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Effective Parameters for Drilling of Carbon Fiber Reinforced Plastic Components with Diamond Like Carbon Coated Cemented Carbide Cutting Tools

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ABSTRACT: The fundamental characteristics in the drilling operation of carbon fiber reinforced plastic (CFRP) plates are investigated in the present paper. When drilling with a high speed spindle, cutting forces during drilling, such as thrust force & torque, were measured by high resolution dynamometer & drill temperature was measured by thermographs. The tool life of CFRP plate drilling is much shorter than that of other plates.

Keywords: CFRP Plates, Cutting forces during drilling, thrust force, Torque, Thermographs

I. INTRODUCTION

CFRP (Carbon Fiber Reinforced Plastic) is well known as a difficult-to-cut material which has very strong physical and mechanical attributes. When the CFRP material is machined by cutting technique, cemented-carbide tool is widely used. The main disadvantage of Carbon fibers is catastrophic mode of failure as carbon fibers are brittle in nature which leads to difficulty in cutting operations.

A. Cemented Carbide (Diamond Like Carbon (DLC) Coated) (Tool Material)

Cemented carbide is a solid, firm, rigid & hard material used extensively in cutting tools to carry out machining operations, as well as for the completion of other industrial applications. It consists of mixture of fine particles of carbide cemented into a composite matrix by a binder metal. Cemented carbides commonly use tungsten carbide (WC), titanium carbide (TiC), or tantalum carbide (TaC) as the main additions. Mostly, carbide cutters will leave a better surface finish on the work part, and allow faster machining, than high-speed steel or other tool steels. Carbide tools can withstand higher temperatures at the cutter-work piece interface than standard high-speed steel tools, which is a primary reason for the faster machining. Carbide is usually superior for the cutting of tough materials such as carbon steel and/ or stainless steel, as well as in situations where other cutting tools have high tool wear, such as high-quantity production runs.

B. Carbon Reinforced Plastic Polymer (CFRP) (Work piece Material)

It is a Polymer Matrix Composite material reinforced by carbon fibers. The reinforcing dispersed phase may be in the state of either continuous or discontinuous carbon fibers of diameter about 0.0004” (10mkm) commonly woven into a cloth. Carbon fibers are exorbitant but they possess the highest specific (divided by weight) mechanical properties such as modulus of elasticity and strength.

Carbon fibers are used for reinforcing polymer matrix due to the following their properties:

-Very high modulus of elasticity as compared to that of steel;

-High tensile strength, which may reach 1000 ksi (7 GPa);

-Low density of the order of 114 lb/ft³ (1800 kg/m³);

-High chemical inertness.

The main disadvantage of Carbon (Graphite) fibers is catastrophic mode of failure as carbon fibers are brittle in nature.

The types of carbon fibers are as follows:

-UHM (ultra high modulus): Modulus of elasticity is greater than 65400 ksi (450GPa).

-HM (high modulus): Modulus of elasticity is in the range 51000-65400 ksi

-IM (intermediate modulus): Modulus of elasticity is in the range 29000-51000 ksi

-HT (high tensile, low modulus): Tensile strength is greater than 436 ksi (3 GPa),

- Modulus of elasticity is less than 14500ksi (100 GPa).

-SHT (super high tensile). Tensile strength is greater than 650 ksi (4.5GPa).

Carbon Fiber Reinforced Polymers are characterized by the following properties:

-They are light in weight.
-They have high strength-to-weight ratio.
-They have very high modulus of elasticity-to-weight ratio.
-They have high fatigue strength.
-They possess good corrosion resistance.
-They have comparatively low coefficient of thermal expansion.
-They consist of low impact resistance.
-They are possessed with high electric conductivity.
-They are highly expensive.

Carbon Fiber Reinforced Polymers are used for manufacturing purposes such as for the manufacturing of automotive, naval and aerospace parts, sport goods, bicycle casings. The attributes of CFRP depend on the designs of the carbon fiber and the fraction of the carbon fibers relative to the polymer. The properties of carbon fiber reinforced plastics differ so much from that of their matrix material, that a relationship is barely perceptible any more. CFRP materials are famed by their extremely high strength and rigidity. Low density, outstanding damping properties and high resistance to impact combined with exactly inconsistent thermal expansion to complement the convoluted characteristics profile. Unlike glass fiber reinforced plastics (GFRP), CFRP exhibit considerably higher rigidity, sharply increased electrical and thermal conductivity and a lower density. Their positive characteristics mean that CFRP materials are typically used in aerospace engineering, in the automotive industry, in motor racing, sport articles subject to high levels of stress and high strength and rigidity parts in industrial applications, such as robotic arms, reinforcement and sleeves in turbo-molecular pumps or drive shafts. CFRP material consists of a polymer (usually thermoplastics) employed as a matrix material in which carbon fibers with a diameter of a few micrometers are embedded. These include fiber winding, board pressing, resin transfer molding or manual laminating for individual and small series production.

C. Failure Modes in CFRPs

The structural failure can occur in CFRP materials due to various reasons such as adhesive failure, cohesive failure, fibre tear failure, inter-phase failure, inter-facial failure, mixed failure, etc. Following are the main modes of failure:

1. The tensile forces stretch the resin matrix more than the fibres, in turn, causing the material to shear at the port between matrix and fibres.
2. The tensile forces towards the end of the fibres (glass, carbon, etc.) exceed the tolerances of the resin matrix, separating the fibres from the matrix.
3. The tensile forces can also overshoot the tolerances of the fibres causing them to fracture which leads to material failure or structure failure.

D. CFRPs: Material Analysis

-CFRPs have poor mechanical integrity & pressure ratings. Although addition of fibers increases tensile strength of the pipe, attention must be given to the internal pressures in the piping system.

-If polymer pipe is subjected to high pressures, mostly at elevated temperatures, overpressure failure around flanges, nozzles or even down the pipe length could occur. Any variability in pipe construction would increase this hazard.

-CFRP's mechanical properties do not degrade until operating temperatures reach 82°C- 104°C depending on the resin system selected.

E. Twist Drill (Cutting Tool)

The cutting action along the tip of the drill is not unlike that in other machining processes because of variable rake angle and inclination. However, there are differences in the cutting action at various radii on the cutting edges. This is complex to achieve due to constraint of the whole chip on the chip flow at any single point along the tip. The machine settings used in drilling operations reveal few important features of this hole- generating operation. Depth of cut, a basic dimension in other cutting processes, correlates with the drill radius. The un-deformed chip width is analogue to the length of the drill lip and depends on the point angle as well as the drill size. For a given working setup, the un-deformed chip width is uniform and fixed in drilling. The feed dimension specified for drilling is the feed per revolution of the spindle. A more fundamental quantity is the feed per lip. For the common two-flute drill, it is half the feed per revolution. The un-deformed chip thickness differs from the feed per lip depending on the point angle. The spindle speed is constant for any one operation, while the cutting speed varies all along the cutting edge. Cutting speed is normally calculated for the outside diameter. At the center of the chisel edge the cutting speed is zero; at any point on the lip it is proportional to the radius of that point. This variation in cutting speed along the cutting edges is an important characteristic of drilling operation. Once the drill engages the work piece, the contact is continuous until the drill breaks through the bottom of the part or is withdrawn from the hole. In this regard, drilling resembles turning and is not like milling.

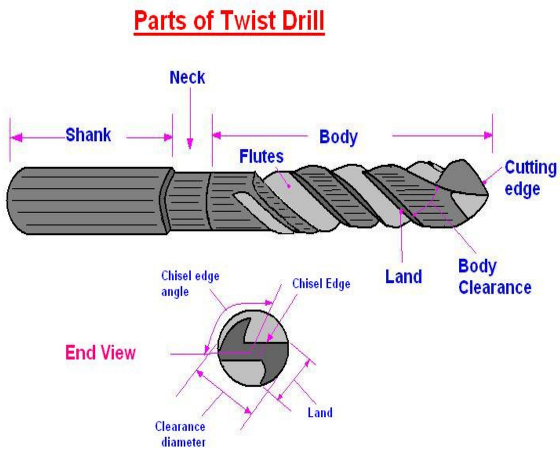

Fig. 1. Nomenclature of Twist Drill.

Under continuous cutting, the steady forces and temperatures may be expected shortly after contact between the drill and the work piece.

II. LITERATURE REVIEW

A concept of delamination factor F_d (i.e. the ratio of the maximum diameter D_{max} in the damage zone to the hole diameter D) is proposed to analyze and compare easily the delamination degree in the drilling of carbon fiber-reinforced plastic (CFRP) composite laminates. Experiments were performed to investigate the variations of cutting forces with or without onset of delamination during the drilling operations. The effects of tool geometry and drilling parameters on cutting force variations in CFRP composite materials drilling were also experimentally examined. The experimental results show that the delamination- free drilling processes may be obtained by the proper selections of tool geometry and drilling parameters. The effects of drilling parameters and tool wear on delamination factor are also presented and discussed. Cutting temperature has long been recognized as an important factor influencing the tool wear rate and tool life. An experimental investigation of flank surface temperatures is also presented in this paper. Experimental results indicated that the flank surface temperatures increase with increasing cutting speed but decreasing feed rate. Optimal cutting conditions are proposed to avoid damage from burning during the drilling processes [1].

A new comprehensive approach to select cutting parameters for damage-free drilling in carbon fiber reinforced epoxy composite material. The approach is based on a combination of Taguchi's techniques and on the analysis of variance (ANOVA). A plan of experiments, based on the techniques of Taguchi, was performed drilling with cutting parameters prefixed in an autoclave carbon fiber reinforced plastic (CFRP) laminate. The ANOVA is employed to investigate the cutting characteristics of CFRP's using high speed steel (HSS) and Cemented Carbide (K10) drills. The objective was to establish a correlation between cutting velocity and feed rate with the delamination in a CFRP laminate. The correlation was obtained by multiple linear regression. Finally, confirmation tests were performed to make a comparison between the results foreseen from the mentioned correlation [2].

Drilling laminates composites materials are significantly affected by delamination tendency of these materials under action of cutting forces (thrust force and torque). On the other hand, drilling is an operation frequently used in industry due to the need for component assembly in mechanical pieces and structures. So the aim of this paper is the study of the cutting parameters (cutting velocity and feed rate) on power (P_c), specific cutting pressure (K_s), and delamination in carbon fiber reinforced plastics (CFRPs). A plan of experiments, based on the techniques of Taguchi, was established considering drilling with prefixed cutting parameters in an autoclave CFRP composite laminate. The analysis of variance was preformed to investigate the cutting characteristics of CFRPs using cemented carbide (K10) drills with appropriate geometries. The objective was to establish a correlation between cutting velocity and feed rate with the power (P_c) specific cutting pressure (K_s) and delamination factor (F_d) in a CFRP material. Finally, this correlation was obtained by multiple linear regression [3].

An evenly and smoothly distributed abrasion wear, observed along the entire cutting edge of an uncoated carbide drill bit in drilling CFRPs, is due to the highly abrasive nature of the carbon fibres. A very few researchers have only quoted this wear mode as being responsible for giving rise to the rounding of the cutting edge, or its bluntness. However, this wear feature has seldom been investigated, unlike the conventional flank wear in practice. This paper offers a new approach in unveiling and introducing the cutting edge rounding (CER) – a latent wear characteristic as a measure of sharpness/bluntness – of uncoated cemented carbide tools during drilling CFRP composite laminates.

Four different types of drills (conventional and specialized) were tested to assess the applicability and relevance of this new wear feature. Mechanical loads (drilling thrust and torque) were recorded, hole entry and exit delamination were quantified. For the utilized tools, the accruing magnitude of CER was also recorded, in parallel with studying their conventional flank wear. Very appreciable correlations between the CER and the drilling loads, and also the quantitative delamination results are observed. Results reveal that this new wear type develops almost similarly for the selected tools and is practically independent of their respective conventional flank wear patterns. Moreover, a distinct, non-zero magnitude of the CER for a very fresh tool state may provide researchers with some lucid information in further studying the results during wear tests, more emphatically. The CER correlations with quantitative delamination results are noticed quite comparable to those of the conventional flank wear via statistical linear regression analyses [4].
A selective overview of group and individual process behavior of combined suction and discharge cycles of a hypothetical oil refinery plant carrying carbon fiber reinforced plastic pipes is presented in this study and a model is proposed to unify new product development and simulation driven design via tank piping [5]. In this study, the technique of ultra-precision cutting using the diamond tool is well-established for soft materials e.g. aluminum, copper, plastic and so on in these days. Using single crystal diamond tool, the ultra-precision cutting of difficult-to-cut metals such as titanium metals and stainless steels as well as soft materials is examined previously at the depth of cut of over 5 micro-meters. The wear of diamond tool, however, becomes huge at the short cutting length cut. Using diamond tool, in the research, the possibility of the ultra-precision cutting of titanium alloy is examined at small depth of cut of 1 micro-meter [6].

III. EXPERIMENTAL SETUP

The experiments are executed by drilling tests of 100 holes on CFRP plates with common twist drills which are set on the vertical type of machining centers as shown in Fig. 2. Each drilled holes on the CFRP panel of 2.88 mm are investigated in terms of cutting forces which are measured with dynamometer setup.
The main experimental conditions are reviewed in Table 1. Drilling tests with the various kinds of twist drills which are made by DLC (Diamond-Like Carbon) coated-cemented-carbide are carried out in dry condition i.e. without cutting fluid. The drilled holes (post drilling operation) are evaluated by diameter of holes and quality of drilled exit side. The drill-out holes are observed with the digital fine scope camera and then the tool wear of every drill used in the conduction of series of experiments which are affected from micro fiber of composite materials is also observed.

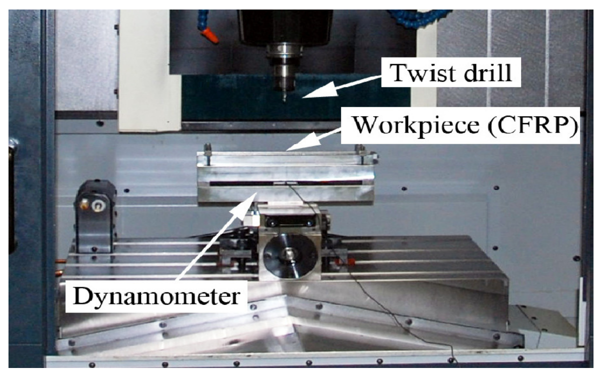

Fig. 2. Experimental Setup on VMC.

Table1: Experimental conditions.

Machine tools: Vertical type machining Center (Macpower)
Cutting tools: Twist drill, Ball nose end mill: Cemented-carbide (DLC coated)
Diameter: d = 6.0 mm
Number of cutting edge: 2
Work piece material: Carbon Fiber Reinforced Plastics (multilayer)
Thickness: h = 2.88 mm
Cutting fluid: Dry (without cutting fluid)
Cutting conditions: Cutting speed: Vc = 120, 144 m/min, Feed rate: f = 0.08 mm/rev

B. Impact of Sharpness on Cutting Edges

Tool wears of twist drill bits are observed after the 100 drilling processes. Flank wears of cemented-carbide and high speed steel twist drills are observed. Flank wear of cutting edge on the top of cemented-carbide twist drill bit is smaller than that of high speed steel. There are huge flank wears on the cutting edge and margin of high speed steel twist drill bit. The bigger wears exist on the outer side of twist drill bit.

In case of high speed steel twist drill, the quality of drilled holes is remarkably downgrade after very short drilling processes which are about only 10 drilling holes. It is declared that cemented-carbide tool is more suitable for CFRP drilling. Cemented-carbide tool can be used for CFRP drilling processes without cutting fluid at least 100 drilling holes. Sharp cutting edge of brand-new high speed steel twist drill is more effective for CFRP drilling because good result of drilled hole is obtained until 10 drilling processes. High speed steel, however, has not enough hardness to cut composite materials like CFRP.

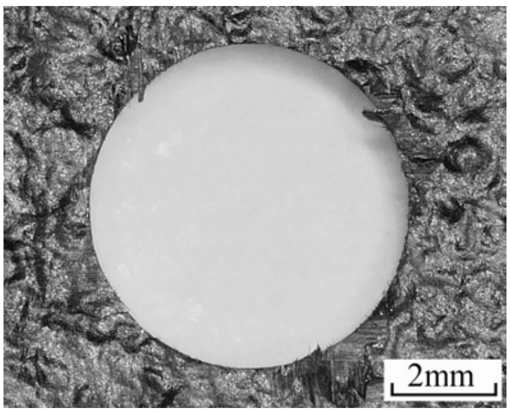

Fig. 3 (a). DLC Coated Cemented Carbide.

Image of exit side on the drilled CFRP plate by using twist drills at Vc = 120 m/min

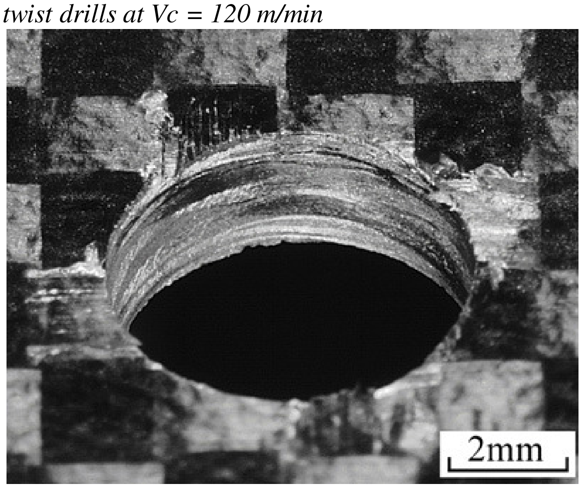

Fig. 3 (b). DLC Coated Cemented Carbide.

Image of exit side on the drilled CFRP plate by using twist drills at Vc = 120 m/min

IV. CONCLUSIONS

It is evaluated that the various twist drill bits and ball end mills affect to the precision drilled holes of CFRP plates. The main conclusions are summarized as follows:

1. The sharp cutting edge of brand-new high speed steel is effective for CFRP drilling until the depth of 28.8 mm when the tool wear is not huge on the cutting edges.
2. The thickness of coating layer on the twist drill affects on the quality of drilled holes and thrust forces in the drilling time because the coating has made the roundness of cutting edge. DLC coating is very thin and efficient for keeping the sharpness of cutting edges.
3. Ball nose end mills are suitable for CFRP drilling at the high cutting speed of 144- 290 m/min. DLC coating ball end mill is also useful to drilling technique of composite materials like CFRP panels.

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