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A COMPARATIVE STUDY ON TOOL WEAR AND LAMINATE DAMAGE IN DRILLING OF CARBON-FIBER REINFORCED POLYMERS (CFRP)

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Abstract-Preliminary to successful assembling, drilling of composites like carbon-fiber reinforced polymers (CFRP) is an important but difficult process. The anisotropic and heterogeneous structure of the laminates and the highly abrasive nature of the carbon fibers make it prone to critical damages in the work piece as well as extensive tool wear. In this work, drill series with uncoated and diamond coated tungsten carbide hard metal tools were performed in two CFRP laminates with significant differences in their microstructure. The tool wear behaviour and the corresponding work piece damage were intensively studied to figure out the correlations between wear on light optical microscopy were applied and critically evaluated and delamination damage.

The abrasive tool wear on uncoated carbide drill can be well described by the cutting edge rounding (CER) allowing strong correlations with the inflicted work piece damage, whereas for coated tools measuring CER is not an appropriate method. The machinability of CFRP was found to be highly influenced by the presence of residual porosity in the composite laminate. Hence, the benefit in lifetime of the diamond coating can only be utilized in machining of high quality laminates.[1]

Keywords- CFRP, Drilling, and Tool wear, Delamination, Carbide tool, Diamond coating

1. INTRODUCTION

Tool wear describes the gradual failure of cutting tools due to regular operation. It is a term often associated with tipped tools, tool bits, or drill bits that are used with machine tools.

Drilling is probably the most frequently used operation in industry.

High-strength carbon fiber reinforced plastic (CFRP) is used as the large commercial aircraft material for manufacturing the main load-bearing structural components. Drilling is the mostly used in final machining process of CFRP laminates, while the delamination and burrs occur frequently at the drill exit in the CFRP laminate.

The carbon fibre reinforced plastics (**CFRP**), owing to their anisotropy and abrasive nature of their carbon fibre content, exhibit totally different drilling results as compared to those of drilling common metals and other materials. Different challenges faced in drilling CFRPs in particular, and machining FRPs in general could be classified on the one hand as the excessive tool wear, while on the other hand as work piece material-related problems

The aim of this study is drilling with a twist drill and a specific cutting tool of structural thin backing plates in carbon/epoxy. Drilling with a twist drill of the bolts' holes to fix a stiff plate reinforcement in front of the damage leads to defects and damages at the entrance, on the hole. Wall and at the plate exit.

The possibility to manufacture carbon/epoxy with a conventional cutting tool was analysed and the limits of the twist drill were shown.Consequently we defined a specific cutting tool. Series of comparative experiments were carried out using a conventional twist drill and thisSpecific cutting tool. The results showed the capabilities of the specific cutting tool because several defects and damages usually encountered

In twist drilled holes were minimised or avoided (entrance damage, roundness and diameter defects and plate exit damage).

The using of composite parts is increasing within the design of plane structural elements. For such structures high performance carbon/epoxy material are mainly used. For definitive assembling or structural temporary repairs, the permanent joints are achieved using bolts and it has been verified that the reliability of assembling is sensitive to the quality of the bolt holes.

The possibility to machine with a conventional tool, generally used to metals, was examined. Afterward, the Causes of various damages, observed on a hole, were analysed. These observations allowed us to define a specific tool better adapted to this type of drilling then; the machining behaviour of this specific tool was compared with that of a double fluted conventional drill. Lastly, the holes drilling are observed.

Drilling and fastening of hybrid materials in one-shot operation reduces cycle time of assembly of aerospacestructures. One of the most common problems encountered in automatic drilling and riveting ofmultimaterial is that the continuous chips curl up on the body of the tool. Drilling of carbon fiber reinforcedplastic (CFRP) is manageable, but when the minute drill hits the aluminium (Al) or titanium

(Ti), the hot and continuous chips produced during machining considerably damage the CFRP hole. Thisstudy aims to solve this problem by employing nano-coated drills on multimaterial made of CFRP andaluminium alloy. The influence of cutting parameters on the quality of the holes, chip formation and tool wear were also analyzed. Two types of tungsten carbide drills were used for the present study, one withnano-coating and the other, without nano coating. The experimental results indicated that the shape andthe size of the chips are strongly influenced by feed rate. The thrust force generated during drilling of thecomposite plate with coated drills was 10–15% lesser when compared to that generated during drillingwith uncoated drills; similarly, the thrust force in the aluminium alloy was 50% lesser with coated drillswhen compared to thrust force generated without coated drills. Thus, the use of nano-coated drills significantlyreduced the surface roughness and thrust force when compared with uncoated tools. [2]

2. DELAMINATION

Delamination is a mode of failure for composite materials and steel. In laminated materials, repeated cyclic stresses, impact, and so on can cause layers to separate, forming a mica-like structure of separate layers, with significant loss of mechanical

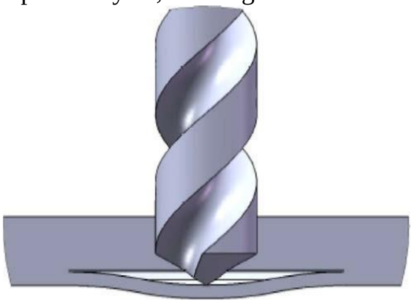

Fig. 1. Delamination mechanism

Delamination also occurs in reinforced concrete structures subject to reinforcement corrosion, in which case the oxidized metal of the reinforcement is greater in volume than the original metal. The oxidized metal therefore requires greater space than the original reinforcing bars, which causes a wedge-like stress on the concrete. This force eventually overcomes the relatively weak tensile strength of concrete, resulting in a separation (or delamination) of the concrete above and below the reinforcing bars.

A lot of research, hitherto, has been carried out by the researchers on quantitatively and qualitatively determining and assessing the extent, type, modes of the tool flank wear in drilling CFRPs, or in machining FRPs, generally. In addition, the effects of flank wear

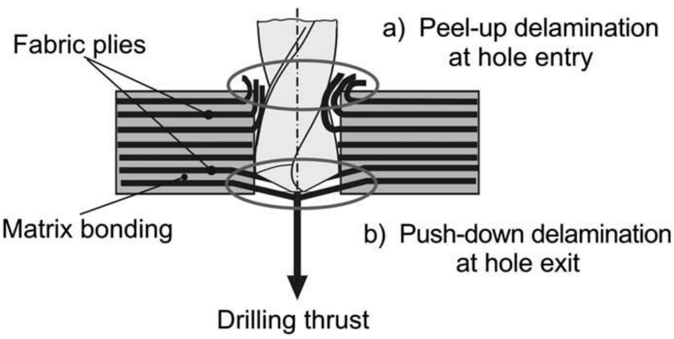

Fig.2. Classification of delamination.

Accruement on the process mechanical loads, like drilling thrust force and torque, and on the material quality have also been profoundly addressed in one of their recent works, Tsao and Hochenghave presented the effect of twist drill wear on hole exit delamination in drilling CFRP. They have analytically predicted thecritical thrust force regarding the onset of delamination, and have empirically proven by correlating and showing that how the thrust force increases due to the excessive tool wear, and thus the magnitude of the delamination too.

The rise in thrust force withincreasing tool wear, as the cutting speed was increasedalso discovered that with increasing speeds, flank wear alsoincreases, giving rise to the thrust force and hence more seriousdelamination. Similarly, increased thrust and torque magnitudeswere also observed byas the wear increased.They found tool coatings as inefficacious in their research. Inferred that in high-speed drilling of CFRP, the flank wear ismainly affected by the cutting speed. Therefore, they argued for using more suitable materials than the cemented carbide in high speed drilling in an interesting work. Used Shaw's equation to predict the maximum drilling thrust and torque, and finally compensated that model for the tool wear by introducing a wear coefficient into it, experimentally. Summarizing the basic findings of some of the researchers, itcan be conceived that the wear is majorly smooth and uniform, and is observed as a rounded pattern along the entire cutting edge of a tool. It is totally unlikely to what in case of metal cutting; where the wear could well be classified into many different independent modes, occurring apart from just the abrasion wear alone. This smooth, rounded and evenly or uniformly distributed wear along the entire cutting edge of a drill bit in drilling CFRPs in particular, makes it feasible to study, test and hence to introduce a totally new wear feature based on the change or increase in cutting edge rounding magnitude (CER). Fig illustrates the comparison in the form of the different magnitudes of the cutting edge rounding of a drill, schematically

The cutting edge rounding – also known as cutting edge roundness; or cutting edge radius; or wedge radius; etc. – has been recognized as one among the key parameters regarding the micro design and geometry of the cutting edges of a cutting tool in machining metals, etc. [3]

3. Carbon fiber reinforced polymer

Carbon fiber reinforced plastic or carbon fiber reinforced thermoplastic (CFRP, CRP, CFRTP or often simply carbon fiber, carbon composite or even carbon), is an extremely strong and light fiber-reinforced plastic which contains carbon fibers. The alternative spelling 'fibre' is common in British Commonwealth countries. CFRPs can be expensive to produce but are commonly used wherever high strength-to-weight ratio and rigidity are required, such as aerospace, superstructure of ships, automotive, civil engineering, sports goods and an increasing number of other consumer and technical applications.

The binding polymer is often a thermoset resin such as epoxy, but other thermo set or thermoplastic polymers, such as polyester, vinyl ester or nylon, are sometimes used. The composite may contain aramid (e.g. Kevlar, Twaron), aluminium, ultra-high-molecular-weight polyethylene (UHMWPE) or glass fibers in addition to carbon fibers. The properties of the final CFRP product can also be affected by the type of additives introduced to the binding matrix (the resin). The most frequent additive is silica, but other additives such as rubber and carbon nanotubes can be used. The material is also referred to as graphite-reinforced polymer or graphite fiber-reinforced polymer (GFRP is less common, as it clashes with glass-(fiber)-reinforced polymer). [4]

4. Diamond coated carbide tools.

Since the invention of low pressuresynthesis of diamond from gaseous phase, continuous effort has been made to use thin film diamond in cutting tool field. These are normally used as thin (<50 μm) or thick (> 200 μm) films of diamond synthesised by CVD method for cutting tools, dies, wear surfaces and even abrasives for Abrasive Jet Machining (AJM) and grinding. Thin film is directly deposited on the tool surface.Thick film (> 500 μm) is grown on an easy substrate and later brazed to the actual tool substrate and the primary Substrate is removed by dissolving it or by other means. Thick film diamond finds application in making inserts, drills, reamers, end mills, routers. CVD coating has been more popular than single diamond crystal and PCD mainly for:

1. Free from binder, higher hardness, and resistance to heat and wear more than PCD and properties close to natural diamond
2. Highly pure, dense and free from single crystal cleavage
3. Permits wider range of size and shape of tools and can be deposited on any shape of the tool including rotary tools
4. Relatively less expensive However, achieving improved and reliable performance of thin film CVD diamond coated tools; (carbide, nitride, ceramic, Sic etc.) in terms of longer

Tool life, dimensional accuracy and surface finish of jobs essentially need:

1. Good bonding of the diamond layer
2. Adequate properties of the film, e.g. wearresistance, micro hardness, edge coverage, edge sharpness and thickness uniformity
3. Ability to provide work surface finish required for specific

4.1 Applications.

While CBN tools are feasible and viable for high speed machining of hard and strong steels and similar materials, diamond tools are extremely useful for machining stones, slates, glass, ceramics, composites, FRPs and non-ferrous metals specially which are sticky andBUE former such as pure aluminium and its alloys. CBN and Diamond tools are also essentially used for ultra-precision as well as micro and Nano machining.

5. Cutting edge rounding, CER

The ‘optical interference fringe projection microscopy’ is a modern technique for measuring accurately as well as precisely the 3D profilography of the components and cutting tools. In this research, the accruing magnitude of the cutting edge rounding was measured using a commercial optical fringe microscope workstation called ‘GFM Mikro CAD System’. This workstation is a very versatile automated means to deal with 3D surface profiles such as surface finish measurement, tool geometry measurements, depth of crater wear and for the measurement of roundness and chamfer of tool cutting edge, within submicron resolution in all axes. This package includes also an interactive, integrated software with many different modules as per user’s requirement. Each cutting edge rounding (CER) value considered, in this study, is an average of 100 discrete values recorded along the main cutting edge of the drill bit to ensure accuracy and precision of the measured results. [3]

6. Effect of ultrasonically-assisted drilling on carbon-fibre-reinforced plastics:-

This research focuses on the effect of ultrasonically-assisted drilling (UAD) on carbon fiber reinforced plastics. High frequency vibration was used to excite a drill bit during its standard operation. A finite-element study was also conducted to understand the nature of drilling-force reduction in UAD.

Carbon-fibre-reinforced plastic (CFRP) composites have strong but brittle carbon fibres embedded into a weaker plastic matrix. The carbon fibres support the load, while the matrix serves to hold and protect the fibres and transmit the load to them. CFRP composites have many superior properties including low density (lower than aluminium), high strength (as high-strength steels), high stiffness (stiffer than titanium), good fatigue and creep resistance, and excellent dimensional stability (close to zero coefficient of thermal expansion). Thus, it is of no surprise that CFRP composites are widely used as structural and functional components in aerospace, biomedical, sports, automotive and defence applications amongst others. Though every attempt is made to manufacture CFRP components to near-net shape, in order to facilitate their assembly, machining of CFRP is unavoidable. For example, to join structures, holes need to be drilled to facilitate riveting and bolting.Thus, drilling in composites is indispensable. However, this process leads to various damage modes in composites, such as delamination, fibre pull-out, holeroundness errors and inter-laminar crack propagation. Amongst these, delamination is a major threat, as it leads to a loss of mechanical and fatigue strength in the drilled-hole area [6]

7. Multi-materials machining

Due to the different mechanical properties of constituent materials in sandwich panels, it is difficult to ensure proper diameter tolerances during drilling for assembly. Also, during dry drilling, we encounter the problem of chip removal and the phenomenon of bonding of aluminium and titanium on the cutting edges of the tool as well as the burr formation at the exit side of the hole. The cutting tests performed on graphite bismaleimide (Gr/Bi) and titanium (Ti) stacks showed the presence of degradation of the resinat the interface. Due to the low thermal conductivity of titaniumduring drilling, removal of heat generated by the interaction tool/part/chips is largely by the cutting tool and chips.The contact of these with the matrix of the composite leads to thermal degradation of the resin due to high temperature titanium (Ti) chips and the cutting tool. The work of Kim and Ramuluhave shown that to achieve holes with acceptable quality during the drilling of a material type Gr/Bi–Ti using a tungsten carbide tool, it is necessary to drill with low cutting speed and low feed rate. However, for drilling with HSS-Co, it is more preferable to select low-cutting speed and high feed rate.

Experimental works ofhave shown that drill using minimum quantity lubrication (MQL) can reduce the adhesion of aluminium on the chip grooves. The works reviewed indicates that, at low spindle speed and low feed rate ensures less surface roughness in aluminium. However, while drilling at low speed and feed generates continuous chips which can damage the surface of the composite hole during their chip removal. In addition, these chips rotate with the drill body and damage the composite when it is stacked at the top of the aluminium. While automating the process of drilling and riveting sandwich panels using a CNC system, discontinuous chips are desirable. Further vacuum pipe is facilitated in automating drilling and riveting machines.

Increase in feed rate during drilling aluminium breaks the chip, which leads to higher values of surface roughness of both materials. For example when the feed rate is increased from 0.05 mm/rev to 0.15 mm/rev, the measured values of roughness in the holes of aluminium plate varies from 0.43 lm to 0.98 lm. The roughness values measured in the carbon/epoxy ranged from 3.3 lm to 6.93 lm. The variations in CFRP are mainly because of high feed rates and also because of continuous chips passing through the hole of CFRP. The industrial need is to drill down to the last layer of the multi-material in a single operation so that the components need not be disassembled, deburred and then joined again. The deburring operations consume almost 30% of the cost of certain structural parts machining [5].

8. Chip shape analysis

The macroscopic analysis of chip formation indicated that the shape and size of the chip in the drilling of CFRP are not influenced by the choice of cutting parameters. On the other hand, while drilling on aluminium, the shape and size of chips are strongly influenced by the feed rate of cutting tool, regardless of the type of drill used (with or without coating). Fig. 3 shows the influence of feed rate on the shape and size of aluminium chips after drilling with coated tools. It was noted that drilling with a low feed rate (f = 0.05 mm/rev) producescontinuous chips when the spindle speed (1050–2750 rpm) was increased no influence on the shape and size of the chips was observed.

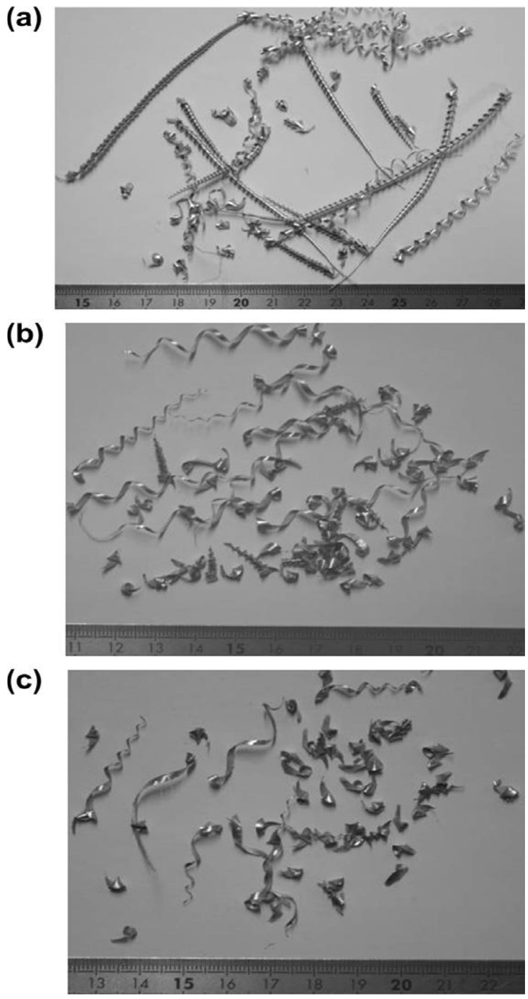

Fig. 3. Influence of the machining parameters on the form of aluminium chips after drilling with coated drill.

That the there is no difference in the use of coated tools when compared to uncoated tools on the CFRP damage caused by the erosion phenomena between the sharp chips and the CFRP. When the chips are continuous, the machining quality is better. However, since after every machined hole, the operator has to remove the chips attached to the body of the tool thus machining time increases. If the chips are curled (entangled) on the body of the drill, two problems may occur. On one hand, automatic drilling and riveting cannot be done; on the other hand, we increase the probability of damaging the hole entry of the composite as well as that of the wall. The visualanalysis of the state of holes achieved with the cutting parameters used has revealed the presence of damage at the holes entry. Also no burr was observed at the exit side of holes drilled in aluminium. Though with higher feed rates (from 0.1 mm/rev to 0.15 mm/rev) chips are broken, which increase thethrust force as well as the surface roughnessof the sandwich structure. [5]

9. Vibration-assisted drilling

The vibration-assisted drilling technique has been applied to drilling composite materials in recent years. The conventional drilling is a continuous cutting process, while the vibration-assisted drilling is a pulsed intermittent cutting process by piezoelectric crystal oscillator. Fig. 4shows the schematics of the set-up. Impacting, intermittent contact, changing the speed and tool angle can be applied in this method. Ram Kumar et al. studied the effect of work piecevibration on drilling of GFRP laminates using three types of drill, e.g. tipped WC, 2-flute solid carbide and 3-flute solid carbide. Among the three drills, the 3-flute solid carbide was found the best. Zhang and Sun founded that the thrust is reduced and delamination-free holes can be obtained in drilling carbon fiber-reinforced polymers. Mechanical models to predict the thrust and torque in vibration assisteddrilling fiber-reinforced composite materials were constructed. At the same cutting conditions, the thrust and the torque by this method are reduced by 20–30% compared with the conventional drilling. The simulation for a low-frequency case showed good agreement between theoretical predictions and the experimental values. On the other hand, Zhang et al. proposed a new hybrid drilling technology with three different drilling stages in order to improve the

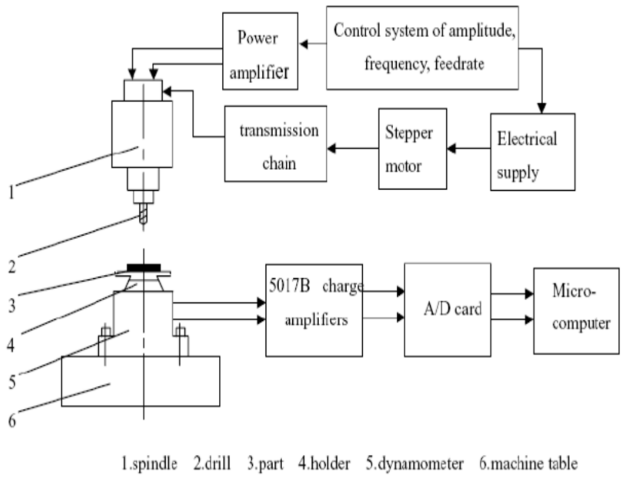

Fig. 4. Schematics of vibration-assisted drilling.

Machining quality with high drilling efficiency. The first stage is constant-parameter drilling. During the initial stage, high constant cutting rates are possible without delamination. During the second stage prior to the emerging of chisel edge, the vibration parameters are varied. This variation is necessary to ensure that the drilling thrust forces are less than the critical thrusts, which reduce rapidly with increasing drilling depth. The third stage is also a constant parameter drilling after the emerging of chisel edge, because the critical thrust force reduces rapidly. At each stage, the vibration parameters of frequency and amplitude are optimized by changing the feed rates to minimize the thrust force. The spindle speed is 22,000 rpm for 4.8mm thick composite laminate plate. The feed rates, vibration amplitude and frequency range from 0.25 to 5 mm/s, from 1 to 10 m and from 100 to 600 Hz, respectively. [7]

10. Electrical discharge machining

Electrical discharge machining (EDM) can also be used for graphite-epoxy laminates since the graphite fibers are electrically conductive. The voltage of 100V and peak discharge current of 0.5–5A were used in die sinking method with the work piece immersed in a dielectric fluid. The hole is produced by a formed electrode tool. The tool is fed downward by a servo system to maintain a constant gap between tool and work piece. Material is removed by a series of discrete

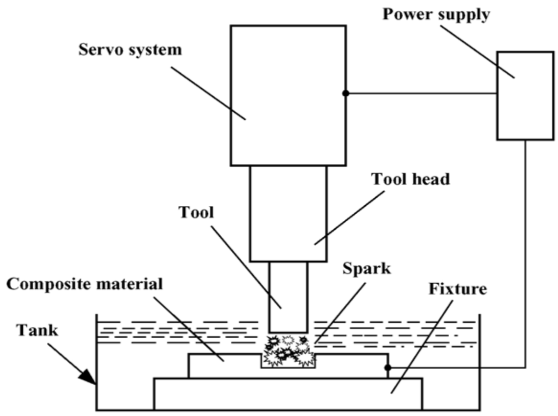

Fig. 5. Schematics of electrical discharge machining.

Erosion caused by electrical discharges (sparks) between the electrode and the work piece. An EDM machine set-up is illustrated in Fig. 5. At high currents, high temperatures are produced which cause severe melting of the compositesurface, thermal expansion of the graphite fibers in the lateraldirection and de-bonding between fibers and the matrix. The effect of polarity was investigated, and positive tool electrodes were shown to yield higher material removal rate (MRR) and lower tool wear. Two important process variables in EDM are the discharge current and frequency of discharges. As either of these parameters increases, the material removal rate increases. The surface roughness is also affected by the current and frequency. The best surface finish is obtained in EDM by operating at high frequencies and low dischargecurrents. Lau et al. found copper electrodes perform better than graphite electrodes in terms of tool wear, and tools with positive polarity give higher material removal rate and lower tool wear ratio in machining carbon fiber composite materials. [7]

11. Tool Wear Mechanism Study

Wear is the removal of the material from the surface of a solid body as a result of mechanical action of the counter body. Wear may combine effects of various physical and chemical processes proceeding during the friction between two counteracting materials such as micro-cutting, micro-ploughing, plastic deformation, cracking, fracture, and welding, melting and chemical interaction. Various forms of tool wear on the drill tools are flank wear, crater wear, chisel edge wear and chipping. Wear on the flank of a cutting tool is caused by friction between the newly machined work piece surface and the contact area on the tool flank. The width of the wear land is usually taken as a measure of the amount of wear and can be readily determined by means of tool maker microscope. The flank wear also increase the cutting forces and also heat between tool and work piece. The wear patter is irregular along the edge of the tool. Often, chipping wear leads to a catastrophic failure early in the life of the tool which masks the failure mode. Mechanical issues such as machine spindle or part fixture vibration will contribute to chipping wear. A tool holder with a large cantilever condition will cause harmonic vibrations to be amplified at the cutting edge. Excessive loads on the tool will cause chipping. [8]

Conclusion.

The difficult-to-machine fiber-reinforced composite materials inspire the progress of drilling technology for making the structural components without delamination to ensure the product reliability. The applications of special drill bits, step drilling, pilot hole, back-up plate and various non-traditional machining methods have been reviewed.

The special drills show different level of the drilling thrust force varying with the feed rate. A feed rate strategy can avoid delamination caused by the thrust in drilling. The comprehensive modelling and analysis of special drill bits, including saw drill, candle stick drill, core drill, etc., illustrate that a distributed thrust toward the drill periphery rather than concentrated at hole canter (twist drill) is advantageous. In otherwords, the special drill bits can be operated at larger feed rate (namely shorter cycle time) without delamination damage compared to the twist drill.

This research has analysed the effects of drilling tool on the drilling of Carbon Fiber Reinforced PolymerFor certain given cutting conditions, it emerges that the geometry of the drill's working section plays a decisive role in the defects and damage observed when drilling

For the tool wear & drill to give good results on CFRP, it is necessary to use diamond coating and carbide tools. Hole in order to neutralise the chisel edge effect and to lubricate the machining process. A decreasing feed rate improves drilling quality, but leads to increased wear and machining time.

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