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Delamination Analysis of GFRP Composites by using Drill Tool

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***Abstract* –A composite material can be defined as 'a multiphase material with chemically dissimilar phases separated by a distinct interphase'. For various engineering applications GFRP composites are steadily replacing the metals. The main objectives of this dissertation are to predict delamination during drilling of composites**

I. INTRODUCTION

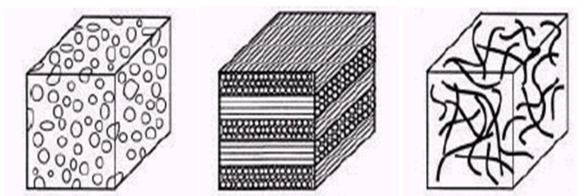
Drilling is arguably most common post-processing operation performed on GFRP composites. In order to understand the effects of process parameters on the delamination, a large number of machining experiments have to be performed and analyzed. Hence empirical and statistical approaches are widely used over the conventional mathematical models. The difference in elastic modulii, coefficient of thermal expansion etc of constituents results in a considerable shift in the material response to the drilling process, as compared to the behaviour of isotropic material. Glass Fiber Reinforced (GFR) composites are usually used in the forms of laminates. A laminate is made by bonding two or more lamina together. Laminas usually are made of parallel fibers set in a polymer matrix at some constant volume fraction. The laminate is assembled with the individual lamina at different fiber orientations. With current trend of challenges in strengthening of existing structure, Composite Fiber is becoming an essential material. The development of composites has opened up vast opportunities to designers and engineers in their search for combination properties not to afford by conventional steel, aluminium or wood.

II. WHY GFRP'S?

The need in industry is to be able to drill through these layers in one operation without need for any rework (i.e. without having to disassemble and clean the parts before fastening). Currently, deburring operations account for about 30% of the total manufacturing cost. The major aircraft manufacturers, Boeing and Airbus, are shifting from traditional aerospace alloys to composite stack ups for use in their new aircraft designs. Boeing is developing composites which can be used in the construction of the airplane fuselage. Usually, the reinforcement provides load bearing properties while the matrix ensures efficient load distribution. On the basis of type of reinforcement, composite materials can be classified as fibre-reinforced and particle-reinforced. Fibre-reinforced composites may be either have continuous, aligned fibres or discontinuous, short fibres as reinforcement. Glass Fibre Reinforced composites are usually used in the forms of lamina. Two or more laminas are bonded together to form a laminate. Laminas are usually set in a polymer matrix at some constant volume fraction and are made of parallel fibres. The laminate is assembled with the individual lamina at different fibre orientations. With current trend of challenges in strengthening of existing structure, Composite Fibre is becoming an essential material. Multilayer materials (or stack ups) are used extensively in the construction of aerospace structural members because these provide increased strength-weight ratios in comparison with traditional structural material. The different layers provide wide range of functionality which increases the utility of the structural member. These Composite materials are used as constituents for the stack ups.

Fiber reinforced composite materials can be divided into two main categories normally referred to as;

A. Short fiber reinforced materials and
B. Continuous fiber reinforced materials



Particulate Composite, Laminated Composite, Fiber Reinforced Composite

Continuous reinforced materials will often constitute a layered or laminated structure. The woven and continuous fiber styles are typically available in a variety of forms, being pre-impregnated with the given matrix (resin), dry, unidirectional types of various width, plain weave and harness satins, braided and stitched. The short and long fibers are typically employed in compression molding and sheet molding operations.

III. OBJECTIVES OF ANALYSIS

In the earlier studies, it has been observed that the extent of delamination is related to the feed, thrust force, speed and material properties etc., and that there is a critical value of the thrust force below which we observe negligible delamination.
The basic objectives of these analyses are:

Prepare experimental set up for conducting drilling of GFRP composite experiments.
Investigating the drilling damage characteristics of GFRP.
To observe the effect of drill tool, speed, and feed rate on the quality of the drilled holes.
Assessing the effect of process parameters spindle speed, feed, type of drill and work piece related parameters on thrust force, cutting torque, delamination and surface roughness.
The present study is an attempt to investigate experimentally the significance of the drill point geometry and the operating variables on the drilling forces and the drilling induced damage. This experimental investigation also studies the influence of drill point geometry, the cutting speed and the feed rate on the drilling forces and the drilling induced damage. Critical defects that weaken the strength of the composite structures are delamination and debonding. These damages can cause the premature collapse of structures as they cannot be visually detected. This Damage assessment is carried out using non-destructive inspections like ultrasonic C-scan and radiography. Damage can be defined as changes in the material, geometry or connectivity of the system that adversely affect its current or future performance. Although defects exist within any engineering material at the microscopic level, it is generally accounted for in the initial design of the structure, such as through the appropriate designation of material yield strength. The main objectives of this dissertation are to predict delamination during drilling of composites. This section describe the experimental analysis in detail to determine the effect of machining process and parameter related with tool on drilling of GFRP composite.

A. *Peel-up Delamination*

It is caused by the cutting force pushing the abraded and cut materials to the flute surface. At the beginning of the contact, the cutting edge of the drill will abrade the laminate. As the drill moves forward it tends to pull the abraded material along the flute and the material spirals up before being effectively cut. A peeling force pointing upwards is introduced that tends to separate the upper laminas of the uncut portion held by the downward acting thrust force. Normally, a reduction in the feed rate adopted can reduce this effect.

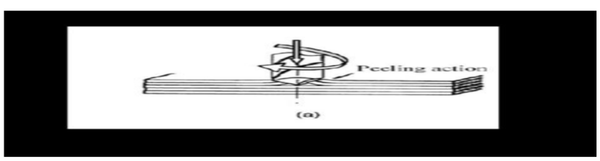


Figure: Peel-up Delamination

B. *Push out Delamination*

On the other hand, push-out delamination is a damage that occurs in interlaminar regions, so it depends not only on fiber nature but also on resin type and respective properties. This damage is a consequence of the compressive thrust force that the drill tip always exerts on the uncut laminate plies of the work piece.

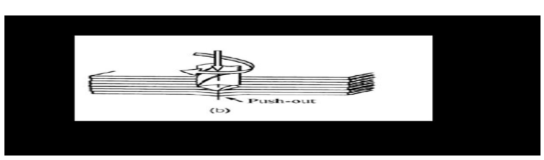


Figure: Push out Delamination

In Taguchi method, it is calculated the deviation between the experimental value and predicted values, the best condition obtained from S/N ratio analysis was verified by the confirmation experiments. The thrust force and cutting torque during drilling were measured by dynamometer and data equating system used for statistical analysis. However, it is seen that analysis of variance from that none of the parameters are statistically significant at 95% confidence interval. The near best condition which produces smaller magnitude of the thrust force and cutting torque is spindle speed at 800 rpm, feed rate of 0.20 mm/rev, fibre orientation of 45° and coated carbide drill bit. Damage can be defined as changes in the material, geometry or connectivity of the system that adversely affect its current or future performance. Although defects exist within any engineering material at the microscopic level, it is generally accounted for in the initial design of the structure, such as through the appropriate designation of material yield strength. Critical defects that weaken the strength of the composite structures are delamination and debonding. These damages may cause the premature collapse of structures. Damage assessment is carried out using non-destructive inspections like ultrasonic C-scan and radiography.

IV. SYSTEM DEVLOPMENT

A Taguchi based design of experiment was used to access the important of drilling parameter (listed as above). This technique of Taguchi in planning and executing experiments was a controlled way and analyzing the data to obtain information about the behaviour of a given process. This technique use orthogonal arrays to design the experimental test matrix with respect to critical factors. The significance of the factors was then identified based on Analysis of Variance (ANOVA).

The main objectives of this dissertation were to predict delamination during drilling of composites. This section describe the experimental analysis in detail to determine the effect of machining process and parameter related with tool on drilling of GFRP composite. The present study is an attempt to investigate experimentally the significance of the drill point geometry and the operating variables on the drilling forces and the drilling induced damage. This experimental investigation also studies the influence of drill point geometry, the cutting speed and the feed rate on the drilling forces and the drilling induced damage.

There has been considerable work in studying the machining of GFRP composites. Komanduri identified that the fiber orientation is the major influencer of the cutting properties of GFRP. According to Saxena and Dr. Bhatnagar, damage during drilling an anisotropic material depends on:

The mechanical characteristics of the long fibers used in the laminate and their nature.
The stacking sequence and mechanical characteristics in differently oriented ply interfaces (matrix), throughout the laminate thickness.
Tool configuration/geometry
Operating environment
Process variable.

The tool geometry plays an important role in delamination reduction as the value of critical thrust force for delamination onset and propagation is dependent on drill bit geometry. There is an influence of drill bit geometry on thrust force measured during drilling. *Dr. John Edward Wyatt* explains the term Machinability related with drilling operation in his paper. According to him, machinability is the world's most common manufacturing process with 10 to 15 % of the cost of all goods being attributed to it. Machining may either be the primary manufacturing process as in the aerospace industry or a secondary process as in the machining of castings, forgings and powder metals. The term machinability is used to describe how easy a material is to machine. The main goal of machining is to remove material to produce a component or product efficiency.

The Glass Fibre Reinforced Plastic (GFRP) specimens used in the present investigation were manufactured using the hand layup technique. Controlled pressure was adopted to make these laminates. A flat plate mould was used for laminating and the laminates were left for 24 hours for room temperature curing. Three test specimens are cut from the sheet of 20 Ply laminate of size: (80 mm * 80 mm * 4 mm) by using diamond impregnated wheel, cooled by air. All the test specimens are finished by abrading the edges on a fine sample wood sand paper. Three GFRP specimens of fiber orientations (45°, 60°, 90°) was used for experimental investigation to assess the effect of fiber orientation on the performance variables during drilling of GFRP composites.

The drill bits used in this experiment was a twist drill with different materials, specifically manufactured for drilling of composites. It is a Multi Facet Drill (MFD) bit used because it can produce high thrust forces, which were required for one or two specimen. As explain in literature review, carbide drills give better surface finish and more number of holes to failure; HSS drills were ruled out from the scope of this study. The range for the spindle speed and the feed rate was selected after pilot experimentation, wherein the minimum damage using visual examination was used as the selection criteria.

A. Experimental Setup

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A schematic diagram of the experimental set up is shown in figure. The drilling experiment was carried out on a HASS TM2 make CNC Tool Room Mill. The specimens are held in rigid fixture attached to a drill dynamometer. The dynamometer signals were then processed to make them suitable for computer capture. This was achieved via charge amplifiers and an Analog to Digital (A/D) converter and then passed to the computer. Torque and thrust force are difficult to measure using dynamometers in production condition. Power of the spindle motor, which is easy to monitor was therefore measured too and used to calculate the torque. The arrangement for measuring power consumed in drilling is also shown in figure. It will be seen from this that the power of the main spindle motor was measured by a power transducer. The signal can be conditioned to remove the offset due to the power required for the idle running of the spindle. The output signals from the dynamometer were fed to the Computer via a charge amplifier and digital storage oscilloscope for further analysis. The signals were processed using filter software without losing the maximum peak forces. All the drilling tests on GFRP specimen were conducted using High speed steel (HSS), Coated Carbide (CC), and Plain carbide (PC) drill bits.

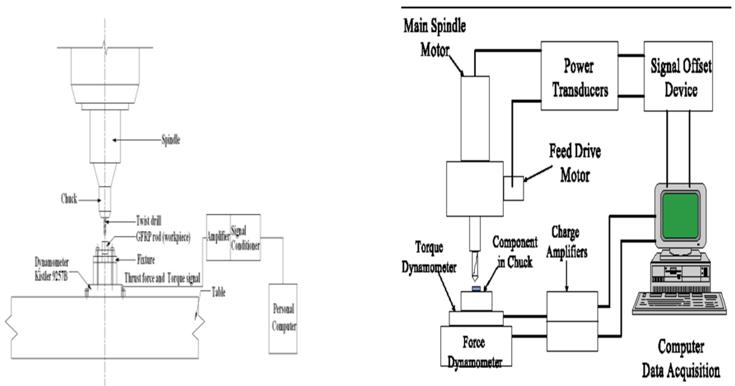


Fig.1 Block Diagram of Actual Experimental Setup

The drilling cycles were incorporated into a CNC program which took account of changes in speed and feed rates. Once the first drill had finished its cutting cycle and had been changed by the machine tool, automatic tool changer for the next drill, the program was stopped to enable the charge amplifiers to be reset and the software reinitialized, so as to capture the torque, axial force and power data coming from the dynamometers. The test was then allowed to continue.

V. TAGUCHI METHOD

Taguchi Method which combines the experiment design theory and quality loss function concept has been applied to the robust design of products and process and has solved some confusing problems in manufacturing. To observe the influence degree of control factors (Cutting Speed, feed rate, Fibre Orientation and Drill material) in drilling, four factors at three levels are considered. Quality engineering popularly known as Taguchi Design is a technology development methodology created by Dr. Genichi Taguchi and was widely adopted in the US as the Taguchi Method in the 1980's, in the automotive industry. It was first introduced in Japanese companies in the 1990's. The quality engineering Forum was established in the 1993 and was later renamed the Quality engineering Society when the Taguchi Method became known as Quality engineering. Quality engineering aims to streamline development by evaluating the good and bad points of various technologies in the upstream stages of the product commercialization process. Quality was the watchword of 1980's and Genichi Taguchi was a leader in the growth of quality consciousness. One of the Taguchi's technical contributions to the field of quality control was a new approach to industrial experimentation. Main purpose of the Taguchi Method was to develop the products that worked well in spite of natural variation in materials, feed rate, operators and environmental change. This is robust engineering. The beauty of Taguchi Design is that multiple factors can be considered at once.

A. The steps include in the Taguchi's Parameter Design are as below

1) Select the proper orthogonal array (OA) according to number of controllable factors (parameters).
2) Running experiments based on the orthogonal array (OA).
3) Analyzing the data.
4) Identifying the optimum condition.
5) Conducting confirmation runs with the optimal levels of all the parameters.
6) Determine the results of parameter design by tightening the tolerance of the significant factor.

B. General Steps in Taguchi Method

1) Define the process objective, i.e. a target value for a performance measure of the process. Our objective is to minimize the torque, thrust force and drilling induced damage. The ideal target value is taken as zero for the thrust force and torque, while unity is taken as ideal target value for damage factor.
2) To determine the design parameters affecting the process. Parameters are nothing but variables within the process that affect the performance measure that can be controlled easily. The number of levels that the parameters should be varied at must be specified. For the drilling of three GFRP specimens, typical control factors include feed rate, drill point geometry and Spindle speed.
3) Create suitable orthogonal arrays (OA) for the parameter design indicating the number of and conditions for each experiment.
4) Conduct the experiments indicated in the completed array to collect data on the effect on the performance measure.
5) Complete data analysis to determine the effect of the different parameters on the performance measure. ANOVA technique is usually used to predict relative significance of the process factors and then to estimate the experimental errors. It gives the percentage contribution of each factor and provides a better feel for the relative effect of the different factors on experimental responses.
6) Finally, the experimental validations of optimum value of the objective function are done as the optimum run may not be necessarily among the many experiments that were already carried out.

C. Analysis of Variance (ANOVA)

ANOVA was developed by the English statistician, R. A. Fisher (1890-1962). Though, initially dealing with agricultural data; this methodology has been applied to a vast array of other fields of data analysis. Analysis of variance is a statistical method used to establish relative significance of the individual independent variables as well as their interaction effects on the behaviour of the response variables. It is based on the Least Square Approach; the error variance is equal to the minimum value of the sum of squares about some reference value divided by the degree of freedom. Where, the degree of freedom is equal to number of independent elements employed in calculating the statistic. The value of variance ratio (F-ratio) and its probability (P-ratio) gives the relative significance of individual factors and their interactions. The P-values are very small and indicating the statistical significance of the model and individual factors.

The both characteristics are express as below;

$$S/N = -10 \text{ Log } 1/n\ (\Sigma\ 1/y^{**}2)$$

Input Variables (Control Factors)	Levels		
	1	2	3
Spindle Speed (rpm)	700	1600	2500
Feed (mm/rev)	0.15	0.20	0.25
Fiber Orientation (Degree)	45	60	90
Drill Bit (Material)	PC	CC	HSS

Table: Factors and Levels of the Variables used in drilling

D. The components of an ANOVA table

1) *Source* - indicates the source of variation, either from the factor, the interaction, or the error. The total is a sum of all the sources.
2) *DF*- degree of freedom from each source, if a factor has three levels, the degree of freedom is 2 (n-1). If you have a total of 12 observations, the degrees of freedom total is 11 (n - 1).
3) *SS* - sum of squares between groups (factor) and the sum of squares within groups (error)
4) *MS* - Mean squares are found by dividing the sum of squares by the degrees of freedom.
5) *F* **-** Calculate by dividing the factor MS by the error MS; comparing this ratio against a critical F found in a table or

the p-valuecan use to determine whether a factor is significant.

6) *P* - Use to determine whether a factor is significant; typically compare against an alpha value of 0.05. If the p-value is lower than 0.05, then the factor is significant.

VI. ANALYSIS OF DELAMINATION AND SURFACE ROUGHNESS

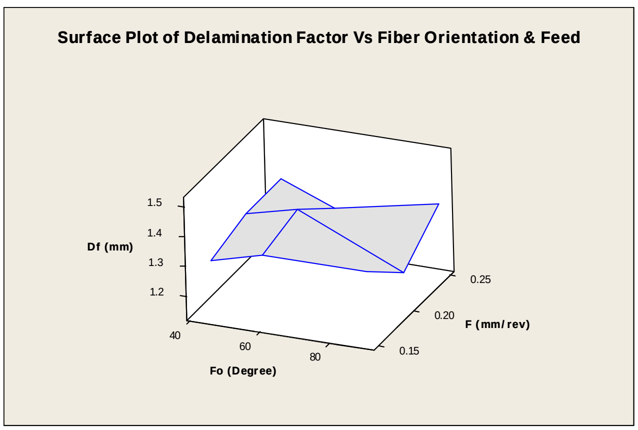
Studies observation shows that the spindle speed followed by fibre orientation has relatively more share in governing the values of thrust forces. However, it is seen from the analysis of variance from that none of the parameters are statistically significant at 90% confidence interval. The near best condition which produces smaller magnitude of the thrust force is spindle speed at 800 rpm, feed rate of 0.20 mm/rev, 45° fibre orientation and coated carbide drill material.

A. Effect of Spindle Speed on Thrust Forces

As the spindle speed increases from 800 to 1700 rpm there is a stiff increase in the thrust forces. However, a further increase in spindle speed rapidly decreases the thrust forces during drilling of GFRP composite. As the cutting speed is increased, generation of heat is more. This heat gets accumulates in the machining zone and edge, leads to softening of the work material. As a result thrust force magnitude decreased.

B. Effect of Feed on Thrust Force

Feed rate is an important factor in case of delamination, as higher feed rate cause higher thrust force and thus increasing the risk of damage around the hole. It is seen from surface plot in that at lower feed, thrust force is low, as mention from the main effect plot.



Graph 1: *The Surface Plot of Delamination Factor Vs Fiber Orientation and Feed*

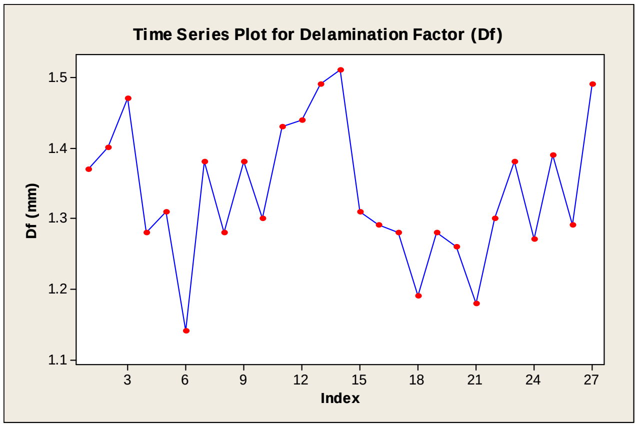
When the drill change from 0.15 mm/rev feed rate of 0.20 mm/rev, the thrust forces decreased, but again increases in spindle speed 2500 rpm and feed to 0.25 mm/rev cause increase in thrust force. Due to the low thermal conductivity of epoxy resin, the heat generated associated with chip removal concentrated in the material adjacent to the tip of the drill. This increase in temperature causes the reduction in the mechanical strength of the epoxy and a consequent decrease in the thrust force.

C. Effect of Fibre Orientation on Thrust Force

It is seen from the main effect plots, that the fibre orientation has linear effect on the variation of thrust forces produced while drilling. It is observed that an increasing fibre angle to 60° and further to 90° increases the magnitude of the thrust force produce during drilling. During drilling of each laminate of different fibre orientations, it is found that cutting edge of the drill bit abraded with the laminates initially and pulls the abraded material along the flute. This in turn, introduces an upward peeling force due to which upper laminate separate from the uncut portion held by the downward acting thrust force.

D. Effect of Drill Type on Thrust Force

It is observed that the drill material has non linear variation and the magnitude of the thrust force produce during drilling of GFRP composite. The lower magnitudes of the thrust force were generated when a coated carbide drill was used. However, the plain carbide drill produced higher magnitude of thrust forces, but a drilling with HSS drill gives a moderate amount of thrust force. As the drill material approach, there is no thrust since the drill has not come into contact with the work specimen. There was an initial rise in the thrust force, When the drill begins to cut through the work material. It was seen that the thrust force tend to drill cut through the glass resin matrix. GFRP which is brittle and can only absorb energy in elastic deformation and through damage mechanism.



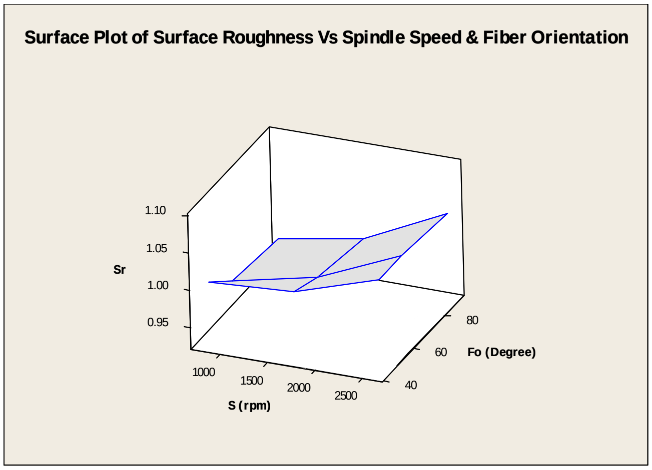
Graph 2: Time Series Plot for Delamination Factor

E. Effect of Spindle Speed on Cutting Torque

It is observed from ANOVA plots that as the spindle speed increases from 700 to 1600 rpm there is a stiff increase in the cutting torque. However, a further increase in spindle speed rapidly decreases the cutting torque as well as thrust forces during drilling of GFRP composite. As the cutting speed is increased, generation of heat is more. This heat gets accumulates in the machining zone and edge, leads to softening of the work material. As a result cutting torque magnitude decreased.

F. Effect of Feed on Cutting Torque

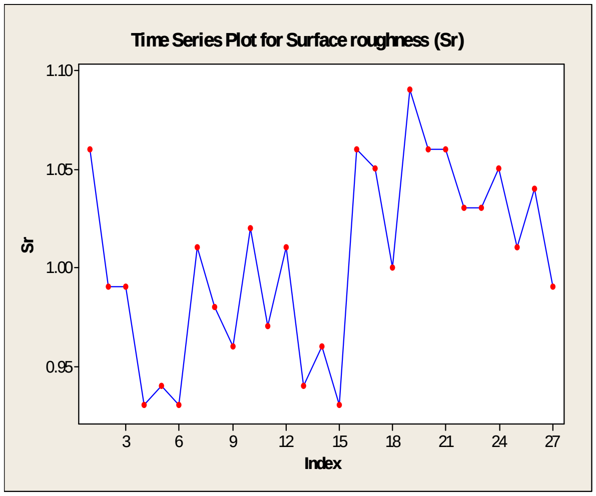
It is observed from the Surface plot that at lower spindle speeds and lower feed, cutting torque is low. When the drill change from 0.15 mm/rev feed to 0.20 mm/rev, the cutting torque decreases, but again increases in feed at 0.25 mm/rev, cause increase in cutting torque. Due to the low thermal conductivity of epoxy resin, the heat generated associated with chip removal concentrated in the material adjacent to the tip of the drill. This increase in temperature causes the reduction in mechanical strength of the epoxy and a consequent decrease in the cutting torque.



Graph 3: *The Surface Plot of Surface Roughness Vs Spindle Speed & Fiber Orient.*

G. Effect of Fibre Orientation on Cutting Torque

The fibre orientation has linear effect on the variation of cutting torque produced while drilling. It is observed that, an increasing fibre angle to 60° and further to 90° increases the magnitude of the cutting torque produce during drilling. During drilling of each laminate of different fiber orientations, it is found that cutting edge of the drill bit abraded with the laminates initially and pulls the abraded material along the flute. This in turn, introduces an upward peeling force due to which upper laminate separate from the uncut portion held by the downward acting thrust force, same effect on the cutting torque.



Graph 4: *Time Series Plot for Surface Roughness*

H. Effect of Drill Type on Cutting Torque

The drill material has non linear variation and the magnitude of cutting torque produce during drilling of GFRP composite. The lower magnitudes of the cutting torque were generated when a coated carbide drill was used. However, the plain carbide drill produced higher magnitude of cutting torque, but a drilling with HSS drill gives a moderate amount of cutting torque and thrust force. A variation of cutting torques in all 27 experiments observed during drilling of GFRP composite.

VII. REGRASSION EQUATION

This section enumerates the linear regression equations developed for output variables, namely thrust force (Th), cutting torque (Tq), delamination (Df) and surface roughness (Sr).

A. Thrust Force

Thrust Force = 36.9 – 0.01 (Spindle speed) – 0.47(Feed) + 2.38(Fiber orientation) – 0.90 (Drill type)

Th = 36.9 -0.01S – 0.47 f + 2.38 Fo-0.90 Dt

B. Cutting Torque

Cutting Torque = 21.2 – 0.267 (Spindle speed) + 0.139 (Feed) + 0.410 (Fiber orientation) – 0.754 (Drill Type)

Tq = 21.2 – 0.267 S + 0.139 f + 0.410 Fo -0.754 Dt

C. Delamination Factor

Delamination Factor = 1.39 – 0.0094 (Spindle speed) – 0.0089 (Feed) – 0.011 (Fiber orientation) + 0.0017 (Drill Type)

Df = 1.39 – 0.0094 S – 0.0089 f – 0.011 Fo + 0.0017 Dt

D. Surface Roughness

Surface Roughness = 0.988 + 0.0317 (Spindle speed) – 0.00833(Feed) – 0.0128 (Fiber orientation) – 0.00278 (Drill type)

Sr = 0.988 + 0.0317 S – 0.00833 f – 0.0128 Fo – 0.00278 Dt

VIII. CONCLUSION

The following conclusions can be drawn from the results of above experimental investigation based on Taguchi Method, carried out on three GFRP composite specimens using High Speed Steel (HSS), Plain Carbide (PC) and Coated Carbide (CC) drill tool:

A. It is observed from the ANOVA, the input factors like feed, spindle speed, fibre orientation and drill material have statistically significant influence on the drilling of GFRP composite.

B. Delamination can be reduced, if proper cutting parameters are selected. Considering the parameter used in this work, the best set (based on the S/N ratio, the optimal parameters for the minimum delamination) quality of hole and surface roughness was a,

Feed Rate: *0.20 mm/rev,* ***Spindle Speed:*** *700 rpm,* ***Drill Material:*** *Plain Carbide and* ***Fibre Orientation:*** *45°.*

C. Out of this, the feed rate and drill diameter are seen to make the largest contribution to the overall performance (Delamination). Generally, the high speed and low feed favour the minimum delamination on both entry and exit of the drilling leads to better surface finish and tool life.

D. From the above drills experimented; HSS twist drill had the lowest results, showing the inadequacy of the use of this material in drilling tools for Glass Fibre Reinforced Plastics (GFRP). Carbide twist drill had the best results for thrust force and Delamination Factor.

E. The confirmation tests were carried out to verify the predicted optimal conditions. Values of estimation gain and confirmation gain were found to close to each other.

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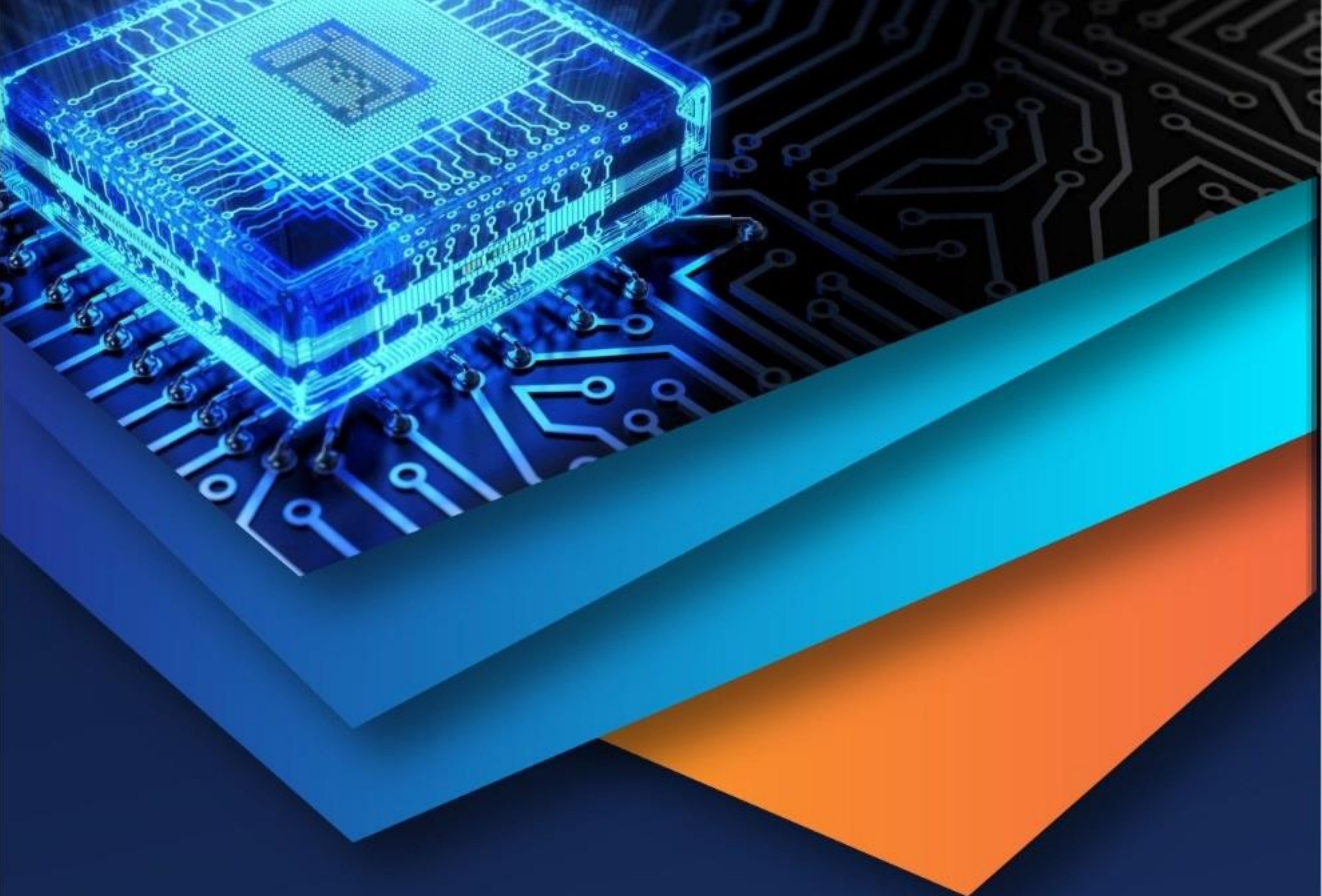

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