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## **THE EFFECT OF OPERATING PARAMETERS AND TOOL MATERIALS ON CUTTER WEAR/LIFE AND HOLE QUALITY WHEN DRILLING AL/SiC METAL MATRIX COMPOSITE (MMC)**

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### **ABSTRACT**

Experimental data is presented relating to tool wear/life, hole accuracy (diameter, out of roundness, cylindricity, edge quality), chip morphology and workpiece surface integrity when drilling an aluminium based metal matrix composite (MMC) reinforced with 15 vol% SiC particulate. The performance of 6.35mm diameter uncoated and TiAlN +TiN coated tungsten carbide (WC) drills as well as brazed polycrystalline diamond (PCD) tools was evaluated, with high pressure cutting fluid at 70 bar employed in all tests. When operating at 160m/min with a feed rate of 0.1mm/rev, flank wear progression of the PCD drill was gradual, with a maximum scar length of only ~60µm after 300 holes. In contrast, the tool life of both the uncoated and coated carbide drills did not exceed 10 holes (based on a flank wear criterion of 0.3mm), despite operating at a lower cutting speed of 80m/min. Corresponding SEM micrographs of the worn drills indicated abrasion was the dominant wear mechanism. Uniform burrs (without caps) were prevalent at both hole entry and exit when employing WC tools, while no sign of burring was evident in any of the holes machined using the PCD drills. Chip morphology was also markedly different, with the WC drills producing fan-shaped chips while needle-like swarf was typically observed when utilising PCD tools. Assessment of hole surfaces revealed the presence of flaws including cavities/voids, grooves, workpiece smearing and flaking/removal of the matrix material when using carbide drills.

**KEYWORDS:** Drilling, metal matrix composite, polycrystalline diamond

### **1. INTRODUCTION**

Metal matrix composites (MMCs) are a class of material that comprise ceramic particulates or fibres distributed within a metallic matrix. Typically such materials have mechanical/physical properties that are superior to conventional alloys including higher specific strength and modulus, superior abrasion/wear resistance and lower sensitivity to temperature change [1]. Despite the attractive properties of MMC materials, their utilisation in industry is limited to specialised, high value applications in the premium automotive and defence sectors. This is partly attributable to their relatively poor machinability as a result of the highly

abrasive reinforcement phase (typically SiC or Al<sub>2</sub>O<sub>3</sub>), which generally necessitates the use of ultra-hard tooling such as PCD.

The drilling of MMC's using conventional carbide tooling is typically characterised by high tool wear rates, poor hole quality and significant workpiece sub-surface damage. In a study of workpiece integrity following the drilling of hybrid metal matrix composites (Al-SiC<sub>p</sub>-graphitic) with carbide tools at cutting speeds of up to 47m/min and feed rates up to 0.25mm/rev, Basavarajappa et al. [2] found that flaws such as microcracks, particle pull-out and scratches were prevalent, with subsurface microstructural deformation extending up to a depth of 150µm below the machined surface. Kannan and Kishawy [3] reported similar defects (microcracks, voids, pits and craters) when machining Al based MMC's, which were predominantly due to particulate fracture and pull-out as well as interfacial debonding. More recently, a comprehensive experimental assessment on the influence of key process variables when drilling Al-SiC<sub>p</sub> MMC's showed that feed rate and tool material were the most significant factors affecting workpiece surface roughness [4]. In comprehensive early research by Coelho et al. [5, 6] involving turning, face milling, drilling, reaming and tapping of Al-SiC<sub>p</sub> under wet conditions, it was concluded that lower feed rate resulted in increased flank wear due to greater contact time and hence rubbing of the tool against the abrasive particles. Work by Ciftci et al. [7] evaluated the effect of uncoated and coated (TiC, Al<sub>2</sub>O<sub>3</sub> and TiCN triple layer coating) tools when turning MMC with the latter typically showing ~10% lower tool wear over the former, which was attributed to the superior wear resistance of the coating and formation of a stable built up edge (BUE) that protected the flank face. This however was at the expense of increased roughness due to edge chipping.

The current paper investigates the performance of different tool materials/coatings as well as varying operating parameters when drilling an Al-SiC<sub>p</sub> MMC material under a high pressure fluid environment.

## **2. EQUIPMENT, WORKPIECE MATERIALS, CUTTING TOOLS AND EXPERIMENTAL DESIGN**

All drilling tests were performed on a Matsuura FX-5 vertical high speed CNC machining centre retrofitted with a through tool coolant spindle adaptor (maximum rotational speed of 6000rpm). The cutting fluid used was a water based emulsion containing 6-8% volume solution of Hocut 3380 mineral oil which was delivered at a flow rate of ~26 litres per minute and corresponding pressure of 70 bar (7 MPa).

The metal matrix composite material employed for the experiments was a wrought aluminium alloy AA2618 reinforced with 15% volume fraction of SiC particles having an average size of 10-15µm. The workpieces were produced by spray deposition and fully consolidated by extrusion. Extruded bars were supplied with a rectangular cross section measuring 25×110mm, which were cut into blocks ~165mm long and the surfaces face-milled (to remove 0.5mm from each side) to a thickness/height of 24mm. These were fixed on a bespoke clamping plate (with a suitable array of pre-drilled clearance holes) for tool life testing. Separate strip specimens with a width of 17mm used for thrust force, torque and surface integrity evaluation, were held on a Kistler 9273 four-component piezoelectric drilling dynamometer connected to appropriate charge amplifiers.

The data from the dynamometer was analysed using Dynoware software. Figure 1 shows the typical microstructure of the material along the extruded direction following etching with Keller's reagent (1% HF, 1.5% HCl and 2.5% HNO<sub>3</sub>) for 30s.

Three different drills were evaluated involving uncoated and TiAlN+TiN coated solid carbide (WC) together with a brazed PCD grade, see Figure 2. Optimum point geometry was selected for the different tool materials. All of the drills were nominally 6.35mm in diameter with the end of test criteria a maximum flank wear ( $VB_{max}$ ) of 0.3mm or 300 holes drilled. For trials utilising the uncoated and coated carbide tools, cutting speed was fixed at 80m/min while feed rate varied from 0.10 to 0.20mm/rev with cutting fluid applied internally through the drills. The PCD drills were assessed at a constant feed rate of 0.1mm/rev over 2 levels of cutting speed (80 and 160m/min) with coolant supplied externally via standard nozzles. The experimental test array is detailed in Table 1.

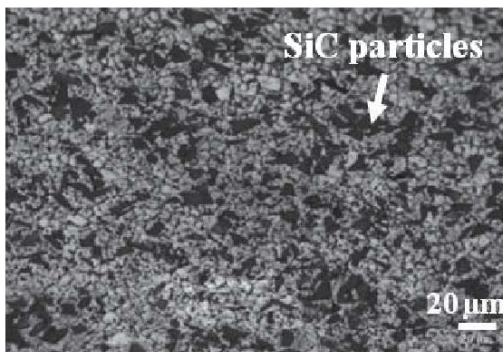


Figure 1: Micrograph of MMC workpiece

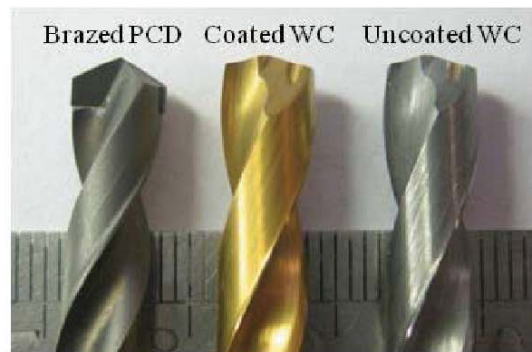


Figure 2: Drills used in trials

Table 1: Experimental test array

Test	Tool materials/ coatings	Cutting speed (m/min)	Feed rate (mm/rev)	Cutting environment
1	Uncoated WC	80	0.10	70 bar (internal)
2	Uncoated WC	80	0.20	70 bar (internal)
3	Coated WC	80	0.10	70 bar (internal)
4	Coated WC	80	0.20	70 bar (internal)
5	Brazed PCD	80	0.10	70 bar (external)
6	Brazed PCD	160	0.10	70 bar (external)

Tool wear and hole edge quality were measured using a WILD M3Z toolmaker's microscope connected to a XY micrometer platform and digital camera. Sectioned holes were cold mounted, ground and polished for burr morphology analysis using a Leica optical microscope. High magnification micrographs of worn drills and hole surfaces were obtained using a JEOL 6060 scanning electron microscopy (SEM), while energy dispersion spectroscopy (EDS) was carried out on adhered material layers observed on drill surfaces. Hole diameter, out of roundness and cylindricity were measured using a Talyrd 300 equipped with a 3mm diameter ball stylus.

### 3. RESULTS AND DISCUSSION

Figure 3 shows tool flank wear progression against number of holes drilled for all tests. For both uncoated and coated drills, tool life was less than 10 holes ( $VB_{max} > 300\mu\text{m}$ ) irrespective of operating conditions, although marginally better performance was observed when operating at higher feed rates (Tests 2 and 4). In contrast, both trials involving the brazed PCD drills produced 300 holes, with corresponding maximum flank wear of  $64\mu\text{m}$  and  $58\mu\text{m}$  in Tests 5 and 6 respectively. This was attributed to the significantly higher hardness of PCD ( $\sim 5,000\text{--}8,000\text{HV}$ ) providing greater resistance against the abrasive SiC particles compared to the WC and hardmetal coatings ( $\sim 2,000\text{HV}$ ). Additionally, the superior thermal conductivity of PCD ( $560\text{W/m}^\circ\text{C}$  compared to  $100\text{W/m}^\circ\text{C}$  for K10 WC) was expected to provide more effective heat dissipation from the cutting zone which further extended tool life [8]. Increasing feed rate when employing the uncoated and coated WC drills reduced tool wear, which was most likely due to lower the contact time between tool and workpiece material.

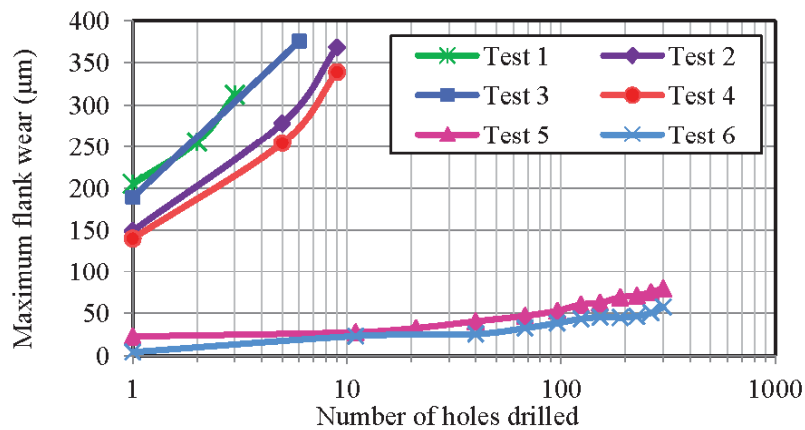


Figure 3: Tool wear progression curves

Figures 4(a), 4(b) and 4(c) details tool wear micrographs at test cessation for Tests 2, 4 and 5 respectively. Severe cutting edge rounding and flank wear was observed on the WC drills due to abrasion by the SiC particles. No obvious signs of built up edge or adhered workpiece material were evident on any of the uncoated and coated tools, which was most likely due to the use of the high pressure through tool cutting fluid environment. In contrast, workpiece adhesion/BUE was apparent on the PCD drills, which was probably the result of insufficient cutting fluid/lubricant (supplied externally) arriving at the cutting zone. Wear along the cutting edge/flank face of the PCD drills however was found to be relatively uniform following removal of the adhered material/BUE by soaking in 25% NaOH solution for 1 min, see Test 5 in Figure 4(d).

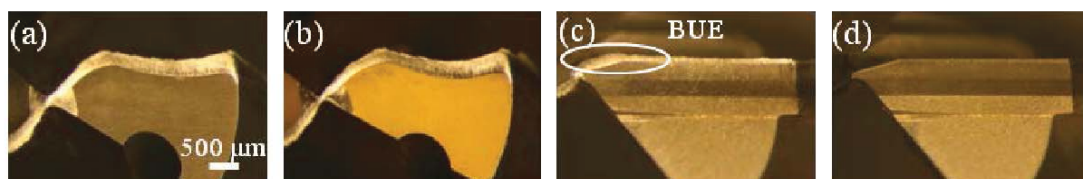


Figure 4: Tool wear scar at test cessation (a) Test 2, (b) Test 4, (c) Test 5 and (d) Test 5 following removal of BUE

Further in-depth analysis of the uncoated WC drills using SEM revealed the presence of a thin built up layer (BUL) of adhered material rather than BUE on the cutting edge, which was verified by subsequent EDS measurements, see Figure 5(a). Grooves/scratches were prevalent on the tool flank face which was indicative of abrasion as the primary wear mechanism. Although there was substantially less adhered material on the coated WC tools, the chisel section was shown to be severely abraded/worn, see Figure 5(b).

The evolution of maximum thrust force and torque values against tool life are shown in Figure 6. For uncoated and coated drills, thrust forces and torque increased significantly (by up to ~100%) after the first hole drilled irrespective of operating conditions, which suggested very rapid rates of tool wear. When utilising brazed PCD tools however, thrust forces and torque were approximately constant over the entire test duration (300 holes). The stable values reflect the relatively low tool wear levels observed with the PCD drills (~60  $\mu\text{m}$ ). For the first hole, the maximum thrust force in Tests 2 and 4 were higher (~15%) compared with Tests 1 and 3, which was attributed to the higher feed rate employed in the former. At test cessation, thrust forces increased by 34%, 57%, 88% and 71% in Tests 1, 2, 3 and 4 respectively compared with those in the first hole, while a rise of approximately 8% and 16% was recorded for Tests 5 and 6.

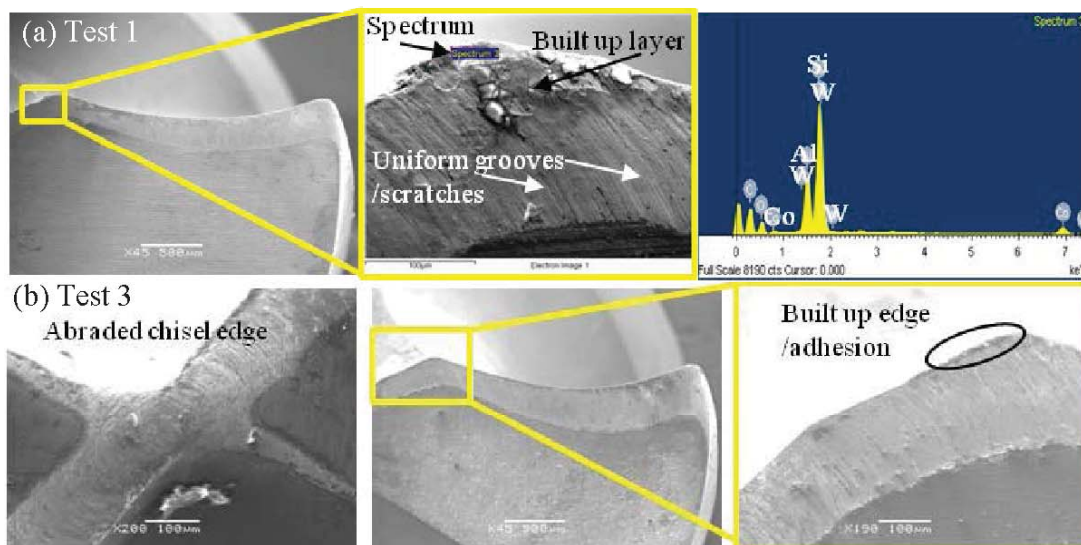


Figure 5: SEM and EDS analysis of worn cutting lips for (a) Test 1 and (b) Test 3

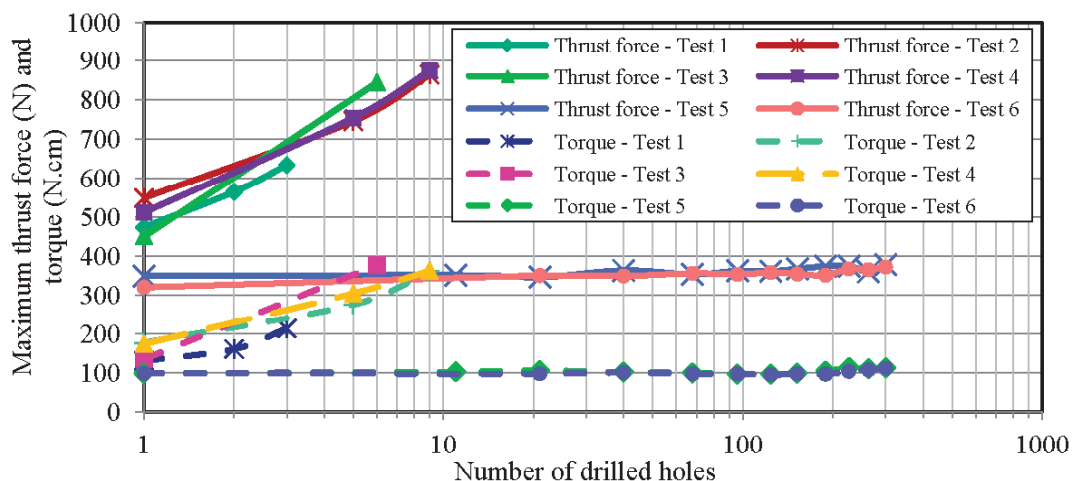


Figure 6: Thrust force and torque results for all the tests

Diameter results for the first and last holes drilled in each test are presented in Figure 7. Most of the holes were oversized irrespective of tool material or operating conditions, with the exception of the last hole in Test 4, which was undersized by 21µm. The deviation from the nominal diameter was possibly due to fabrication tolerances during tool manufacture. With PCD drills, the change in diameter after 300 holes was minimal with a maximum reduction of 5µm.

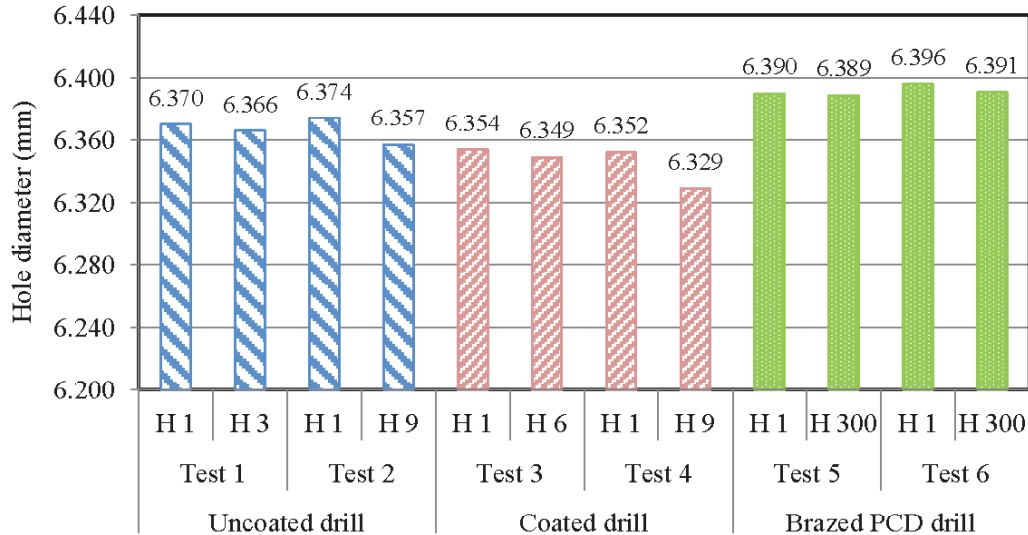


Figure 7: Hole diameter results for the first and last holes in all tests

Hole geometrical accuracy measurements in terms of out of roundness and cylindricity are detailed in Figure 8. Surprisingly, the roundness of the first hole produced by the uncoated and coated drills was better compared with those machined using PCD tools. This could have been due to the increased burnishing/honing effect of SiC particles trapped between the tool and drilled hole caused by the application of internal high pressure coolant [9]. Similarly, the cylindricity of the first hole produced using the carbide tools was generally lower compared to those machined with PCD drills. Increasing feed rate did not appear to improve hole roundness or cylindricity. With PCD tools, higher cutting speed however led to lower hole out of roundness and cylindricity levels.

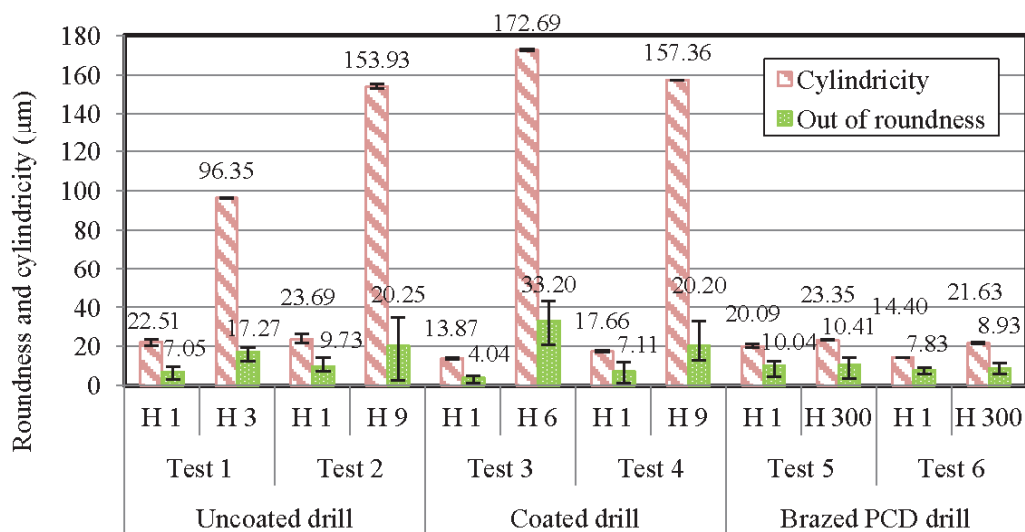


Figure 8: Hole out of roundness and cylindricity measurement results

In general, uniform burrs (without caps) up to a height of 0.45mm were obtained at the hole exit when employing uncoated and coated tools irrespective of process parameters, while both the entry and exit edges of holes produced with brazed PCD drills were free from burring throughout the experiment, see Figure 9. When machining with new tools (first hole), minimal burring or damage was seen at the hole entry location however fracture of the exit burrs was typical when using worn uncoated and coated drills, as shown in Figure 10. This was possibly due to the relatively low ductility of the strain hardened workpiece material.

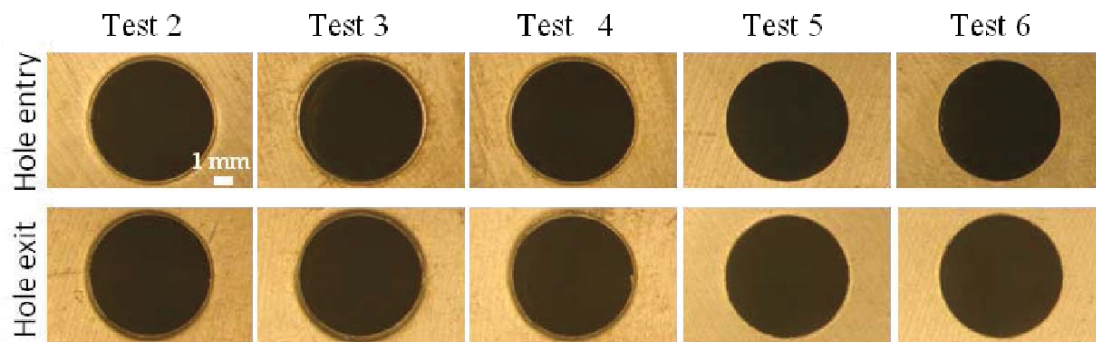


Figure 9: Hole edge quality for the last hole drilled

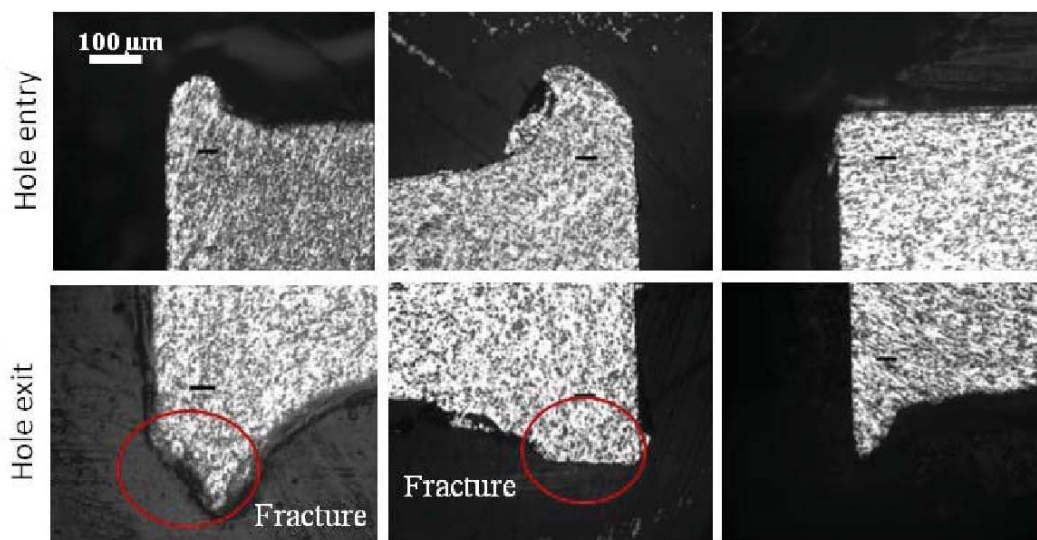


Figure 10: Burr morphology at hole entry and exit of the hole

Figure 11 shows the various types of chips collected following each trial. Typically, uncoated and coated drills generated fan-shape chips irrespective of cutting parameters, while the PCD tools produced shorter, needle-like swarf. Due to the material's low ductility, the chips were unable to withstand the severe deformation during the drilling process, with a tendency to fracture under tension to form fan-shape swarf [10]. An example of the crack initiation (from the chip inner side) can be seen in Figure 12 for Test 2. As for the different chip shape when utilising PCD drills, this was attributed to the presence of BUE (see Figure 4(c)) along the cutting edges, which caused uneven chip flow and subsequently severe up-curling leading to the generation of needle-like chips [10, 11].



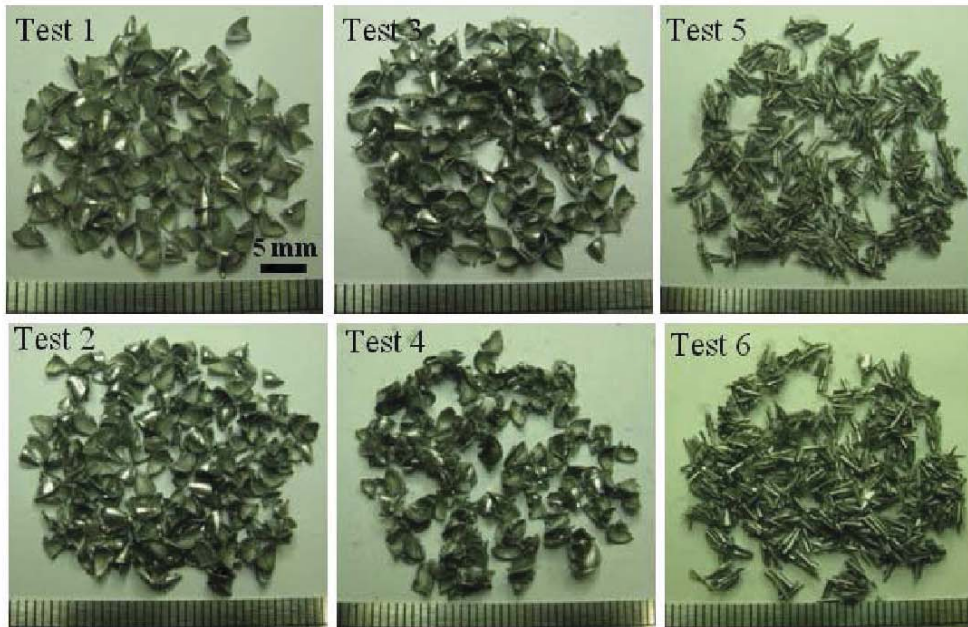


Figure 11: Chips/swarf produced following each test

Further SEM analysis showed the presence of cavities/voids on the underside of chips when using coated and uncoated drills, which suggested that pull-out of SiC particles from the matrix material occurred during drilling, see Figure 12. This was probably the result of high tool wear rates leading to dull/blunt cutting edges, which also resulted in the saw-tooth profile observed at the top edge of the chips. Conversely, the lamella-like structures observed on the inner surface of the chips were due to shear localisation [11]. In terms of the needle-like swarf, the underside surfaces were generally defect free except for some evidence of smeared material while the top edge was continuous.

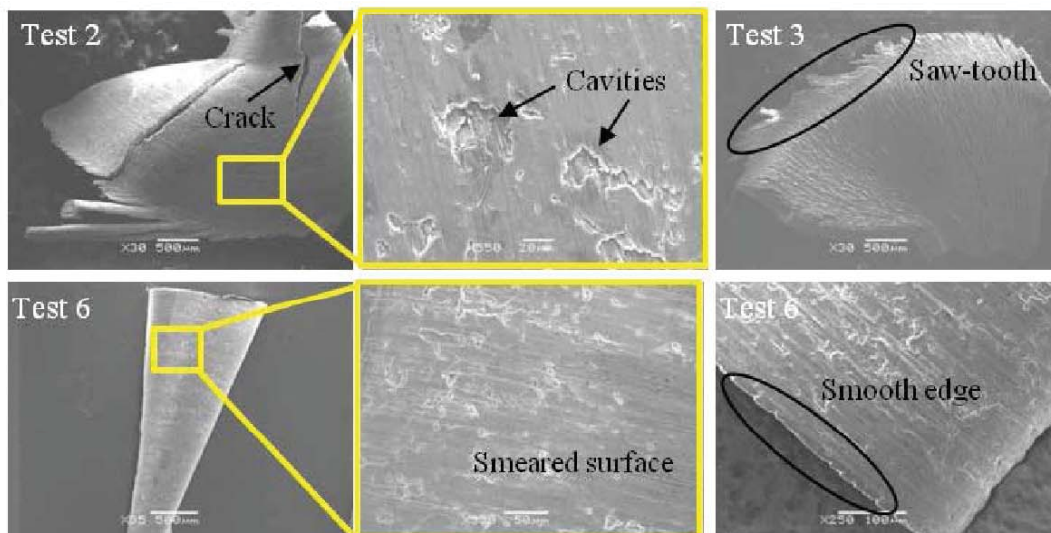


Figure 12: Chip morphology following different drilling tests

Figure 13 shows SEM images of machined hole surfaces from various tests. In terms of hole surface integrity, there was a high incidence of surface defects comprising cavities/voids, workpiece smearing and surface material

flaking observed when employing uncoated/coated WC drills caused by the extensive tool wear and poor swarf/chip extraction. In contrast, the surfaces produced using the PCD tools were relatively smooth with no obvious signs of damage even after 300 holes.

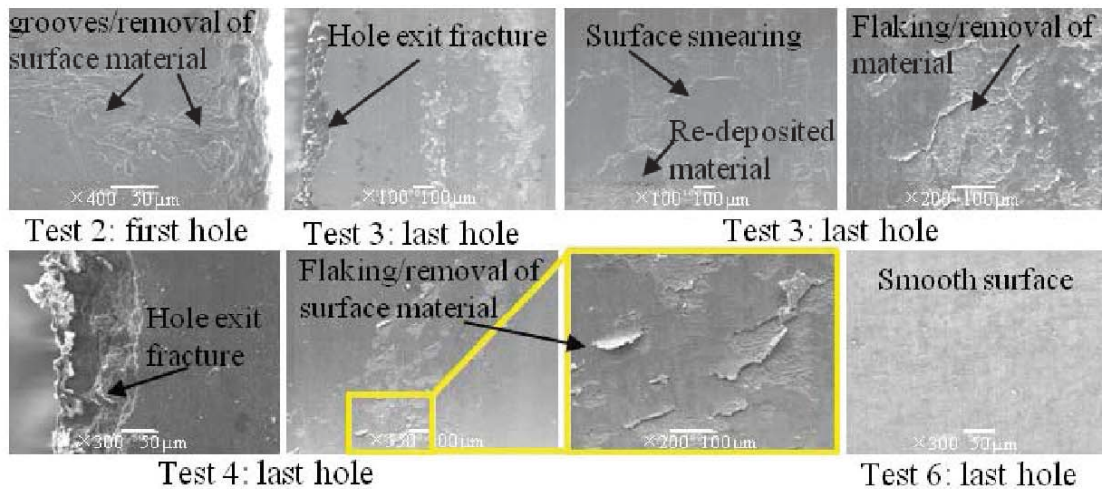


Figure 13: SEM images of machined surface quality

#### 4. CONCLUSIONS

- Severe abrasion was found to be the dominant tool wear mechanism particularly for the WC drills when drilling Al-SiC<sub>p</sub> MMC material.
- The PCD tools showed superior performance compared with uncoated and coated WC drills in terms of tool wear, productivity, hole quality and surface integrity. Both uncoated and coated WC drills operated for <10 holes although increasing feed rate from 0.10 to 0.20mm/rev resulted in marginally better tool life. The use of coatings did not provide any significant benefits when drilling MMC in comparison with uncoated tools.
- Flank wear on the PCD drills was only ~60 µm after drilling 300 holes at a cutting speed of 80m/min. Increasing the cutting speed to 160m/min did not accelerate tool wear.
- Cavities/voids were observed on the internal hole surface and underside surface (in contact with tool rake face) of the chips when using coated and uncoated WC drills. This suggested that a degree of ploughing occurred instead of shearing leading to SiC particle pull out from the Al matrix during drilling, due to the limited abrasion resistance/lower hardness of the WC tools in comparison with the reinforcement phase.
- No apparent formation of BUE was observed on the coated and uncoated carbide drills although a thin BUL was evident on the uncoated drills. This was likely due to the use of internal high pressure fluid delivery which was effective in restricting major material build up between the tool and workpiece.

#### 5. ACKNOWLEDGEMENTS

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