STUDY OF HOLE QUALITY PARAMETERS IN DRILLING OF CARBON FIBER REINFORCED PLASTICS (CFRP) USING DESIGN OF EXPERIMENTS

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ABSTRACT : *In drilling operation, the quality of hole is an important requirement for many applications. Thus, the choice of optimized cutting parameters is very important for controlling the required hole quality. The focus of present experimental study is to optimize the cutting parameters through work piece circularity and hole size. This paper reports an experimental investigation of a full factorial design performed on thin CFRP laminates using coated Solid carbide drill with point angle 60^0 and helix angle 30^0 by varying the drilling parameters such as spindle speeds (1500, 2500, 3500, 4500 and 6000 rpm) and feed rate (0.01, 0.03, 0.07, 0.1 and 0.15 mm/rev) to determine optimum cutting conditions. The hole quality parameters analyzed include hole diameter and circularity. Analysis of variance (ANOVA) was carried out for hole quality parameters and their contribution rates was determined. Design of Experiments (DOE) methodology by full factorial Design was used in the multiple objective optimizations (using Mini Tab 15, software) to find the optimum cutting conditions for defect free drilling.*

KEYWORDS: Drilling, circularity, Full factorial design, ANOVA, CFRP

1. INTRODUCTION

Composite materials play an important role in the field of engineering as well as advance manufacturing in response to unprecedented demands from technology due to rapidly advancing activities in aircrafts, aerospace and automotive industries.[1,2] These materials have low specific gravity that makes their properties particularly superior in strength and modulus to many traditional engineering materials such as metals. As a result of intensive studies into the fundamental nature of materials and better understanding of their structure property relationship, it has become possible to develop new composite materials with improved physical and mechanical properties.[3] These new materials include high performance composites such as reinforced composites. Carbon Fiber Reinforced Plastic (CFRP) composite materials have potential applications in various domains like aerospace, automobile.[4,5] In machining, drilling is essentially required to join different structures but CFRP drilling poses many problems encountered include surface delamination, internal delamination, fiber/resin pullout, hole shrinkage, last ply damage, hole surface roughness, and higher tool wear due to abrasion by hard fibers that decrease the quality of holes.[6] In order to minimize these machining problems, similar to metals, there is need to develop scientific methods to select cutting conditions for damage-free drilling of composite materials.[7]

Delamination is a major problem associated with drilling fiber reinforced composite materials and in addition to reducing the structural integrity of the material, it also leads to poor assembly tolerances and has the potential for long-term performance deterioration. There are two different mechanisms of delamination, normally referred as: peel-up and pull-out.[10] These are illustrated in Fig.1. In the peel-up delamination mechanism, due to the advance of the drill, the upper layers of the material tend to be pushed through the cutting faces of the drill instead of being cut. This damage can be avoided using low feed rates. The push-down delamination is resultant from the indentation effect caused by the quasi-stationary drill chisel edge, acting over the uncut layers of the laminate.[12] The delamination takes place when the thrust force exerted by the drill exceeds the interlaminar fracture toughness of the layers. The most used method to reduce the push-down delamination is to use a support plate under the work piece.[13] Several studies have been done to analyze delamination both at the entry exit points of the hole.

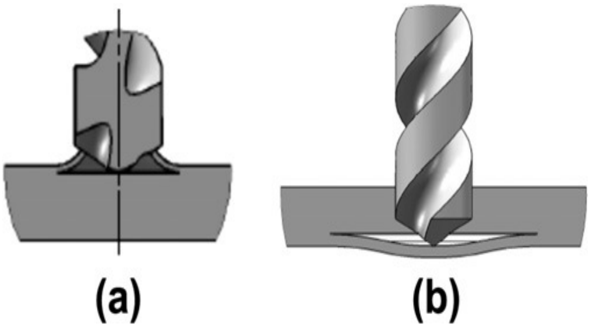

Fig.1: Delamination mechanisms: (a) Peel-up and (b) Push-down [11]

A number of work done in drilling of composites show that the defect is influenced by the choice of the machining parameters[16], the geometry of the cutting tool tip[12], the nature of its material[18], as well as the composite plate manufacturing process and the prepreg form (unidirectional or woven)[5]. E. Ugo. Enemuoh et.al in 2001 conducted an approach for development of "damage free drilling of carbon fiber reinforced thermosets". They presented a 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 experimental analysis technique and a multi-objective optimization criterion. They determined the effect of feed rate, cutting speed and point angle of drill on drilling performance parameters. They concluded that high speed and low drilling feed rate are recommended for the production of delamination free and good surface finish holes in epoxy composites.[7] V.N Gaitonde et. al in 2007 investigated the effect of Cutting speed (60, 120 and 600 m/min), Feed rate (1, 3 and 5 m/min) and point angle of drill on delamination factor at the entrance of drilled holes with three levels defined for each of the process parameters. The cemented carbide (grade K20) twist drills of 5 mm diameter with 25^0 helix angle with 85^0, 115^0 and 130^0 point angles were utilized for the experiments. The computed values of delamination factors are empirically related to process parameters by developing a second order non-linear regression model based on response surface methodology (RSM). The effects of cutting speed, feed rate and point angle on delamination factor were analyzed using the models by generating response surface plots. The investigations revealed that the delamination tendency decrease with increase in cutting speed. The study also suggests low values of feed rate and point angle combination for reducing the damage.[12] Luis Miguel P. Durao et. al in 2009 presented the effect of feed rate (0.02,0.06 and 0.12mm/rev) and different tool geometries (twist 85^0,twist 120^0,brad, dagger and step drills) on delamination of carbon fiber reinforced plastics when drilling with constant cutting speed (53 m/min) and drill diameter size (6mm). It was observed that with 0.06 mm/rev feed rate and twist 1200 drill producing minimum delamination.[9] In 2012, Vijayan Krishnaraj measured the circularity for various spindle speed and feed combinations during the high speed drilling of CFRP laminate. It can be seen that the circularity decreases with an increase in spindle speed, while it remains almost constant for increase in feeds. The rotational stability of the drill is better at higher speeds than at lower speeds. It explains the lesser circularity error at high speeds. A low feed rate of 0.01 mm/rev creates greater circularity. This could be because of ploughing and frictional heating. From the ANOVA calculations, it can be inferred that the circularity is influenced solely by spindle speed (85.95%).[2]

The aim of this experimental investigation is to evaluate the effects of the process parameters (spindle speed, Feed rate) on CFRP composite laminate by employing full factorial design and Analysis of Variance (ANOVA) using coated solid carbide drill on VMC under dry environment.

2 EXPERIMENTAL WORKS

2.1. Specimens

The composite material was fabricated from autoclave moulding with fiber orientation of $0/90^0$, as we can observe in Fig. 1and mechanical properties of CFRP described in Table 1.

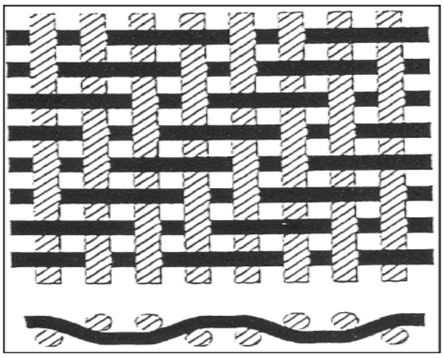

Figure1 : Pattern of fiber orientation [1]

Table 1: Properties of CFRP

Young's Modulus 0° E_1 (GPa)	Young's Modulus 90° E_2 (GPa)	Poisson's Ratio	Ultimate. Tensile Strength 0° X_t (MPa)	Ultimate Compressive Strength 0° X_c (MPa)	Ultimate Tensile Strength 90° Y_t (MPa)	Ultimate Compressive Strength 90° Y_c (MPa)
70	70	0.1	600	570	600	570

Here for the CFRP having dimension of 150x150x2 mm is used for the experiment purpose. It consists of bidirectional Woven, Carbon Fiber and Generic Epoxy composite with a fiber volume of 50% at room temperature and in dry condition.

2.2 Cutting tool

For this experiment study coated Solid carbide (K20) twist drill with point angle of 600 and diameter of 6.5 mm are used for drilling operation.

Table 2. Chemical composition of WC

Cf	Fe	Mo	K	Na	Si	Al
0.06	0.02	0.1	0.0015	0.0015	0.004	0.002

2.3 Experimental Set up

The experimental set-up is shown in Fig. 2. The workpiece was mounted on the wood sheet as a backup plate which was fixed on the bed of a vertical machining center with help of clamps and the drill was fed into the workpiece. A vertical machining center made of Haas Inc. with 22.4 kW power rating and a maximum speed of 8000 rpm was used to perform the experiments. Drilling trials were carried out using 6.5 mm diameter coated solid carbide drill. Table 3 summarizes the experimental conditions.

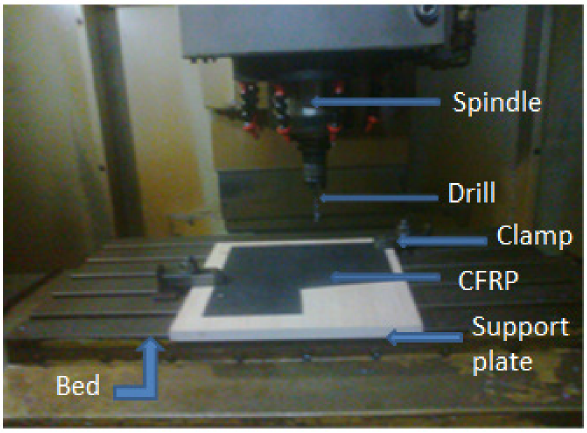

Figure 2: Experimental set-up

2.4 Full factorial design

Full factorial design is used for simultaneous study of several factor effects on the process. By varying levels of factors simultaneously we can find optimal solution. Responses are measured at all combinations of the experimental factor levels. The combination of the factor levels represent the conditions at which responses will be measured. Each experiment condition is a run of an experiment. The response measurement is an observation. The entire set run is a design. It is used to find out the variables which are the most influence on the response and their interactions between two or more factors on responses.[17]

3. RESULTS AND DISCUSSION

Experiments are conducted to investigated the effects of cutting parameters like spindle speed and feed rate on hole quality parameters like circularity and hole size of CFRP laminates.

3.1 Analysis of variance (ANOVA)

Presents study used ANOVA to determine the optimum combination of process parameter more accurately by investigating the relative importance of process parameters.

3.2 Main effect plots analysis for circularity

The analysis is made with the help of a software package MINITAB 15. The main effect plots are shown in fig.3. These show the variation of response with the three parameters i.e. cutting speed and feed separately. In the plots, x axis indicate the value of each parameter at five level and y- axis the response value. Horizontal line indicates the mean value of the response. The main effects plots are used to determine the optimal design conditions to obtain the optimum circularity.

Circularity is one of the most important parameter to check hole quality performance. It is defined as a two dimensional geometric tolerance that controls how much a feature can deviate from a perfect circle. Measurement of circularity is done by Co-ordinate measuring machine (CMM) at inspiron engineering private limited.

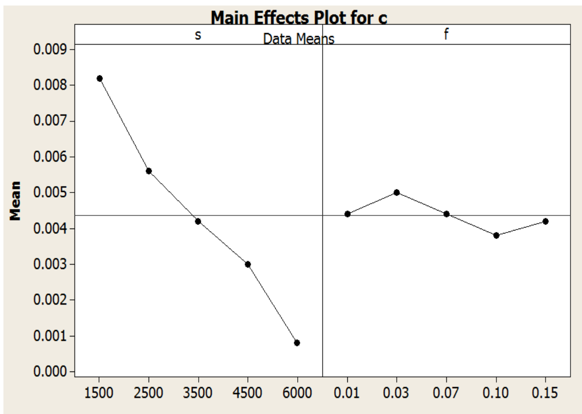

Figure: 3 Main effect plot for circularity

Fig.3 shows the main effect plot for surface roughness. According to this main effect plot, the optimal conditions for minimum circularity are at cutting speed 1500 rpm and feed rate 0.01 mm.

Table 3. Cutting Parameters

FACTORS	LEVEL 1	LEVEL 2	LEVEL 3	LEVEL 4	LEVEL 5
Spindle speed (rpm)	**1500**	**2500**	**3500**	**4500**	**6000**
Feed rate (mm/rev.)	**0.01**	**0.03**	**0.07**	**0.1**	**0.15**

3.3 Analysis of variance (ANOVA) for Circularity

Table 4 presents the results of ANOVA for circularity. It is observed from the ANOVA table, the feed is the significant parameter for the circularity. However, the speed has least effect of in controlling the circularity. Statistically, F-test decides whether the parameters are significantly different. A larger F value shows the greater impact on the machining performance characteristics. Larger F- values are observed for spindle as 78.35%.

Table 4. ANOVA Result for circularity

Source	DF	SS	MS	F	P
Speed	4	0.0001542	0.0000385	78.65	0.000
Feed	4	0.0000038	0.0000009	1.92	0.156
Error	16	0.0000078	0.0000005		
Total	24	0.0001678			

S = 0.0007, R-Sq = 95.27%, R-Sq (adj) = 92.91%

3.4 Main effect plots analysis for Hole size

The analysis is made with the help of a software package MINITAB 15. The main effect plots are shown in fig.4. These show the variation of response with the two parameters i.e. Spindle speed and feed separately. In the plots, x axis indicate the value of each parameter at five level and y- axis the response value. Horizontal line indicates the mean value of the response. The main effects plots are used to determine the optimal design conditions to obtain the optimum hole size.

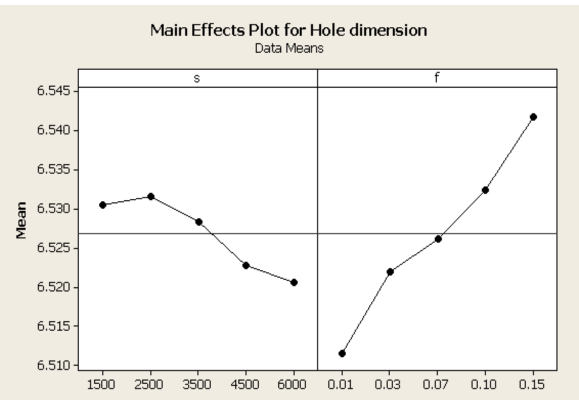

Figure: 4 Main effect plot for Hole Size

Fig.4 shows the main effect plot for hole dimension. According to this main effect plot, the optimal conditions for minimum hole dimension are at cutting speed 6000 rpm and feed rate 0.01 mm/rev.

3.5 Analysis of variance (ANOVA) for Hole size

Table 5 presents the results of ANOVA for hole size. It is observed from the ANOVA table, the feed is the significant parameter for the hole size. However, the speed has least effect of in controlling the hole size. Statistically, F-test decides whether the parameters are significantly different. A larger F value shows the greater impact on the machining performance characteristics. Larger F- values are observed for feed as 29.91.

TABLE 5. ANOVA Result for Hole size

Source	DF	SS	MS	F	P
Speed	4	0.0004724	0.0001181	5.83	0.005
Feed	4	0.0025540	0.0006385	29.91	0.000
Error	16	0.0003416	0.0000214		
Total	24	0.0033680			

S = 0.004621, R- Sq = 89.86%, R-Sq (adj) = 84.79%

4. CONCLUSION

This study discussed an application of the full factorial design for optimizing the cutting parameters in drilling operations performance measures circularity and hole size. From this research, following conclusions could be reached with an optimum amount of response:

1.Circularity : Speed 6000 RPM and feed 0.01 mm/rev.

2. Hole Size : Speed 6000 RPM and feed 0.01 mm/rev.

So we concluded from above result that Spindle speed is most effective parameter during measuring circularity and feed is most effective parameter hole size through drilling operation.

5. SCOPE FOR FUTURE WORK

In this present study only two parameters have been studied in accordance with their effects. View of future scope, other factors like Drill geometry, types of drill, Laminates configurations can be studied. Also, the other outputs like surface roughness, tool life, delamination, thrust force etc. can be added.

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