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Research Article

Optimization of Drilling Parameter and Surface Roughness using different Tool Material by Drilling of CFRP Composite Material

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Abstract

Drilling of CFRP composite materials finds widespread applications in many engineering fields. The drilling of FRP composite materials is different from the approach adopted for the conventional materials. Fiber pull-out, spalling, fuzzing, fiber breakage, delamination are some of the problems encountered while drilling these materials. To reduce these defects and to investigate the suitability for many applications, a study of drilling of composite structures is required. This research describes the work material along with its properties, specifications and fabrication of CFRP composite plates. The different tool materials used in the present study along with its point angle are presented. The various drilling parameters and the responses are explained. The experimental setup and the experimental procedure are discussed. Finally, the experimental results obtained for each tool is tabulated.

Keywords: *CFRP composite laminates;* HSS, carbide and PCD drill bit, *Surface roughness, Drilling parameters, Delamination factor, VMC*

1. Introduction

Composite material is a heterogeneous material that is formed by the combination of two or more materials in order to obtain favorable characteristics of each. The constituents are combined at a macro level and are not soluble in each other. The CFRP composite material is widely used in various engineering applications. The significance of CFRP composites as compared to the metallic and other composite alternatives like steel, aluminium alloys, pinewood and other FRPs. It is obvious from this comparison CFRP composite is an emerging material that can be optimally matched to any application. The CFRP composite properties vary depending on the use of different matrix materials and fiber types. This permits optimal adjustment to the specific requirements of a component. CFRP composite materials are unique for critical and demanding high-tech applications that require high strength and stiffness with simultaneously low weight. The mechanical properties of the CFRP composite material utilized to full extent to overcome the physical limits of the conventional materials. Vital applications of CFRP composite materials are transportation, sporting goods, computer industry, biomedical industry (Barbanti *et al,* 2006; Wei-Cheih *et al,* 2009), telecommunication and civil applications (Garden *et al,* 1998;Haddad *et al*,2008).

Drilling experiments were carried out by many researchers and the quality of drilled holes was improved through a consistent study of drilling parameters. (Zhang *et al*, 2001) investigated the formation of the exit defects in CFRP composite plates and characterized their features in terms of drilling conditions. High speed drilling of CFRP composite material was reported by Lin and Chen (Lin *et al*, 1996). Thrust force with respect to feed rate was analyzed and concluded that tool wear is one of the major problem encountered when drilling CFRP composite plate at high speed. The delamination factor in drilling is studied by Chen (Chen *et al*, 1997) with respect to tool geometry, cutting temperature, cutting speed and feed rate. Three types of drill bits, based on the type of material are used in the experimentation, viz., HSS, carbide and PCD coated drill bits. Each type of drill bit is designed with three different point angle 100°, 118° and 135°. The experimental plan is based on Taguchi's L_9 orthogonal array of experiments. The experiment is carried out on a computer numerical controlled vertical machining center.

2. Problem Formulation

Composite materials are emerging in all domains of engineering and hence machining of composite materials is to be essentially studied. CFRP composite material is considered to be one of the widely used composite materials in all such domains. Though near-net shaping of composite material is possible through molding and other similar techniques based on the requirements, still assembly and joining of various parts (either metallic or composites) together is essentially required in order to bring to a desired shape and structure of dimensional

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accuracy. While joining parts, drilling is an indispensable operation to be performed. During drilling of CFRP, it is identified from the studies (Zhang *et al*, 2001) in) that there are variety of damages encountered, viz. delamination, and fiber pull-out, de-bonding and cracking. These damages are produced mainly due to the following factors:

- The structure and the characteristics of the carbon fiber, the type of the matrix used, and the stacking sequence used in the formation of CFRP composites.
- Material of the tool used and the tool geometry.
- Input parameters that control the quality of holes produced.

A lot of research studies have been carried out by the researchers to determine the extent and type of damages produced due to the above factors. However, in CFRP composites the application and comparison of the tools including carbide, HSS and PCD coated is not reported much. There is no systematic and comprehensive study of optimization of drilling parameters for drilling of CFRP composites. The identification of these factors motivated for this research work to study the damages caused in the form of delamination, eccentricity and surface roughness using HSS, carbide and PCD coated drills.

2.1. Objectives of study

The present research problem is formulated as an experimental investigation and optimization of machining parameters in drilling of CFRP composite materials. The scope and objectives of the present research work is listed below:

- To conduct drilling experiments on a VMC with the variables set as spindle speed and feed rate. The work piece chosen for drilling is CFRP composite plates manufactured using hand layup technique.
- To use three different drill tool materials each at three different point angles
- To study different responses such as thrust force, torque, entry-delamination, exit-delamination, eccentricity and surface roughness for improving the quality of drilled holes.

3. Preparation of Work Piece Material

The work piece material used in the present research work is CFRP composite material. The advantages of CFRP material include lighter weight, high strength-to-weight ratio, directional strength, corrosion resistance, environmental durability, dimensional stability including low thermal expansion and low thermal conductivity. CFRP composite materials include mainly carbon fibers and resins. Additionally fillers and additives may be added to suit the requirements.

The important considerations for the design of work piece include the type of fiber reinforcement, fiber weight fraction in percentage, orientation of fiber and type of resin. In the present work, the type of fiber used is carbon fiber whose strands measure 4.61 microns. The fiber weight fraction used is 60% with unidirectional continuous fibers. The mechanical properties of the CFRP composite plate are listed in Table 1.

Table 1: Mechanical Properties of the Unidirectional Carbon Fiber

Material	Standard grade of Carbon fiber
Diameter of carbon fiber (μm)	4.61
Tensile strength (GPa)	5.15
Tensile modulus (GPa)	275
Density (g/cm3)	1.7
Specific strength (GPa)	2.0

3.1 Fabrication of CFRP Plates

Hand lay-up technique is used to fabricate the CFRP composite plates that comprises of carbon fiber reinforcements and epoxy resin. The composite fabrication process is illustrated as follows.

(a) A glass plate is laid on a flat surface over which wax is laid. A plastic sheet with wax on both sides is laid over the glass sheet. This step is required to give a smooth finish to the composite plate on the bottom side. The mixture of resin and hardener is then coated on this plastic sheet with wax using a common paint brush.

(b) The carbon fibers are placed over the resin mixture with a 0° orientation. (c) The resin mixture is further laid on the carbon fiber and a next layer of carbon fiber is laid with a 90° orientation.

(d) The laid fiber layers are then pressed with a grooved metal roller in order to remove the air bubbles from the composite plate.

(e) Carbon fiber layers are laid in $[0/90\ /0/90]_S$ the sequence resulting in a composite plate of 3 mm thickness.

(f) At the top layer of the plate, the plastic sheet with wax at the bottom is pasted and is pressed in order to give a smooth finish.

(g) The curing is done at room temperature for 20 hours.

(h) After curing, the plastic sheets at the top and bottom sides are removed. The composite plate is then cut to the required dimension of 120 mm x 48 mm for experimentation.

Figure 1: CFRP composite plate

4. Tool Material

Drill bits are used as tool for producing holes that removes the material from the work piece. Drill tools are classified as solid, tipped. Solid and composite drills based on their construction. The drill tools used in the present research work are of solid type that is made up of HSS, carbide, PCD coated (Garrick *et al*, 2007). The straight shank twist drill tool with two flutes with the point angles of 100°, 118° and 135° and a diameter of 6 mm is used in the experimentation. The standard drill tool with a point angle of 118° is purchased. The desired point angles are then obtained by grinding the tool using optical profile grinder.

4.1 Polycrystalline Diamond (PCD) Coated

PCD coating on the K20 grade carbide drill tool was obtained by chemical vapor deposition (CVD) process at CemeCon AG, Germany. A head coating technology applied constant coating thickness of about 6 microns on the functional area of the tool. It has a smooth coating with nearly cluster free surface.

4.2 Carbide

The carbide drill tools are of K20 grade and are made of micro grain Tungsten carbide material. It has exceptional advantages of high strength and toughness with very good breakage resistance and strong edge sharpness.

4.3 High Speed Steel (HSS)

High speed steel is a type of steel used for high speed applications as in drilling. It is an alloy that contains several metals such as Tungsten, Chromium, Molybdenum and Cobalt. HSS (High-Speed Steel) drill bits are specially designed for drilling through metal. HSS drill bits are often black in color.

5. Drilling Parameters

The identification of the drilling parameters is based on the extensive literature survey presented n chapter 2 and the initial experiments conducted. The drilling parameters identified are process parameters that include spindle speed and feed rate and tool parameters that include tool geometry and the tool material. The drilling parameters chosen for this experimentation is spindle speed, point angle and feed rate.

5.1 Spindle speed

It is understood from the literature survey that higher cutting speed produces low thrust force and better surface finish. However, excessive speed leads to tool wear and a rough surface finish of the work piece. Hence, the spindle speed chosen in the present study are 1000, 2000 and 3000 rpm.

5.2 Point angle

Velayudham and Krishnamurthy (Velayudham *et al*, 2007) studied the effect of point geometry and their influenceon thrust and delamination in drilling of polymeric composites. As, the tangential force (i.e. torque) decreases with increasing point angle and the thrust force increases with increasing point angle, the smaller point angle is a good choice for the drilling of CFRP composite materials. The point angle of the twist drills chosen for the experimentation is 100°, 118° and 135°.

Figure.2: Point angle of the twist drills used in experiments

6. Experimental Setup

A computer numerical control (CNC) vertical machining center is used to set the prefixed drilling conditions, viz. the speed at which the spindle rotates and the rate at which the drill advances (feed rate). The specification of the CNC vertical machining center is specified in Table 2. A Kistler make piezoelectric dynamometer is used to observe the thrust force and torque while machining is carried out. Drill jig is designed A such that 9 holes are drilled in each plate. The overall dimension of the drill jig is 100 mm x170 mm, in order to fix it appropriately on the dynamometer. The bottom plate of the jig is fixed on the dynamometer while the top plate is designed to accommodate the work piece intact. The top plate is drilled in such a way that it guides the drill tool to the work piece drilled.

Table 2: Specification of CNC vertical machining center

Capacity	Longitudinal axis	700mm
	Cross axis	350mm
	Vertical axis	150mm
Table	size	1270×254mm
Spindle	speed	60-5000rpm
Feed Rate		Up to 3000mm/min

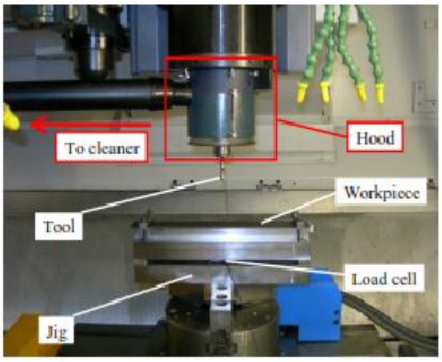

Figure 3: vertical machining centre

(a) Entry (top) side of the plate

(b) Exit (Bottom) side of the plate

Figure 4: Sample of the CFRP composite drilled plates

6.1. Experimental Plan

Drilling is an operation that produces holes of desired diameter on a plate. The quality of holes differs based on the work material and the tool used for drilling. In general, the drilling operation differs greatly between conventional metals and composites. However, it is identified that CFRP composite drilling plays a major role in many of the emerging applications.

Hence, it is decided to test and thereby produce good quality of holes in drilling of CFRP composites. The various responses that determines the quality of holes includes the actual diameter of the holes, delamination at the entry and exit of the tool, roundness, eccentricity, surface roughness, fiber pull-out, matrix cracking, etc. The experiments are planned based on the design of experiments using Taguchi's approach (Taguchi *et al*, 1987). The orthogonal array is used to study the entire parameter space with less number of experiments. Taguchi's L_9 orthogonal array for three factors, three level experiments was used.

Table 3:A general orthogonal L_9 array

A	B	C
1	1	1
1	2	2
1	3	3
2	1	2
2	2	3
2	3	1
3	1	3
3	2	1
3	3	2

Table 3 shows the L_9 orthogonal array and the columns used for the experimental plan. In the present study, 3 process parameters are used up to 3 levels. Total degree of freedom is 6 hence L_9 OA is used.

Experiment was designed according to the L_9 orthogonal array of Taguchi method. A general orthogonal L_9 design is shown below in table 3. Where A, B and C represents the process parameters and 1, 2, 3 represents the different levels. A real extension of this design is shown in table

Table 4: Factors and levels for drilling experiments

Drilling parameters	Level 1	Level 2	Level 3
Spindle Speed (v) in rpm	1000	2000	3000
Point angle (θ) in degrees	100	118	135
Feed rate (f) in mm/min	100	300	500

7. Responses Obtained

In order to produce good quality holes, the different types of responses are analyzed by various researchers. A careful study of the literature review has led to the study of the following responses in this research work:

7.1 Thrust Force

The axial force required to drill a work piece is called as thrust force. It is measured in Newtons. It is observed through Kistler make piezoelectric dynamometer by means of force sensors. The higher the thrust force, the greater is the damage of the work piece (Mellinger *et al*, 2003). Hence the analysis of thrust force is required for various combinations of cutting conditions. Measuring force as function of time, displacement or angle is an ideal method for monitoring, controlling and documenting the processes.

7.2 Delamination factor

Delamination is one of the major problems that encountered in drilling of composite laminates as compared to that of metals. It is generally regarded as a resin or matrix dominated failure (Jain *et al*, 1994). It appears as peeling away of the bottom ply or plies and is attributed to the thrust of the drill which pushes the layers apart rather than cutting through them. The delamination depends on the induced thrust force during drilling and varies almost linearly with a change in the thrust force of drilling due to the increased bluntness of the tool. Hocheng and Tsao (Hocheng *et al*, 2003) presented a comprehensive analysis of delamination in use of various drill types, such as saw drill, core drill and step drill.

7.2.1 Toolmakers Microscope

A toolmaker's microscope well suited for measuring linear dimensions and angles of features on small work pieces with the XY stage and rotating eyepiece scale. Micrometer heads are optional to enable a choice of digital or non-digital types to be fitted. The microscope can also be used to check the form of screw threads and gears by attaching an optional reticle from the wide range available. The compact body makes it ideal for use on shop floors with limited space for measuring instruments. Standard magnification is 30X, which can be increased up to 200X with optional objectives and eyepieces or reduced to 20X by interchanging the eyepiece.

Table 5: Specification of surface roughness measuring instrument

Model	SURFCORDER SE 3500
Make	Kosaka Laboratory Ltd., Tokyo, Japan
Standards	JIS (2001/94/82), DIN, ISO, ASME, etc.
Measuring range	Z: 600 µm X: 100 mm
Measuring magnification	Z: 50 - 500,000 X: 1 - 5,000
Measuring speed	0.05 – 2 mm/s
Z traverse range	250 mm
Recording	Free layout

Table 6: Drilling conditions and the responses obtained for HSS drill

Ex No.	Speed rpm	Point angle in degree	Feed rate in mm	Thrust Force in N	Delamination Factor		Surface Roughness
					Entry	Exit	in µm
1	1000	100	100	99.64	1.343	1.350	1.55
2	1000	118	300	253.29	1.436	1.773	2.81
3	1000	135	500	310.06	1.497	1.968	3.26
4	2000	100	300	154.01	1.392	1.513	2.09
5	2000	118	500	271.81	1.460	1.881	2.85
6	2000	135	100	150.75	1.381	1.418	1.95
7	3000	100	500	165.81	1.409	1.613	2.48
8	3000	118	100	130.62	1.358	1.384	1.79
9	3000	135	300	226.03	1.428	1.687	2.57

Table 7: Drilling conditions and the responses obtained for carbide drill

Ex No.	Speed rpm	Point angle in degree	Feed rate in mm	Thrust Force in N	Delamination Factor		Surface Roughness
					Entry	Exit	in µm
1	1000	100	100	76.29	1.220	1.330	0.93
2	1000	118	300	181.07	1.322	1.591	1.77
3	1000	135	500	266.72	1.512	1.768	2.28
4	2000	100	300	107.42	1.258	1.407	1.18
5	2000	118	500	213.42	1.361	1.662	1.87
6	2000	135	100	90.33	1.240	1.398	1.02
7	3000	100	500	134.89	1.288	1.471	1.41
8	3000	118	100	76.70	1.222	1.367	0.85
9	3000	135	300	152.59	1.311	1.522	1.63

Table 8: Drilling conditions and the responses obtained for PCD Coated drill

Ex No.	Speed rpm	Point angle in degree	Feed rate in mm	Thrust Force in N	Delamination Factor		Surface Roughness
					Entry	Exit	in µm
1	1000	100	100	60.22	1.199	1.262	0.70
2	1000	118	300	152.18	1.239	1.496	1.35
3	1000	135	500	194.09	1.317	1.820	1.53
4	2000	100	300	92.98	1.199	1.360	1.10
5	2000	118	500	173.13	1.301	1.589	1.44
6	2000	135	100	82.40	1.199	1.353	0.98
7	3000	100	500	113.32	1.207	1.413	1.14
8	3000	118	100	71.21	1.199	1.273	0.94
9	3000	135	300	134.28	1.211	1.465	1.20

The Mitutoyo TM 500 toolmakers' microscope of 1μm resolution with 30X magnification was employed to measure the delamination damage of holes. The value of delamination factor (F_d) can be obtained by the following equation (Chen *et al*, 1997):

$$F_d = D_{max} / D$$

Where, D_{max} is the maximum diameter of the damage around the hole periphery and D is diameter of the drill.

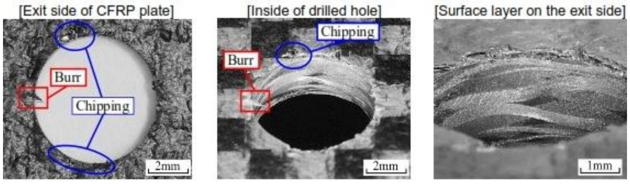

Figure 5: Microphotographs of drilled holes on the 1st drilling process

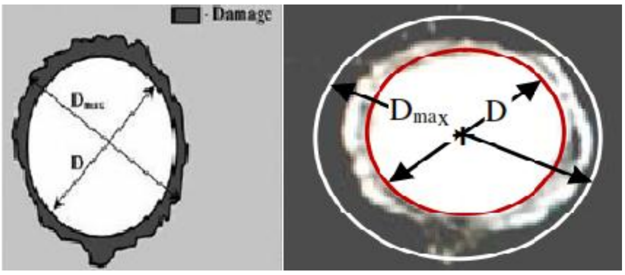

Figure 6: Schematic of delamination

7.3 Surface roughness

Surface roughness indicates the roughness of the walls of the drilled hole. It is measured in microns using a surface roughness measuring machine.

There are many different roughness parameters in use. Generally, the roughness parameter, arithmetic mean average roughness (Ra), is used to indicate the roughness of a drilled surface. It is defined as the average of the vertical deviations of the roughness profile from the mean line. It is given by the following equation:

$$R_a=1/L\{\int_0^{-1}[y(x)]dx\}$$

Where R_a is the roughness parameter in microns
y is the ordinate profile and L is the sampling length

A surface roughness measuring machine, SURFCORDER SE 3500, from Kosaka Laboratories is used in this work to measure the surface roughness of the drilled holes. The specification of the machine is shown in Table 5. It has an interchangeable stylus arm that scans the walls of the drilled hole. The stylus is attached to the data acquisition system of the machine is used to calculate the value of surface roughness of the drilled holes.

8. Experimental Results

The experiments were conducted as explained in the previous sections and the results obtained are given in Table 6, 7 and 8 for drill tools made of HSS, carbide and PCD coated respectively. The experiments are repeated thrice for each set of input combinations and the average values of the responses are tabulated in order to reduce the error in the experimentation.

Conclusion

This research presents the details about the experimental plan, fabrication of the CFRP composite plate (work piece), drill tools used with their geometry and material, the experimental setup for drilling holes in the work piece, various responses chosen for analysis along with their measuring techniques and the equipments used for the measurements, and finally the experimental results are summarized. It is concluded that in general, a combination of high spindle speed, low point angle and low feed rate leads to Lower thrust force required to drill and thereby less damage caused:

- Lower delamination at the entry and exit side of the CFRP composite plate.
- Good surface finish

However, in order to produce a low torque a combination of high spindle speed of 3000 rpm, 118^o point angle and 100 mm/min feed rate is required in drilling of CFRP composite plate. Thus the interaction plots with clear ascent and descent were used for prediction of various responses for any given input drilling conditions or to obtain an optimum drilling condition for minimum damage in drilling of CFRP composite plates. The analysis of various responses were studied and found that PCD coated drills are more suited for producing less damage in drilling of CFRP composite plates. Interaction effects of spindle speed, point angle and feed rate on various responses in drilling of CFRP composite plates using HSS, carbide and PCD coated drills were studied.

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