a tensile strength of 1200 MPa and modulus of 145 GPa. Each of the layers comprised plates 10 mm thick with dimensions of 120 x 120 mm, which were bonded together using a cured film adhesive; 3M AF163-2X (overall stack thickness of 30 mm). Smaller workpiece strips measuring 120 x 17 x 30 mm were also produced but instead were mechanically joined using two M6 button head screws for thrust force/torque evaluation and subsequent hole surface roughness, roundness and cylindricity analysis.

The trials utilised uncoated (denoted as T-type) and TiAlN/TiN coated (denoted as M-type) solid tungsten carbide (WC) twist drills having relief, helix and point angles of 14° , 30° and 140° respectively, see Figure 1. All drills were 6.35 mm in diameter and incorporated through-tool coolant holes. The mechanical/physical properties of the WC substrate and physical vapour deposited (PVD) coating are detailed in a previous publication [26]. The experiments were conducted on a Matsuura FX-5 vertical machining centre retrofitted with a through spindle coolant adaptor (maximum rotational speed of 6000 rpm), see Figure 2. The cutting fluid was a water based emulsion with a 7-8% concentration of soluble mineral oil supplied internally at a pressure of 70 bar and a flow rate of 30 l/min.

Fig. 1. Micrographs of (a) uncoated (T-type) and (b) TiAlN/TiN coated (M-type) WC twist drills

Fig. 2. Experimental setup

2.2. Experimental design, equipment and test procedures

A full factorial experiment was performed to investigate the effect of drill coating, feed rate and drilling strategy (each at 2 levels), when single shot drilling Ti/CFRP/Al stacks. This involved the T-type and M-type WC drills, feed rates of 0.05 and 0.08 mm/rev as well as trials carried out either with or without a pecking cycle (2 mm retraction of the drill at stack material boundaries). The feed rate levels selected were based on results from previous research [26] as well as recommendations from the tooling supplier and industrial end user, which are representative for drilling such material stack combinations. Table 1 details the variable factors together with their corresponding levels while the full factorial test array is shown in Table 2. A dual level cutting speed was utilised, which was kept constant at 30/120/120 m/min for the Ti/CFRP/Al layers respectively. The influence of variable factors on performance measures including thrust forces/torque, drill life/wear, burr size, chip morphology, hole quality and surface integrity was evaluated, with statistical analysis undertaken using Minitab software. The end of test criteria was an average flank wear of 0.3 mm or a maximum of 180 holes drilled. No replications were performed due to limitations in workpiece material and tooling availability.

Table 1 Variable parameters and levels

Factor	Level 1	Level 2
Tool material	Uncoated WC	TiAlN/TiN coated WC
Feed rate	0.05 mm/rev	0.08 mm/rev
Drilling strategy	Without pecking	With pecking

Table 2 Full factorial test array

Test No.	Tool material	Feed rate	Drilling strategy
1	Uncoated WC	0.05 mm/rev	Without pecking
2	TiAlN/TiN coated WC	0.05 mm/rev	Without pecking
3	Uncoated WC	0.08 mm/rev	Without pecking
4	TiAlN/TiN coated WC	0.08 mm/rev	Without pecking
5	Uncoated WC	0.05 mm/rev	With pecking
6	TiAlN/TiN coated WC	0.05 mm/rev	With pecking
7	Uncoated WC	0.08 mm/rev	With pecking
8	TiAlN/TiN coated WC	0.08 mm/rev	With pecking

Thrust forces and torque were measured at periodic intervals by drilling the strip specimens mounted (via a bespoke fixture) on a two component Kistler 9273 dynamometer. The force signals were transmitted through a series of Kistler 5011A charge amplifiers connected to a PC installed with Dynoware software for data acquisition and manipulation. The plate

workpiece stacks for tool life testing were clamped onto a baseplate with an array of pre-drilled (9 mm) holes to provide support and clearance during exit of the drill from the material. Tool flank wear was measured using a toolmaker's microscope equipped with an X-Y platform driven by digital micrometres having a resolution of 1 μm . A 10 megapixel digital camera was installed on a special adaptor to capture images of the drills, which were held on a modified rotary tilting table (0-45° angle) attached on the measuring stage. Assessment of burr height was conducted using a conventional height gauge that was equipped with a dial gauge having a precision of 0.01 mm. The mean of four quadrant points around the hole entrance and exit of the metallic layers were recorded at intervals of 10 or 20 holes drilled.

Hole quality in terms of diameter, out of roundness and cylindricity were analysed using a Taylor Hobson Talyrond 300 system. Diameter measurements were taken at 9 axial positions (entry, mid-point and exit location in each material section) over the stack height. Three hundred points around the hole circumference were probed at each height location with the diameter of each material layer calculated and a Gaussian filter applied for smoothing of the scanned profile. In contrast, the evaluation of overall hole cylindricity (over the entire stack) involved a least square regression analysis of the data from the 9 measured axial positions. The out of roundness was determined by measuring the offset distance between the centres of the drilled holes and a corresponding calibration ring gauge. Holes drilled in the strip stack specimens were initially sectioned using wire electrical discharge machining (WEDM) for workpiece surface roughness investigation. This was performed using a Taylor Hobson Talysurf 120L with a diamond tipped stylus (2 μm radius) involving a cut-off of 0.8 mm and evaluation length of 4 mm for 2D line roughness measurements (R_a and R_t), while for 3D parameters (S_a and S_t) an area of 2.7×0.75 mm was scanned. The metallic layers (Ti and Al) of the sectioned samples were then hot mounted in bakelite, ground and polished for microhardness evaluation, followed by etching using Keller's reagent and a solution of 2% HF + 10% HNO_3 for the Al and Ti specimens respectively. Microhardness depth profile measurements were carried out using a Mitutoyo MVK-G3 hardness tester with a Knoop indenter at a load of 25 g over a 15 s period. Workpiece subsurface microstructural analysis was undertaken using a Leica DMLM optical microscope as well as a JEOL 6060 scanning electron microscope (SEM) for high magnification images.

3. Results and discussion

3.1. Thrust force and torque

Figure 3 shows the mean thrust force and torque recorded in each layer of the stack after drilling 90 holes in all tests. Drilling with the higher feed rate at 0.08 mm/rev generally resulted in a ~12% reduction in thrust force especially in the Ti layer, when compared with trials at 0.05 mm/rev. This could have been due to an increase of the effective drill rake angle (static rake angle and dynamic feed angle) as outlined by Astakov [27], when operating at the higher feed rate. In contrast, the use of coated drills led to a rise in thrust forces of ~12-18% in the majority of cases, probably as a result of the larger cutting edge radius (lower sharpness) compared to uncoated tools (discussed further in the next section). The coated drills however produced up to ~10% lower torque values, compatible with the improved wear resistance afforded by the TiAlN/TiN coating at the peripheral corners.

Fig. 3. Thrust forces and torque in each material section after drilling 90 holes

The application of a pecking cycle did not appear to have any noticeable effect on thrust force or torque. This was corroborated by the analysis of variance (ANOVA) in Table 3, which indicated that both tool coating and feed rate were statistically significant factors affecting thrust force and torque only in the Ti layer. In the Al section, feed rate was found to be the sole parameter having a major influence on thrust force and torque, with percentage contribution ratio's (PCR's) of ~56 and 55% respectively, although the high residual/error levels (43.7% and 35.4%) suggests that interaction between the factors may also have had an effect. In contrast, none of the variables were significant (at the 5% level) with respect to thrust force and torque for the CFRP layer.

Table 3 ANOVA table for thrust force and torque in each material layer after 90 holes

Thrust force		Ti layer				
Source of variances	D.F.	Seq S.S.	M.S.	F	P	PCR
Tool material	1	112812	112812	23.16*	0.009	45.0%
Feed rate	1	107184	107184	22.01*	0.009	42.7%
Drilling strategy	1	24	24	0.01	0.01	0%
Residual	4	19482	4871			12.1%
Sum of square variances	7	239503				
Torque		Ti layer				
Source of variances	D.F.	Seq S.S.	M.S.	F	P	PCR
Tool material	1	2903.2	2903.2	19.97*	0.011	28.0%
Feed rate	1	5995.1	5995.1	41.23*	0.003	59.4%
Drilling strategy	1	353.8	353.8	2.43	0.194	2.1%
Residual	4	581.6	145.4			10.5%
Sum of square variances	7	9833.7				
Thrust force		CFRP layer				
Source of variances	D.F.	Seq S.S.	M.S.	F	P	PCR
Tool material	1	7503	7503	7.23	0.055	39.3%
Feed rate	1	4773	4773	4.6	0.099	22.7%
Drilling strategy	1	19	19	0.02	0.900	18.9%
Residual	4	4151	1038			19.1%
Sum of square variances	7	16445				
Torque		CFRP layer				
Source of variances	D.F.	Seq S.S.	M.S.	F	P	PCR
Tool material	1	730	730	1.45	0.295	4.6%
Feed rate	1	1389.2	1389.2	2.76	0.172	18.2%
Drilling strategy	1	726.2	726.2	1.44	0.296	4.5%
Residual	4	2013.9	503.5			72.7%
Sum of square variances	7	4859.2				
Thrust force		Al layer				
Source of variances	D.F.	Seq S.S.	M.S.	F	P	PCR
Tool material	1	169.3	169.3	0.44	0.545	0%
Feed rate	1	3461.1	3461.1	8.91*	0.041	56.3%
Drilling strategy	1	266.8	266.8	0.69	0.454	0%
Residual	4	1554	388.5			43.7%
Sum of square variances	7	5451.2				
Torque		Al layer				
Source of variances	D.F.	Seq S.S.	M.S.	F	P	PCR
Tool material	1	200.0	200.0	0.35	0.587	0.00%
Feed rate	1	6267.0	6267.0	10.92*	0.03	55.1%
Drilling strategy	1	1562.4	1562.4	2.72	2.72	9.5%
Residual	4	2298.2	574.6			35.4%
Sum of square variances	7	10332.6				

(* Significant at the 5% level, $F_{cal\ 1,4} = 7.71$)

3.2. Drill wear/life

Figure 4 details the progression of tool flank wear against number of holes drilled for all trials. Tests involving coated drills produced between 90 and ~148 holes before reaching the tool life criterion of 0.30 mm flank wear, whereas 180 holes was achieved with the uncoated drills for a flank wear not exceeding 0.23 mm. The influence of feed rate was also apparent, with drill wear rate up to ~28% lower when operating at the higher value of 0.08 mm/rev, which was most likely due to the reduced contact time between the tool and workpiece. Corresponding ANOVA calculations detailed in Table 4 showed that both tool coating and feed rate were statistically significant factors relative to drill wear, with the former having an overwhelming PCR of ~78.4%. This substantiates the lower thrust forces observed when utilising uncoated drills and higher feed rates as detailed in the previous section. Despite reducing tool wear by up to ~10% when applying a pecking cycle, drilling strategy was not found to be statistically significant at the 5% level.

Fig. 4. Drill flank wear progression in all tests

Table 4 ANOVA table for drill flank wear at test cessation

Tool wear		Ti/CFRP/Al stack				
Source of variances	D.F.	Seq S.S.	M.S.	F	P	PCR
Tool material	1	0.028203	0.028203	81.19*	0.001	78.4%
Feed rate	1	0.005050	0.005050	14.54*	0.019	13.2%
Drilling strategy	1	0.000861	0.000861	2.48	0.190	1.4%
Residual	4	0.001389	0.000347			7%
Sum of square variances	7	0.035504				

(* Significant at the 5% level, $F_{cal 1,4} = 7.71$)

Figure 5 shows SEM micrographs of cross-sectioned cutting edges from new uncoated and coated drills, which clearly highlights the larger edge radius of the coated ($\sim 33 \mu\text{m}$) compared to the uncoated WC tool ($\sim 22 \mu\text{m}$). Further examination of the worn drills (both uncoated and coated) showed the presence of extensive adhered workpiece material and built up edge (BUE), together with signs of abrasion on the flank face of the tools, with wear patterns similar in all tests, see examples in Figure 6. The adhered material was primarily aluminium alloy (confirmed by energy dispersive X-ray spectroscopy analysis), which extended almost across the entire length of the cutting lips, irrespective of machining conditions. The thickness of the BUE layer was generally larger on the coated drills, as was the darkened region apparent beneath the abrasion wear scar on all tools. This was thought to be carbon deposits from vaporised cutting fluid [28], which was more prevalent towards the drill corners due to the higher temperature associated with the higher cutting speed at this location. Therefore, aside from the elevated thrust forces, the greater affinity for workpiece material adhesion could also have contributed to the lower tool life of the coated drills. Isolated regions of adhered epoxy resin from the CFRP material were also visible on the flank face in the majority of tools.

Fig. 5. Cutting edge radius and WC substrate microhardness of the (a) uncoated and (b) coated drills

None of the drills were seen to exhibit chipping or fracture even at test cessation, contrary to published results involving diamond like carbon (DLC) and CVD-diamond coated WC tools under similar operating conditions [29]. Here the authors suggested that despite their superior hardness (3 to 6 times that of the WC substrate), the repeated build-up and removal of adhered material during drilling led to micro-chipping and delamination of the DLC and CVD-diamond coatings after only ~ 20 holes, which ultimately resulted in catastrophic corner edge fracture of the drills after ~70 holes. In other work, peeling/flaking of the coating (after only several holes) and eventual corner edge chipping/fracture, was also reported as the dominant tool failure mode by Shyha et al. [5] when drilling Ti/CFRP/Al stacks using CVD-diamond coated WC drills.

Fig. 6. Optical and SEM micrographs of workpiece adhesion/BUE and abrasion wear on (a) coated and (b) uncoated drills at end of test

3.3. Burr formation on metallic layers

Images of burrs formed at hole entrance (Ti) and exit (Al) of the stack for the last hole drilled in each test are detailed in Figure 7(a). All of the burrs observed at the hole entrance were Type II uniform burrs [30]. In contrast, leaned-back burrs [31] were generally present at the exit location of the Al layer. Examples of the typical burr shape/form generated on the Ti and Al sections are shown in Figure 7(b) and Figure 7(c) respectively.

Fig. 7. (a) Images of burrs at hole entrance and exit of the stack in each experiment and SEM micrographs showing typical morphology of (b) entrance; and (c) exit burrs at test cessation

Figure 8 shows the progression of entrance burr height in the Ti layer for all trials, which increased from ~0.03 mm to a maximum of ~0.23 mm over the test duration. While not shown here, the corresponding ANOVA indicated that only drilling strategy had a statistically significant effect on burr height in the Ti section, with a PCR of ~56%. Here, burr height increased when employing a pecking strategy for both coated and uncoated drills regardless of the feed rate. Nevertheless, the growth in entrance burr height with increasing number of drilled holes implies that tool wear also has a dominant influence on burr formation.

Fig. 8. Progression of entrance burr height in Ti layer

In contrast, burr size was typically larger at the exit location in the Al layer, which varied from 0.05 mm when using a new tool to 0.34 mm at test cessation; see Figure 9. In general, drilling with the higher feed of 0.08 mm/rev was found to generate smaller burrs, possibly due to the lower thrust forces recorded producing less plastic deformation of the workpiece. Despite this, none of the variable factors were found to be significant with respect to burr height at the exit location. Additionally, interlayer burr height recorded at the exit of the Ti section ranged between 0.16-0.35 mm whilst those at the entrance of the Al layer were considerably smaller, varying from 0.01 to 0.09 mm, due to suppression by the preceding CFRP layer.

Fig. 9. Progression of exit burr height in the Al layer

3.4. Hole diameter, out of roundness and cylindricity

The average hole diameters in each of the material sections as well as the overall diameter measured across the 3 layer stack at test cessation are shown in Figure 10. Although the range of individual hole diameter measurements varied between 6.300-6.395 mm, the mean values were all within 6.350 ± 0.035 mm. Despite the majority being undersized, holes produced by the coated drills at test cessation (tool lives between 90 – 148 holes drilled) exhibited superior accuracy in terms of diameter with lower deviations (maximum of 0.02 mm) from the nominal value (6.35 mm) compared to the uncoated tools (all achieving 180 holes). This was attributed to the lower wear level (33%) at the peripheral corners of the coated drills, partly as a result of the lower number of holes produced. In addition, tool coating was found to be the

principal factor affecting hole diameter in both the Ti and CFRP layers with PCR's of 64.5% and 57.5% respectively, see Table 5. Similarly, drilling strategy had a significant effect in the Ti layer while feed rate was only seen to influence hole diameter in the CFRP section.

Fig.10. Average hole diameter for the stack and individual material layers at test cessation

Table 5 ANOVA table for hole diameter

Diameter		Ti layer				
Source of variances	D.F.	Seq S.S.	M.S.	F	P	PCR
Tool material	1	0.0005595	0.0005595	33.51*	0.004	64.5%
Feed rate	1	0.0000521	0.0000521	3.12	0.152	4.2%
Drilling strategy	1	0.0001626	0.0001626	9.74*	0.036	17.3%
Residual	4	0.0000668	0.0000167			14%
Sum of square variances	7	0.0008409				

Diameter		CFRP layer				
Source of variances	D.F.	Seq S.S.	M.S.	F	P	PCR
Tool material	1	0.0003044	0.0003044	32.72*	0.005	57.5%
Feed rate	1	0.0001688	0.0001688	18.15*	0.013	31.0%
Drilling strategy	1	0.0000026	0.0000026	0.28	0.625	0%
Residual	4	0.0000372	0.0000093			11.5%
Sum of square variances	7	0.0005130				

Diameter		Al layer				
Source of variances	D.F.	Seq S.S.	M.S.	F	P	PCR
Tool material	1	0.0001761	0.0001761	2.78	0.171	21.0%
Feed rate	1	0.0000971	0.0000971	1.53	0.283	18.2%
Drilling strategy	1	0.0000095	0.0000095	0.15	0.718	6.3%
Residual	4	0.0002532	0.0000633			54.5%
Sum of square variances	7	0.0005360				

(* Significant at the 5% level, $F_{cal 1,4} = 7.71$)

Figure 11 details the typical hole cross-sectional profile and corresponding out of roundness measurements in each material layer of the stack in Test 3 after 90 holes. While none of the variables had a major effect on out of roundness in the CFRP and Al layers, tool material/coating was found to be significant at the 5% level in the Ti layer. All of the holes examined in the Ti layer showed a tri-lobed shape, most likely caused by helical wander of the drill. This typically occurs due to either inaccuracies in the drill geometry/dimensions (irregular cutting lip lengths/angles, off-centre chisel point, etc.) or when employing drills having longer chisel edge lengths. Under such conditions, the drill has a tendency to ‘walk’ upon initial contact with the workpiece surface [32], which causes bending of the tool resulting in dynamic instability and asymmetric reaction forces on the cutting lips leading to a lobed profile similar to that shown in Figure 11(a). When moving deeper into the stack, constraints of the hole wall neutralised/reduced the initial eccentric forces acting on the drill, which not only restored the circularity of the hole but also significantly decreased the out of roundness levels in the CFRP and Al layers of the stack, as detailed in Figures 11(b) and 11(c).

Fig. 11. Out of roundness measurements of the (a) Ti, (b) CFRP and (c) Al layers after drilling 90 holes in Test 3

Average hole cylindricity at test cessation was found to vary from 74 to 157 μm whereas the average out of roundness in the Ti, CFRP and Al layers ranged between 53-121 μm , 33-109 μm and 25-78 μm respectively, depending on the operating conditions, see Figure 12. Figure 13 outlines example 3D hole profiles produced using an uncoated and coated drill for the last holes drilled from Test 5 and Test 6 respectively. In general, holes drilled using the uncoated tool demonstrated inferior cylindricity over the entire stack, despite the lower flank wear level. This was possibly due to greater wear at the tool periphery/margin region, making it less efficient in counteracting the unbalanced forces/tool deflection during drilling.

Fig. 12. Average hole out of roundness in each material layer and overall stack cylindricity at test cessation

Fig. 13. Cylindricity form profile of the last holes drilled in Tests 5 and 6

3.5. Hole surface roughness

Figure 14 shows the average surface roughness (R_a) results in each material section over the test duration for all tests. The R_a in the Ti, CFRP, and Al layer of the stack ranged between 0.35-1.74 μm , 0.53-11.68 μm , and 0.11-0.69 μm respectively, depending on drilling parameters. While there was no obvious correlation between drill flank wear and measured R_a in the Ti and Al layers of the stack (regardless of drill material), the hole surface roughness in the CFRP section was found to deteriorate with increasing wear of the tool. The maximum average surface roughness (R_a) of 11.68 μm was recorded in Test 6 due to the high flank wear value of 0.3 mm measured near the peripheral corners after drilling 120 holes. Therefore, the average roughness in the CFRP was strongly influenced not only by the individual ply fibre orientation, but also the sharpness/condition of the drill's corner geometry. As wear of the peripheral corner increased, greater rubbing/ploughing of the workpiece material occurred resulting in delamination, matrix cracking, fibre protrusion, voids and redeposited/adhered resin material on the drilled surface.

Fig. 14. Average hole surface roughness (Ra) in each material layer over test duration

Figure 15 details the average peak-to-valley surface roughness (R_t) over the test duration, which provides a better indication of the actual variation in surface height profile in comparison to Ra data. The results showed that average R_t roughness in the CFRP layers when drilling with pecking were between 35.9-52.2 μm , but however ranged from 7.94 to 77.69 μm over the experiment duration, which was possibly caused by the different fibre orientation cross plies leading to different surface textures [33]. Conversely, average R_t was up to 58% higher when operating without pecking, although corresponding ANOVA calculations revealed that drilling strategy was only significant at the 5% level in the Ti layer with a PCR of ~55%, albeit with an elevated residual/error value of ~44%. None of the other variables was found to have a major influence on R_t in any of the stack layers as seen in Table 6. The extremely high residual levels of up to ~96% particularly for results associated with the CFRP and Al layers suggest that interactions between the factors was likely to have a significant influence on workpiece R_t , but which could not be considered/evaluated in the current experimental design employed.

Table 6 ANOVA table for peak-to-valley roughness (Rt) in each material layer

Rt		Ti layer				
Source of variances	D.F.	Seq S.S.	M.S.	F	P	PCR
Tool material	1	2.055	2.055	1.06	0.361	0.42%
Feed rate	1	0.582	0.582	0.30	0.613	0%
Drilling strategy	1	17.122	17.122	8.83*	0.041	55.2%
Residual	4	7.754	1.939			44.38%
Sum of square variances	7	27.514				

Rt		CFRP layer				
Source of variances	D.F.	Seq S.S.	M.S.	F	P	PCR
Tool material	1	20.97	20.97	0.42	0.551	0%
Feed rate	1	22.40	22.40	0.45	0.538	0%
Drilling strategy	1	63.36	63.36	1.28	0.321	4.5%
Residual	4	198.16	49.54			95.5%
Sum of square variances	7	304.90				

Rt		Al layer				
Source of variances	D.F.	Seq S.S.	M.S.	F	P	PCR
Tool material	1	0.9429	0.9429	1.40	0.303	6.5%
Feed rate	1	0.3067	0.3067	0.45	0.537	0%
Drilling strategy	1	0.1220	0.1220	0.18	0.693	0%
Residual	4	2.7036	0.6759			93.5%
Sum of square variances	7	4.0752				

(* Significant at the 5% level, $F_{cal\ 1,4} = 7.71$)

Fig. 15. Average peak-to-valley surface roughness (Rt) in each material over test duration

Figure 16 shows the influence of peck cycle on 3D surface topography of the Ti layers (factor significant at 5% level for surface roughness) for the last holes drilled in Tests 4 and 8, together with the typical surface generated on the CFRP and Al sections (without pecking from Test 4). While the difference in Sa results was minor (0.382 vs. 0.335 μm), the Ti surface drilled using a pecking strategy (from Test 8) exhibited a smoother profile particularly towards the exit location/stack material boundary, see Figure 16(a), compared to results from Test 4 undertaken without pecking as shown in Figure 16(b). This was most likely due to a reaming effect caused by the drill retraction during the pecking process. The corresponding St values however were considerably higher when utilising pecking, which was influenced by the presence of high peaks on the surface profile near the hole entry location. This was possibly due to chatter during entry of the drill into the workpiece, which was further exacerbated by the tri-lobed shape of the hole in the Ti section. As for the CFRP section from Test 4 (without pecking), the drilled surfaces were generally characterised by deep grooves as a result of fibre/matrix pull out, which was especially pronounced at the 135° plies, leading to relatively high roughness values of 42.2 μm St, see Fig. 16(b). Conversely, the hole surface topography in the Al layer were largely consistent, similar to that shown in Figure 16(b), irrespective of the machining conditions.

Fig. 16. Three-dimensional topography plots of hole surfaces in; (a) Ti layer from Test 8 (with pecking); (b) Ti, CFRP and Al layers from Test 4 (without pecking)

3.6. Microhardness

When drilling without pecking, microhardness depth profile measurements revealed a hardened layer of up to $\sim 415 \text{ HK}_{0.025}$ ($\sim 12\%$ increase over bulk hardness) to a depth of $\sim 65 \mu\text{m}$ in the majority of the Ti samples evaluated, see Figure 17(a). Conversely, when operating with pecking, a reduction in workpiece microhardness of ~ 8 to $\sim 12\%$ was observed in two of

the trials as seen in Figure 17(b). Sample SEM micrographs of cross-sectioned hole subsurface microstructure in the Ti section drilled without and with pecking are detailed in Figure 18. The former showed evidence of a plastically deformed layer extending up to ~30 μm below the machined surface while no obvious signs of microstructural alteration were seen in the latter. Use of a pecking strategy may have led to relief of elastic stress in the workpiece during the tool retraction cycle whereas a continuous build-up of stress in the material eventually resulting in plastic deformation and strain hardening was anticipated when drilling without pecking.

Fig. 17. Microhardness depth profile at the last hole in Ti layer when drilling (a) without pecking and (b) with pecking for all tests

Fig. 18. Sample subsurface microstructure of the last hole in Ti layer when drilling; (a) without pecking and (b) with pecking

The microhardness depth profile in the Al layer measured at the last hole for all tests is presented in Figure 19. All of the samples analysed showed marginal workpiece softening (2-10% below bulk material hardness) at the hole surface, which then increased to ~180-190 $HK_{0.025}$ at a depth of ~200 μm . Examination of the cross-sectioned holes in all tests however showed very limited subsurface microstructural alterations (~5-10 μm) and were similar to the example shown in Figure 20.

Fig. 19. Microhardness depth profiles for the last hole drilled in Al layer for all tests

Fig. 20. Sample workpiece microstructure of the last hole in Al layer from Test 4

3.7. Chip morphology

Figure 21 shows the types/form of Ti and Al chips produced under different operating conditions in trials undertaken without pecking. The morphology of the swarf can be broadly categorised into 5 types based on the ISO chip form classification system [34]. These include; (i) long (7-8 turns) continuous washer-type helical chips, (ii) short (3-4 turns) continuous washer-type helical chips, (iii) short (1-2 turns) conical helical chips, (iv) packed (3~4 layers) elemental chips and (v) loose elemental chips.

		Feed rate=0.05mm/rev			Feed rate=0.08mm/rev		
		Hole 30	Hole 90	Hole120	Hole 30	Hole 90	Hole 120
Coated carbide tool	Ti-6Al-4V alloy	(a) Loose elemental chips			Washer-type helical chips Elemental chips		
	A7050 alloy	Curl/folded elemental chips			Elemental chips		
Uncoated carbide tool	Ti-6Al-4V alloy	Packed elemental chips			(b) Washer-type helical chips		
	A7050 alloy	Loose elemental chips			Elemental/transition chips		

Fig. 21. Chip morphology against cutting conditions and tool material recorded at holes 30, 90 and 120

While short washer-type helical chips were initially generated at the entrance of the Ti layer when drilling with coated carbide tools at the low feed rate condition (0.05 mm/rev), these subsequently changed to loose elemental swarf as the drill moved further into the material, see Figure 21(a). This was due to relatively low shear zone temperatures at the start of cutting [35], with the increased thermal softening of the Ti material altering the chip morphology as cutting progressed, although no sign of serrated chips was seen in any of the tests. As the drill entered the CFRP layer, powder-like swarf was produced that mixed with the emulsion to form slurry but which was evacuated by the flow of the cutting fluid. Chips from the Al layer however were typically short curl/folded elemental chips throughout the test duration. When employing uncoated carbide drills at the higher feed rate of 0.08 mm/rev in the Ti section, long and short continuous helical chips together with sporadic elemental swarf were prevalent, see Figure 21(b). The regular and stable chip formation was also a possible reason for the lower tool wear observed when operating at 0.08 mm/rev, as outlined previously in Section 3.2. Elemental chips however were evident when drilling Al at the higher feed rate (0.08 mm/rev), possibly due to the relatively stronger strain hardening effects, compared to when operating at lower feed rate (0.05 mm/rev).

4. Conclusions

- The uncoated carbide drills showed longer tool life (by up to 90 holes) compared to equivalent coated drills irrespective of the feed rate and pecking strategy employed, with flank wear not exceeding 0.3 mm even after 180 holes. This was primarily attributed to the lower cutting edge radius (higher sharpness) of the uncoated drills.
- The principal wear mechanisms of both the uncoated and coated drills following machining of the 3-layer stacks were abrasion and adhesion together with built up edge formation (mainly consisting of Al workpiece material).
- Drilling at the higher feed of 0.08 mm/rev generated lower thrust forces, particularly in the Ti layer due to the increase in effective rake angle.
- Increasing the feed rate was seen to suppress burr formation at the hole exit due to greater shearing rather than plastic deformation.
- Despite lower tool life (based on flank wear criterion), the TiAlN/TiN coated drills generally resulted in superior hole diameter accuracy due to lower wear levels at the peripheral corners compared to the uncoated drills.

- Use of the pecking strategy reduced the maximum roughness in the CFRP layer due to greater rubbing action during tool retraction however roughness of the Ti layer near the hole entry location deteriorated when employing a peck cycle as a result of possible drill chatter/vibration.
- Drilling without a pecking cycle typically resulted in a hardened layer extending to ~40 μm beneath the hole surface in the Ti section.

Acknowledgements

The authors would like to thank GKN Aerospace, Seco Tools and Element Six for providing workpiece material, tooling and financial support for the research. We would also like to express our appreciation to Will Thomas (formerly of GKN Aerospace) for his assistance in coordinating the research project.

References

- [1] Lantrip J. 2008. New tools needed. *Cutting Tool Engineering* 2008;60(8):72-84.
- [2] Teti R. Machining of composite materials. *Ann CIRP* 2002;51(2):611-34.
- [3] Whinnem E, Lipczynski G. Drilling mixed stack materials for the BOEING 787. SAE Technical Paper 2010;2010-01-1867.
- [4] Jawahir IS, Brinksmeier E, M'Saoubi R, Aspinwall DK, Outeiro JC, Meyer D, et al. Surface integrity in material removal processes: Recent advances. *CIRP Ann – Manuf Technol* 2011;60(2):603-26.
- [5] Shyha IS, Soo SL, Aspinwall DK, Bradley S, Dawson S, Pretorius CJ. Drilling of titanium/CFRP/aluminium stacks. *Key Eng Mater* 2010;447-448:624-33.
- [6] Engdahl NC. CVD diamond coated rotating tools for composite machining. SAE Technical Paper 2006;2006-01-3153.
- [7] Zhang J, Wang X, Shen B, Sun F. Effect of boron and silicon doping on improving the cutting performance of CVD diamond coated tools in machining CFRP. *Int J Refract Met Hard Mater* 2013;41:285-92.
- [8] Heath PJ. Developments in applications of PCD tooling. *J Mater Process Technol* 2001;116:31-38.
- [9] Montoya M, Calamaz M, Gehin D, Girot F. Evaluation of the performance of coated and uncoated carbide tools in drilling thick CFRP/aluminium alloy stacks. *Int J Adv Manuf Technol* 2013;68:2111-20.
- [10] Zhang L, Liu Z, Tian W, Liao W. Experimental studies on the performance of different structure tools in drilling CFRP/Al alloy stacks. *Int J Adv Manuf Technol* 2015;81:241-51.

- [11] Segawa S, Tamura J, Suzuki S, Oka H, Meguro K, Satou Y. Development of a drill bit for CFRP/Aluminum-alloy stack: To improve flexibility, economical efficiency and work environment. SAE Technical Paper 2013;2013-01-2227.
- [12] Zitoune R, Krishnaraj V, Collembet F. Study of drilling of composite material and aluminium stack. Compos Struct 2010;92:1246-55.
- [13] Zitoune R, Krishnaraj V, Almagoubacif BS, Collombet F, Sima M, Jolin A. Influence of machining parameters and new nano-coated tool on drilling performance of CFRP/aluminium sandwich. Compos Part B 2012;43(3):1480-8.
- [14] Sahin FB, Borchers H-J, Ucar C. Automated drilling of fabric woven CFRP and aluminium laminates with PCD cutters using drilling robot. SAE Technical Paper 2016;2016-01-2077.
- [15] Wang X, Kwon PY, Sturtevant C, Kim D, Lantrip J. Comparative tool wear study based on drilling experiments on CFRP/Ti stack and its individual layers. Wear 2014;317:265-76.
- [16] Wang X, Kwon PY, Sturtevant C, Kim D, Lantrip J. Tool wear of coated drills in drilling CFRP. J Manuf Process 2013;15:127-35.
- [17] Xu J, El Mansori M. Experimental study on drilling mechanisms and strategies of hybrid CFRP/Ti stacks. Compos Struct 2016;157:461-82.
- [18] Park KH, Beal A, Kim D, Kwon P, Lantrip J. Tool wear in drilling of composite/titanium stacks using carbide and polycrystalline diamond tools. Wear 2011;271:2826-35.
- [19] Mueller-Hummel P. Process understanding of dry drilling CFRP/Aluminium and AL/AL stacks in IT8 quality. SAE Int J Aerosp 2016;9(2):217-22.
- [20] Kim D, Beal A, Kwon P. Effect of tool wear on hole quality in drilling of carbon fiber reinforced plastic-titanium alloy stacks using tungsten carbide and polycrystalline diamond tools. J Manuf Sci Eng 2016;138(3):031006-031006-11.
- [21] Wu Q, Rosenberger F, Gey C. Efficient drilling of advanced aerospace materials with PCD solutions. In: Proceedings of the International Technical Conference on Diamond, Cubic Boron Nitride and Their Applications (INTERTECH 2013), Baltimore, USA, 6-8 May 2013. p. 12-24.
- [22] Brinksmeier E, Janssen R. Drilling of multi-layer composite materials consisting of carbon fiber reinforced plastics (CFRP), titanium and aluminum alloys. Ann CIRP 2002;51(1):87-90.
- [23] Shyha IS, Soo SL, Aspinwall DK, Bradley S, Perry R, Harden P, et al. Hole quality assessment following drilling of metallic-composite stacks. Int J Mach Tools Manuf 2011;51(7-8):569-78.
- [24] Kuo CL, Soo SL, Aspinwall DK, Thomas W, Bradley S, Pearson D, et al. The effect of cutting speed and feed rate on hole surface integrity in single-shot drilling of metallic-composite stacks. Proc CIRP 2014;13:405-10.
- [25] Goto M, Meguro K, Tamura J. Development of CVD diamond coated cutting tools for CFRP machining. In: Proceedings of the International Technical Conference on Diamond, Cubic Boron Nitride and Their Applications (INTERTECH 2013), Baltimore, USA, 6-8 May 2013. p. 46-53.

- [26] Kuo CL, Soo SL, Aspinwall DK, Thomas W, Carr C, Pearson D, et al. Performance of multi-margin coated tools in one-shot drilling of metallic-composite stack materials under varying feed rate and pecking conditions. In: Li, L., Hinduja, S., Jywe, W.Y. (Eds.), Proceedings of the 38th International MATADOR Conference, Huwei, Taiwan, 28-31 March 2015. p. 231-238.
- [27] Astakov VP. Geometry of single-point turning tools and drills. London: Springer-Verlag, 2010.
- [28] Bermingham MJ, Palanisamy S, Kent D, Dargusch MS. A comparison of cryogenic and high pressure emulsion cooling technologies on tool life and chip morphology in Ti–6Al–4V cutting. *J Mater Process Technol* 2012;212(4):752-65.
- [29] Kuo CL, Soo SL, Aspinwall DK, Bradley S, Thomas W, M'Saoubi R, et al. Tool wear and hole quality when single-shot drilling of metallic-composite stacks with diamond-coated tools. *Proc Inst Mech Eng Part B, J Eng Manuf* 2014;228(10):1314-22.
- [30] Aurich JC, Dornfeld D, Arrazola PJ, Franke V, Leitz L, Min S. Burrs -Analysis, control and removal. *CIRP Ann – Manuf Technol* 2009;58(2):519-42.
- [31] Dornfeld DA, Kim JS, Dechow H, Hewson J, Chen LJ. Drilling burr formation in titanium alloy, Ti-6Al-4V. *CIRP Ann – Manuf Technol* 1999;48(1):73-6.
- [32] Smith GT. Industrial metrology. London: Springer-Verlag London Limited, 2002.
- [33] Wang XM, Zhang LC. An experimental investigation into the orthogonal cutting of unidirectional fibre reinforced plastics. *Int J Mach Tools Manuf* 2003;43(10):1015-22.
- [34] International Standards Organization, 1993. ISO 3685:1993 Tool-life testing with single-point turning tools, Annex G: 41.
- [35] Jawahir IS, van Luttervelt CA. Recent developments in chip control research and applications. *Ann. CIRP* 1993;42(2):659-93.