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Experimental Investigation of Thrust Force in Drilling of Glass Fiber Reinforced Plastic(GFRP) Composite Laminates

Lenin V R
Assistant Professor,
Department of Mechanical Engineering,
Mahendra Institute of Engineering and Technology,
Namakkal – 637503, India.

Ramkumar R
Assistant Professor,
Department of Mechanical Engineering,
Mahendra Engineering College,
Namakkal – 637503, India.

Senthilkumar M
Visiting Faculty,
Department of Mechanical Engineering,
Sree Kumaraguru Polytechnic College,
Dharmapuri – 636905, India.

***Abstract*—Fiber Reinforced Polymer (FRP) composite materials are finding increased applications in variety of engineering fields such as automotive, aeronautical, etc and subsequently, the accurate machining is need for the composites has increased enormously. The mechanism behind the machining of fiber reinforced polymer composite is quite different from the metals, and it brings about so many undesirable results, such as sub-surface layer with cracks and delaminating. Glass fiber reinforced polymer (GFRP) composites have been steadily replacing metals as a better choice in place of engineering materials for various applications. Drilling holes efficiently in order to minimize the waste and defects of GFRP, it is most essential to understand the machining behavior of GFRP. There is a need to turn to analytical and experimental approaches to fully understanding the machining process. This work aimed to make an experimental investigation on drilling behavior of the GFRP and also to optimize process parameters.**

Keywords—GFRP; Composite; Feed Rate; Thrust force; Delamination.

I. INTRODUCTION

Composite materials are continuously replacing traditional materials due to their excellent and flexible properties. A large single part made of composites can replace many metal parts. They have high stiffness to density ratio thereby providing greater strength at lighter weights. The light-weight use of materials means an increase in the fuel efficiency of airplanes and automobiles. Most composites are made up of plastics or resins and hence provide a high level of resistance to corrosion, to prevent corrosion aluminum and iron need special treatments like alloying to protect them from corrosion [1]. Composites have a low co-efficient of thermal expansion, the greater dimensional stability can provide when required. Machining of glass fiber reinforced composite materials is not the same as the machining of conventional metals. The spindle speed, drill bit diameter, feed rate of the machining operation selected should be carefully in the machining of fiber composite materials. Composite materials drilling parameters were analyzed by many researchers [2].

Drilling is an important process for making and assembling components made from Glass Fiber Reinforced Plastic (GFRP). Various processes like conventional drilling, ultrasonic assisted drilling and vibration assisted drilling have been attempted in order to maintain the integrity of the material and obtain the necessary accuracy in drilling of GFRP [3]. An evenly and smoothly distributed abrasion wear were observed along the cutting edge of an uncoated carbide drill bit in drilling CFRP, due to the highly abrasive nature of the carbon fibers [4]. 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 [5].

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 aerospace, aircrafts and automotive industries. Composite materials have low specific gravity that makes their properties particularly superior in strength and modulus to many traditional engineering materials such as metals. Result of intensive studies into the fundamental nature of materials and better understanding of their relationship between structure property, it has become possible to develop new composite materials with improved physical and mechanical properties. These composite materials include performing high composites such as reinforced composites [6]. Fiber reinforced polymer matrix (FRP) composites are extensively used in airframe structural applications. Carbon (CFRP), Glass (GFRP) and Kevlar (KFRP) are the most commonly used composite materials in aerospace industry [7-9]. Some of the general applications of composite materials in helicopter airframe structures include, the empennage consisting of vertical fin, horizontal stabilizers and end plates made from CFRP, GFRP and KFRP, main rotor hub and blade made from CFRP and GFRP, tail rotor blades made from KFRP and GFRP, while cockpit frame is made from CFRP and KFRP composites [10-12].

Drilling of composite materials is different than drilling of metals as drill has to pass alternatively through plastic (matrix) and fiber (reinforcement) which have different properties. The difference in the physical and chemical properties of the constituents makes the understanding of the mechanism of material removal quite complex. Material removal during drilling of composites involves series of fractures aided by diverse nature and uneven load sharing between matrix and fiber [13-15].

The usages of the composite materials range from simple household to light-to-heavy industrial purposes including oilfield applications. All the available composite materials that are normally used especially in oilfield and surface pipeline applications. From those, four fiberglass-reinforced plastic materials (i.e., AR-glass, boron free E-glass, C-glass, and E-glass) were most common in acidic and alkaline environments. The AR-glass is corrosion resistant at high temperature and high acidic and alkaline environments. The loss of weight due to corrosion is less than the all other three materials. Boron free E-glass also better than C-glass and E-glass, especially in acidic environment. In another aspect of this research is to find out a research gateway the development toward sustainable composites [16].

The performance comparison of Carbide and HSS drills when drilling a glass fiber reinforced general purpose resin composite by many researches. Delamination is a major issue of the quality of a drilled hole on composite, which in turn is primarily dependent on the thrust force. The comparison of thrust force and the corresponding delamination produced has been made with reference to drilling by HSS and Carbide tools with the independent variables being cutting tool geometry, material thickness, drill diameter, feed rate and speed [17].

However, problems exist, such as high rejection ratio of the product and severe tool-wear usually due to the mechanical and thermal properties of this fiber- reinforced material. The abrasive nature of CFRP material often leads to a high tool-wear rate and some related defects such as delamination; cutting temperature is an another problem 2 that causes defects due to the low thermal conductivity of this material. Many factors influence the quality of the borehole, which leads to rejection of the products. These factors are cutting parameters, type of tools used for cutting and cooling conditions and its environment.

Achieving a lower thrust force is the first priority during drilling process since thrust force is highly related to delamination. The primary mode of failure is delamination, which happens in drilling of laminate material, when thrust force exceeds a certain value, it would cause layers of multilayer material such as CFRP to become separated. This failure would cause the material a significant loss of mechanical toughness, and would extremely diminish inter-laminar strength. Avoiding delamination becomes the main objective of drilling CFRP material since the CFRP material continues to grow in the aerospace and automobile industries, and the safety issue has become the most cared-for aspect. Structures and parts with delamination would very likely reduce the reliability of the product and endanger the safety of the passengers. The optimum cutting parameters should be determined in order to reach a lower thrust force, and for achieving a delamination-free borehole. A relatively low feed rate (lower than 0.1 mm/rev) and a high cutting speed (lager than 800 rpm) are recommended for drilling CFRP material, On the other hand, thermally-induced damage is another aspect of defect that cannot be ignored. Low thermal conductivity of CFRP would lead to an extremely high cutting temperature and make the expansion of the drill bit, which would influence the dimensional accuracy of the boreholes. Also, degradation would occur in matrix due to the high temperature. Traditionally there are two cooling conditions for use, i.e., dry and flood cooling, and recently the usage of MQL (minimum quantity lubrication) has emerged. Applying cooling would, to some degree, reduce the cutting temperature, and then reduce the defect related to thermal damage. But, a chemical reaction might happen between the coolant liquid and the CFRP material, which would diminish the properties of the material. This factor should also be considered when drilling CFRP material. Meanwhile, to the best of our knowledge, the influence of cryogenic cooling in drilling performance has not yet been studied. High cutting temperatures can negatively affect the structure of CFRP and the shape of machined surfaces. Applying cryogenic cooling might significantly influence the hole quality by reducing the cutting temperature, thus preventing pyrolysis and material-softening, and thermally–induced defects from happening.

The purpose of this project is to investigate the influences of cryogenic cooling on drilling CFRP plate. An assumption has been made that the hole quality can be enhanced by lowering the cutting temperature through cryogenic cooling. Different aspects of the drilling performance, such as the torque, the thrust force, the hole quality, and the tool-wear, have been studied under different cutting parameters and cooling conditions. Besides, analytical models are also used in this project for the purpose of establishing the relationship between thrust force and delamination.

Machining GFRP composite materials raise some specific problems due to their unique nature of inhomogeneous and anisotropic properties. It has been observed improper cutting parameters or tool-wear lead to damages such as delamination, cracks, fiber or matrix de-bonding, fiber breakage and matrix thermal melting. Since they are very abrasive, fibers used as reinforcement rapidly increase the tool-wear rate, and therefore the drill is worn quickly and can no longer maintain the edge sharpness. Researchers also found that if the cutting edge radius increases to a certain level, the thrust force will surpass a critical value, when the delamination is most likely to happen at the exit side of the machined surfaces. Not only does tool-wear bring the problem of delamination, also the blunt drill also causes the problem of excessive burr generation.

II. EXPERIMENTAL SETUP

A. *Tensile Test and Hardness Test*

The tensile test is used to measure the yield strength and the ultimate strength. In this test the ends of the test piece are fixed into the grips connected to a straining device and to a load measuring device. If the applied load is small enough the deformation of any solid body is entirely elastic. An elastically deformed solid body will return to its original form as soon as load is removed. If the load is large, the material can be deformed permanently. The initial part of the tension curve is termed as elastic (which is removable immediately after unloading). The curve which represents the manner in which the material undergoes plastic deformation is termed as plastic. The stress below which the deformation is entirely elastic is known as the yield point. However, some materials do not exhibit a sharp yield point. During plastic deformation, at larger extensions, strain hardening cannot compensate for the decrease in section. At this stage the ultimate strength which is defined as the ratio of load on specimen to original cross sectional area reaches maximum value. Further loading will eventually cause rupture. Specimen used for the testing is 185 X 50 X 2 (Dimensions are in mm) plate. Specimen is loaded at two ends using hook joints. Specimen is fractured at the load of 400 kg.

The Rockwell Hardness test is used to apply a specific load and then measure the depth of the resulting impression. The indenter may either be a steel ball of some specified diameter or a spherical diamond-tipped cone of 120° angle and 0.2 mm tip radius, called a brale. A minor load of 10 kg is first applied, which causes a small initial penetration to seat the indenter and remove the effects of any surface irregularities. Then, the dial is set to zero and the major load is applied. Upon removal of the major load, the depth reading is taken while the minor load is still on. The hardness number may then be read directly from the scale. The indenter and the test load used determine the hardness scale that is used (A, B, C, etc). For soft materials such as copper alloys, soft steel, and aluminium alloys a 1/16" diameter steel ball is used with a 100-kilogram load and the hardness is read on the "B" scale. In testing harder materials, hard cast iron and many steel alloys, a 120 degrees diamond cone is used with up to a 150 kilogram load and the hardness is read on the "C" scale. There are several Rockwell scales other than the "B" & "C" scales, (which are called the common scales). A properly reported Rockwell value will have the hardness number followed by "HR" (Hardness Rockwell) and the scale letter. For example, 50 HRB indicates that the material has a hardness reading of 50 on the B scale. Size of the Specimen is 95 X 90 (Dimension in mm). Ten numbers of Trials were taken and the details listed below.

TABLE I. MATERIAL COMPOSITION TEST RESULTS

S.No.	**Composition**	**Yield Strength in Mpa**	**Hardness Number**
1.	GFRP	52	45
2.	GFRP (60%Fiber 40%Resin)	54.4	48

B. GFRP Drilling

The materials used for the investigation is glass fiber reinforced polymer (GFRP). In the present work the composites material used for the investigation is manufactured through hand lay-up process. Work piece material consists of glass fibres with polyester resin. Material thickness is 7.5mm with five layers. Material is coated with wax. The drill bits used for the investigations are HSS drill having diameter 6 mm, 8 mm and 10 mm. Three levels of speeds are 700rpm, 1170rpm, and 1900rpm. Three levels of feeds are 10mm/min, 20mm/min and 35mm/min.

III. RESULTS

From the experimental study, the three parameters and three levels are used for Taguchi method with very careful understanding of the levels taken for the factors. The standard orthogonal arrays made available in Drilling dia – Speed – Feed (DD-S-F) as shown in Fig. 1.

It is observed that, the values of Drilling diameter, speed and feed are set at minimum level to the maximum, the thrust force and torque getting increased with increase in DD-S-F. The highest value is found for highest DD-S-F at 10-1900-35.

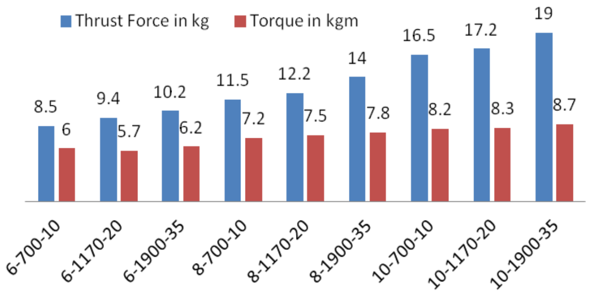

Fig. 1. DD-S-F Vs. Thrust Force and Torque

The optimization of the observed values is determined by comparing the standard method and analysis of variance (ANOVA) which is based on the Taguchi method. Table 6.3 shows the experimental design for L9 orthogonal array. In the Taguchi method, all the observed values are calculated based on the concept higher the better and smaller the better. In this analysis, the observed values of thrust force, and torque are set to the minimum as possible.

IV. ANALYSIS OF VARIANCE

Analysis of variance (ANOVA) is used to analyze the experiment data as follows.

Sound to noice ratios

$$S/N = -10 \log 1/n \, \Sigma \, y_i^2 \qquad (1)$$

Where,

y_i is the output or performance characteristic
N is the total number of experiments

In this study, the objective is to reduce the thrust force and torque in order to the analysis of variance (ANOVA) and to establish the optimum conditions based on the Taguchi method.

Fig. 2-3 shows the effects of thrust force and torque of each factor for various level conditions. From the fig. 2 it is clear, that the thrust force is minimum with all the parameters i.e. the drill diameter, speed and feed rate. The rate of decrease for the thrust force is lower for 6mm drill diameter, 700rpm speed and 10mm/min feed rate when compared with the remaining parameters.

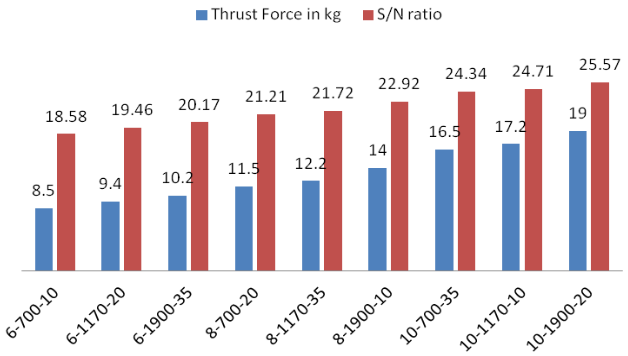

Fig. 2. DD-S-F Vs. Thrust Force and S/N Ratio

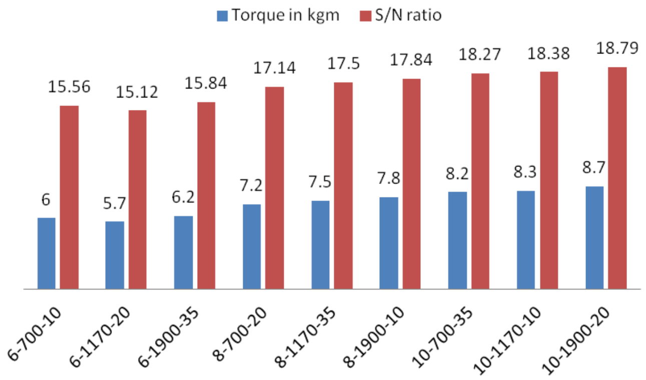

Fig. 3. DD-S-F Vs. Torque and S/N Ratio

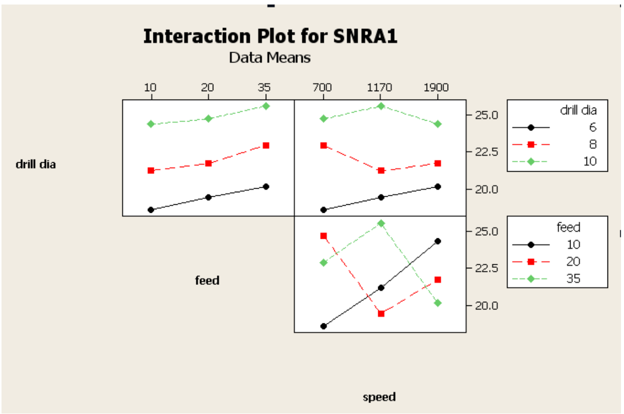

Fig. 4. Interaction of parameters on thrust force

Fig. 3 shows the variation of DD-S-F vs. Torque and S/N ratio, the variation of torque with all the three parameters, the rate of decrease for torque is lower for 6mm drill diameter, 1170rpm speed and 20mm/min feed rate when compared with remaining parameters. values from theoretical calculation shows that the rate of decrease for thrust force is lower for 6mm drill diameter, 700 rpm speed and 10mm/min feed rate compared with remaining parameters. It is also absorved for the fig. 4 and fig.5 lower diameter, lower speed and feed the S/N ratio is lower.

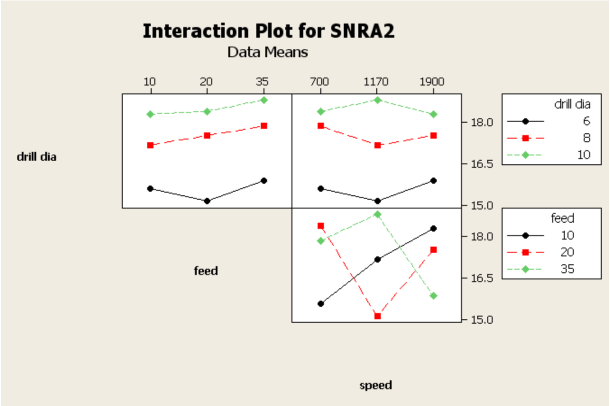

Fig. 5. Interaction of parameters on torque

V. DELAMINATION

The model estimates edge-defects by looking at the lamina that has delaminated during drilling. We know that the thrust force from drilling causes delamination in the FRP's lamina. As drilling continues after delamination, the delaminated lamina suffer bending from the thrust forces. When the lamina get cut by the drill they are in a deformed state due to the thrust force. Assuming elastic deformation behavior, it is possible to characterize the deformed state of the fibers as a function of the thrust force. The model does not take into account the deformation behavior of the composite matrix and entirely ignores its effect in causing the edge defect. This is a valid first-order assumption as the matrix is usually a soft, pliable plastic that does not remain uncut unlike the hard, brittle fibers. It is also hard to distinguish between the matrix and the fiber and since the model assumes isotropic plate behavior, the matrix's effect is taken into consideration implicitly.Once the drilling stops, the thrust force is removed from the fibers and as the deformation is elastic, they revert to the undeformed state. When the length of fiber that has been removed in the deformed state is calculated, it is apparent that lesser fiber than required by the hole dimensions has been removed. This difference in required length removed and actual length removed manifests as the edge defect.

The delamination factor (F_d) is determined by the ratio of the maximum diameter (D_{max}) of the delamination zone to the diameter of the hole (D). The value of delamination factor can be expressed as follows

$$\text{Delamination Factor } (F_d) = D_{max} / D \qquad (2)$$

The speed of a drill is usually measured in terms of the rate at which the outside or periphery of the tool moves in relation to the work being drilled. The common term for this is "surface feet per minute", abbreviated as sfm. Every tool manufacturer has a recommended table of sfm values for their tools.

Fig. 6. Shows the delamination of the composite at entry to the exit. It is absolved that, for all DD-S-F variations the delamination occurs. But the delamination were minimum in case of lower DD-S-F (6-700-10) and slightly higher in case of higher DD-S-F.

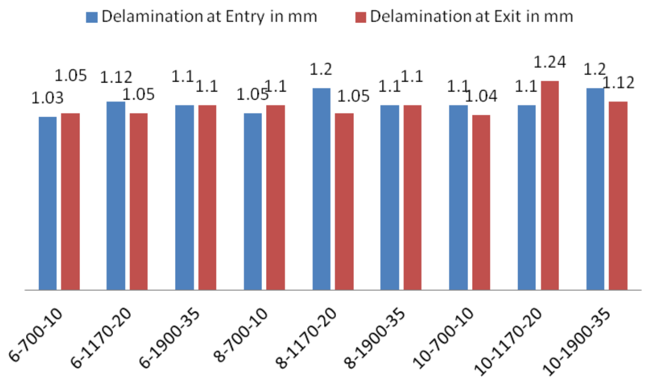

Fig. 6. Delamination of the composite at Entry and Exit.

However the delamination exists for all the cases. But it slightly varies with DD-S-F ratings. The entry delamination is found from 1.03 to 1.2 mm, which is increased by 14.16%. also the exit delamination shows the same trend which is found from 1.05 mm for lower DD-S-F to 1.24 mm for higher DD-S-F, increased by 15.32%.

Due to increase in thrust force, the surpass approaches a critical value, when delamination is most likely to happen at the exit side of the machined surfaces. Not only the tool-wear brings the problem of delamination, the blunt drill also causes the problem of excessive burr generation. The main reason for burr generation is outer corner wear.

Meanwhile, as a consequence of low thermal conductivity of GFRP, the heat generated during the cutting process could not be effectively transferred. This leads to an extremely high cutting temperature generation during the machining process, resulting in more severe expansion of cutting tool diameter during drilling of GFRP. This overheating problem causes matrix material of glass fiber reinforced composite to get burned, as well as with a larger deviation on the diameter of the bored holes by mean of delamination as a resultant.

VI. CONCLUSION

Different types of FRP materials and its properties were collected and studied. The following results were absolved for the experiment

1. The tensile test and the hardness test were carried out and compared with the conventional GFRP. It is clear that the yield strength and hardness of the materials is greater than the conventional GFRP.
2. Thrust force and torque are the major influence of defects. From the results it is clear that the thrust force and torque were minimum when drilling at lower speed, feed and drill bit diameter.
3. The delamination defects are reduced when drilling at minimum drilling parameters.
4. The value of equivalent stress and strain was minimum at low drilling parameters.
5. In order to eliminate defects in drilling of GFRP and to achieve boreholes with acceptable hole quality and surface integrity, to establish the cutting parametric conditions during drilling of GFRP in order to achieve optimized results in machining.

Therefore the material is suitable for drilling at lower spindle speed, feed and at 6mm drill bit diameter with lower speed and feed.

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