

Cutting Tools for Machining Composites



Rangasamy Prakash and Vijayan Krishnaraj

Abstract The machining of composite components finds lot of challenges due to the abrasive nature of the fibres used. The problems such as delamination, fibre pull-out and resin degradation which may be encountered during machining of workpiece and deciding its quality characteristics. Also, the tool wear is a major concern which has to be considered in controlling tooling cost and impact final product cost. Therefore, it is necessary to appropriately select the suitable cutting tool which is expected to cause minimum damages to workpieces. This chapter discusses the cutting tools used when machining (mainly drilling and milling) polymer matrix composites (PMC). The chapter will also discuss cutting conditions, cutting tool materials, cutting tool geometry and coatings. The machinability characteristics due to the effect of cutting parameters and tool materials/geometries during drilling various composite materials will be compared. High speed edge trimming of carbon fibre reinforced polymer (CFRP) materials using fluted and router tools is also discussed to determine the effect of tool geometry and tool coating materials on surface roughness of machined surfaces and the tool wear. This chapter also discusses the cutting tools for machining of metal matrix composites (MMC) and ceramic matrix composites (CMC).

1 Introduction

Composite materials find extensive applications in aerospace, naval, space, and automotive industries due to their unique characteristics such as strength to weight ratio and stiffness to weight ratio, etc., Machining is an essential post processing required to produce components to their final dimensional requirements and to make them assembly ready.

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The machining of composites faces a lot of challenges not only with respect to work parts and also in cutting tools used. The cutting tool for machining composites decides the various process criteria such as material removal rate, surface quality and tool wear. Therefore, the selection of cutting tools rests on the nature of matrix and also on the reinforcement materials of composites. Hence, it is necessary to select the cutting tool of right material, right geometry to extend the tool life in order to improve the part quality and to minimize cost of machining involved.

The main aspect of machinability is to discuss in detail the force, torque, tool life, and surface finish. Though there are a number of interrelated factors which affect the machinability of the material, the most important factors are the cutting parameters, the properties of the work and tool materials, geometry of the cutting tool, clamping of work and the type of machine tool.

Therefore, in this chapter cutting tool requirements for different types of composites are discussed.

2 Classification of Cutting Tools

The cutting tool for machining composite is selected based on the following criteria:

- i. Type and percentage of matrix used
- ii. Type and percentage of reinforcement used
- iii. Cutting conditions
- iv. Surface finish
- v. Material removal rate
- vi. Tool life
- vii. Tool cost.

The cutting tools used for machining of composites are classified based on tool geometry and tool material as follows:

- i. **Based on tool geometry:**
 - Single point cutting tool
 - Drill tool
 - End mill
 - Straight fluted
 - Helical fluted
 - Single helix
 - Double helix
 - Router
 - Trapezoidal shape tooth
 - Pyramidal shape tooth

- Diamond grit grinding wheel
- ii. **Based on tool material:**
- (i) Solid tools
 - High speed steel (HSS)
 - Tungsten Carbide (WC)
 - Polycrystalline diamond (PCD)
 - Cubic boron nitride (CBN)
 - Polycrystalline boron nitride (PCBN)
 - Diamond
 - (ii) Coated tools
 - TiN, TiAlN, TiCN and Al₂O₃ coated
 - Diamond like carbon (DLC) coated
 - PVD—Diamond coated over carbide substrate
 - CVD—Diamond coated over carbide substrate

3 Tool Requirements for Machining Polymer Matrix Composites

3.1 Introduction

Even though the fiber-reinforced composite components are produced to near net shape through various moulding methods, it is important to perform machining in order to produce components to their final dimensional requirements and to make them assembly ready. In these composite structures, cut-outs and holes are to be produced in large numbers. For example, in an aircraft fuselage structure, millions of holes are required for joining purposes. Drilling and milling of such materials is a challenging task to manufacturing engineers because of differential machining properties.

The cutting parameters in drilling are the spindle speed, and feed rate and in milling are the spindle speed, feed and depth of cut. The tool parameter involves the tool material and tool geometry. Though the machining technique on PMC material is similar to that of metals, the fiber proportion and their orientation in PMC (fibers in continuous or chopped strands, fibers in unidirectional or bi-directional) play an important role in deciding the machinability of the material.

Drilling and milling are the two most common machining processes involved. Certain applications of composite materials, such as in aircraft structures or in machine elements, require accurate surfaces for bearing mounting or adhesive joints. Hence machining processes such as edge trimming have to be done at the edges to ensure the desired surface quality and dimensional stability of the composite components. Hence, manufacturing composite parts for various applications involves a

sequence of processes such as moulding, machining and joining. These composite parts need to be manufactured without any damages or defects in order to meet the functional and assembly requirements.

3.2 *Cutting Tools for Drilling of Polymer Matrix Composites*

3.2.1 Introduction

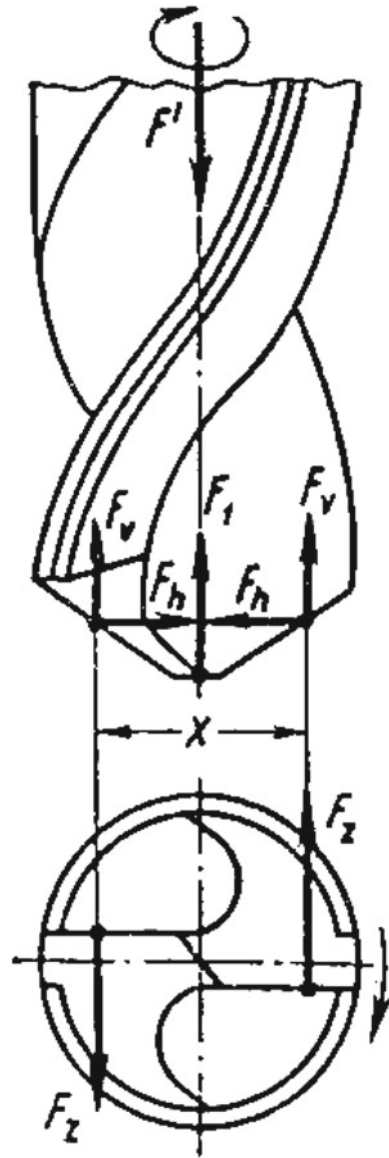
Polymer matrix composite materials are increasingly used in high performance applications because of superior strength to weight ratio and stiffness to weight ratio. Cut-outs and holes exist in most of the composite structures. Due to their laminated constructions several types of damages like matrix cracking and thermal alterations, fiber pullout and fuzzing, are introduced during drilling in addition to geometrical defects similar to those found in metal drilling. About 60% of the rejections are due to the defects in the holes. These defects would create reduction in structural stiffness, leading to variation in the dynamic performance of the whole structure. Many of these problems are due to the use of non-optimal cutting tool designs, rapid tool wear, and machining conditions (Konig et al. [1]; Komanduri et al. [2]). Bhatnagar et al. [3] have modelled the mechanism of chip formation of UD-CFRP and showed that cutting forces are dependent on the fiber angle as well as the direction of cutting.

According to the Polymer technology (Lubin [4]) series data the cutting speeds from 77.36 to 154.72 m/mm, point angle 60–120°, helix angle 10–50°, clearance angle 9–20° can be selected for drilling PMC material. Apart from the drill diameter and feed employed, the torque and thrust force in drilling are mainly influenced by work material, drill geometry, drill wear and related features. The total drill torque is only slightly affected by the chisel edge length. By thinning the web, it is possible to reduce the axial thrust by 30 to 35%. Both thrust and torque rise sharply if the drill is allowed to dull too much. Figure 1 shows the thrust force and torque acting on a standard twist drill (Arshinov and Alekseev [5]).

In PMC, delamination near the entry and exit portion of the hole, fiber pull out, excessive tool wear are the main problems during drilling. In drilling, the drill always exerts a compressive thrust force on the work piece. The laminate under the drill thus tends to be drawn away from the interlaminar bond around the hole. As the drill approaches the end, the uncut thickness becomes smaller and the resistance to deformation decreases. At some point the loading exceeds the interlaminar bond strength and delamination occurs. This happens before the laminate is completely penetrated by the drill as shown in Fig. 2a. The chisel edge of the drill will first abrade the laminate initially. It, then by moving forward, tends to pull the abraded material away along the flute. The material spirals up before it is machined completely as shown in Fig. 2b.

This action introduces a peeling force upwards to separate the upper laminate from the uncut portion held by the downward acting thrust force. The cutting force acting in the peripheral direction is the driving force for delamination. It generates a peeling

Fig. 1 Forces acting on a drill (Arshinov [5])



force in the axial direction through the slope of the drill flute and is a function of tool geometry and friction between the tool and workpiece. Delamination caused by peel-up becomes progressively more difficult as drilling proceeds, since the thickness resisting the lamina bending becomes greater.

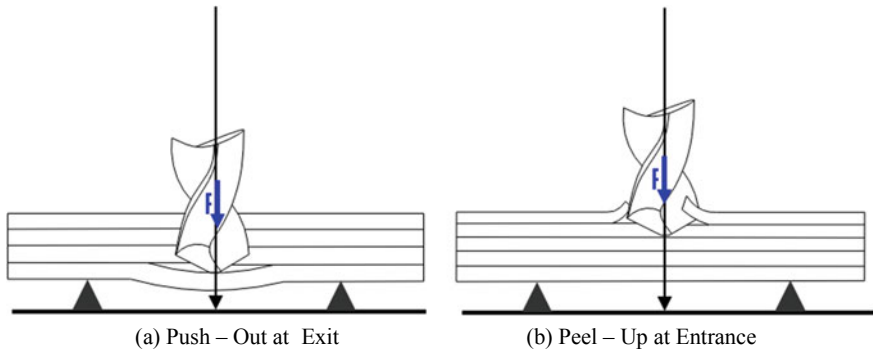


Fig. 2 Drill bit showing delamination at exit and at entrance (Zitoune [6])

3.2.2 Effect of Tool Material

In general, the desirable properties for a cutting tool material are, small grain size to be able to produce a sharp cutting edge, high hot hardness to provide excellent abrasive wear resistance, good toughness to maintain a sharp cutting edge without chipping or deformation under a cutting force's dynamic action, good thermal conductivity to remove heat from cutting zone, and thermal stability to maintain integrity at cutting temperatures and low chemical affinity to the workpiece material. The degree to which each of these properties is needed depends on the workpiece material. The micro constituents in the work material reduce the tool life. In case of fiber reinforced composite materials, the fiber size, shape, position (orientation) and proportion influence the cutting forces and tool life.

As high speed steel is less resistant to wear, its tool life is less when used on fibers like glass and graphite which are highly abrasive in nature. Sakuma et al. [7] drilled holes using four drill materials and investigated drill wear pattern, thermal conductivity of tool material, flank wear width and cutting forces and reported that K01 grade carbide drill has the highest wear resistance when compared to HSS, P10 grade carbide and ultra-fine grain drills. It is found that when cutting speed is increased, the rate of wear on the nose in every tool material starts to increase remarkably at a certain speed. Davim and Reis [8] investigated drilling of CFRP using HSS, cemented carbide (K10) helical flute and cemented carbide four flute drills and concluded that helical flute carbide drill is better because of the hot hardness when compared to HSS drill and positive rake angle when compared to four flute cemented carbide drills. The various types of wear were classified into four groups which may depend upon the cutting speed, feed rate, and geometry of contact, coolant, tool material and work material. The types of wear include adhesive, abrasive, fatigue, and corrosive wear. One of the best methods to improve the productivity or tool life of a drill is to add a coating or surface treatment. Coatings and surface treatments build a barrier between the drill and the workpiece but coatings do not seem to have influence while drilling of PMC materials. Ramulu, et al. [9] have showed that better quality

holes can be achieved while drilling Graphite/Bismaleimide composites using PCD four-faceted drill.

Table 1 gives the typical tool materials used for drilling and its critical machining parameters. For drilling PMC, carbide drill of grade K10 or K20 and PCD is found suitable. While drilling with carbide drills, thrust force was found to be smaller than that of HSS drills, whereas the thrust force of the polycrystalline diamond drill was one third of that of the HSS drill. The PCD drills produced the highest quality holes and suffered the least amount of wear, but the number of literature related to the life or economy seems to be less. Apart from tool materials, tool geometry has direct influence on forces, and quality of drilled holes.

Quality of the holes drilled in PMC has been investigated using Tool maker’s microscope, enhanced radiography, computerized tomography (CT), ultrasonic C scan, digital analysis. Ravishankar et al. [10] showed that, it is possible to evaluate the drilling induced damages in composites through AE signal characterization. A simple and cost effective technique to evaluate delamination in drilling composite laminates using digital scanning has been proposed by Khashaba [11]. Seif et al. [12] used Shadow Moiré laser based imaging technique for dark composite parts where visual inspection is difficult. Zitoune et al. [13] have studied further delamination

Table 1 Typical tool materials and critical drilling parameters on composites

| Cutting parameters | | Machinability characteristics | | | | | | |
|--------------------|-----------------------------|-------------------------------|----------|------|-------|-----------|----------|---------|
| Work material | Cutting tool | Vc m/min | f (mm/r) | Fz N | Tq Nm | Wear mm | No holes | Ra (µm) |
| CFRP Vf 0.62 | WC One shot drill, Φ6.35 mm | 60 | 0.048 | 60 | 0.2 | 0.07 | 32 | |
| GFRP Vf 0.4 | Tipped WC Φ6 mm | 18.85 | 0.02 | 30 | – | – | 50 | – |
| | TiN HSS Φ6 mm | 18.85 | 0.02 | 35 | – | – | 30 | – |
| | HSS Φ6 mm | 18.85 | 0.02 | 40 | – | – | 30 | – |
| GF/Polyester | Carbide tipped Φ6 mm | 47 | 0.1 | 74 | – | 0.13–0.21 | 30 | – |
| Gr/Bi | HSS Φ6.35 mm | 54 | 0.028 | 150 | – | 0.45 | 18 | 5.24 |
| | PCD Φ6.35 mm | 54 | 0.028 | 50 | – | – | 40 | 1.13 |
| KFRP Vf0.55 | HSS Candle stick drill | 30 | 0.1 | 410 | – | – | 250> | 2–3 |

Vc = Cutting speed m/min, f = Feed rate mm/rev, Fz = Thrust N, Tq = Torque Nm, Ra = Surface roughness (Ra in µm)

at entry and exit while drilling of long fiber composite, and reported that there is influence of manufacturing processes of the composite plate materials and concluded that the delamination of the laminates manufactured in oven is larger compared to the one of the drilled plates manufactured in autoclave. While drilling T700-M21 (3rd generation resin) in comparison with T2H-EH2 (2nd generation resin) presented enhanced machining conditions i.e. better surface finish and minimal defect at hole exit (Zitoune et al. [6]) because of the presence of thermoplastic nodulus.

Khashaba [11] showed that by increasing the cutting speed in drilling cross-winding, woven and chopped composites reduced the push-out delamination as a result of decreasing the thrust force. The depth of the affected zone and the severity of the damage decreases with an increase in cutting speed. At lower feed rates, delamination occurred at the sub-laminate, whereas at higher feed rates it occurred at the early stage of the drilling. The relationship between spindle speed and feed rate are important in terms tool life and quality of hole. The effect of spindle speed on hole quality and cutting force is less when compared to feed rate. Increasing cutting speed resulted in lower thrust force and torque due to the high temperatures produced which softens the matrix. Ramkumar [14] showed that maintaining critical thrust below 70 N improves the quality of the hole, and proposed to use a cutting speed of 12 m/min, feed rate of 0.04 mm/rev with workpiece vibration. A spindle speed of 1000 rpm (5 m/min) and a feed rate of 0.02 mm/rev is reported to be better in case of drilling glass fiber reinforced plastic (Arul et al. [15]). For high volume fraction glass fiber reinforced plastics, Velayudham [16] suggested to use a cutting speed of 80 m/min, feed rate of 0.1 mm/rev and maintain thrust force during drilling below 100 N. Spindle speed of 490 rpm (10 m/min), and feed rate of 0.02 mm/rev is reported to be the critical process parameters for glass fiber reinforced plastics (Zitoune [6]). Table 2 presents preferred cutting speeds and feeds for various combinations.

The variations in the preferred process parameters (Table 3) are based on manufacturing process, volume fraction of the composite, tool material and geometry. In general high spindle speed and low feed rate is preferable for drilling polymer matrix composites (Enemuoh [17]). The data available in the Tables 1, 2 and 3 were collected from various literatures.

But at very high speeds, tool wear is a major problem; still there is a gap in the literature in the fields of optimum parameters at high spindle speed, drill life and economy of using high spindle speed. It is presumed that there is a critical thrust force beyond which delamination is initiated.

Table 2 Typical tool geometries and critical drilling parameters on composites

| Cutting parameters | | Machinability characteristics | | | | |
|--------------------|--|-------------------------------|---|------------------------------------|-------------|-------|
| Work material | Tool geometry | Vc (m/min) | Feed (mm/rev) | Thrust (N) | Torque (Nm) | Df |
| KFPR Vf 0.36 | Candle stick drill HSS Φ 10 | 30 | 0.01 | 430 | – | – |
| CFRP | Special drill Φ 10 Carbide K20 | 18 | 0.05 | 120 | 0.3 | – |
| GFRP Vf 0.4 | Trepanning tool HSS Φ 10 | 50 | 0.2 | 40 | 0.5 | – |
| CFRP | Φ 6.35 Point angle of 75° to 160° | 45–65 | 0.03–0.04 | 40 | – | – |
| CFRP Vf 0.55 | Helical flute Φ 5 Carbide K10 | 16 | 0.04 | – | – | 1.042 |
| CFRP Vf 0.55 | Brad & Spur Φ 5 Carbide K10 | 30 | 0.05 | – | – | 1.01 |
| GFRP Vf 0.65 | Brad & Spur Φ 5 Carbide K10 | 55 | 0.05 | 6.27 | – | 1.024 |
| CFRP Vf 0.55 | Candle stick Saw drill | 31 | 0.02 | – | – | 1.30 |
| CFRP Vf 0.55 | Twist drill Step drill Saw drill Candle stick Core drill | 28–31 | 0.007 0.049 0.0051 0.069 0.0047 | 35 29.8 28.6 25.1 42.6 | – | – |
| CFRP Vf 0.55 | Step core drill | 1200 rpm | 0.006 | – | – | – |
| GFRP Vf 0.4 | Φ 6, 3 flute solid carbide | 12 | 0.04 | 20 | – | – |
| UD GFRP Vf 0.56 | Φ 6 HSS 90° point angle | 28 | 0.075 | 60 | – | 1.03 |

Vc = Cutting speed m/min, f = Feed rate mm/rev, Fz = Thrust N, Tq = Torque Nm, Df: Delamination factor

3.3 Cutting Tools for Milling (Edge Trimming) of CFRP Composites

3.3.1 Introduction

Unlike in the case of metals, the machining of Fiber-Reinforced Composites (FRPs) is characterized by uncontrolled fracture and the machining forces oscillate due to the subsequent constituents. Owing to the inhomogeneous and anisotropic material properties, machining of CFRP comes along with certain difficulties such as fiber pull-out, delamination and decomposition of matrix material, which results in a degradation of the surface quality and the material properties. The different material

Table 3 Critical drilling parameters on composites

| Cutting parameters | | Machinability characteristics | | | |
|--------------------|--|-------------------------------|---------------|----------|-------|
| Work material | Tool geometry | Speed (m/min) | Feed (mm/rev) | Thrust N | DF |
| GFRP Vf 0.4 | HSS $\Phi 6$ mm | 12 | 0.04 | 30 | – |
| GFRP Vf 0.4 | Tipped WC $\Phi 6$ mm | 18.5 | 0.02 | 30 | 1.005 |
| GFRP Vf 0.63 | Tripod, Carbide K10, $\Phi 6.5$ mm | 80 | 0.1 | 50 | 1.02 |
| GFRP Vf 0.66 | Tipped carbide K10, $\Phi 6.5$ mm Point angle 85° | 80 | 0.08 | 50 | – |
| GFRP Vf 0.63 | Coated carbide | 19 | 0.08 | – | – |
| GFRP Vf 0.65 | Carbide K20 $\Phi 6$ mm | 10 | 0.02 | – | – |

F_z = Thrust N, Df: Delamination factor

properties of the constituent phases and the different failure modes drastically reduce the tool life. Hence, specially designed tools are required for machining of FRPs.

Machinability is mainly influenced by the mechanical properties of the CFRP which is determined by the type of fiber, the matrix material, the fiber volume content, the fiber orientation and the manufacturing process. For the application of composite materials, such as in the case of aircraft structures or in machine elements, some accurate surfaces for bearing mounting or adhesive joints are required. Hence it is important to carry out proper machining such as edge trimming in order to ensure surface quality and dimensional stability at the edges of parts.

Peripheral milling is normally known as ‘edge trimming’ because the tool diameter is small and the axial engagement encompasses the entire thickness of the workpiece. Figure 3 presents the schematic diagram of edge trimming operation and the direction of the cutting forces induced.

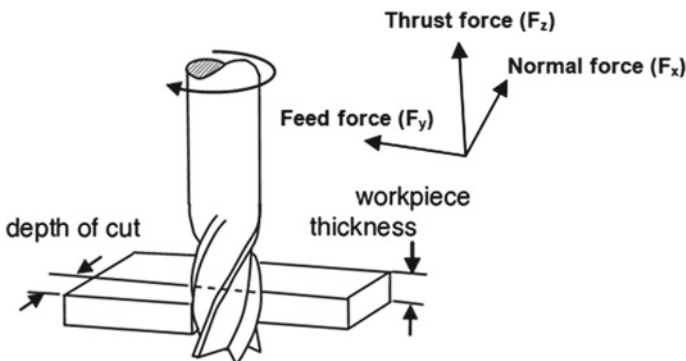


Fig. 3 Edge trimming

3.3.2 Fluted and Router Cutting Tools for High Speed Edge Trimming of CFRP Composites

Materials and Methods

This section presents the effect of various cutting conditions and different types of the cutting tools such as helical flute, and router type tools during edge trimming of quasi-isotropic CFRP laminate. The effect of cutting tool geometries and cutting parameters on cutting forces, the surface quality of the trimmed edges of CFRP laminates is studied. The modern cutting tools (router tools) selected for machining CFRP, have complex geometries in cutting edges and surfaces. Hence, the traditional method of direct tool wear evaluation is both difficult and inadequate. Taking this into consideration, an acoustic emission (AE) sensing has been employed for online monitoring of the performance of router tools to determine the relationship between AE signal and the length of machining.

The quasi-isotropic CFRP as shown in Fig. 4 is made using unidirectional prepregs supplied by Hexcel Composite Company, referenced under HEXPLY UD T700 268 M21 34% (T700-M21). The quasi-isotropic CFRP laminate has the stacking sequence of $[90^\circ/-45^\circ/0^\circ/+45^\circ]_{2s}$. CFRP laminates are compacted using a vacuum pump and then cured in an autoclave. The nominal fibre volume fraction is found to be 0.59.

As the CFRP materials are highly abrasive in nature, it is necessary that cutting tools incorporate a unique tool geometry that can effectively respond to these requirements.

Two varieties of router tools with different geometries and one helical fluted tool made up of tungsten carbide of grade of K600 (ultra-fine grain cemented carbide) are considered to investigate the performance on edge trimming. The teeth on the router tool are shaped by two intersecting flutes, right angle and left angle. The right angle flutes were inclined at 15 degrees. The intersection of these flutes creates cutting teeth of trapezoidal and pyramidal shapes.

Figure 5a–c shows the three tools of $\varnothing 6$ mm made up of tungsten carbide namely router type—trapezoidal tooth (Tool T1), router type—pyramidal tooth (Tool T2) and four fluted helical end mill (Tool T3).

Table 4 shows the detailed specification of three different tools for edge trimming of CFRP material.

Fig. 4 Quasi-isotropic CFRP laminate (Prakash [18])



Fig. 5 a Tool T1 b Tool T2
c Tool T3

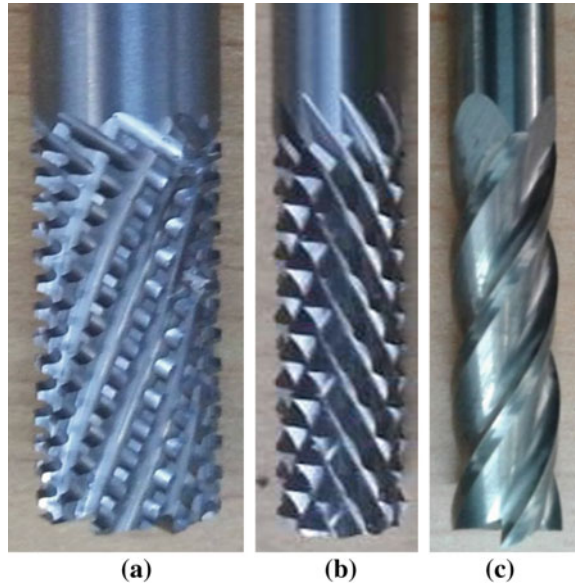


Table 4 Cutting tools and their specification (Prakash [18])

| Tool | Specification | Tool image | Tooth shape | Tooth profile |
|---------|----------------------------|------------|-------------|---------------|
| Tool T1 | Pitch = 3.42 mm | | | |
| | No. of flutes-12 | | | |
| | Tooth shape-trapezoidal | | | |
| Tool T2 | Pitch = 2.42 mm | | | |
| | No. of flutes-12 | | | |
| | Tooth shape-pyramidal | | | |
| Tool T3 | Helix angle 30° | | | |
| | No. of flutes-4 | | | |
| | Tooth shape- helical flute | | | |

Figure 6 shows the schematic representation of set up used for edge trimming and the online measurement of cutting forces, cutting tool temperatures, and tool wear.

Table 5 presents the different machining parameters at different levels selected provided with, the axial depth of cut of 4.16 mm, the radial depth of cut of 0.5 mm,

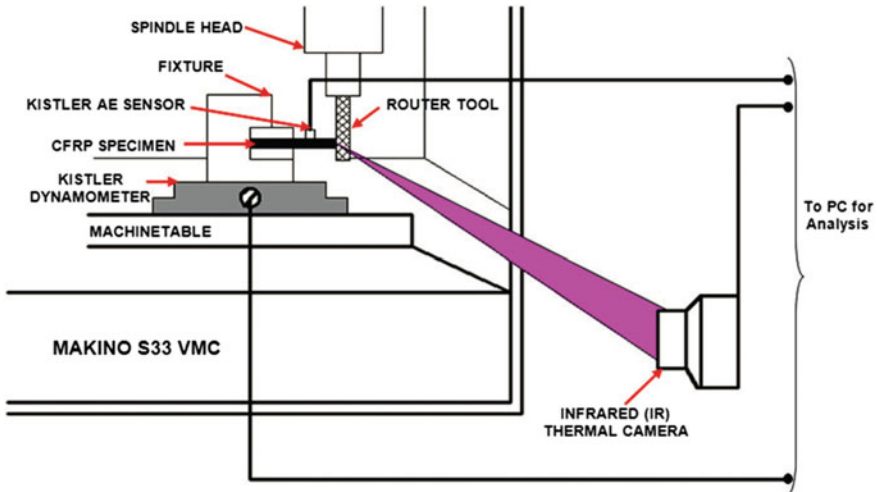


Fig. 6 Schematic diagram of experimental setup for edge trimming (Prakash [19])

Table 5 Machining parameters (Prakash [18])

| S.No. | Cutting parameters | Levels |
|-------|--------------------------|------------------|
| 1 | Spindle speed (rpm) | 3000, 6000, 9000 |
| 2 | Feed (mm/rev) | 0.1, 0.15, 0.2 |
| 3 | Radial depth of cut (mm) | 0.5 |

and the cutting configuration of up milling with dry condition for all the cutting trials during edge trimming operations.

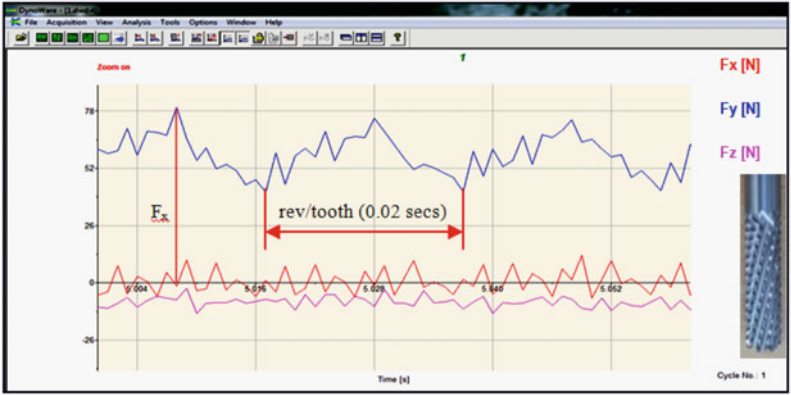
Effect of tool geometries and cutting parameters

Cutting Forces

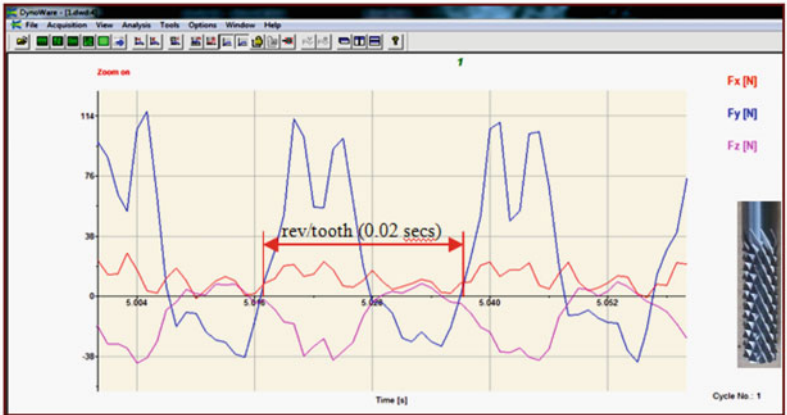
The cutting force is one of the important process criteria for considering the surface damage of workpieces and failures in the cutting tool. The resultant cutting force $R(N)$ is calculated using the Eq. (1) from the three forces, feed force F_y (cutting force acting along the direction of the feed), normal force F_x (cutting force acting perpendicular to the feed) and thrust force F_z (cutting force acting along the axis of the cutting tool) generated during the edge trimming process.

$$R(N) = \sqrt{(F_x)^2 + (F_y)^2 + (F_z)^2} \tag{1}$$

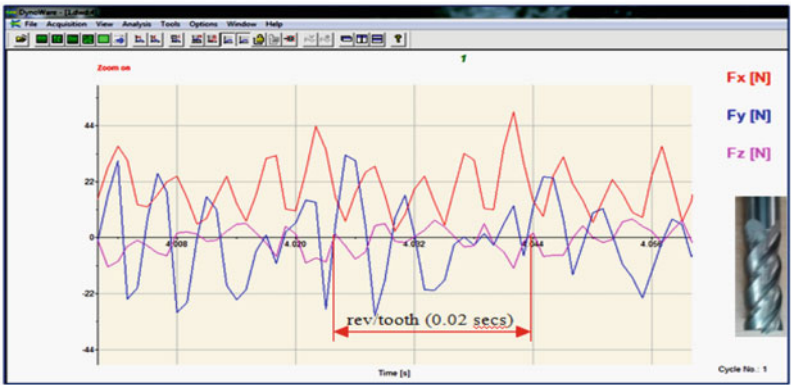
Figure 7a–c are the force graphs representing the machining behaviour of three different tools at the machining conditions of spindle speed 3000 rpm, feed rate 0.1 mm/rev and radial depth of cut 0.5 mm. From these force graphs it is observed that the lowest magnitude and fluctuations of feed force (F_y) generated while using



(a)



(b)



(c)

Fig. 7 Cutting forces graphs at 3000 rpm; 0.1 mm/rev and WOC = 0.5 mm observed for a Tool T1; b Tool T2, and c Tool T3

trapezoidal tooth router tool (T1) when compared to other tools. Whereas the normal force (F_x) and the thrust force (F_z) induced in this case are very low in magnitude, though the fluctuations are high. Therefore the geometry of trapezoidal tooth of this kind of router (T1) performs well in chip removal with lesser damages or defects. However, in the case of pyramidal tooth router tool (T2), the normal force induced with high magnitude and fluctuations results in more damages in the workpiece.

The resultant cutting force increases with an increase in spindle speed as well as feed for all the three kinds of tools. It is also inferred that tool T1 generated lower cutting force when compared to other two tools because of the trapezoidal shape of the cutting teeth. Tool T2 has generated comparatively higher cutting forces because of the pyramidal shape with smaller cutting edge and clearance face, when compared to trapezoidal cutting edge. Also tool T2 induced greater ploughing action and improper shearing of fibers resulting in increased fiber protrusion on the edges of the plies of the CFRP laminate.

The mean percentage of increase in cutting force with tool T2 when compared to tool T1 at all three spindle speeds as 56.7% and mean percentage of increase in cutting force with tool T3 when compared to tool T1 at all three spindle speeds as 58.66%. When machining with tool T1, the minimum force measured was 15.21 N at a spindle speed of 3000 rpm and feed of 0.1 mm/rev. When machining with helical fluted tool T3, the maximum force measured was 59.26 N at a spindle speed of 9000 rpm and feed of 0.2 mm/rev. The reason for these highest forces in tool T3 is that the tool cuts the largest chip per tooth (three times as large as the other tools T1 and T2 which have the 12 number of flutes which is 3 times more when compared to tool T1 with 4 flutes).

Surface Roughness

Tool T1 gives a moderate surface roughness due to the trapezoidal shape of cutting teeth when compared to tools T2 and T3. The mean percentage decrease in surface roughness value with tool T1, when compared to T2, is 32.87%. The surface roughness obtained using tool T3 at all spindle speeds is less because of tool T3 has helical flutes. The mean percentage decrease in surface roughness value with tool T3, when compared to T2 is 57.89%. However, the scooping action of these flutes while machining results in lowering the roughness in the edges of the machined workpieces. Tool T2 gives the higher surface roughness value at all spindle speeds due to the presence of a sharp cutting edge of pyramid shaped tooth profile.

Delamination

Delamination is one of the important measure of surface quality of the trimmed edges of the CFRP laminates. It is observed that there is no delamination occurred while using tool T1 and tool T2. Since the axial force developed was small, the delamination of top plies was controlled to a very minimum level. This is due to unique geometry of cutting tooth with more number of flutes on router tools T1 and T2. A significant delamination value was measured while using tool T3 because the tool tends to develop a high axial force which in turn separates or disintegrates the extreme top plies of CFRP laminate. Yet another reason for delamination with the

helical fluted tool is that the chip per tooth is three times higher than the other tools, as the number flutes in the helical flute tool is one-third of the number of flutes in both the router tools. Further, the chip is not broken into small segments because of the continuous cutting edge in the helical flute tool. These continuous chips make the impact of the cutting edge on the laminate to cause severe delamination.

Acoustic Emission (AE) Signal Measurement

Crack propagation is one of the macroscopic sources of AE. Cracks and other discontinuities in a work material concentrate on stresses. Crack jumps are accompanied by a rapid release of potential energy, a small part of which is released in the form of stress waves. Materials produce acoustic emissions when they are stressed beyond their normal design ranges to final failure. During plastic deformation, dislocations move through the material’s crystal lattice structure producing low-amplitude AE signals, which can be measured only over short distances under laboratory conditions. AE waves generated are related to failure propagated such as deformation or damages during cutting. Therefore, AE waves caused by cutting action between the cutting tool and the workpiece is considered as part of the performance of the cutting tool. AE Out (Filter) mean value increases as the wear in the tool increases during continuous machining. The magnitude of the AE signal is considered as the measure of performance of the tool. Higher the AE signal, the poorer is the performance of the tool.

The AE signals were recorded on edge trimming under the cutting conditions of high spindle speed of 9000 rpm and high feed of 0.2 mm/rev for 1 m length of machining of CFRP laminate.

From the Fig. 8, it is observed that AE Out (Filter) value increases with an increase in the length of machining for all the three types of tools. In other words, tool performance decreases as the length of machining progresses. AE signal level is the function of machining performance. Since the router tool T1 has the lowest chip thickness/tooth and better tool geometry when compared to tool T2 & T3, it results in

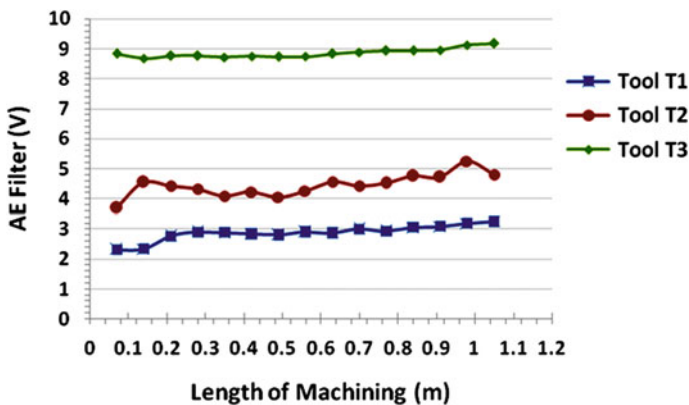


Fig. 8 AE Out (filter) values Vs Length of machining for different tools (Prakash [18])

Table 6 Consolidated results (Prakash [18])

| Tool | Output Responses | | | |
|---------|------------------|-------------------|--------------|--------------------|
| | Cutting Force | Surface Roughness | Delamination | Cutting Efficiency |
| Tool T1 | Low | Moderate | Low | High |
| Tool T2 | Moderate | High | Low | Moderate |
| Tool T3 | High | Low | High | Low |

lowest signal values of AE out filter values (in Volts). Therefore, tool T1 is considered to provide better cutting efficiency when compared to tools T2 and T3. The flute tool has the highest AE out filter, values which in turn indicate the poor cutting efficiency while trimming of CFRP laminate.

Table 6 depicts the output responses such as cutting force, surface roughness, and delamination for the three different tools used for edge trimming of CFRP laminate. From the analysis, it is inferred that tool T1 generates low cutting force, offers no delamination with a moderate surface roughness, and also provides high cutting efficiency, while the tool T3 generates a higher cutting force, increased delamination with a good surface finish. Tool T2 seems to provide a moderate cutting force, with a high surface roughness and low delamination.

Summary

- It was found that the trapezoidal tooth router (T1) generated lower cutting force and moderate surface roughness with no delamination while machining of CFRP materials. The performance of the tool was also found to be the superior among the three tools, as the cutting tooth of trapezoidal shape with more cutting area creates lower surface damages in the trimmed edges.
- It was observed that the machined edges of CFRP specimens have no delamination as both the router tools (T1 and T2) have discontinuous cutting edges unlike in the case of continuous edge in the helical flute tool.
- The pyramidal tooth router (T2) generated higher surface roughness when compared to the other two types of tools. The cutting tooth has a small flat edged pyramid form creates more indentations on the workpiece surface. This, in turn, results in increasing the surface roughness.
- The helical flute end mill (T3) generated higher cutting forces and more delamination when compared to router tools (T1 and T2). The continuous flutes with higher helical angle cause the pulling action of the extreme top and bottom plies of the laminate, which results in delamination.

Fig. 9 Cutting Tools
(Router type) (Prakash [19])



3.3.3 Coated Router Tools for High Speed Edge Trimming of CFRP Composites

Introduction

This chapter presents the investigations on effect of coatings on surface quality of trimmed edges and tool wear, during high-speed edge trimming of CFRP materials. Two different coated router tools (trapezoidal tooth type) namely titanium aluminium nitride (TiAlN) coated and diamond like carbon (DLC) coated routers were used for studying the effect of coatings during high-speed edge trimming operation. The experimental study gives the effect of machining parameters (cutting speed and feed) and coating materials, on cutting force, cutting temperatures, which significantly influence surface roughness of the workpiece and tool wear.

Materials and Methods

Hardness of the tool material and coefficient of friction between tool/work interface play a major role in attaining the desired surface quality of the work and longer tool life. Figure 9 shows the cutting tools selected for conducting this study. Two different coatings, namely titanium aluminium nitride (TiAlN) and diamond like carbon (DLC) coatings were selected for achieving quality trimmed edge surfaces and extended tool life due to their excellent tribological properties.

These coatings are thin, chemically inert and also have a low surface roughness. The standard thickness of the coatings is $4\ \mu\text{m}$ and it was deposited on tungsten carbide router tools using the PVD magnetron sputtering technique. Table 7 shows the specification and the properties of three different router tools used in the experiment.

Table 8 shows the machining parameters considered with their different levels to conduct edge trimming operation using uncoated and coated router tools while keeping the radial depth of cut of 0.5 mm as constant and the axial depth of cut is equal to the laminate thickness of 4.16 mm.

Effect of coatings and cutting parameters

Cutting Force

In edge trimming, more than one cutting edge is engaged in cutting at the same time which presents difficulty to the process with respect to fibre orientation, chip size, and cutting forces. The cutting forces generated have a direct relationship between

Table 7 Specification and properties of router tools (Prakash [19])

| Tools used | Uncoated router tool | TiAlN coated router tool | DLC coated router tool |
|---|---|--------------------------|------------------------|
| Specification | Material—Tungsten Carbide, Diameter = 6 mm, Pitch = 3.42 mm, No. of flutes (right-handed) = 12, Tooth shape—Trapezoidal | | |
| Vickers Hardness | 2500 HV | 3500 HV | 3000 HV |
| Coefficient of friction | 0.6 | 0.5 | 0.1–0.2 |
| Thermal conductivity W/m ² K | 88 | 4.63 | 100–150 |

Table 8 Machining parameters (Prakash [19])

| Cutting Parameters | Levels |
|--------------------------|----------------|
| Cutting speed (m/min) | 226, 283, 339 |
| Feed rate (mm/rev) | 0.1, 0.15, 0.2 |
| Radial depth of cut (mm) | 0.5 |

the thickness of the chip produced while trimming. Therefore, the lesser the chip thickness, lower the cutting forces. As the chip thickness is also the function of feed value from the Eq. (2), a smaller feed will result in smaller chip thickness, thus reducing the cutting force generated.

$$\text{Maximum chip thickness } a_{\max} = \frac{v_f \sin \phi}{TN} \tag{2}$$

(Source: Jamal Sheikh-Ahmad [20])

Where, v_f —feed speed, T —Number of cutting edges, N —Spindle speed, and ϕ —Total engagement angle.

The resultant cutting force is the function of cutting speed and feed. It is further observed that the resultant cutting forces systematically increases with an increase in feed for all three cutters. This is due to the geometrical increase in chip thickness as a result of increasing the feed. However, the behaviour with cutting speed is not always consistent.

In case of uncoated and TiAlN coated tool, for most feeds, the resultant force tend to increase with an increase in cutting speed and decreases with a further increase in cutting speed. Since the chip thickness does not change with the increase of cutting speed, this force behaviour might be a result of the dynamic response of the cutter/spindle at this particular cutting speed. In the case of DLC coated tool, the resultant force does not change significantly with cutting speed as the expected and the resultant forces are comparatively lower than those obtained for the other

tools. This could be attributed to the properties of low coefficient of friction and high thermal conductivity.

Cutting Temperature

The rise in temperature is an inevitable factor regarding high-speed machining processes. Hence it is necessary to monitor the cutting temperatures in edge trimming of CFRP laminate under high-speed conditions. The cutting temperature generated during machining is also the function of cutting speed and feed. It is observed that the cutting temperature does not change significantly with process parameters for the uncoated tool and the DLC coated tool. However, the behaviour of the cutting temperatures for the TiAlN coated tool is similar to that of the resultant force. Furthermore, the cutting temperatures for the uncoated and DLC coated tools are lower than those for the TiAlN coated tool. The cutting tool temperature is generally lower for cutting tools with a high thermal conductivity. It is observed that the cutting temperatures for all the cutting conditions fall below the glass transition temperature ($T_g = 187^\circ\text{C}$) of CFRP material, which ensures the absence of thermal damage.

The maximum temperature is attained at the intermediate cutting speed of 283 m/min and low feed of 0.1 mm/rev with TiAlN-coated router due to the reason of high heat accumulation at the machining zone (i.e. shear zone where exact shearing of material takes place). Further, heat dissipation is comparatively slower due to its poor thermal conductivity. DLC coated routers, generates less temperature when compared to TiAlN coated routers. This is because of the DLC coating which has very low coefficient of friction and excellent thermal conductivity when compared to TiAlN coating.

Surface Roughness

Surface roughness (Ra) value increases with an increase in feed, as deduced from the equation for ideal surface roughness. However, the behaviour of surface roughness with speed is similar to that of the cutting forces. An increase in feed per tooth (resulting from increasing the feed rate) causes an increase in surface roughness as well. This may be attributed to the heat generated as a result of higher friction. An increase in feed rate causes a sharp rise in feed force, which in turn causes higher friction. Surface roughness tends to decrease with an increase in cutting speed. Among all the factors, the feed rate is the most influential one in determining surface roughness.

As the cutting speed increases, the Ra value increases initially and then decreases. Surface roughness is the highest at the intermediate level of cutting speed (i.e. at 283 m/min) and at all feeds the cutting forces generated were higher as the frictional resistance developed to cut the material is high, thereby the temperature generated at this condition is also showing with higher values. At this stage of higher temperature, the resin gets softened and facilitates further machining with less cutting force. These reasons will also be considered for the result of higher surface roughness at this intermediate condition. While a low surface roughness value is obtained at 339 m/min and 0.1 mm/rev while using DLC coated tool, a high surface roughness value is obtained at 283 m/min and 0.2 mm/rev while using the TiAlN coated tool. DLC

coated tools provide better surface quality with minimum damages when compared to the other tools at high cutting speed conditions. Since the surface roughness is the measure of cutting force and the cutting temperature generated, the surface roughness observed in the trimmed edges of CFRP work materials using DLC coated router is lower which is because of its unique composition and structure with its salient characteristics of low coefficient of friction and excellent thermal conductivity, and wear resistance and non-sticking characteristics.

Tool Wear

Since tool wear leads to undesirable consequences such as increased cutting forces, cutting temperatures, and degradation of surface finish, therefore, it is extremely desirable to control the same. Abrasion is the primary wear mechanism when trimming CFRPs. Therefore, a great deal of resistance to abrasive wear and high fracture toughness are essential for cutting tools during trimming. Thermal conductivity is an important property because most of the heat generated during cutting has to be dissipated through the cutting tool. The fine-grained cemented carbides with coatings such as TiAlN and diamond like carbon (DLC) tend to meet these requirements.

Tool wear occurs both on the face and flank, but depending upon the machining conditions, one of these types of wear may predominate. Figure 10a, b presents the wear of the uncoated tool occurred as rounding of the cutting edge at tooth corner. Flank wear is measured as the width of the wear land on the clearance side as shown

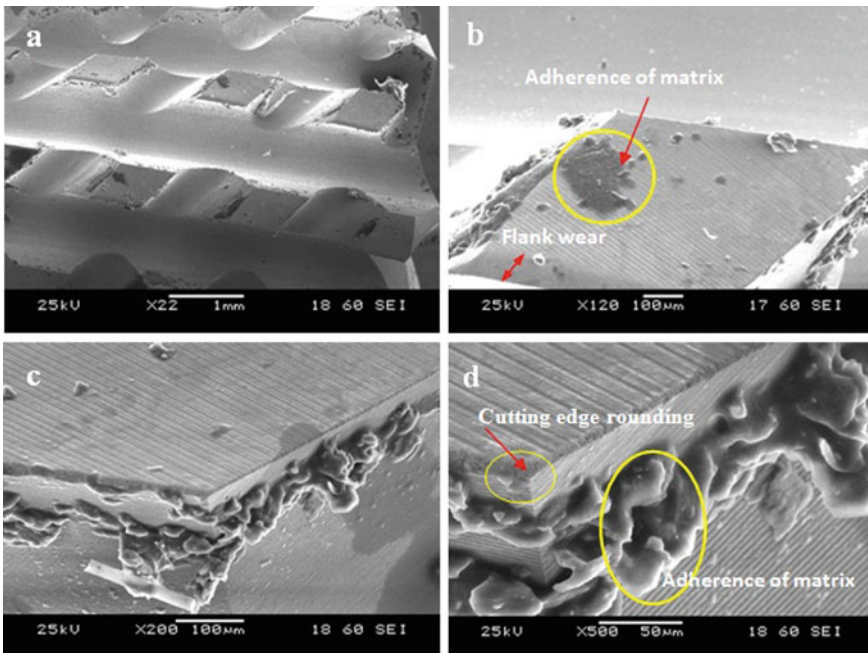


Fig. 10 a–d SEM Images of uncoated router tool (after machining) (Prakash [19])

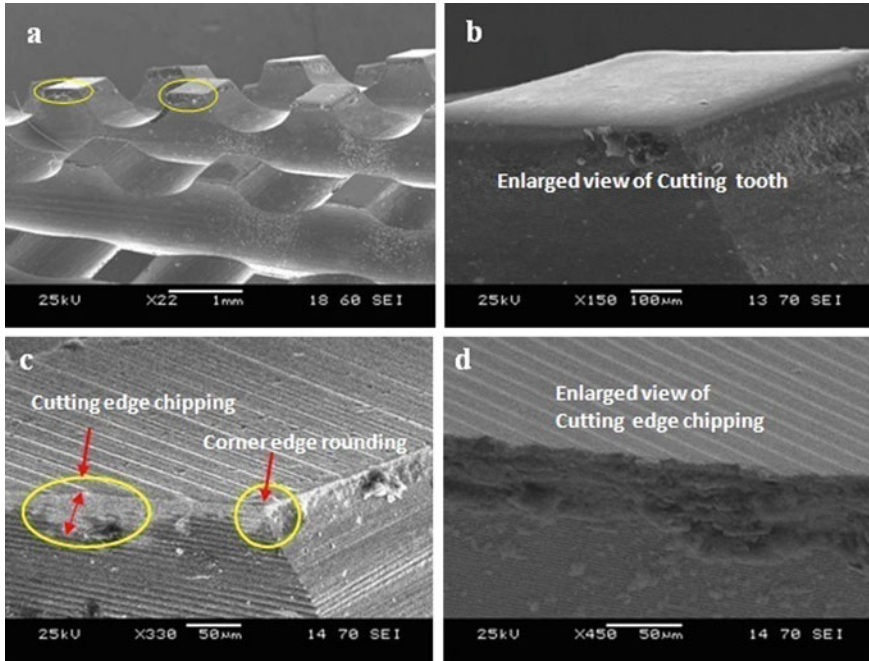


Fig. 11 a–d SEM Images of TiAlN coated router tool (after machining) (Prakash [19])

in Fig. 10b. Figure 10c, d shows the damage at the corners (Cutting edge rounding (CER)) and the adherence of matrix at the tool faces (Ali Faraz et al. [21]).

The wear of the TiAlN coated tool seems to occur due to chipping of the coating and rounding of the uncovered substrate, as shown in Fig. 11a, b. Figure 11c, d shows the CER and the cutting edge chipping.

Wear of the DLC coated tool was also found to be uniform rounding of the edge and corner of the tooth, as shown in Fig. 12a, b. Figure 12c, d shows the CER at the DLC coated tool. The wear of DLC cutter was relatively smaller than that of the TiAlN coated and uncoated tools. The main reasons could be its very low coefficient of friction, and hardness of the DLC coated router. SEM images also show matrix adhering to the surface of the tool due to high cutting temperatures.

Figure 13 shows the effect of direct tool wear (measured using tool makers microscope) on length of machining for uncoated and coated router tools at the machining conditions of intermediate cutting speed 283 m/min and a feed 0.2 mm/rev. From the comparison of among three tools, it reveals that the DLC coated routers seem to perform better well with lesser tool wear and fewer surface damages on the trimmed edges.

Tool Wear Monitoring Using AE

The crest factor (C) is defined either by Eq. (3) and is a monitoring index that gives an idea of how much of impact occurring in a time waveform.

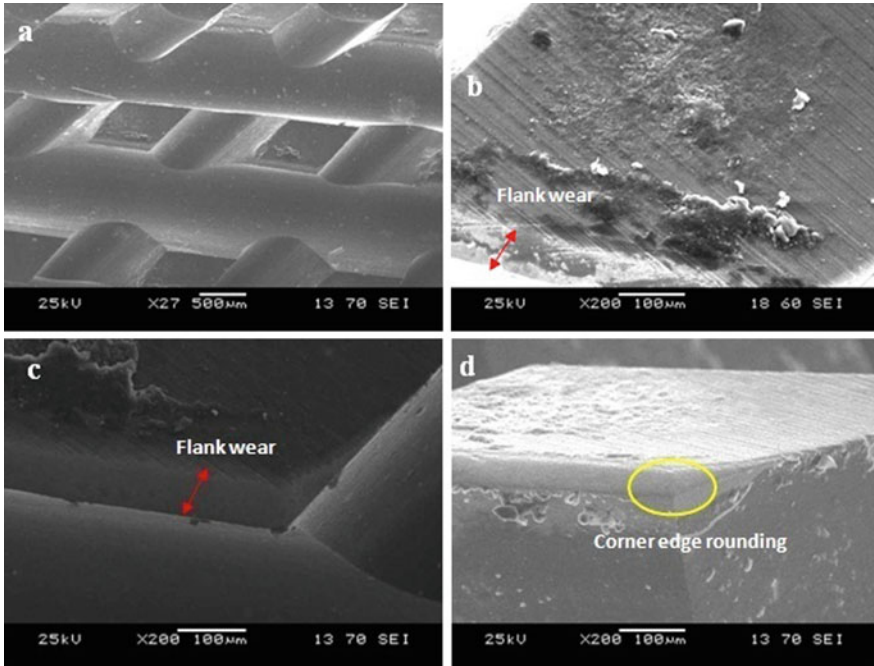
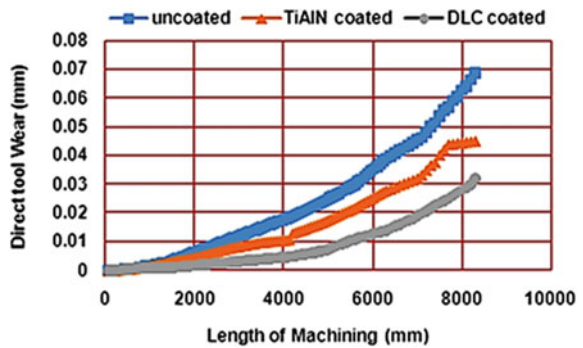


Fig. 12 a–d SEM Images of DLC coated router tool (after machining) (Prakash [19])

Fig. 13 Comparison of direct tool wear for the three tools (Prakash [19])



$$Crest\ factor(C) = \frac{Peak\ amplitude\ of\ a\ waveform}{RMS} \tag{3}$$

The crest factor is trended over time to see if the amount of impacting increases or stays the same.

Acoustic emission online tool condition monitoring and evaluation of tool wear is performed at the cutting speed of 283 m/min and a feed of 0.2 mm/rev. The variation

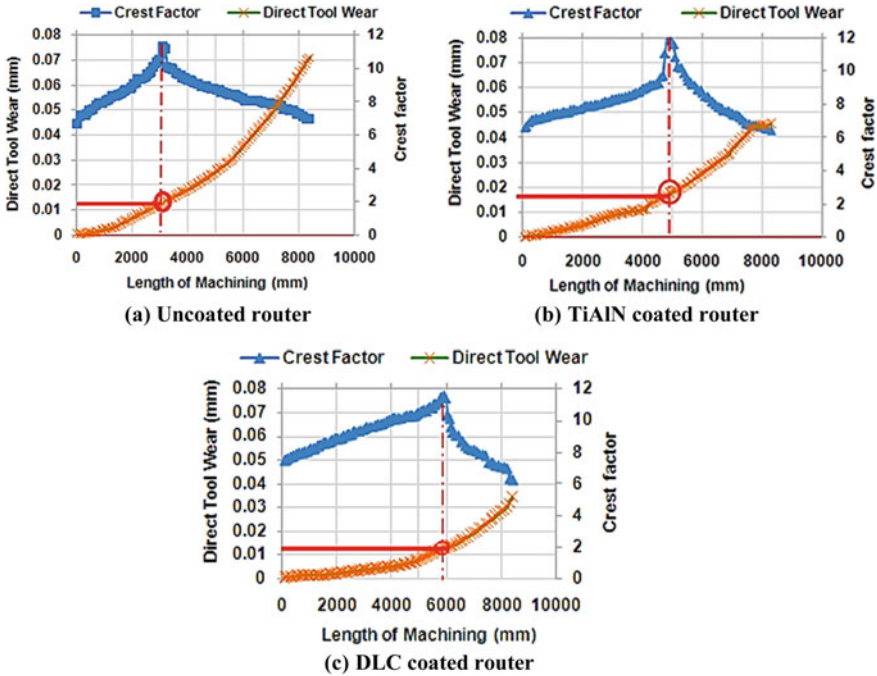


Fig. 14 a–c Tool wear monitoring for the three tools (Prakash [19])

in the AE signal crest factor and direct tool wear with the length of machining are presented in Fig. 14a–c.

It is understood that the value of the crest factor increases rapidly up to a certain length of machining, and then decreases rapidly with a further increase in cutting length. This decrease is possibly due to the rubbing of worn router flank with work material, resulting into low energy release. Further, a decrease in monitoring index beyond a certain value of wear could be due to dampening of the AE signals by the thermal influence associated with worn cutting edges in rubbing mode at higher tool wear condition. Corresponding to change in the trend of the monitoring index is a sudden increase in tool wear, which clearly indicates a threshold for limiting the usable router condition for trimming of CFRP composite (Velayudham [22]). Thus, from the graph, a control monitoring strategy can be determined at the point where the change in the curve of crest factor indicating that thereafter, the tool could be considered as a worn tool. Thus, the life of the three tools regarding machining length before regrinding/recoating can also be predicted. The tool life in terms of total machining length (in mm) for the three tools was determined from the graphs for all the three tools.

Table 9 shows the comparison of tool life for all tools and the DLC coated router tool provides a high total machining length with fewer surface damages on CFRP trimmed edges.

Table 9 Tool life (total machining length) for the three tools (Prakash [19])

| Tool | Tool life in terms of total machining length in mm |
|--------------------------|--|
| Uncoated router tool | 3150 |
| TiAlN Coated router tool | 4830 |
| DLC Coated router tool | 5880 |

Summary

- High-speed edge trimming with a low coefficient of friction DLC-coated router tool generated cutting tool temperature well below the glass transition temperature. Also, it was observed that there were no defects due to thermal degradation of resins with DLC-coated router tool.
- DLC-coated router tool trimmed the edges with a good surface finish of lower surface roughness value is achieved due to its better surface characteristics when compared to other two types of router tools.
- While considering the performance of the tool, the DLC-coated router tool performs well for the highest machining length of around 5.9 m which is about 46% increase in length of machining when compared to the value of uncoated router with relatively fewer surface damages. This significant increase in length of machining causes significant reduction in tooling cost which is an essential requirement in industry perception.
- Although TiAlN-coated router tool produced less tool wear and higher tool performance than uncoated router tool, TiAlN-coated router tool generated higher cutting forces at certain conditions when compared to uncoated tools because of the coating thickness which may reduce the cutting edge sharpness (i.e. increase the edge radius).
- Online tool condition monitoring using AE approach is found to be an appropriate technique for measuring the performance of cutting tools having high complex geometry such as router tools for machining polymer composites.

4 Cutting Tools for Machining Metal Matrix Composites

4.1 Introduction

Metal matrix composites (MMCs) offer high strength-to-weight ratio, high stiffness and better damage resistance over a wide range of operating conditions, making them an attractive option in replacing conventional materials for many engineering applications. Typically the metal matrix materials of MMCs are aluminum alloys, titanium alloys, copper alloys and magnesium alloys, while the reinforcement materials are silicon carbide, aluminium oxide, boron carbide, graphite etc. in the form of fibres, whiskers and particles [23].

MMCs are shown to cause excessive tool wear, which in turn induces such damage phenomena as fiber pullout, particle fracture, delamination and debonding at the fibre or particle and matrix interface. The parameters that are the major contributors to the machinability of these composites are the reinforcement type and orientation, tool type and geometry and the machining parameters. Although MMCs are generally processed near-net shape, subsequent machining operations are inevitable. On machining of MMCs it is obvious that the reinforcement material, type of reinforcement (particle or whisker), volume fraction of the reinforcement, and matrix properties as well as the distribution of these particles in the matrix are the factors that affect the overall machinability of these composites.

Machining Al/SiC composites is one of the major problems which resist its widespread engineering applications. Previous studies have shown that the tool wear is excessive, and the surface finish is poor when carbide tools are used. The SiC particles are much harder than the WC tool material that leads to a high wear rate by abrasion. The cutting edge is rapidly worn, and that results to poor surface finish. In addition, due to friction, high temperature and pressure, the Al/SiC composite work-material adheres to the cutting edge to form a built-up-edge (BUE) which also has a negative effect on surface finish [24].

This chapter deals with the cutting tool requirements for machining metal matrix composites. The tool materials normally available are ranging from high-speed steel to poly crystalline diamond including diamond coated tools. Improper tooling not only escalate the component cost, also induce subsurface damage of a MMC component. The hardness of matrix is the most significant characteristics which affects the machinability of MMC. Higher the matrix hardness shortens the tool life. The reinforcement hardness is also a dominant factor for tool wear. The coarser reinforcements and higher volume fractions largely influenced the tool performance and required cutting tools with high hardness.

4.2 Cutting Tools

The most commonly used tool material is polycrystalline diamond (PCD) [25], although cubic boron nitride (CBN), alumina, silicon nitride and tungsten carbide (WC) tooling are used as cutting materials. Cutting speed, feed and depth of cut in machining of particulate MMCs have a similar effect on tool life and surface finish to that of machining metals although some differences are noticeable due to the ceramic particles. The ceramic-reinforced particles tend to dislodge from the matrix and roll in front of the cutting tool, thereby plowing through the machined surface and generating grooves on it [26].

Hung et al. [27] reported that the cubic boron nitride (CBN) and poly-crystalline diamond (PCD) tools are better than a tungsten carbide (WC) tool in terms of wear resistance. The PCD tools can be used for the finishing operations resulting with minimum sub-surface damages, while a WC tool could be used economically for a roughing operation. The parameter, grain size of the cutting tool influences a major

role in deciding the tool life. The tool life of the large grain sized PCD tools are higher as they are not chipped off even at higher cutting conditions. The tool life can also be improved better by diamond coating of carbide tools with complex geometry. The PCD tools can be used effectively to machine MMCs in turning, milling, facing, drilling, boring, reaming, threading, tapping, and grinding.

The less expensive diamond-coated tools offer as a promising alternative to solid diamond tool, if adequate adhesion of the coating is guaranteed. PCD diamond tools are the most preferred, while carbide tools are preferred over ceramic tools [24]. While machining of these composites with carbide tooling, low-cutting speeds and high-feed rates are utilized to minimize tool wear. At higher cutting speeds, the carbide tool is subjected to catastrophic failure.

Tomac and Tonnessen [28] investigated the machinability of Al-SiC MMCs using PCD, chemical vapor deposition (CVD), and coated tungsten carbide tools and revealed that abrasive wear is the main mode of tool failure. The PCD tools had over 30 times higher tool life than carbides they used under similar cutting conditions. In addition, the CVD tools were better than other less hard cutting tools except PCD. While comparing the performance of chemical vapor deposition (CVD) coatings of TiN, TiCN and Al₂O₃, the inserts with TiN coating performed the best in maximizing the tool life. Tonshoff and Winkler [29] reported that the TiN coatings have shorter life and the PCD-coated tools showed good performance before the deterioration of the coating film. Compared to coated of PCD tools, PCD-tipped tools showed better results. To minimize the surface roughness and sub-surface damage PCD tools are preferred since the wear rate associated with them is the lowest among available tool materials. Although PCD tools are used for machining Al/SiC composites, the high cost associated with them limits their use [30].

Since abrasion is the primary source of tool wear at different feed rates, the recommendations are to use high feed rates and depths of cut during roughing operations. Several researchers have also indicated that polycrystalline diamond (PCD) tools are the only tool material that is capable of providing a useful tool life during the machining of particulate light metal MMCs. PCD is sufficiently harder than most of the ceramic reinforcements and has no chemical tendency to react with the workpiece material. Furthermore, PCD tools contain larger grain structures that withstand more abrasion wear by micro-cutting compared to tools with a smaller grain structure. El-Gallab and Sklad [31], studied the performance of PCD tools during turning MMCs. Grooves on the tool face along the chip flow direction were observed. The grooves on the rake face filled with smeared work material and formed a built-up edge, which seemed to be beneficial since it protected the tool rake from further abrasion.

Coelho et al. [32] continued their attempts by developing PCD tipped drill bits to drill MMC and presented a comparison among the results of different drill tests including the PCD drill bits and other tools such as HSS, diamond coated HSS, WC and TiN coated carbide tools. PCD-tipped drill bits perform the best under different cutting conditions among all the drill materials.

Varadarajan et al. [33] studied that polycrystalline boron nitride (PCBN) tools outperformed coated carbides in terms of tool wear and surface finish. Ding et al.

[34] studied the machinability characteristics with various PCBN and PCD tools. Compared to PCBN tools, the improved tool life was found when using PCD tools.

Diamond tools seem to be the best tool to machine Al/SiC MMCs with acceptable tool life [35]. Diamond is harder than SiC and does not have chemical tendency to react with work material. For cutting tools, diamond is mainly used in two forms: either brazed PCD or chemical vapor deposition (CVD). PCD tools consist of a thin layer of fine diamond particles sintered together and brazed onto a cemented carbide substrate. CVD diamond is a more recent super hard tool material; it consists of pure diamond coating over a carbide substrate. Compared to PCD, CVD diamond is harder, exhibits a lower-friction coefficient, higher abrasion resistance, higher-thermal conductivity and better chemical and thermal stability. Other drawbacks associated to PCD tools are the presence of cobalt binder, which limits the cutting speed and also costs higher [36]. The high thermal conductivity of CVD diamond tool allows heat dissipation and leads to a more uniform and a reduced level temperature distribution avoiding tool failure and limiting adhesive wear [37].

5 Cutting Tools for Machining Ceramic Matrix Composites

Advanced ceramic materials have been used increasing use in industrial applications because of their superior thermal, chemical, and wear-resistance characteristics of ceramics as compared to those of traditional materials. However, a primary obstacle to the use of ceramics for many applications is the high cost of machining these hard materials.

Diamond-cutting tools specifically, diamond-grit grinding wheels are needed in machining ceramics because of the high hardness of the materials. The high price of diamond grinding wheels the expense associated with using diamond materials and the costs of wheel conditioning (e.g., trueing and dressing) makes machining of ceramics difficult. Of all machining processes, grinding is unmatched for the most precision operations. The current requirement is that they should not only machine these ceramic materials but also produce a workpiece with precise dimensions and surface quality.

In the last three decades, an enormous interest in advanced ceramic materials has emerged. However, due to the high cost of ceramic machining, the use of ceramic components is not as enormous as the interest. Currently, diamond grinding accounts for more than 80% of the total ceramic machining [38] and remaining techniques for machining include ultrasonic machining (USM), electrical discharge machining (EDM), abrasive water jet machining (AWJ), laser machining (LM), laser-assisted machining (LAM), plasma-assisted machining, single-point machining, electron-beam and ion-beam machining, microwave machining, and combined machining. Some researchers (Ives et al. [39]) demonstrated that a ductile regime takes place on a localized scale when the grit penetration is limited to a small size, and in this ductile manner there is a decrease in the subsurface damage. But this ductile regime grinding requires low and precise feeds, very small grit depths, and extremely low

material removal rate. The single point turning operation for ceramic machining was also studied in laboratory. Kiso et al. [40] reported that turning with sintered polycrystalline diamond tool is a promising machining process for ZrO₂, but not for Si₃N₄ because of short tool life. Researchers investigated that, in single-point turning, there is a critical-depth parameter which defines the transition from brittle to ductile behaviour in the machined workpiece surface, and in this ductile manner the sub-surface damage can be reduced [41–45].

6 Review Questions

- (1) What are the important factors influencing machinability? And also discuss the significance of cutting tool parameters on machinability of Polymer matrix composites.
- (2) List out the various damages introduced during machining of FRP. Also list the reasons for them.
- (3) Discuss (i) the forces induced on a standard twist drill and (ii) the effect of forces to cause delamination during drilling of FRP.
- (4) What are the important properties of tool material? And also discuss the effect of drill tool material on tool wear and quality of drilled holes.
- (5) Describe the effect of typical tool materials and critical drilling parameters on PMC composites.
- (6) Describe the effect of typical tool geometries and critical drilling parameters on PMC composites.
- (7) Describe the effect of critical drilling parameters on machinability of PMC composites.
- (8) What is edge trimming process? And discuss the various forces induced during this machining process.
- (9) Discuss the various tool geometries of cutting tools used for edge trimming.
- (10) Discuss the effect of tool geometries and cutting parameters on cutting forces, surface roughness and delamination caused during edge trimming operation.
- (11) Describe the importance of online condition monitoring of cutting tool using acoustic emission technique.
- (12) Discuss the effect of coatings (TiAlN and DLC) and cutting parameters on cutting forces, cutting temperature and surface roughness and tool wear caused during edge trimming operation.
- (13) What is the crest factor in acoustic emission technique? And also discuss the significance of crest factor in determining the tool life in length of machining.
- (14) Discuss the various tool requirements for machining metal matrix composites.
- (15) What does ductile regime mean? And list the various machining processes used for machining ceramic matrix composites.

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