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Experimental investigation of mechanical characterization and drilling of fabricated GFRP composites reinforced with Al₂O₃ micro particles

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ABSTRACT

Nowadays composites became very popular due to its eminent physical and mechanical attributes. Composites are widely used in all the industries like the construction sector, ships, aerospace, automobile etc. One of the most indispensable attributes of the composites is a higher strength to weight ratio because of which it is widely used in aerospace parts. Further to ameliorate the properties of the composites microparticles could be added. In this thesis fabrication of glass fiber composites with microparticles in order to ameliorate the mechanical attributes such as tensile, flexural, impact strength and hardness by conducting tests such as tensile strength test, flexural strength, impact and micro Vickers hardness test, respectively. Machining of the composites has always been a complex problem in the case of glass fiber reinforced polymer matrix composites because of the laminar nature of the composites. In order to assemble the structural parts made by composites with the help of rivets and joints or nut-bolts, it is obligatory to drill the composites to make a hole. During the exit and the entry of the drill bit in the hole, composites undergo severe damages in the topmost layer and bottom-most layer which in turn results in the delamination of the layers. So in this thesis, the drilling process parameters cognate speed, feed and the weight percentage of alumina microparticles were optimized in order to optimize the output parameters like thrust force and delamination factor of the composites. The optimization of the parameters was done according to retaliation surface paradigm concept. The optimum values of input parameters are 1213 rpm speed, 0.16 mm/rev feed and 5.2 % wt. % of alumina microparticles. The corresponding optimal parameters for these parameters are 179.4 N thrust force, entry delamination factor 1.12 and exit delamination factor 1.17 with the desirability of 0.838.

Keywords: GFRP, Fabrication, Mechanical characterization, Drilling, Parameters, Response surface methodology optimization, Design expert software

1. INTRODUCTION

1.1 Composite materials

Fabrication of a material which consists of two or more than two physically distinct and mechanically separable components is known as composite materials. Figure 1.1 shows the two different components of the composites. One of the components which transfer the load in the composite is known as Matrix and another component which is used to bear the load in the composite is known as the Reinforcement. Matrix and reinforcement is mixed in a suitable way to obtain the desired properties which are superior to both the components

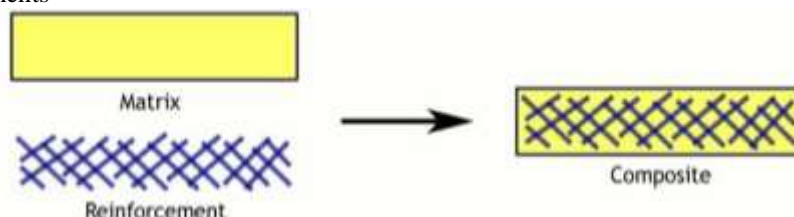


Fig. 1.1: Schematic diagram of components present in the composites

The various application areas of composite materials are Automobile industries, Marine industries, Aeronautical applications, Communication antennae, Electronic PCBs, Safety equipment, bridges, and buildings etc.

1.2 Classification of composite material

Broadly, composite materials can be categorized into three groups on the basis of the matrix material. They are metal matrix composites (MMCs), ceramic matrix composites (CMCs), and polymer matrix composites (PMCs). Fig1. 1 shows the major

classification of composites based on matrix materials. On the basis of reinforcing materials, composites materials are classified into three class i.e. Particulate reinforced Composites, Fibrous reinforced Composites, and structurally reinforced composites. Fig.1.3 shows the classification of composites based on reinforcement material.

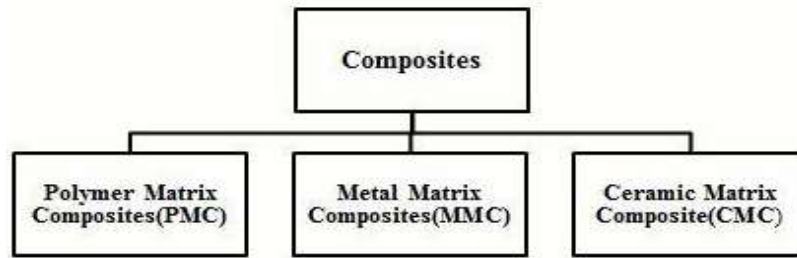


Fig 1.2: Major classification of composites based on matrix materials

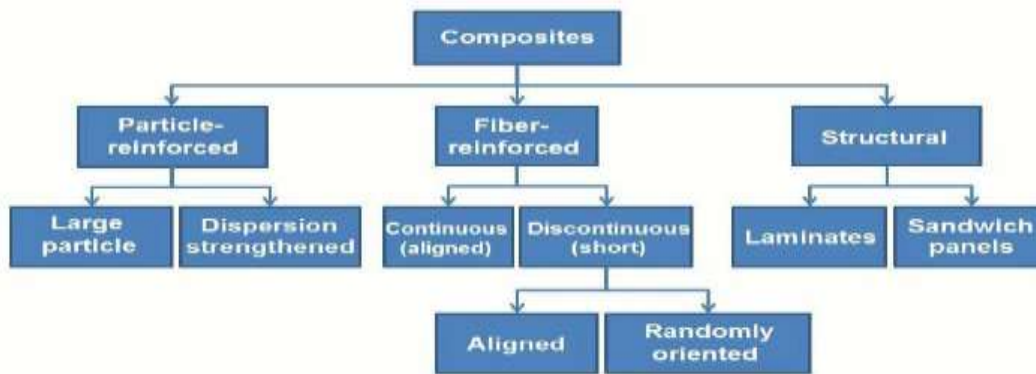


Fig. 1.3: Classification of composites based on reinforcement material

1.3 Mechanical properties of composites

The various advantages of composite material in terms of mechanical attributes are high flexural modulus, high impact strength, high creep resistance, wear resistant, corrosion resistant, high toughness, high tensile strength, high hardness etc.

1.3.1 Addition of microparticles to the composites: The above mechanical attributes can be furthermore ameliorated by the addition of micro and nanoparticles to the composite materials. These micro and nanoparticles provide better adhesion between the layers because of the large surface to volume ratio which allows the better contact of reinforcements and matrix. These micro and nanoparticle are generally added to the composite materials to enhance their processability and mechanical properties and also to reduce the material costs. The various behavior shown by the filler particles are due to the various factors like particles of a size, surface area, shape, and surface chemistry etc.

1.4 Fabrication of composites

The various fabrication techniques of composite materials are Hand lay-up, Spray-up, Vacuum Bagging, Automated tape laying, Closed Mold Processes, Filament Winding, Pultrusion Processes etc.

1.5 Mechanical Characterization

To study the effect of adding micro particles in glass fiber reinforced composites by mechanical characterization. The tests are being executed on four different specimens of composites. Various mechanical characterization of Glass fiber reinforced polymer are in terms of tensile strength, flexural strength, Impact strength and hardness and these are conducted by a tensile test, Three points bending test, Charpy impact test, and micro Vickers hardness test respectively.

2. OPTIMIZATION

In this work process parameters of a fabricated GFRP composite is optimized in order to get a minimum damage to the composite structure during the drilling of the holes. The various process parameters which are optimized in this thesis are spindle speed (rpm), feed rate (mm/rev), amount of weight percentage of the alumina micro particles. The optimized output process parameters are thrust force, exit delamination factor and entry delamination factor.

2.1 Materials & Fabrication of GFRP composites

The glass fiber reinforced polymer composite is prepared by hand layup process. The matrix used is Epoxy resin LY 556 and E-Glass fiber in mat form is used as reinforcement. HY 951 is used as a hardening agent and ratio of resin and hardener is 100:10. The curing is done at room temperature, for 24 hours.

2.2 Accessories required for fabrication

In this work, we used glass fiber as the reinforcement. Wooden molds with dimensions of 200x200x5 mm³ are used for the fabrication of composites. The volume ratio of the epoxy and glass fiber used in this thesis is 40:60. 10 percentage by weight hardener is added to the epoxy resin. Figure 3.1 shows the mold used to fabricate the composite.

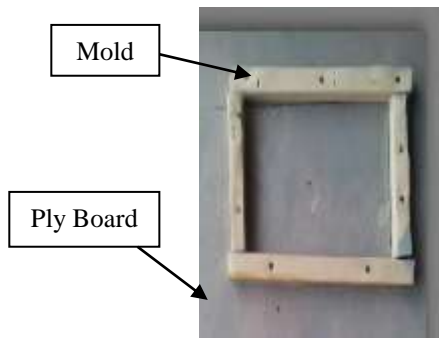


Fig. 2.1: Mold used for the fabrication of composites

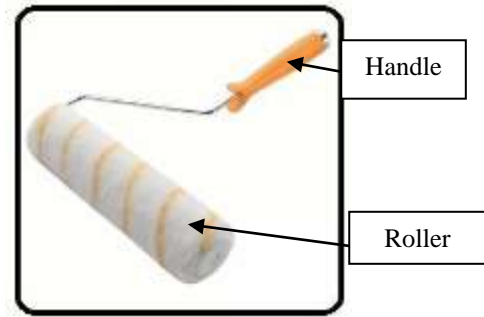


Fig. 2.2: Roller used for the leveling of the composites

3. OPTIMIZATION METHODOLOGY

In this work, we have used Response Surface Methodology as an optimization technique. The various factors which are selected for the design of the experiment are spindle speed, feed rate and the weight percentage of alumina microparticles. There are three levels for each of the factors selected for the design of the experiment in the RSM. The output process parameters which are going to optimize in this thesis are drilling thrust force, entry delamination behavior and exit delamination behavior. The software Design expert 10 is used for the optimization of the responses of drilling.

3.1 Introduction to response surface methodology

The adequate compilation of the mathematical and statistical methods to formulate an empirical model is generally known as response surface methodology. By frugal design of experiments, in the response surface methodology, the goal is to optimize a result (output variables) which are affected by several individual variables (input variables). An experiment is a chain of tests, generally known as runs, in which alterations are made in the input parameters in order to observe the reasons for alterations in the response. The application of response surface methodology is to design the optimized empirical model. The response can be represented graphically, either in the three-dimensional space or as contour plots that help visualize the shape of the response surface.

3.2 Design of experiments

3.2.1 Full factorial design

To prepare a conjecture model that can catch interactions between the N designs parameters, one full factorial commence is necessary to scrutinize all possible cases. A factorial test is an experimental scheme in which design variables are varied all at a time, rather of one at a time. The lower and upper jumps of each of N design parameters in the optimization model should be identified. The allowable bound is then defined at different levels. If each of the parameters is identified at only the lower and upper rang (two levels), the experimental model is called 2N full factorial design. Similarly, if we include the midpoints of the variables then this would be known as 3N full factorial.

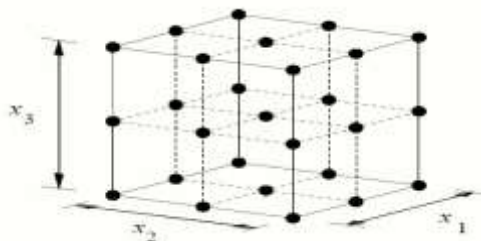


Fig. 3.1: A 33 full factorial design (27 points)

For fitting the second-order models we can use the factorial designs because comparing to the first-order model, the second-order model ameliorates the optimization process more significantly. Generally, a second-order model can be defined as given below:

$$y = a_0 + \sum_{i=1}^n a_i x_i + \sum_{i=1}^n a_{ii} x_i^2 + \sum_{i=1}^n \sum_{j=1, j \neq i}^n a_{ij} x_i x_j \quad (1)$$

Here x_i and x_j represent the design variables and a represents the tuning parameters.

3.2.2 Central composite design

A central composite design is the most commonly used response surface designed experiment. Central composite designs are a factorial or fractional factorial design with center points, augmented with a group of axial points (also called star points) that let you estimate curvature.

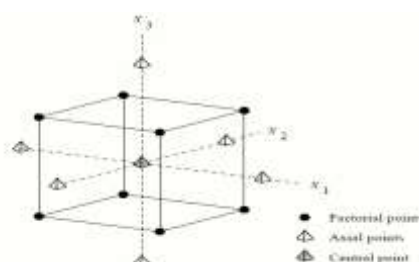


Fig. 3.2: Central composite design for 3 design variables at 2 levels

3.3 Design expert software

Design Expert is a chunk of software developed to help with the draft and elucidate of multifactor experiments. In polymer testing, we might use the programs to help us develop a model to see how parameters such as tensile strength alter with changes in the preparing conditions - e.g. alteration in rotor speed or pressure of the ram. The software provides a wide range of models, involving factorials, fractional factorials and also composite designs. The software can handle both process parameters, such as rotor speed, with mixture parameters, such as the amount of resin in the plastic compound. Design Expert software offers computer duly generated D-optimal models for cases where standard models are not applicable. Design Expert is a demographic software collection from Stat-Ease Inc. that is originally dedicated to solving design of experiments (DOE). Design-Expert provides comparative tests, scrutinizing, characterization, intensification, robust parameter design, mix designs, and combined models. Design-Expert offers test matrices for scrutinizing up to 50 factors. Statistical importance of these parameters is established with (ANOVA). Graphs tools help to identify the effect of each parameter on the desired responses and reveal abnormalities in the model.

4. RESULTS AND DISCUSSION

4.1 Mechanical characterization

4.1.1 Micro-hardness

Vickers hardness number is measured by Vickers microhardness tester. As we are dealing with the improvement of mechanical properties of glass fiber reinforced polymer composites because of the addition of the alumina microparticles into the composites so we have taken glass fiber and epoxy specimen as a reference specimen. The value of microhardness of the reference specimen is 10.77 HV and after the addition of microparticles to this specimen the hardness value increases by about 41.3 % and reaches to 15.22 HV. Microhardness of epoxy alumina is 12.4 HV which is also 15 % more than the reference specimen and the value of microhardness of epoxy with microparticles is also about 30% more than the reference specimen. Also fig. 4.1 shows the bar graph of the average microhardness values of various test specimens.

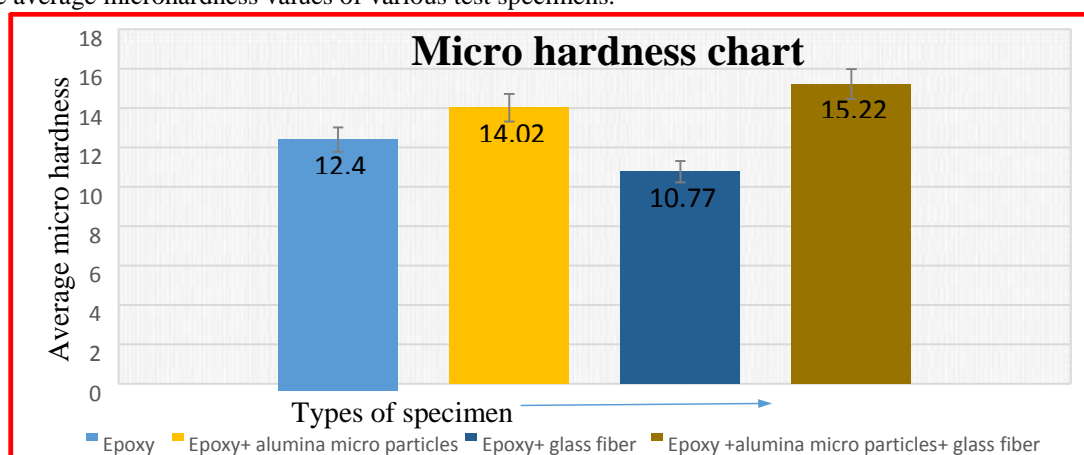


Fig. 4.1: Bar graph for micro hardness values of test specimens

In hardness test, a compressive load is in action and therefore the polymer matrix phase and the solid fiber and or filler phase would be pressed together and they are bound to each other more tightly. Thus, the interface can transfer load more effectively, although the interfacial bond may be poor. This might have resulted in enhancement of hardness. The improvement of the micro hardness value of GFRPs may also be due to the higher hardness of the micro particles which creates the resist to indentation more effectively.

4.1.2 Impact energy

Impact energy of the composites is measured by the Charpy impact testing machine. The values of the impact energy of the various test specimens are listed in fig 4.2. Comparisons of impact strength of the composite specimen are done in the fig4.2. The composite specimen epoxy with glass fiber is taken as the reference for the comparisons of impact strength of test specimens. Comparisons of impact strength show that the impact strength of the composite is increased by about 6.15% by adding the 10% alumina micro particles in the composites. Composites fabricated without glass fiber are having the lesser impact energy because epoxy is extremely brittle which is mainly responsible for the lower impact strength.

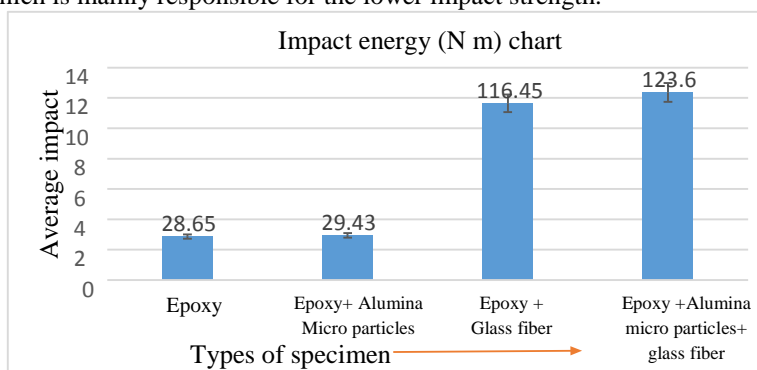


Fig. 4.2: Bar graph for an impact energy of test specimens

Since the surface area to volume ratio of the microparticles is more so, this provides the better adhesive bonding between the glass fiber and the epoxy polymer which in turn increase the impact strength of the GFRPs. Due to the small size of the microparticles, it provides the more roughness in the composites which hinders the path of deformation in the composites. These micro particles also improve the wettability of the epoxy polymer and the glass fiber which provide the higher bond strength between the epoxy polymer and glass fiber.

4.1.3 Flexural strength

The bending or flexural properties of the GFRPs were measured by a three-point flexural tests machine. The composite specimen epoxy with glass fiber is taken as the reference for the comparisons of flexural strength of test specimens. Comparisons of flexural strength show that the flexural strength of the composite is increased by about 42.18% by adding the 10% alumina micro particles in the composites. Composites fabricated without glass fiber are having the lesser flexural strength because of lower interfacial interaction between the glass fibers and epoxy polymers.

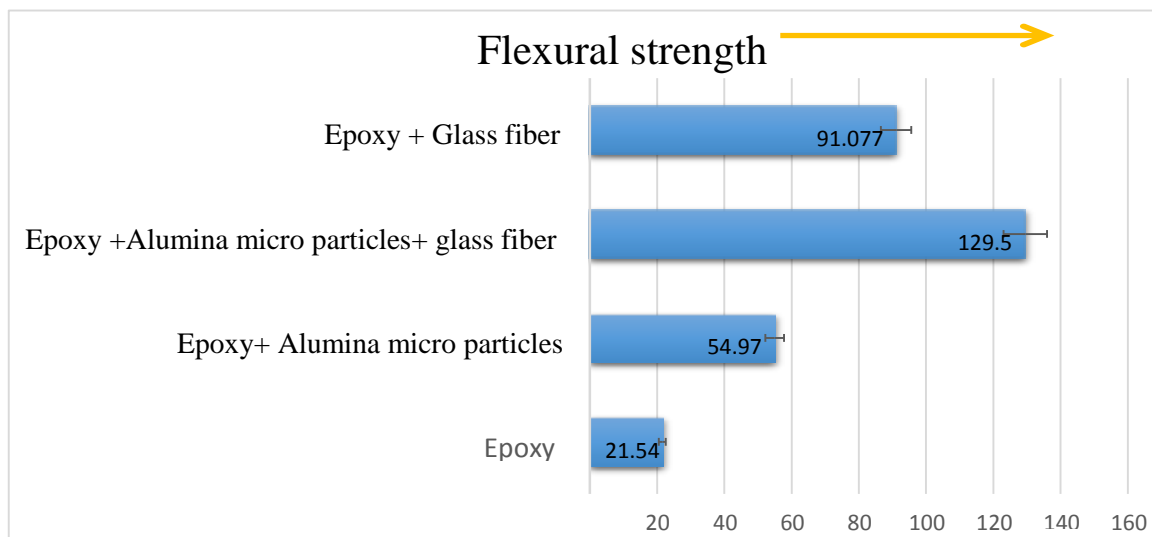


Fig. 4.3: Bar graph flexural strength of test specimens

The improvement in the flexural strength may be related to the presence of micro alumina at the interface of the fiber and the matrix. The alumina microparticles may enhance the interfacial properties up to certain loading. It is well-known that the interfacial bonding or adhesion between the fiber/filler and the matrix and the uniform dispersion of filler have a significant influence on the mechanical characteristics of particulate and GFRPs.

4.1.4 Tensile strength

Tensile properties are measured by the electromechanical universal testing machine. The results are tabulated in table 4.1. As we are dealing with the improvement of mechanical properties of composites due to the addition of the alumina micro particles into the composites so we have taken glass fiber and epoxy specimen as a reference specimen. The value of tensile strength of the reference specimen is 53.37 N/mm² and after the addition of micro particles to this specimen, the tensile strength increases by about 49.44 % and reaches to 79.76 N/mm². Table 4.1 and 4.2 indicates the tensile strength of various test specimens and the percentage increase in tensile strength by the addition of micro-particles respectively.

Table 4.1: Tensile properties values of various test specimens

Types of specimen	Peak load (kN)	Displacement at Peak load (mm)	Tensile strength (N/mm ²)	Tensile strain (N/mm ²)	Modulus of Elasticity
Epoxy + alumina micro particles +glass fiber	5.81	6.1	89.38	0.12	744.84
	5.65	6.29	72.67	0.137	530.44
	5.02	7.01	77.23	0.1422	543.10
Average values	5.494	6.467	79.76	0.133	606.18
Epoxy + glass fiber	3.18	5.47	48.9	0.1082	451.94
	3.59	4.33	55.23	0.0848	651.29
	3.64	4.62	56	0.055	1018,18
Average values	3.47	4.80	53.37	0.0826	707.10

Table 4.2: Percentage improvement of Tensile strength by the addition of micro particles

Types of specimen	Average Tensile strength (N/mm ²)	Reference Tensile strength (N/mm ²) value	Percentage increase in tensile strength (N/mm ²) value
Epoxy + glass fiber	53.37	53.37	0%
Epoxy + alumina micro particles + glass fiber	79.76	53.37	49.44%

The added alumina micro particles were expected to enhance the interfacial bonding strength between glass fibers and epoxy resins which in increases the tensile strength of the composites. Since the micro particles have a larger surface area to volume ratio

which provides the better adhesion between the epoxy polymer and glass fibers which strengthen the tensile strength of the composites.

4.2 Drilling experiment results

4.2.1 Experimental values of machining response

The responses of machining and the results are reported on Thrust force, Entry F_d and Exit F_d

Table 4.3: Responses of machining process in terms of Thrust force, Entry F_d and Exit F_d

Std.	Run	Speed rpm	Feed mm/rev	Wt.% of micro particles	Mean Thrust force	Entry F_d	Exit F_d
2	1	1510	0.1	5	340.3	1.02	1.13
9	2	480	0.3	10	152.6	1.2	1.22
15	3	1005	0.3	10	166.4	1.27	1.07
17	4	1005	0.3	10	115.9	1.17	1.08
18	5	1005	0.3	10	132.6	1.15	1.59
5	6	480	0.1	15	347.2	1.31	1.30
8	7	1510	0.5	15	167.2	1.19	1.58
3	8	480	0.5	5	153.9	1.5	1.32
1	9	480	0.1	5	587.1	1.13	1.42
10	10	1510	0.3	10	112.9	1.37	1.13
6	11	1510	0.1	15	200	1.02	1.13
11	12	1005	0.1	10	157.6	1.32	1.17
14	13	1005	0.3	15	246.9	1.58	1.25
4	14	1510	0.5	5	146.9	1.42	2.32
12	15	1005	0.5	10	165.2	1.17	1.32
7	16	480	0.5	15	62.56	1.34	1.58
16	17	1005	0.3	10	166.1	1.25	1.15
19	18	1005	0.3	10	158.1	1.33	1.17
13	19	1005	0.3	5	125.0	1.18	1.13
20	20	1005	0.3	10	162	1.15	1.15

4.2.2 ANOVA for Thrust force

Table 4.4: Analysis of variance table [Partial sum of squares - Type III] for thrust force

Source	Sum of squares	df	Mean square	F value	P value	Prob. > F	
Model	2.478E+005	9	27536.66	53.50	< 0.0001		Significant
A – speed	11293.16	1	11293.16	21.94	0.0009		
C – wt.	7309.78	1	7309.78	14.20	0.0037		
AB	30176.25	1	30176.25	58.63	0.0001		
AC	5577.79	1	5577.79	10.84	0.0081		
BC	11947.49	1	11947.49	23.21	0.0007		
B ²	4977.41	1	4977.41	9.67	0.0111		
C ²	13474.31	1	13474.31	26.18	0.0005		
A ² B	1.114E+005	1	1.114E+005	216.44	< 0.0001		
A ² C	21841.74	1	21841.74	42.43	< 0.0001		
Residual	5147.11	10	514.71				
Lack of Fit	2943.96	5	588.79	1.34	0.3791		Not significant
Pure Error	2203.15	5	440.63				
Cor Total	2.530E+005	19					

From the ANOVA table, we can say that only speed and weight percentage of alumina micro particles are having a significant effect on the thrust force. Spindle speed is having no any significant effect on the thrust force.

4.2.3 ANOVA for Entry F_d

Table 4.5: Analysis of variance table [Partial sum of squares - Type III] for Entry F_d

Source	Sum of squares	df	Mean square	F value	P value	Prob. > F	
Model	0.16	3	0.052	3.41	0.0433		Significant
B – feed	0.067	1	0.067	4.39	0.0525		
BC	0.041	1	0.041	2.65	0.1230		
AC ²	0.049	1	0.049	3.19	0.0932		
Residual	0.25	16	0.015				
Lack of Fit	0.22	11	0.020	3.55	0.0863		Not significant
Pure Error	0.028	5	5.560E-003				
Cor Total	0.40	19					

From the ANOVA table, we can say that only feed is having a significant effect on the Entry Fd. Spindle speed and the weight percentage of alumina Micro particles are having no any significant effect on the thrust force.

4.2.4 ANOVA for Exit F_d

Table 4.6: Analysis of variance table [Partial sum of squares - Type III] for Exit F_d

Source	Sum of squares	df	Mean square	F value	P value Prob. > F	
Model	0.66	2	0.33	5.97	0.0109	Significant
B – feed	0.39	1	0.39	7.02	0.0168	
B ²	0.27	1	0.27	4.91	0.0406	
Residual	0.94	17	0.055			
Lack of Fit	0.75	12	0.063	1.65	0.3026	Not significant
Pure Error	0.19	5	0.038			
Cor Total	1.60	19				

ANOVA table indicates that only feed is having a significant effect on the Exit Fd. Spindle speed and the weight percentage of alumina Micro particles are having no any significant effect on Exit F_d

Table 4.7: Goals set and limits used for the optimization

Constraints						
Name	Goal	Lower Limit	Upper Limit	Lower Weight	Upper Weight	Importance
A:speed	is in range	480	1510	1	1	3
B:feed	is in range	0.1	0.5	1	1	3
C:wt.	is in range	0.5	15	1	1	3
Thrust force	Minimize	62.56	587.1	1	1	3
Entry F_d	is target= 1.02	1.02	1.58	1	1	3
Exit F_d	is target= 1.07	1.07	2.32	1	1	3

4.2.5 Optimal Contour 3 D Plots

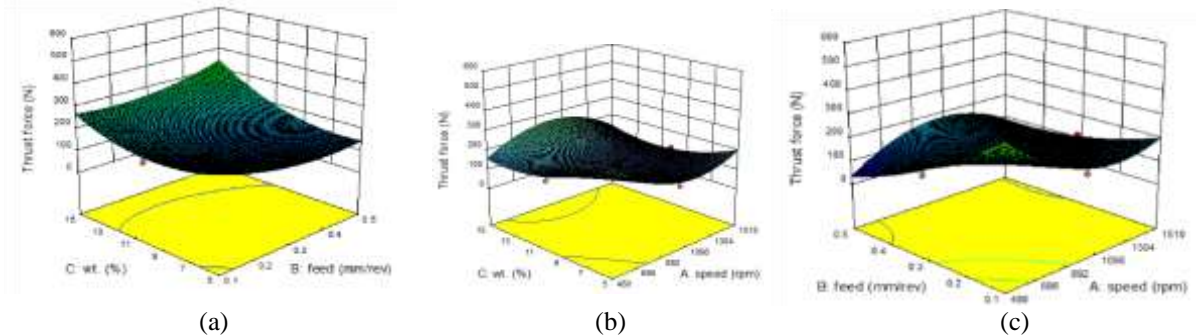


Fig. 4.4: 3D graph shows the interaction effects of thrust force due to (a) wt. % and feed, (b) wt. % and speed, and (c) feed and speed

From the above 3D plots it is observed that the thrust force depends on all the three input parameters i.e. speed, feed and wt% of alumina micro particles. It is clear from the above plots that if one can go with any of the two parameters at a time there is an optimal solution for each of three combinations. The optimum value of the thrust force (minimum value) can be obtained by considering any two parameters at a time. The red points on the plots show the values which are deviations from the predicted value based on the response surface methodology concept.

Design-Expert® Software

Factor Coding: Actual

Exit F_d

- Design points above-predicted value
- Design points below predicted value



2.32
1.07
X1 = B: feed
X2 = A: speed
Actual Factor
C: wt. = 13

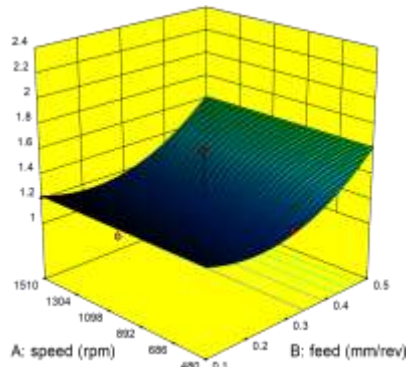


Fig. 4.5: 3D graph shows the interaction effects on exit delamination due to feed and speed

From the ANOVA table of the exit delamination factor, it is clear that only feed is having the significant effect on the exit delamination factor while speeding and wt. % of alumina micro particles is not having any significant effect on the exit delamination factor. So the 3D plot generated for the exit delamination factor depends on only one factor i.e. feed of the drilling process. From the above plot, it is observed that lower feeds are having the optimal values of the exit delamination factor as the desired exit delamination factor is minimum. The red points on the plots show the values which are deviations from the predicted value based on the response surface methodology concept.

Design-Expert® Software

Factor Coding: Actual

Entry F_d

- Design points above-predicted value 1.58

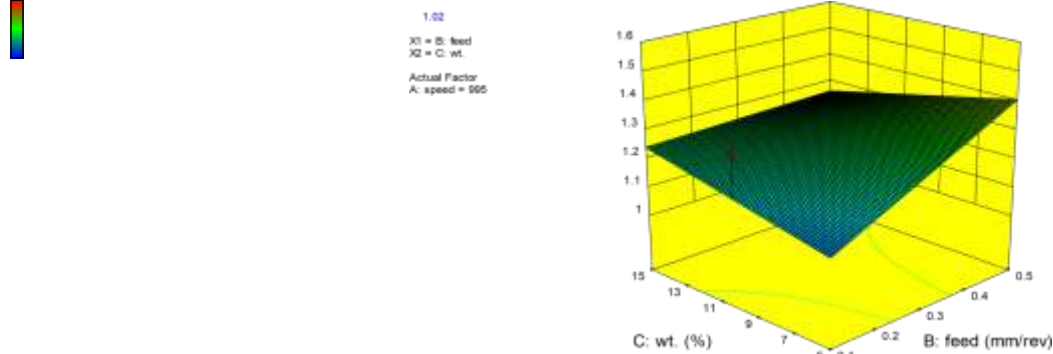


Fig. 4.6: 3D graph shows the interaction effects on Entry delamination due to wt. % and feed

From the ANOVA table of the entry delamination factor, it is clear that only feed and wt. % of alumina micro particles are having the significant effect on the entry delamination factor while speed is not having any significant effect on the entry delamination factor. So the 3D plot generated for the entry delamination factor depends on only feed and wt. % of alumina micro particles. From the above 3D plots it is clear that the lower feed rate and lower wt. % of alumina micro particles are providing the optimal values of the entry delamination factor as the desired entry delamination factor is minimum. The red points on the plots show the values which are deviations from the predicted value based on the response surface methodology concept.

5. CONCLUSIONS

In this project made an attempt to fabricate composite made up of epoxy as matrix and glass fiber as reinforcement with and without the addition of 10% micro particles and to characterize the properties of the fabricated composite by mechanically and metallurgically and to optimize the drilling process parameters for the composites with the addition of varying percentage of micro particles.

The results of the study are as follows:

5.1 Fabrication

The four specimens of GFRP composites of size 200x200x5 mm³ are fabricated for the mechanical characterization. The four types of samples are pure epoxy, Epoxy with 10% wt. alumina, Epoxy with glass fiber and Epoxy with alumina and glass fiber. The three specimens of size 200x200x5 mm³ of GFRP composites with various wt. % of alumina micro particles are fabricated for the drilling operation. The three types of samples are of Epoxy with alumina and glass fiber by 5%, 10% and 15% by weight respectively.

5.2 Mechanical Characteristics

Improvement in the mechanical properties of GFRP composites reinforced with alumina microparticles compared to GFRP composite is as follows:

- 15.22 HV is the Hardness of GFRP Composites Reinforced with Al₂O₃ and shows 41.3 % improvement compared to the hardness of GFRP composite.
- 123.6 N-m is the Impact energy of GFRP Composites Reinforced with Al₂O₃ and shows 6.15% improvement compared to Impact energy of GFRP composite.
- 79.76 N/mm² is the tensile strength of GFRP Composites Reinforced with Al₂O₃ and shows 49.44% improvement compared to the tensile strength of GFRP composite.
- 129.5 N/mm² is the flexural strength of GFRP Composites Reinforced with Al₂O₃ and shows 42.18% improvement compared to the flexural strength of GFRP composite.

5.3 Drilling Optimization

In this project work, the application of Response surface methodology and Central composite design for modeling the effect of machining parameters on thrust force, entry delamination factor and exit delamination factor investigated. In this thesis, the Second-order single-valued model based on Response surface methodology is designed using as per CCD. The process parameters of this model are spindle speed, feed rate, and wt. % of alumina micro particles are examined for the model development. The developed Response surface methodology models are checked through ANOVA and they are found to be appropriate at 95% confidence interval. The significant conclusions of this thesis work are as follows:

- Central composite design can be used to establish mathematical models for forecasting thrust force, entry delamination factor and exit delamination factor.

- ANOVA clearly shows only feed and the weight percentage of alumina Micro particles are having a significant effect on the thrust force.
- From the ANOVA table, we can say that only the weight percentage of alumina Micro particles is having a significant effect on the Entry F_d .
- From the ANOVA table, we can say that only feed and product of speed and are having a significant effect on the Exit F_d .

The optimum values of input parameters are speed 1213.18 rpm, feed 0.16 mm/rev and wt. % of alumina micro particles is 5.20%. The corresponding optimal parameters for these parameters are thrust force 179.4, entry delamination factor 1.12 and exit delamination factor 1.17 with the desirability of 0.838.

6. REFERENCES

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