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# **THE PERFORMANCE OF COATED WC DRILLS WHEN MACHINING CARBON FIBRE- REINFORCED EPOXY COMPOSITE MATERIALS**

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## **ABSTRACT**

This paper is concerned with the effect of coatings on the performance of tungsten carbide (WC) drills in the drilling of carbon fibre-reinforced epoxy. Although composites are becoming increasingly popular there is a deficit in the existing knowledge of drilling composites, in particular carbon fibre-reinforced epoxy resins. Two coated drills namely titanium nitride (TiN) coated and diamond-like-carbon (DLC) coated, were investigated and for comparative purposes an uncoated. The testing involved drilling a series of consecutive holes. During these tests the thrust forces and torques were monitored, following which the tool was inspected for flank wear and the workpiece inspected for damage in terms of hole tolerance, delamination and spalling.

For all three tool types (Uncoated, TiN coated and DLC coated) only a small number of drilled holes were found to satisfy a H8 tolerance criterion. An investigation of the hole diameter through the thickness of the composite revealed that it was the outermost plies that caused the hole to fail this tolerance criterion. The effect of tool wear resulted in the measured thrust forces and torques to increase over the life of the tool. While the degree of measured tool wear was small by comparison with that associated with drilling conventional materials the effects were found to result in unacceptable damage to the composite. The damage was apparent in the form

of spalling, chip-out and matrix cracking. The coatings were not found to reduce either tool wear or damage to the composite.

**Keywords:** Drilling, coatings, tungsten carbide, titanium nitride, diamond-like carbon, carbon fiber-reinforced epoxy

## NOTATION

$F$  Thrust force

$F$  Feed rate

$M$  Torque

$n$  Number of holes drilled

$t$  Time

$v_B$  Flank wear

$v_c$  Cutting speed

$x$  Composite thickness

## 1. INTRODUCTION

Composite materials possess several desirable properties when compared against conventional metals such as their higher specific strength and specific modulus, their variable directional strength properties and their better fatigue strength [1]. As a result, the use of composites has grown considerably, particularly in the aerospace, aircraft, automobile, sporting goods and marine industries. While most components produced from composites are moulded to near net shape, machining is often necessary for final part surface finish, dimensional accuracy and assembly. Machining of these materials poses particular problems that are seldom seen with metals due to the non-homogeneity, anisotropy and abrasive characteristics of the composites.

Conventional machining practices such as turning, milling and drilling are used with composites because of the availability of equipment and experience in conventional machining. Although some of the fibres used in composites are hard (sometimes even harder than the tool material) and abrasive, conventional machining is still used as the fibres are very brittle and material removal is accomplished by a series of brittle fractures rather than plastic deformation ahead of the tool [2,3]. However, in many machining applications the cutting tool materials are chosen to minimise wear due to the hard abrasive constituents of the fibres.

When drilling composites, one of the main problems is that of the damage caused to the workpiece. One of the principal mechanisms of damage is that of delamination [4-13]. Delamination is generally regarded as a resin or matrix dominated failure behaviour, which usually occurs in the interply region. It is apparent by the bottom ply or plies of a laminate peeling away from the rest of the laminate and is attributed to the force of the drill, which pushes the layers apart rather than cutting through them. A pointed drill bit can prevent delamination and fibre breakout because of the lower thrust forces on the final plies of the laminate. Theoretical models have been developed that predict the critical thrust force that will cause the onset of delamination [10-13]. Inoue et al. [14] found that significant damage was induced in a composite when drilling GFRP with large diameter drills. In relation to the drills, very little wear was found on drills that were less than 1mm in diameter, whereas 3mm and 5mm drills had significant wear. It was found that a low feed rate produced a small number of holes of high tolerance whereas drilling with high feed rates produced more holes of consistent, albeit lower, quality. Other damage mechanisms include matrix cracking, fibre pull-out and spalling.

The focus of this paper is concerned with the use of high performance tungsten carbide (WC) drills in machining carbon fibre-reinforced epoxy matrix materials. Due

to the abrasive nature of the fibres, tool wear is an important issue when drilling these materials. In order to combat the high wear rates on the WC drills, the use of speciality coatings including titanium nitride (TiN) and diamond-like-carbon (DLC) has been investigated. The performance of the coatings has been analysed in terms of damage to the composite, the thrust force and torque that are produced during the drilling process.

## 2. EXPERIMENTAL

The drill used is a single pass solid Tungsten Carbide (WC) type as shown in Figure 1. It has been specifically designed to drill fibre-reinforced composites, comprising four straight flutes and a nominal diameter of 6.35 mm ( $\frac{1}{4}$  inch).

The grade of carbide used is K20-K40 with 10% cobalt. It is a sub micron grade of carbide, the average grain size being  $\odot$  0.7  $\mu\text{m}$ . The high hardness (1550 Hv) of this grade of carbide makes it extremely wear resistant. This allows for a longer tool life through lower wear rates and also offers the possibility of machining high hardness and abrasive materials. It has a high compressive strength (5.9 GPa) due to the very fine grain structure and the homogeneity of the hardmetal structure. This allows for an improvement in the quality and stability of the cutting edge.

In order to further improve the properties of the drill thin coatings were applied to the tool. One set of drills were coated with a titanium nitride (TiN) coating to a nominal thickness of 1.4  $\mu\text{m}$ , while a second set was coated with diamond-like carbon to a nominal thickness of 2.4  $\mu\text{m}$ . Both coatings were applied using physical vapour deposition (PVD) techniques [15].

The material that was drilled was a carbon fibre-reinforced epoxy resin. It consisted of 30 plies with a stacking sequence of  $\{+/-, 90,+45,-45,0,0,-45,+45,-45,+45,+45,-45,90,0,90\}_s$ , as shown in Figure. 2. This material was manufactured

using an autoclave process and square plates 210 x 210 mm were provided. These plates were manufactured in an aerospace production environment in accordance with material suppliers recommended curing conditions. The quality of these plates was confirmed defect free using ultrasonic C-Scan within this production environment. These plates were cut into 25 mm wide strip specimens using a diamond coated rotary saw for the subsequent drilling tests.

The material thickness varied from 4 to 4.5 mm depending on the amount of matrix present. The individual ply thickness was  $0.13 \pm 0.01$  mm. The complete laminate had a fiber volume fraction of  $62 \pm 4$  %, a void content of 2 % and a glass transition temperature of  $162^{\circ}\text{C}$ . The mechanical properties of the cured laminate are given below in Table 1.

Drilling tests were carried out on a Microcut 837 I milling machine, which was set up for drilling. A milling machine was used specifically to allow controlled repetition of the drilling process. The cutting speed and feed rate chosen were 3000 rpm ( $v_c = 60$  m/min) and 0.0485 mm/rev, respectively. From initial testing, it was found that the chosen feed rate was the optimal of the three that were available on the machine. The other feed rates, which were higher, resulted in greater amounts of tool wear and damage to the composite material. No cutting fluid was used in any of the tests to avoid any chemical reaction with the matrix of the composite, thereby weakening it. Additionally, the dynamometer could only be used for dry machining processes.

Thrust force and torque measurements were taken during each of the drilling tests. This was achieved using a Kistler quartz 4-component dynamometer type 9272 and the signal was amplified with a Kistler type 5019 charge amplifier. The signal from the amplifier was passed through signal conditioning equipment, which in turn

was connected to a PC via a 12-bit data acquisition card. The experimental set-up is shown schematically in Figure 3.

After each drilling test the drill was inspected for flank wear and the drilled hole inspected to establish whether a H8 tolerance criterion for aerospace applications was satisfied. The flank wear was measured using a Mitutoyo BI-5 toolmakers microscope, while the H8 tolerance was measured using a go/no-go gauge. The tool life was characterised relative to the H8 tolerance test. The drilled holes were subsequently examined for diameter and roundness using a co-ordinate measuring machine (CMM). These measurements were taken 1 mm below the top surface and 1 mm above the bottom surface in order to calculate the hole diameters. Four measurements were taken for the top and bottom of each hole (eight in total for each hole). The roundness values were calculated from the measurements taken 1 mm into the hole. Finally, electron microscopy techniques were employed to examine the damage caused to the composite. As the epoxy matrix is not conductive, the specimens were gold sputter coated. They were then examined using a JOEL35 scanning electron microscope with a charge voltage of 15kV.

### **3. RESULTS AND DISCUSSION**

#### **3.1 Thrust Force and Torque**

Figures 4 and 5 show typical thrust force and torque profiles, in the case shown for an uncoated tool. The profiles were obtained from the dynamometer signals during the drilling of 32 consecutive hole. For clarity only some of the signals are illustrated.

The general form of the thrust force profiles, Figure 4, comprises six main stages. Initially, there is a sharp increase in thrust force due to the initial entry of the drill into the composite. This is followed by a further increase in the force as the second cutting edge enters the workpiece. The maximum force occurs as the tip of the tool breaks

through the bottom ply of the laminate. This is followed by a sharp reduction of the force due to the fact that the tip of the tool has broken through the back face of the workpiece. When the first chisel edge breaks through the back face of the laminate the reduction in force becomes more gradual. The final stage sees the force drop to zero as reaming takes place.

The general form of the torque profiles, Figure 5, comprises six distinct stages. The initial entry of the drill into the composite causes a sharp increase in torque. This is followed by further increases in the torque as the second cutting edges enter the workpiece. As the tip of the tool breaks through the back face of the torque reaches a maximum. Following this there is a slight drop in the torque. The torque is then seen to increase as the remainder of the second cutting edge enters the workpiece. The final stage sees a reduction in the torque as reaming takes place.

It is clear from Figures 6 and 7 that, as the number of holes drilled increases, so too does the magnitude of both the maximum torque and thrust force. Similar profiles were noted for both the uncoated and coated tools. In the case of the thrust force it was noted that the maximum force occurs as the tip of the tool breaks through the bottom ply of the laminate. However, in the case of the torque it can be seen that it is that part of the drill associated with the second cutting edge corner breaking through the bottom face that actually results in the maximum torque for the first few holes. However, as the tool wears it was found that the chisel edge breaking through the bottom of the laminate was associated with the maximum torque. Figure 6 shows a combination of the maximum thrust force and torque. Also included are the flank wear results, which show wear in the order of 0.07 mm after 32 drilling operations. This level of flank wear is low by comparison with results presented in the literature. For example Morin et al [16], for example, reports flank wear in the region of 0.4 mm when drilling metal matrix composite.

With reference to Figure 8 it is clear that the maximum thrust force, maximum torque and flank wear curves for the three drill types exhibit similar trends. Both the thrust force and torque curves rise sharply in the initial stages after which the subsequent rate of increase is seen to reduce. A change in form of both these curves is apparent in the region  $5 < n < 10$ , drilled holes.

These trends compare well with wear patterns found when drilling conventional materials (e.g. mild steel, aluminium) which exhibit three distinct stages, namely primary, secondary and tertiary wear [17]. It is possible that the two stages observed in the present work correspond to primary and secondary wear zones. A further investigation into tool could run the tool into the tertiary zone where a sharp increase in wear would be anticipated. This was not undertaken in the present work as the experiments were terminated when damage to the workpiece was deemed unacceptable and the holes failed to satisfy the aerospace H8 tolerance criterion.

### **3.2 H8 Tolerance and Hole Diameters**

The results of the H8 tolerance tests using the go/no-go gauge are presented in Table 2. From Table 2 it can be seen that the uncoated tools perform best with an average of 6 holes drilled in tolerance, this is followed by the TiN with 3 holes and DLC with an average of 1. This would imply that the uncoated tool performs best using the go/no-go gauge method. However, this method only measures the top and bottom plies of the laminate. Therefore it is only possible to conclude from this work that the top and bottom plies are out of tolerance.

Having examined each of the holes for H8 tolerance, it was decided to measure the diameter of the hole through the thickness of the hole. Measurements were taken 1mm from the top and 1 mm from the bottom surfaces, as shown schematically in Figure 9. The results of this work are shown in Table 3.

In general it was found that more holes were in tolerance for the lower half of the hole than the top half, for all three drill types. Based on the hole diameter measurements 1 mm from the top it can be seen that the uncoated, on average performed best followed by TiN and DLC, respectively. This is the same order as was observed for the H8 tolerance results using the go/no-go gauge. However, the reverse order is noted for the hole diameter measurements 1 mm from the bottom. These results suggest that the top and bottom plies (tested using the no/no-go gauge) are causing the holes to be out of tolerance. This may be due to the fact the top and bottom plies are woven and therefore more difficult to machine than the intermediate plies which are unidirectional.

### **3.3 Scanning Electron Microscopy**

In order to analyse the damage caused to the laminate resulting from the above forces and wear, a scanning electron microscopy investigation was carried out. Holes drilled during the initial (n=1,2), intermediate (n=16) and final stages (n=32) of tool life for each of the drill types were examined.

Figure 10 shows the hole surface produced by an uncoated tool in the initial stages of tool life. From Figure 10 it can be seen that there is no spalling at the top and bottom edges of the hole. Also, no damage was observed on the surface of the hole, although this is not presented here. These features can be attributed to the sharpness of the cutting edges during the initial stages of tool life. From this it can be seen that there is almost no damage to the composite. Initial holes drilled by the coated tools were observed to have similar features.

Figure 11 shows micrographs of a hole produced at the end (n=32) of tool life for an uncoated tool. The damage produced at the end of tool life, as shown in Figure 11, was found to be severe. The drill no longer cuts the fibers cleanly. As a result, the

fibers are being pushed aside by the cutting edges of the drill rather than being. Micrographs for the central portion of the hole have been omitted. Fibre and matrix pull-out was observed in this region.

#### 4. CONCLUSIONS

- An increase in overall thrust force with increasing number of holes drilled was observed. The rate of increase was most significant in the early stages of tool life (up to approximately 10 holes).

The maximum thrust force occurred when the tip of the tool broke through the bottom face of the laminate. This corresponds to the point where the cutting edges are in full contact with the workpiece. This is significant in that delamination is most likely to occur during the drilling of the bottom plies.

- The overall torque was found to increase with tool life in a similar manner to that observed for the thrust force. Again, the rate of increase was most significant during the early stages of tool life.

The maximum torque was initially found to occur where the second cutting edge corner was entering the laminate. This corresponds to the outermost corners of the drill entering the workpiece. With increasing wear it was noted that the maximum torque occurred when the tip of the tool was breaking through the laminate.

- The results of the flank wear inspections show a general increase in flank wear with increasing tool life. It is noted that a reduction in the rate of flank wear occurs in the region  $5 < n < 7$  holes drilled. This correlates with the change in form observed for both the thrust forces and torque and may correspond to the transition between primary and secondary wear zones.
- A small number of in tolerance holes were produced using a go/no-go gauge test for all drill types.

- The hole diameter measurements show that more holes are in tolerance than indicated using the go/no-go gauge. This suggests that the woven top and bottom plies (tested using the no/no-go gauge) are causing the holes to be out of tolerance. This may be due to the fact that they are more difficult to machine than the unidirectional intermediate plies.
- From the qualitative scanning electron microscopy analysis negligible damage was observed on holes drilled in the early stages of tool life. An increase in tool wear results in damage to the fibres in terms of pull-out and spalling. The damage that was induced on the laminate from the drilling process was found to be similar for all types of coatings used.
- Overall the use of coatings were found to be of no benefit when machining carbon/epoxy composites.

## **5. ACKNOWLEDGEMENTS**

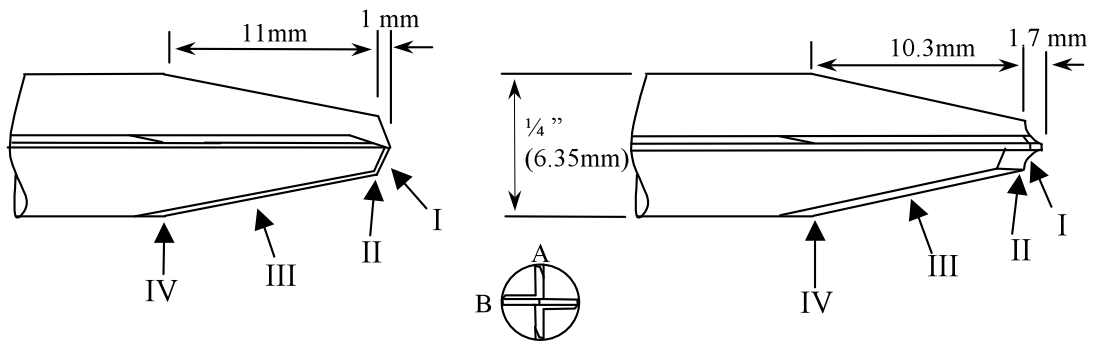
Funding for this work has been provided by Enterprise Ireland under the Strategic Research Programme (ST/97/104). The provision of drills, coatings and composite laminates by Mohawk Europa Ltd, the Coatings Unit in Enterprise Ireland and Bombardier Shorts is gratefully acknowledged.

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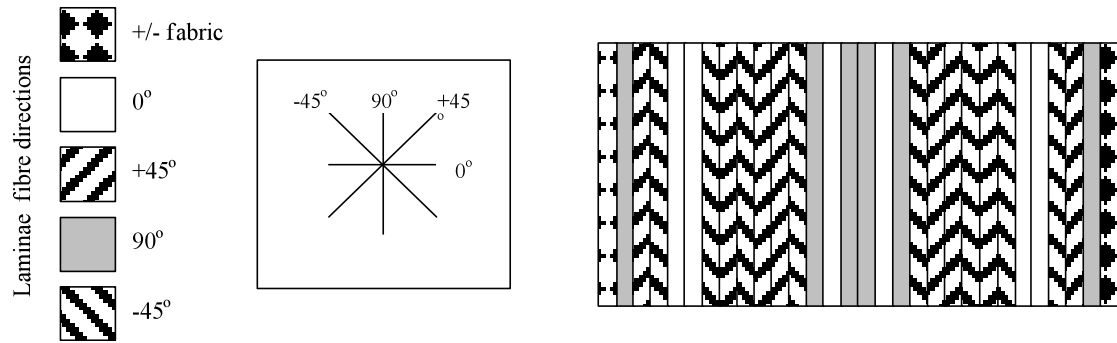
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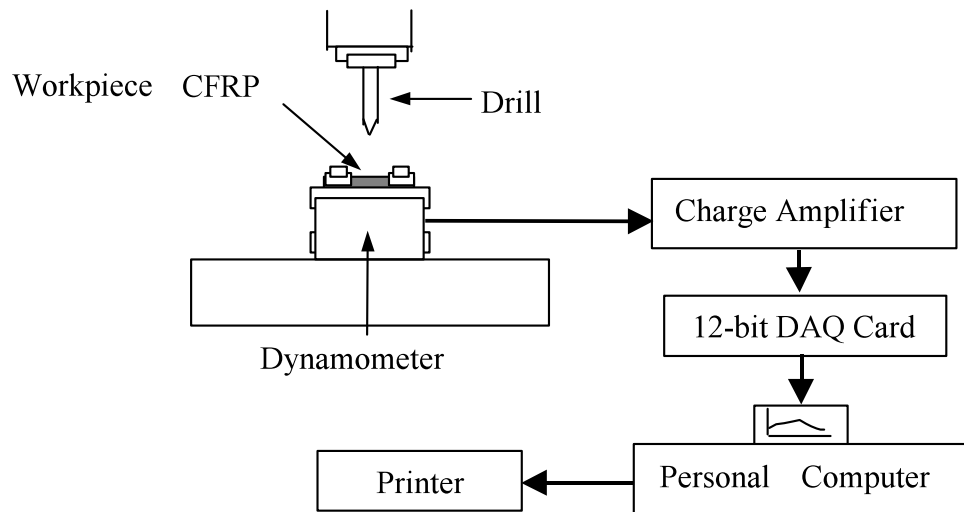
*I: First lip, II: First chisel edge corner, III: Second lip, IV: Second chisel edge corner.*

**Figure 1** Schematic of drill used for experiment

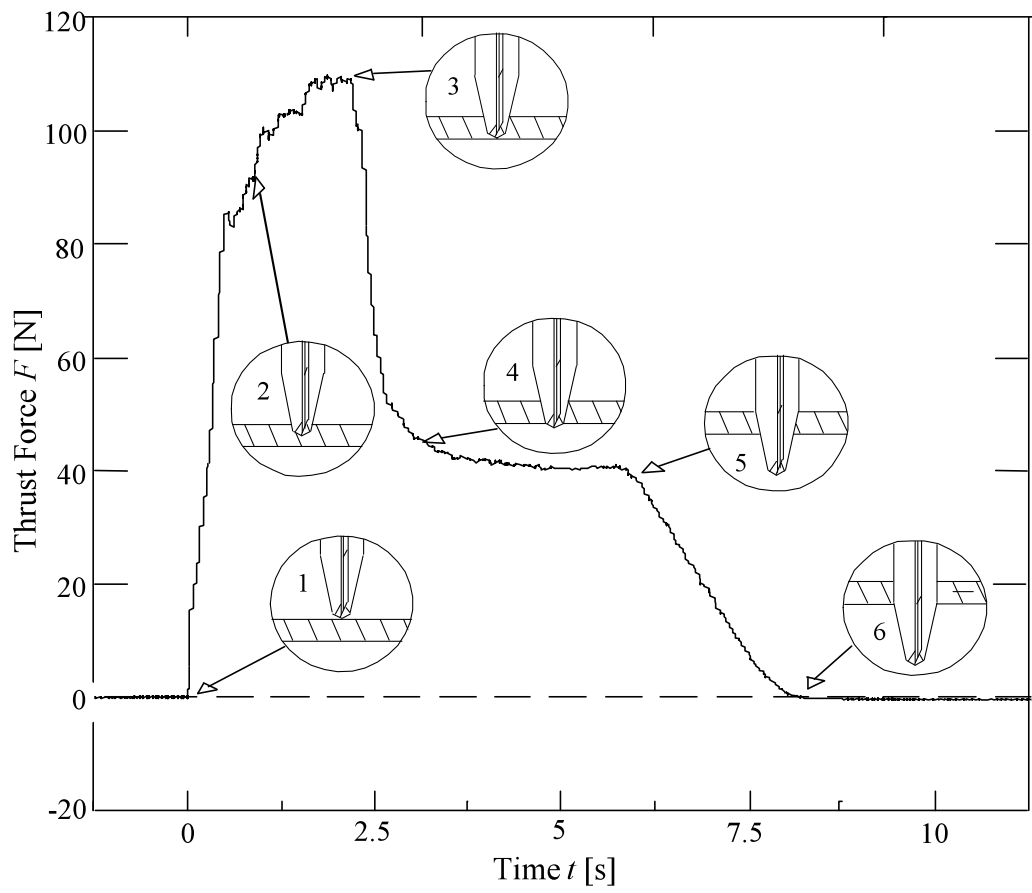
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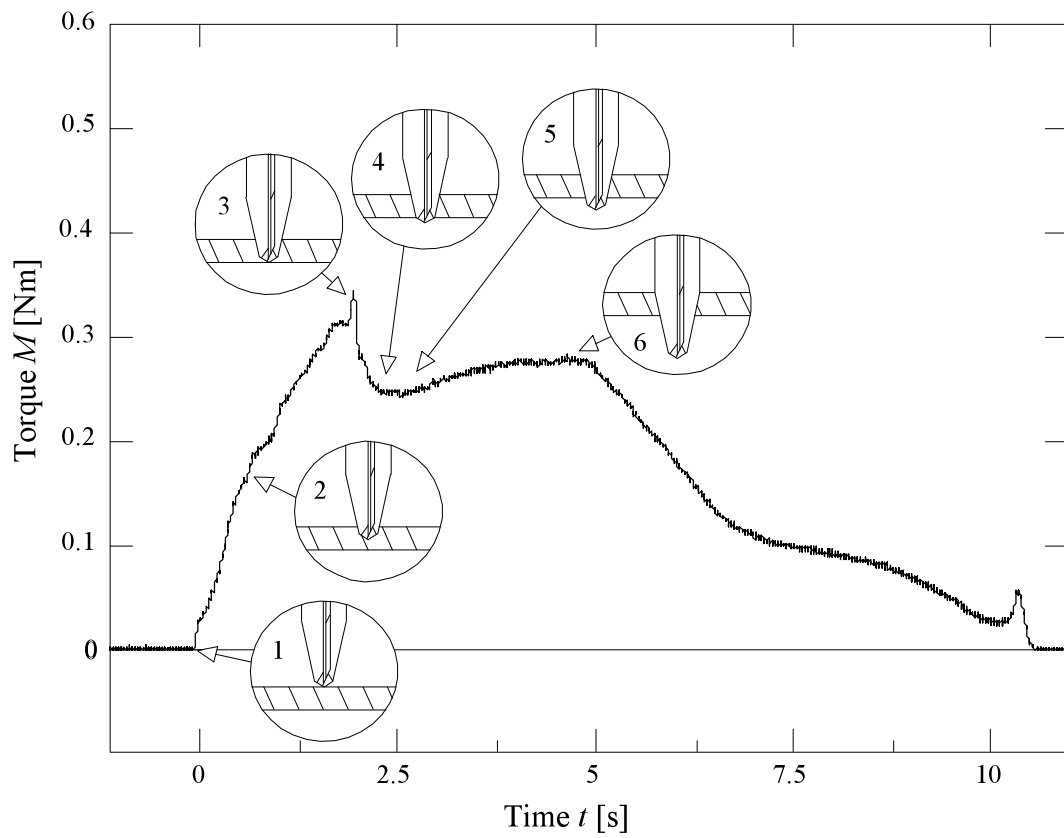
**Figure 2** Stacking sequence of the laminate



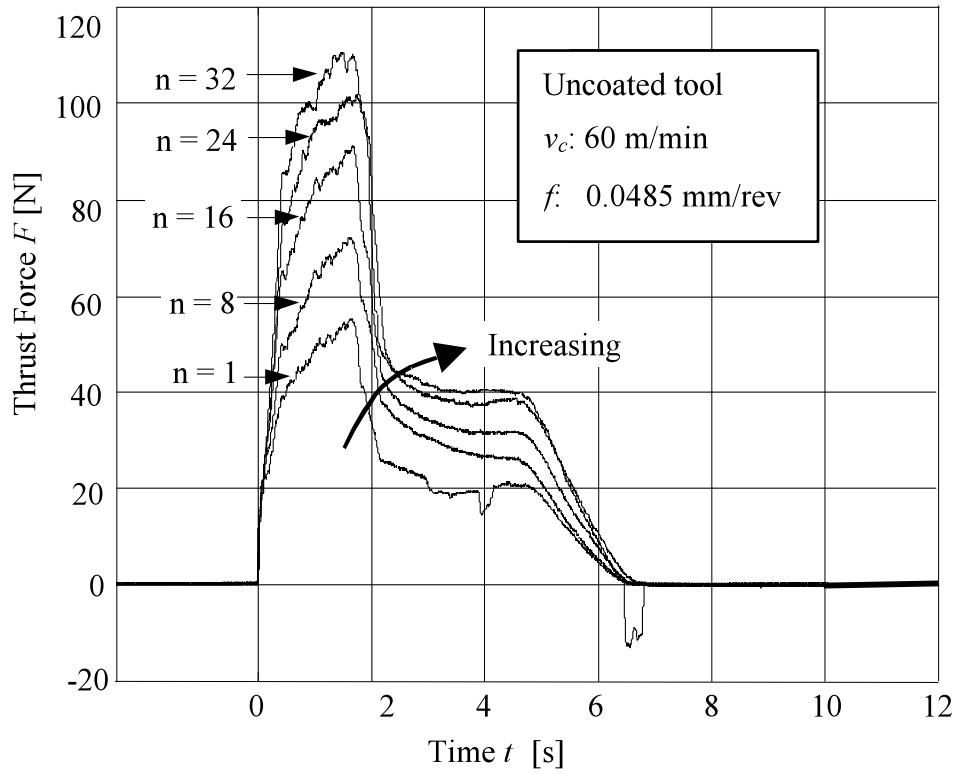
**Figure 3** Schematic of experimental set-up



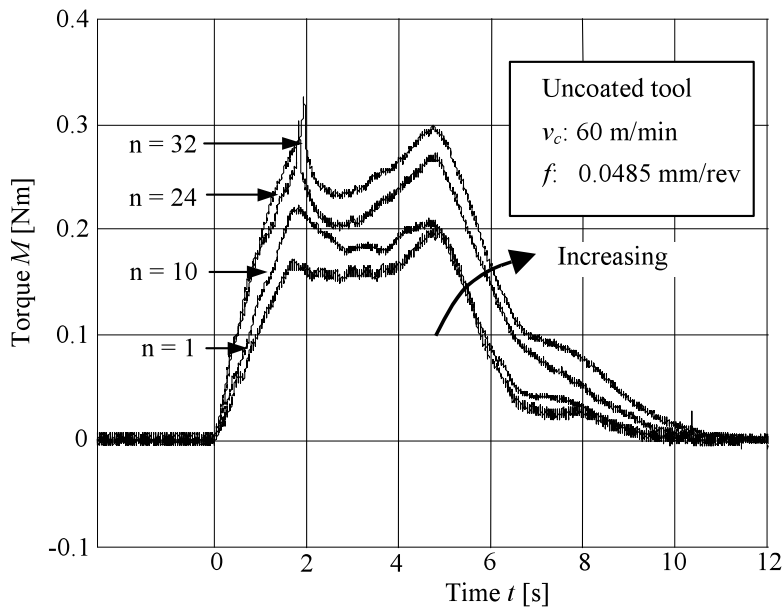
**Figure 4** Typical thrust force verses time plot for a single cutting operation



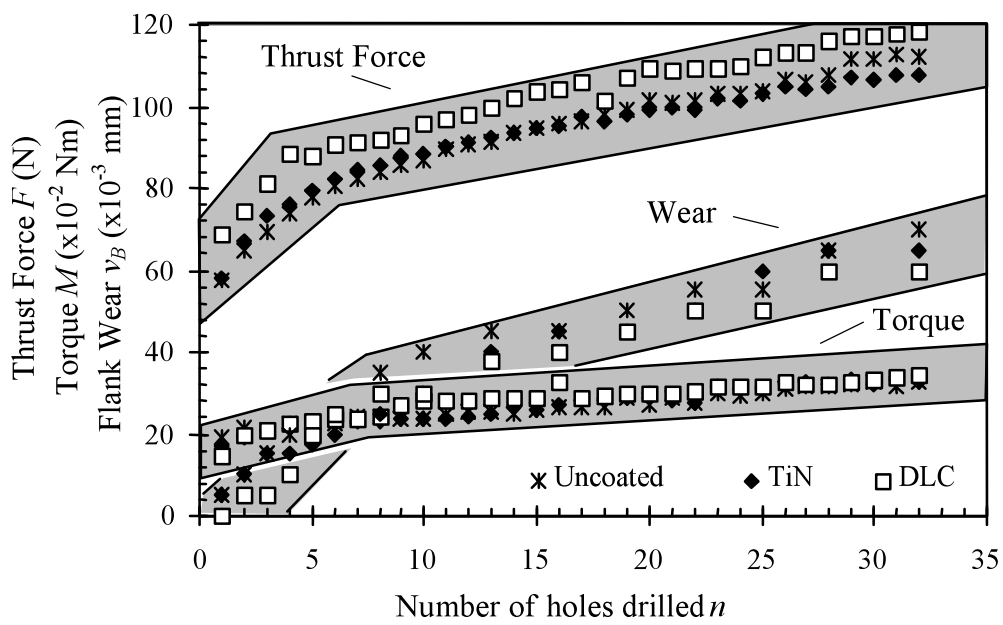
**Figure 5** Typical torque verses time plot for a single cutting operation



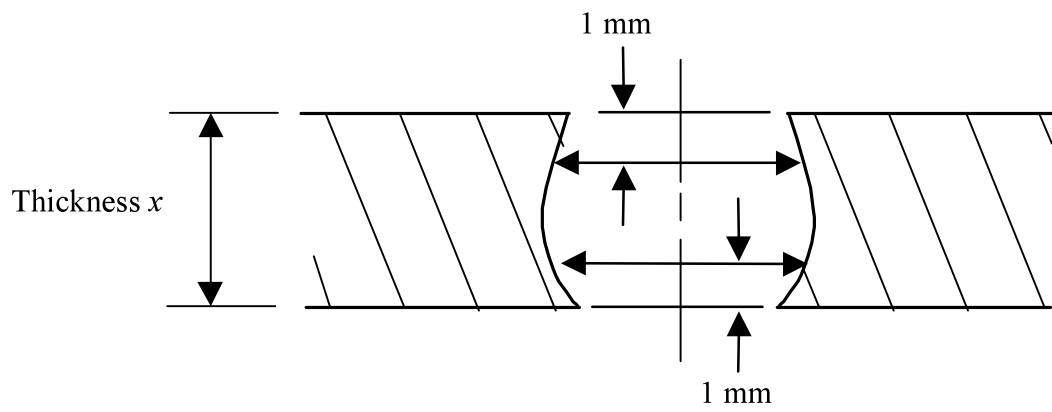
**Figure 6** Variation in thrust force when using an uncoated tool to drill carbon/epoxy



**Figure 7** Variation of torque when using an uncoated tool to drill carbon/epoxy

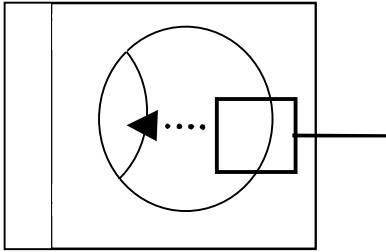


**Figure 8** Variation of maximum thrust force, torque and flank wear with number of drilled holes



**Figure 9** Schematic showing variation in diameter through the thickness of the hole

◀... Direction of Drilling

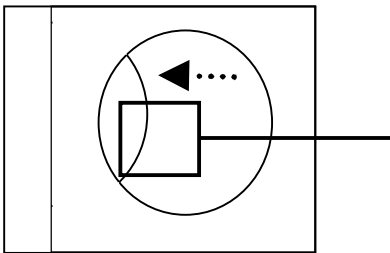


Picture 124

100 μm

(a)

◀... Direction of Drilling



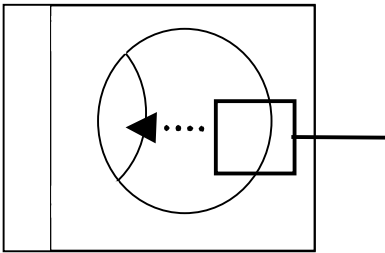
Picture 121

100 μm

(b)

**Figure 10** SEM micrographs showing (a) entry; (b) exit of an initial hole drilled for an uncoated tool.

◀.... Direction of Drilling

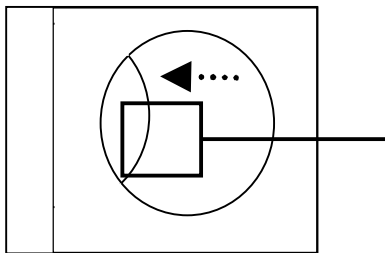


Picture 64

100 μm

(a)

◀.... Direction of Drilling



Picture 47

100 μm

(b)

**Figure 11** SEM micrographs for hole 32 uncoated tool (a) hole entry; (b) hole exit

Laminate Properties	Longitudinal (GPa)	Transverse (GPa)
Ultimate tensile strength	2.16	0.05
Tensile modulus	157.9	8.29
Ultimate compressive strength	1.42	0.2
Compressive modulus	151	8.96
Ultimate flexural strength	1.51	
Flexural modulus	143	

**Table 1** Mechanical properties of carbon/epoxy laminate of stacking sequence

{+/-, 90,+45,-45,0,0,-45,+45,-45,+45,+45,-45,90,0,90}<sub>s</sub>.

	Drill No. 1	Drill No. 2	Drill No. 3	Average
Uncoated	4	9	6	6
TiN Coated	5	2	6	3
DLC Coated	0	3	0	1

**Table 2** Summary of H8 tolerance results. The numbers indicates number of drilled holes in tolerance. (Total number of holes drilled for each coating: 96 holes [32 holes \*3 repetitions])

	Drill 1		Drill 2		Drill 3		Average	
	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom
Uncoated	10	23	26	31	20	21	19	25
TiN coated	19	25	10	25	16	32	15	27
DLC coated	15	31	15	32	1	30	10	31

**Table 3** Summary of hole diameter tolerance results. The numbers indicated number of drilled holes in tolerance, average presented is a rounded figure. (Total number of holes drilled for each coating: 96 holes [32 holes \*3 repetitions]) Top indicates measurements taken 1 mm from the top of the laminate; bottom indicates measurements taken 1 mm from the bottom of the laminate.

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**Figure 2** Stacking sequence of the laminate

**Figure 3** Schematic of experimental set-up

**Figure 4** Typical thrust force verses time plot for a single cutting operation

**Figure 5** Typical torque verses time plot for a single cutting operation

**Figure 6** Variation in thrust force when using an uncoated tool to drill carbon/epoxy

**Figure 7** Variation of torque when using an uncoated tool to drill carbon/epoxy

**Figure 8** Variation of maximum thrust force, torque and flank wear with number of drilled holes

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