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Effect of Tool Geometry in Drilling of Aerospace Materials

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Abstract— Carbon fiber reinforced plastics (CFRP's) have many desirable properties like high strength-to-weight ratio, high corrosion resistance, and low thermal expansion. These properties make CFRP more suitable in structural components in aerospace application. Drilling is the most common machining operation in CFRP composites and it becomes difficult due to the extreme abrasive nature and low thermal conductivity of CFRP. The objective of this study is to compare and study the effect of tool geometry in drilling of CFRP composite through an experimental approach. A standard tool and double cone drills are employed in the drilling experiments of aerospace materials like CFRP. Thrust force, torque, tool wear and surface roughness were documented at regular intervals during drilling. Mathematical model for double cone tool geometry is developed.
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Index Terms— Drilling, Carbon Fibre Reinforced Plastics (CFRP), Double cone tool geometry, Standard tool geometry, Thrust Force, Tool Wear, Surface roughness.

1 Introduction

There has been a growing interest to use composite material for structural application like aircraft and automotive industry. Composites like carbon fiber reinforced plastics (CFRP) are being utilized at a greater extent due to its beneficial properties. CFRP can be made stronger and lighter than the conventional engineering metals. Carbon fiber is commonly used to reduce the weight of the structural components on aircraft and thereby improve fuel economy, reduce emissions and increase carrying load of the aircraft. 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 1985, Komanduri 1993, 1997, Kohkonen 1998).

Krishnaraj.V (2005) drilled composites at high spindle speed and studied the influence of tool geometry. They reported that double cone drill offers better surface finish when compared to standard twist drill and Brad&Spur drill.

Among the various tool geometries investigated, double cone drill offers many advantages when compared to the modified geometries. Only a few investigations on drilling of CFRP laminates have been reported using double cone drill. In the literature, the double cone drills are optimized for drilling of metallic materials (steel or aluminum). However for composite materials we don't have any information about the influence of the geometry of the double cone drill on the quality of holes machined. In this paper, experimental study on drilling of CFRP laminate sandwiched with copper mesh has been carried out using carbide drills (K20) to study the influence of spindle speed, feed rate and lip length of the double cone drill on force, hole diameter, circularity and delamination.

2 Experimentation

2.1 Workpiece Details

The CFRP composite specimen used in the investigation was 6.86 mm thick. The laminate was made out of 34 unidirectional plies of 0.196 mm thickness each and one woven ply with 0.1 mm of thickness. The 34 unidirectional plies are made of carbon/epoxy prepreg and manufactured by Hexcel Composite Company with the reference T700-M21e. At the top of the laminate a copper mesh has been placed in order to improve the electrical conductivity. In aeronautics field, copper mesh is used on the top of the laminate in order to avoid the damages of the composite parts by the lightning effect (struck by lightning). At the bottom of the laminate, a thin layer of carbon/epoxy woven (0.1 mm) has been used in order to avoid the delamination at the exit of the hole during drilling.

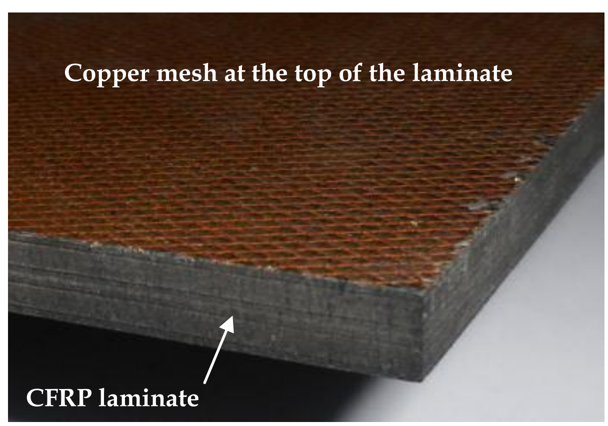


Fig. 1. CFRP workpiece with copper mesh at the top.

2.2 Experimental Details

The workpiece is mounted on the dynamometer which is fixed on the bed of a precision milling machine and the drill is fed into the workpiece. Two spindle speeds and four feed rates are selected to study the effect of spindle speed and feed rate. Table.1 shows the summary of experimental conditions. Spindle speeds are selected such a way that it suit the requirements of drilling of CFRP. All the trials were conducted without coolant. The thrust force and torque during machining was measured using piezo-electric dynamometer (type Kistler 9272). The charge amplifier (model 5019) converts the resulting charge signals, which are proportional to the force, to voltage and managed through the data acquisition system.

TABLE 1SUMMARY OF THE EXPERIMENTAL CONDITIONS

Machine tool	Makino vertical machining Centre model S33, Spindle power 11kW
Workpiece material	CFRP (58% Vf, 4.2 mm thick) tools
Carbide tools (K20)	Diameter = 6.35 mm
Machining parameters	Spindle speed (rpm) 2020 and 2750; Feed rate (mm/rev) 0.05, 0.10, 0.15 and 0.3.

2.3 Drill geometry

Table 2 presents the geometric characteristics of the Standard tool (ref-tool) and the modified double cone tool. The double cone tools are characterized by two point angles 90° and 136°. Drilling trials have been carried out using a 6.35 mm of diameter made of tungsten carbide (K20).

TABLE 2 CHARACTERISTICS OF STANDARD AND DOUBLE CONE TOOL.

Tools properties	Standard twist drill	Double cone tool
diameter (mm)	6.35	6.35
Web thickness: (mm)	0.16	0.16
Pointe angle 1: (°)	136	136
Pointe angle 2: (°)	-	90
Clearance angle: (°)	8.58	8.65
Helix angle: (°)	32.5	32.5

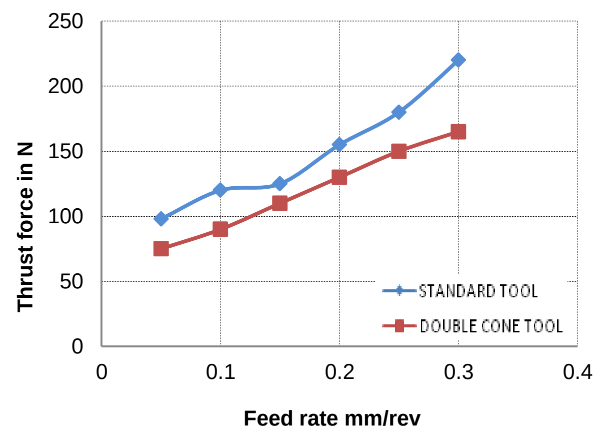
3 RESULTS AND DISCUSSIONS

3.1 Effect of speed and feed on thrust force

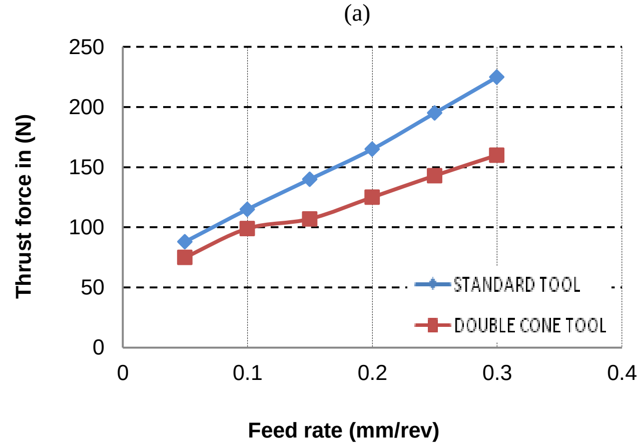
Fig.2. shows the effect of the feed rate and tool geometry (Standard tool and double cone tool) on the thrust force for two spindle speed used. We observe that, drilling with the Standard tool leads higher thrust force compared to the double cone tool. Form the figure 4-(a) it can be noted that, when the feed rate increases from 0.05 mm/rev to 0.3 mm/rev, the thrust force goes to a peak value of 165 N. This result concerns the case of drilling with a spindle speed of 2020 rpm. Rate increases in the same order of magnitude are observed when drilling with double edge tools.

The increasing of the spindle speed helping to raise the temperature of machining, therefore, results in a softening of the material and a reduction in the mechanical properties of composite. The Oscilloscope was used to capture the force vs time diagram.

3.2 Comparison of thrust forces for two different Spindle speeds



(a)



(b)

Fig.2. Influence of the thrust force vs. the feed rate for the Standard tool and double cone tools. (a) for spindle speed of 2020 rpm, (b) for spindle speed of 2750 rpm.

3.3 Comparison of torque for two different spindle speeds

Fig. 3 shows the effect of feed rate and tool geometry (Standard tool and double cone tool) on torque for two spindle

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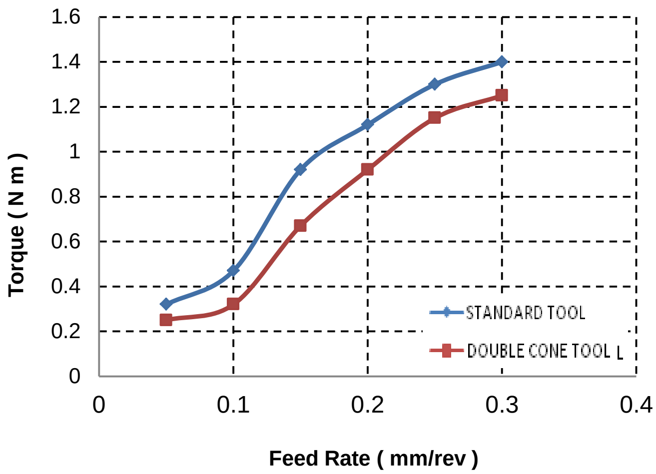
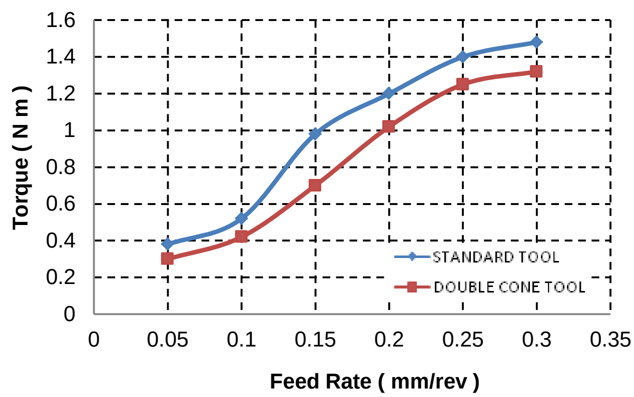
speed used. We observe that, drilling with the Standard tool leads to higher torque when compared to double cone tool.



(a)



(b)

Fig. 3. Influence of the torque vs. the feed rate for the Standard tool and double cone tools. (a) For a spindle speed of 2020 rpm, (b) for spindle speed of 2750 rpm

3.4 Effect of tool geometry on surface roughness

The surface roughness value tends to increase as the hole number increases and at the end of 80th hole the surface roughness values increases rapidly and reaches the maximum value of 4 microns as shown in fig. 5 for the standard twist drill whereas the double cone tool produces the gradual increase in the surface finish.

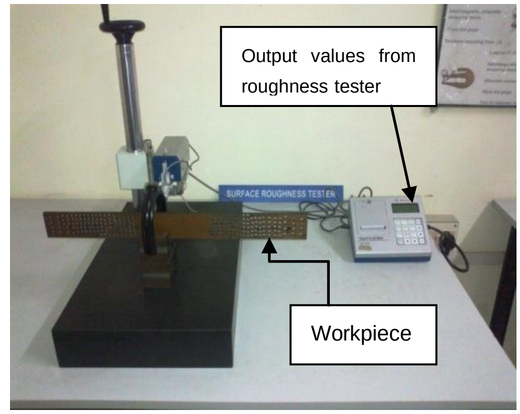


Fig. 4. Experimental setup for measuring the roughness values.

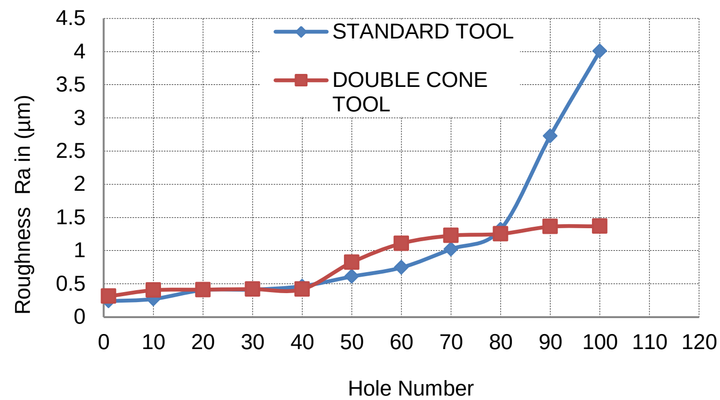


Fig.5. comparison of surface roughness

3.5 Effect of tool geometry on tool life

Fig. 6 shows that in the case tool wear also the double cone drill is superior to the standard twist drill the deviation of tool wear is less during the initial drilling. As the hole number increases the value of tool wear for the standard twist drill reaches a maximum of 0.213 microns whereas the double cone wear to an extent of only 0.134 microns which is less when compared to that of standard drill for the same number of holes.

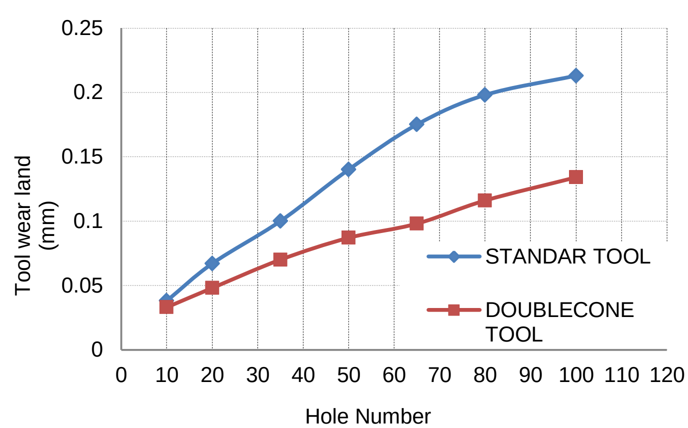


Fig.6. Comparison of tool wear

Fig.7 shows the thrust force developed during the drilling for standard drill is higher than that of double cone and highest value of thrust force for standard twist drill is 264.87 N whereas the double cone gives only 206.1 N at the end of 100 holes.

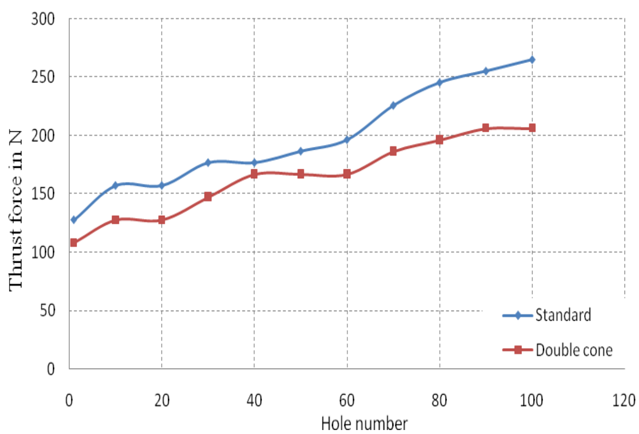


Fig.7. Comparison of thrust forces

4. MATHEMATICAL MODELING

In this work, we aimed to derive the machine force equation in drilling of CFRP composites by using double cone drill. Thus CFRP composite material were drilled in specially designed drilling system and drill torques and thrust force fluctuations were recorded with dynamometer at different feed rates and drill diameters. The appropriate model for drilling of CFRP by using double cone drill has been detected to test performance of it on CFRP. Experimental data were appreciated using mathematical model to investigate empirical relation between essential parameters. Cutting forces on drilling of CFRP materials were calculated by investigated empirical equation.

4.1 Drilling of CFRP material

In order to derive mathematical model for double cone tool tests were performed without using any coolant in drilling operation. Revolution of drill machine spindle was set to a constant speed of 2020 rpm and varying drill diameters.

TABLE 3 DRILL FORCE MEASUREMENT PLAN

Spindle speed rpm	Drill diameter mm	Feed rate mm/rev			
2020	5	0.04	0.08	0.12	0.16
2020	6.35	0.04	0.08	0.12	0.16
2020	8	0.04	0.08	0.12	0.16
2020	11	0.04	0.08	0.12	0.16

To obviate vibration during machining, drill dynamometer was fixed to table of the machine table rigidly without distortion of the sensitive part of the device. Then all connections between stations for measuring and data acquisition were made. Each drill has been worked with samples four different feed rates. These combinations were repeated two times on the CFRP samples. The collected results were analyzed with the help of oscilloscope. Mean values of fluctuation curve due to thrust force and torque were determined and tabulated those data were used for investigation of empirical equations. Table 4 presents the measured Thrust force and Torque variations corresponding to drill diameter and feed rate.

TABLE 4 MEASURED THRUST FORCE AND TORQUE VARIATION CORRESPONDING TO DRILL DIAMETER AND FEED RATE

Diameter mm	Feed mm/rev	0.04	0.08	0.12	0.16
5	Thrust Force N	107.91	147.15	166.77	186.9
	Torque N m	0.3924	0.6867	0.981	1.1772
6.35	Thrust Force N	147.15	196.2	225.63	235.44
	Torque N m	0.5886	0.8829	1.1772	1.4715
8	Thrust Force N	206.01	245.25	255.06	304.11
	Torque N m	0.8829	1.2753	1.5696	1.7658
11	Thrust Force N	215.82	274.68	323.73	362.97
	Torque N m	1.1772	1.4715	1.7658	1.962

4.2 DERIVATION OF DRILL TORQUE EQUATION ON CFRP

For investigation of empirical equations related to cutting forces in drilling performed on CFRP, a model for drilling has been selected. It was preferred as Shaw and Oxford's drill model. Though the model is proposed on metal cutting, the experimental values validate the proposed model is also suitable for the prediction of cutting forces on CFRP.

Using equation (1) and collected test data, empirical torque equation with respect to drill diameter, drill feed rate was determined. In the equation (1), "a" is evaluated by the relation between specific cutting energy, "u" and "fd". Let us assume that for a given CFRP materials, "s" is considered as constant (s=1) for simplification of complex calculations.

$$\frac{M_d}{d^3} = k_6 \frac{s^{2a} f^{1-a}}{d^{1+a}} \left[\frac{f^{0.8} 1-\left(\frac{c}{d}\right)^2}{d^{1.2} 1+\left(\frac{c}{a}\right)^a} + k_7 \left(\frac{c}{d}\right)^{2-a} \right] \quad (1)$$

Md = Drill Torque, N m
H = Shore D Hardness of CFRP Samples = 93 D scale
F = Feed rate, mm/rev
d = Drill diameter, mm
s = Average distance between imperfections
a, K6, K7 = Constants

Then test data is checked using equation (1), whether there is correlation between measured and calculated values. Specific cutting energy is represented as given in the equation (2).

$$U = \frac{8\, M_d}{fd^2} \quad (2)$$

Using test results on evaluation of specific cutting energy versus to fd is compared in logarithmic scale.From the inclination of the regression curve, "a" value has been determined as 0.56

After appreciation of drill torque data, feed vs drill torque and drill diameter vs drill torque graphs have been drawn in the logarithmic scale to find out relations between them.

The mean slope of the plot drill torque vs drill feed rate is 0.58 and for drill torque vs drill diameter is 0.96. The ratio [c/d], which is the ratio of length of chisel edge to drill diameter, has been considered to be constant as 0.213 for the drills used in the experiments. Consequently equation (1) can be transformed into simplified form as given in equation (3) by substituting these numerical values.

$$M_d = k_8 f^{0.58} d^{0.96} \quad (3)$$

or

$$M_d = k_9 H_b f^{0.58} d^{0.96} \quad (4)$$

The value of specific energy on the vertical line cut by regression curve has been observed as 1340 N/mm2. Using this value, equations 5, 6 and 7 can be derived for the drill torque on CFRP.
Since the comparison is made in logarithmic scale hence the equation of the regression line is of the form $Y = \frac{a}{X^m}$, where "a" is Y intercept and "m" is slope of the regression line. From this the equation (5) is arrived.

$$U = \frac{8\, M_d}{fd^2} = \frac{1340}{(fd)^{0.56}} \quad (5)$$

$$M_d = \frac{1340\, fd^2}{8\,(fd)^{0.56}} = 167.5\, f^{0.44} d^{1.191.44} \quad (6)$$

Equating equations (4) and (6) we can get the final equation,

$$M_d = 167.5\, f^{0.44} d^{1.44} = k_8 f^{0.58} d^{0.96} \quad (7)$$

$$k_8 = 167.5\, \frac{d^{0.48}}{f^{0.14}} = k_9 H_b \quad (8)$$

$$k_9 = 1.8\, \frac{d^{0.48}}{f^{0.14}} \quad (9)$$

The equation (9) is inserted in (4). So, required drilling torque on Carbon fiber reinforced plastics composite can be derived as given in equation (10).

$$M_d = 1.8\, H\, f^{0.44} d^{1.44} \quad \text{N mm} \quad (10)$$

$$M_d = 1.8 * 10^{-3}\, H\, f^{0.44} d^{1.44} \quad \text{Nm} \quad (11)$$

4.3 DERIVATION OF THRUST FORCE EQUATION ON CFRP

With the help of dimensional analysis, Shaw and Oxford's parametric relation for drill thrust force as represented in equation (12).

$$\frac{T}{d^2 H} = k_{13} \frac{s^{2a} f^{1-a}}{d^{1+a}} \left[\frac{1-\frac{c}{d}}{\left(1+\frac{c}{a}\right)^a} + k_7 \left(\frac{c}{d}\right)^{2-a} \right] + k_{12} \left(\frac{c}{d}\right)^2 \quad (12)$$

T = Axial force, N
a = 0.56
K12, K13, K14 = Constants

In the equation (12), the value of "a" has been calculated as 0.56. More over "s" which is distance between imperfections in the material is considered as 1 for simplification.

Then the thrust force equation can be defined as in equation (13)

$$\frac{T}{d^2 H} = k_{13} \frac{f^{0.16}}{d^{1.84}} \left[\frac{1-\left(\frac{c}{d}\right)^1}{1+\left(\frac{c}{a}\right)^{a0.84}} + k_{14} \left(\frac{c}{d}\right)^{0.16} \right] + k_{12} \left(\frac{c}{d}\right)^2 \quad (13)$$

After performing the machining, collected data related to thrust force are plotted in logarithmic scale and corresponding graphs are drawn with combination of "Thrust force Vs feed rate" and "Thrust force Vs drill diameter."

Measured data are applied into the thrust force equation (13). Then the relation between the parameter $\frac{T}{d^2 H}$ Vs $\frac{f^{0.44}}{d^{1.56}}$ can be detected by means of plotting of them as graph.

$$\frac{T}{d^2\ H} = 0.01291 + 1.930\ \frac{f^{0.44}}{d^{1.56}} \qquad (14)$$

$$T = 1.930\ H\ f^{0.44} d^{0.44} + 0.01291\ d^2\ H \qquad (15)$$

5. CONCLUSIONS

Tool geometry

- The double cone drill performs much better when compared to standard tool due to the result of reduced thrust force during drilling.
- Tool life for double cone is longer than standard tool. At the end of 100 holes double cone tool wears to 0.134 mm and standard wears to an extent of 0.213 mm
- The double cone tool gives better surface finish than the standard twist drill.

Mathematical modelling

From the study on derivation of empirical equations related to CFRP with double cone drill, the following results can be summarized.

- It was determined that when drill diameter and feed rate are increased on machining of CFRP, thrust force and drill torque increases because of increase in chip volume. This means that for processing of continuously chip formation at high feed rates, high power requirement is demanded by tool to get rid of cutting and friction and extrusion forces. Therefore they create high torque and thrust force in machining operations.
- In the study, the model developed for metals by Shaw and Oxford's, is derived for drilling of carbon fiber reinforced plastics. The empirical relation for Torque and Thrust force is given eq (11) and (15).

6. ACKNOWLEDGMENTS

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