Fabrication, Testing and Machinability Evaluation of Glass Fiber Reinforced Epoxy Composites

S. S. Panda, Arkesh Chouhan, Yogesh Deshpande

***Abstract*—**The present paper deals with designing and fabricating an apparatus for the speedy and accurate manufacturing of fiber reinforced composite lamina of different orientation, thickness and stacking sequences for testing. Properties derived through an analytical approach are verified through measuring the elastic modulus, ultimate tensile strength, flexural modulus and flexural strength of the samples. The 0^0 orientation ply looks stiffer compared to the 90^0 ply. Similarly, the flexural strength of 0^0 ply is higher than to the 90^0 ply. Sample machinability has been studied by conducting numbers of drilling based on Taguchi Design experiments. Multi Responses (Delamination and Damage grading) is obtained using the desirability approach and optimum cutting condition (spindle speed, feed and drill diameter), at which responses are minimized is obtained thereafter. Delamination increases nonlinearly with the increase in spindle speed. Similarly, the influence of the drill diameter on delamination is higher than the spindle speed and feed rate.

***Keywords*—**Delamination, FRP composite, multi response optimization, Taguchi design.

I. Introduction

COMPOSITE materials have characteristics different from the constituent materials. It has high strength to weight and modulus to weight ratio. Also, composites exhibit resistance to corrosion. This has spurred applications of composites in areas such as car design, aerospace industry and household items. It is necessary to understand and document mechanical properties of composites to augment their usage in a variety of applications.

Shrivastava et al. [1] studied the tensile properties of short glass fiber and random glass fiber reinforced epoxy resin on the addition of fly-ash filler. An increase in the moduli of the composite was obtained by filing fly-ash particles and coating the fibers. Paliwal and Chaturvedi [2] investigated glass-epoxy composites with Calcium Carbonate as filler material for tensile strength. Using the hand layup technique to manufacture the specimens, they found that the tensile strength of the composite increased with an increase in weight percentage of glass fiber. Also, as weight percentage of Calcium Carbonate increased, the tensile strength of the composite decreased. Deogonda and Chalwa [3] used TiO_2 and ZnS as filler materials for glass fiber reinforced epoxy composites and found an increase in strength of the composite for an increase of volume percentage of filler material, irrespective of whether it was TiO_2 or ZnS. Also, the ZnS filled composite samples showed higher strength than the TiO_2 filled composite samples for the same volume percentages. Hussain et al. [4] used Al2O3 particles as filler to compare carbon fiber reinforced composites with and without filler. Adem [5] did a thesis on mechanical characterization of glass reinforced epoxy and polyester composites for automotive body applications. After conducting mechanical testing using a universal testing machine to determine tensile, compression, shear and flexural strength, Scanning Electron Microscopy was used to study in-homogeneity, porosity and fracture behavior. Also, the effect of the strain rate on material properties was studied and documented. Nunes et al. [6] subjected anisotropic polymeric composite discs to three-point bending test to study their behavior in complex flexural loading situations. The focus was on the dependence of flexural behavior on factors like fiber orientation, laminate stacking, surface waviness and molding temperature. The experimental data was validated by finite element analysis. Chamis [7] described a method of analysis for a three-point bending test applicable to materials with linear, but unequal tensile and compressive stress-strain relations. The method provides numerous equations derived using structural mechanics principles. It also describes procedures for determining local stress concentration at the load point and failure mode at critical stress locations. Eneyew and Ramulu [8] conducted an experimental study of surface quality and damage when drilling unidirectional CFRP composites. Among other things, the delamination factor was determined and its value was related with the drill rpm and feed rate. The delamination factor was found to have a linear relationship with speed and feed rate independently. Nagaraja et al. [9] conducted an investigation into the effects of process parameters on delamination during drilling of CFRP composites. The investigation covered the effects of spindle speed, feed rate and drill diameter on the delamination factor. Three different speeds, feed rates, point angles and drill diameters each were used. It was concluded that spindle speed and drill diameter were the most significant design parameters that influence the delamination. Spindle speed and point angle had a minimal contribution in changing the delamination factor. Cauich-Cupul et al. [10] studied the effect of moisture uptake in epoxy matrix-carbon fiber composite in controlled humidity environments. A deterioration in mechanical properties resulted from absorption of moisture and it was attributed to a decrease in the glass transition temperature of the composite. The results suggested that the contribution of

S. S. Panda is with Indian Institute of Technology Patna, Bihta, Patna, Bihar, Pin-801103, India (corresponding author, phone: +91 612-302-8037; fax: +91 612-302-8628, e-mail: sspanda@iitp.ac.in).

Arkesh Chouhan and Yogesh Deshpande are with Indian Institute of Technology Patna, Bihta, Patna, Bihar, Pin-801103, India (e-mail: arkesh.me11@iitp.ac.in, yogesh.me11@iitp.ac.in).

radial stresses on interfacial shear properties, as understood by a micromechanical model, decreased with a rise in moisture content. Sanjeevamurthy and Srinivas [11] subjected natural fiber reinforced epoxy composites to water immersion tests to study the effect of water absorption on mechanical properties. The percentage of moisture uptake increased with the increase in fiber content. The tensile and flexural properties of epoxy composites reinforced with sisal and coconut fibers were found to decrease with an increase in percent moisture uptake. Hanter and Hasan [12] used epoxy matrix-glass fiber composites and studied the effect of water absorption on their hardness properties. The Shore D Hardness of all samples was determined before and after immersion in water at room temperature. Their results show that the value of hardness decreases with increase in the time of immersion in water. The absorbed weight of water increases with increase in time for the first week.

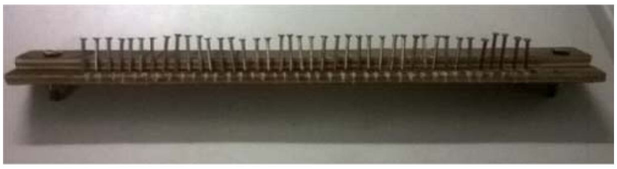

Fig. 1 One half of the clamp apparatus

Fig. 2 Fiber alignment in clamps

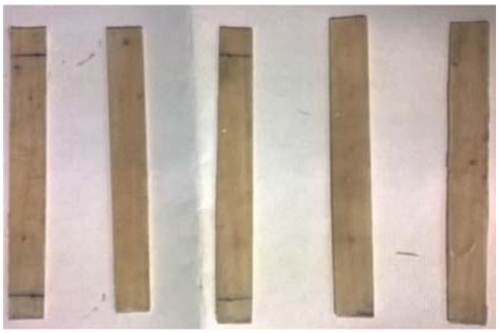

Fig. 3 Test sample

II. Sample Fabrication and Characterization

A. Apparatus Design

An apparatus (Fig. 1) was made that will ensure that the fiber strands stay parallel and equidistant to one another during the process of making composites. The apparatus would essentially work like a pair of clamps. A pair will grab the fibers at an equal length from each other. The fibers are held in place by notches made on the lower halves of each of the half-clamps. The nails ensure alignment. This will keep the fibers taut and parallel. The ratio by mass of the fibers to the resin is 35.05:100. Sample (Figs. 2 and 3) of 15 cm X 10 cm X 0.3 cm with adjacent fiber strands of 0.5 cm was prepared.

B. Sample Characterization

The test sample prepared as per ASTM D3039/3039M for tensile test and ASTM D7264/D7264M for a 3-point bending test. The tensile test of materials is used to determine material properties such as elastic modulus, ultimate tensile strength, yield point, etc. For this test, laboratories use a Universal Testing Machine. The theoretical calculations are done for tensile tests of 0^o and 90^o test samples. The theoretical analysis is given below:

For 0^o test sample loading in the longitudinal direction,

$$E_{th} = V_f * E_f + (1 - V_f) * E_m \quad (1)$$

where, E_{th} = theoretical Young's modulus, V_f = volume fraction of fiber, E_f = Young's modulus of fiber, E_m = Young's modulus of matrix. For 90^o test sample loading in the transverse direction,

$$\frac{1}{E_{th}} = \frac{V_f}{E_f} + \frac{(1-V_f)}{E_m} \quad (2)$$

The maximum stress at any point during three point bending test is given by

$$\sigma = \frac{3PL}{2bh^2} \quad (3)$$

where σ = stress at the outer surface at mid-span, MPa, P = applied force, N, L = support span, mm, b = width of beam, mm, h = thickness of beam, mm. The maximum strain is given by

$$\varepsilon = \frac{6\delta h}{L^2} \quad (4)$$

where ε = maximum strain at the outer surface, mm/mm; δ = mid-span deflection, mm; L = support span, mm; h = thickness of beam, mm.

$$E_{flexural} = \frac{\Delta\sigma}{\Delta\varepsilon} \quad (5)$$

where, Eflexural = flexural modulus of elasticity, MPa; Δσ = difference in flexural stress between the two selected strain points, MPa; Δε = difference between the two selected strain points.

Test speed was 3 mm/min for tensile tests and 1 mm/min for three-point bending tests. The strain range considered for the three-point bending tests is 0.39% to 0.78%. Table I shows the comparison of the theoretical and experimental results for the tensile test and Table II shows the experimental result of the 3-point bending test for the 0^0 and 90^0 samples.

TABLE I
TENSILE TEST

Angle of orientation	Sample number	Experimental Young's Modulus	Theoretical Young's modulus	Ultimate Tensile Strength
0^o	1	3.7145 GPa	4.74 GPa	10.4 Mpa
	2	3.956 GPa	4.74 GPa	131 MPa
	3	3.6 GPa	4.74 GPa	122.25 MPa
90^o	1	0.97 GPa	1.47 GPa	5.212 MPa
	2	0.84 GPa	1.47 GPa	3.9 MPa

Sample size 15cm*1.5cm*0.3cm

TABLE II
3 POINT BENDING TEST

Angle of orientation	Sample number	Flexural Modulus	Flexural Strength
0^o	1	2.184 GPa	20.492 MPa
	2	2.876 GPa	20.74 MPa
	3	2.1 GPa	16.35 MPa
90^o	1	272.24 MPa	2.161 MPa
	2	330 MPa	2.727 MPa

Sample size 12cm*1.3cm*0.3cm

III. MACHINABILITY STUDY

A. Experiment Conducted

The test sample prepared was then taken for understanding the behavior under machining environment. Hence to study the machinability condition, a sample was used for drilling operation based on Taguchi Design. Three levels of control factor setting for spindle speed, feed rate and drill diameter was used to drill total nine holes on the test sample using L9 design. Drilling on composite test was done to collect the responses such as delamination factor and damage grading of test hole. Drilling through the composite causes inter-laminar fracture around the hole. The area affected by delamination is represented by a circle of some diameter. The delamination factor is defined as the ratio of the diameter of the circle with area equivalent to the affected area to the diameter of the drilled hole. That is, Delamination Factor:

$$D.F. = \frac{D_{outer}}{D_{inner}} \quad (6)$$

After processing the high resolution images in ImageJ®, measuring the affected area and calculating the equivalent diameter, the delamination factor is found as shown in Fig. 4. The experimental result is shown in Table III. Similarly, looking into the different holes damage induced due to drilling was qualitatively accessed and shown in Table III. As observed that hole number 7 induced maximum damage through visual inspection and minimum delamination, whereas hole number 3 induces maximum delamination. Similarly, the effect of spindle speed on delamination is shown in Fig. 5. It could be observed that the higher the speed, the higher will be the plugging force which will tear out the fiber from the matrix resulting in more delamination.

TABLE III
EXPERIMENTAL RESULT BASED ON L9 DESIGN

Hole. No.	A	B	C	E	D	DF	G
1	4	40	500	17.702	4.747508	1.186877	0.5
2	4	60	1000	18.663	4.874671	1.218668	0.2
3	4	80	1000	20.446	5.102215	1.275554	0.2
4	6	40	1000	39.458	7.087974	1.181329	0.3
5	6	60	1500	37.927	6.949104	1.158184	0.6
6	6	80	500	38.431	6.995124	1.165854	0.5
7	8	40	1500	57.984	8.592284	1.074036	0.9
8	8	60	500	63.402	8.984751	1.123094	0.8
9	8	80	1000	66.237	9.183429	1.147929	0.7

Drill Diameter in mm (A), Feed Rate in mm/min (B), Spindle Speed in rpm (C), Delaminated Area in mm^2 (E), Delaminated Diameter in mm (D), Delamination factor (DF), Grading by visual inspection (G).

Fig. 4 Delaminated hole for hole 3

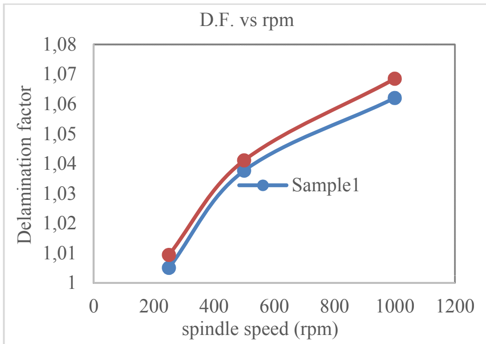

Fig. 5 Variation of delamination factor with Speed

B. Optimization

For optimization of machining parameters, we have analyzed the means of S/N ratios using MINITAB 10. S/N refers to the ratio of signal to noise and for minimizing the delamination factor, as well as damage grading; smaller is the better characteristic, as is used in [13], and as shown below. Smaller is the best characteristic:

$$\frac{S}{N} = -10 \log \frac{1}{n}\left(\sum y^2\right) \quad (7)$$

where $\bar{y}$ the average of observed data, $s_y^2$is is the variation of y, n is the number of observations and y is the observed data. We now calculate a desirability index for each of the output parameters, i.e., delamination factor and damage grading. It can vary from 0 to 1 with 0 indicating lowest desirability and 1 indicating high desirability.

For the-smaller-the-better response characteristic, the

Taguchi method defines desirability index as:

$$d_t = \begin{cases} 1 & \text{for } \hat{y} \le y_{min} \\ \left(\dfrac{\hat{y} - y_{max}}{y_{max} - y_{min}} \right)^r & \text{for } y_{min} \le \hat{y} \le y_{max} \quad r \ge 0 \\ 0 & \text{for } \hat{y} \ge y_{max} \end{cases} \quad (8)$$

where y_{min} and y_{max} represent the lower and upper tolerance limits of $\hat{y}$, r represents the weight. The weight is assigned on the basis of requirement. If the corresponding response is expected to be closer to the target, the weight is set to a larger value. If the response is expected to stray, then the weight is assigned a smaller value. We denote d_t of DF by D_1, d_t of damage grade by D_2, and assign a weight of 0.5 each to both with an assumption that both are equally important. Thus we get composite desirability:

$$D = (D_1 * D_2)^{0.5} \quad (9)$$

For minimum delamination factor, optimal setting evaluated using Taguchi design is shown in Fig. 6. It could be observed that at level A3B1C3, i.e. drill diameter = 8 mm, feed rate = 40 mm/min, spindle speed = 1500 rpm, delamination factor is minimum. Similarly, the effect of input parameters (drill diameter, spindle speed and feed rate) on the delamination factor is shown in Table IV which shows that influence of drill diameter is higher than spindle speed, than feed rate.

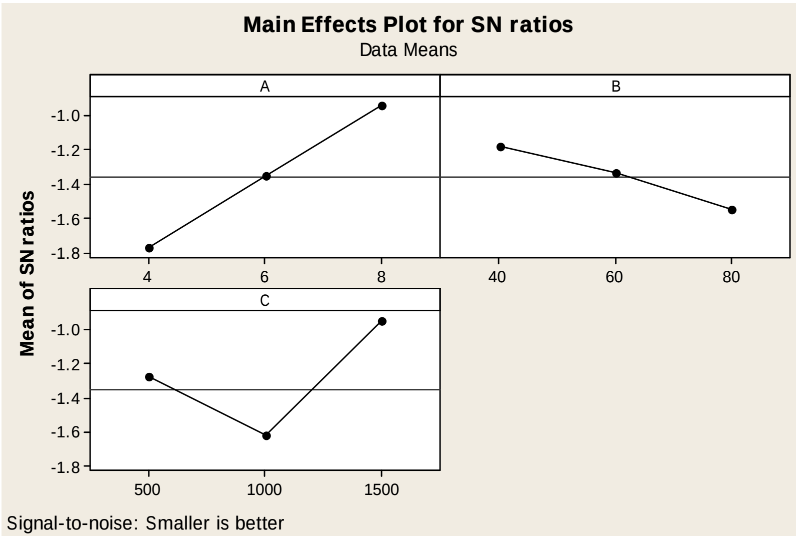

Fig. 6 Optimal Level of S/N ratio of delamination factor

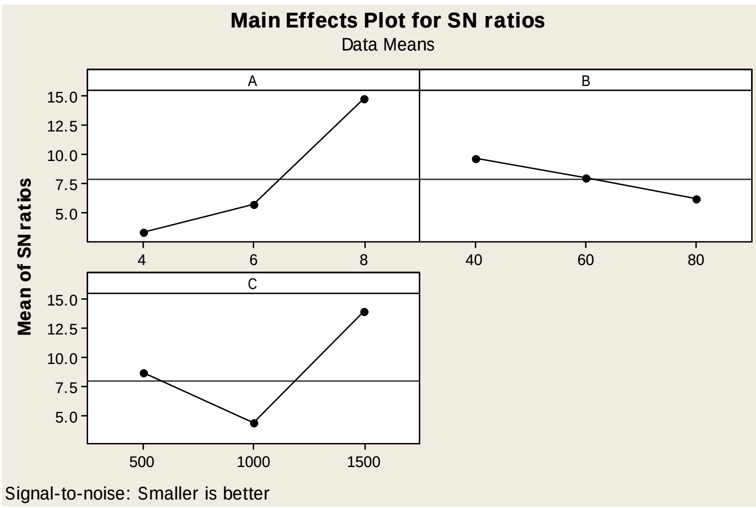

Fig. 7 Optimal Level of S/N ratio of damage grading

TABLE IV
RANKING OF PARAMETER INFLUENCE ON DELAMINATION

Level	A	B	C
1	-1.7733	-1.1853	-1.2764
2	-1.3520	-1.3339	-1.6194
3	-0.9423	-1.5484	-0.9480
Delta	0.8309	0.3631	0.6714
Rank	1	3	2

For minimum damage grading of the sample through visual inspection during drilling is also one of the primary concerns and optimal setting evaluated in this case is shown in Fig. 7. It could be observed that at level A3B1C3, i.e., drill diameter = 8 mm, feed rate = 40 mm/min, spindle speed = 1500 rpm, damage grading is minimum. Similarly, the effect of input parameters (drill diameter, spindle speed and feed rate) on damage grading is shown in Table V, which shows that the influence of drill diameter is higher than spindle speed, than feed rate.

TABLE V
RANKING OF PARAMETER INFLUENCE ON DAMAGE GRADING

Level	A	B	C
1	3.299	9.706	8.674
2	5.692	7.959	4.358
3	14.812	6.139	13.979
Delta	11.513	3.567	9.621
Rank	1	3	2

Finally, composite desirability has been used to obtain the multiple characteristics of response as shown in Table VI by giving equal importance to both delamination and damage grading. After obtaining multiple characteristics, S/N ratio is obtained considering higher is the better criteria and optimal setting evaluated for higher desirability index of multiple characteristic is A3B1C3 (shown in Fig. 8) ,which is the same as for individual response as described above. Similarly, the effect of input parameters (drill diameter, spindle speed and feed rate) on multiple characteristic is shown in Table VII, which shows that influence of drill diameter is higher than spindle speed, than feed rate, as similar to individual responses.

TABLE VI
COMPOSITE DESIRABILITY

DF	D1	Grade	D2	Composite desirability (D)
1.186877	0.440045	0.5	0.428571	0.43427
1.218668	0.282287	0.8	0	0
1.275554	0	0.8	0	0
1.181329	0.467576	0.7	0.142857	0.25845
1.158184	0.582429	0.4	0.571429	0.576903
1.165854	0.544368	0.5	0.428571	0.483012
1.074036	1	0.1	1	1
1.123094	0.756558	0.2	0.857143	0.805281
1.147929	0.633318	0.3	0.714286	0.672585

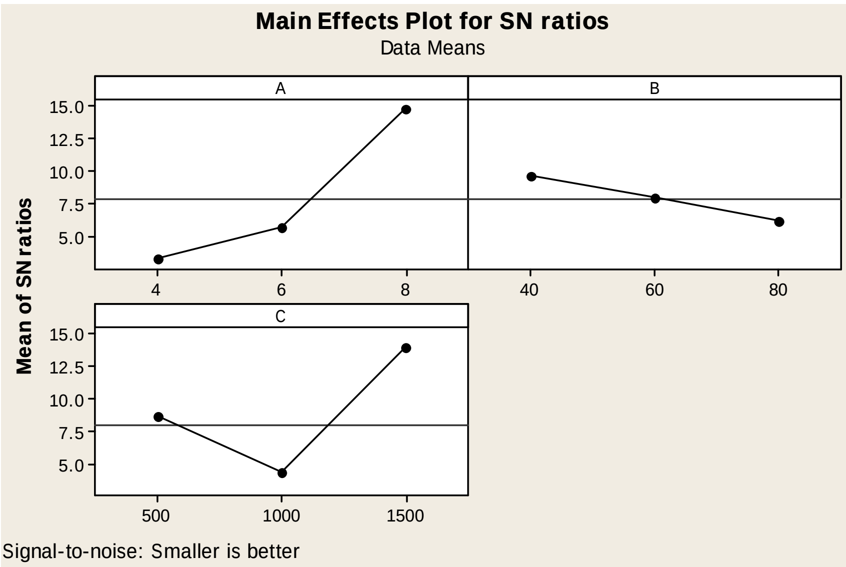

Fig. 8 Optimal Level of S/N ratio of multiple characteristic

TABLE VII
RANKING OF PARAMETER INFLUENCE ON MULTIPLE CHARACTERISTIC

Level	A	B	C
1	-95.748	-6.332	-5.149
2	-7.617	-48.886	-73.799
3	-1.775	-49.922	-2.389
Delta	93.973	43.590	71.410
Rank	1	3	2

IV. CONCLUSIONS

The fabrication process is found to be reasonably accurate since the properties of the prepared composites are found to be as expected. It has been observed from our results that elastic modulus and tensile strength are both higher for composites with 0^o orientation as compared to composites with 90^o fiber orientation. Similar nature trend of flexural modulus and flexural strength also observed for both 0^0 and 90^0 ply. It has also been observed that absorption of moisture causes a marked decrease in properties. As can be seen from the results, low amount of delamination means less damage and therefore more desirable in machining composite. For domain of experiments conducted, it is found that optimum condition is A3B1C3 i.e. drill diameter = 8mm, feed rate = 40mm/min and spindle speed = 1500 rpm, where responses such as delamination and grading by visual inspection are both minimal. It is also observed that drill diameter have high influences on responses, as compared to spindle speed and feed rate.

References

[1] V. K. Srivastava, Effect of filler on fracture of short glass fiber reinforced epoxy,1989 pp. 113-119

[2] Mukul Kant Paliwal, Sachin Kumar Chaturvedi, An Experimental Investigation of Tensile Strength of Glass Composite Materials with Calcium Carbonate (CaCO3) Filler, International Journal of Emerging trends in Engineering and Development, Issue 2, Vol. 6, 2012.

[3] Patil Deogonda, Vijaykumar N Chalwa, Mechanical Property of Glass Fiber Reinforcement Epoxy Composites, International Journal of Scientific Engineering and Research (IJSER),Volume 1 Issue 4, December 2013

[4] Manwar Hussain, Atsushi Nakahira, Koichi Niihara, Mechanical property improvement of carbon fiber reinforced epoxy composites by Al2O3 filler dispersion, Elsevier,1995, 185-191

[5] Esmael Adem, Mechanical Characterization of E-Glass Reinforced with Epoxy &polyester Composite for Automotive body Application, Addis Ababa University, 2013.

[6] Nunes J.P., Pouzada A. S., Bernardo C. A., 2001 March, The use of a three-point support flexural test to predict the stiffness of anisotropic composite plates in bending, Polymer Testing 21(2002), pg 27-33, www.elsevier.com/locate/polytest

[7] Chamis C., 1974 March, Analysis of the three-point-bend test for materials with unequal tension and compression properties, NASA TN D-7572, NASA technical notes

[8] Eneyew E., 1Ramulu M., October-December 2014, Experimental study of surface quality and damage when drilling CFRP composites, Volume 3 Issue 4, Pages 354-362, Journal of Materials Research and Technology

[9] Nagaraja, Herbert M.A., Shetty D, Shetty R, Murthy BRN, June 2013, Investigation into the effects of process parameters on delamination during drilling of BD-CFRP composite using Taguchi design of experiments and response surface methodology, Volume 4 Issue 3 pp. 136-148, International Journal of Mechanical Engineering and Technology

[10] Cauich-Cupul J.I., Valadez-Gonzalez A., Herrera-Franco P.J., Effect of moisture absorption on micromechanical behavior of carbon fiber-epoxy matrix composites, 16th International Conference on Composite Materials

[11] Sanjeevamurthy G.C., Srinivas G.R., September 2012, Sisal/coconut coir natural fiber-epoxy matrix composites: water absorption and mechanical properties, International Journal of Engineering and Innovative Technology, Vol.2, Issue 3

[12] Hanter F.H., Hasan H.S., September 2011, effect of water absorption on hardness property for epoxy composites reinforced by glass fibres, Journal of University of Anbar for pure science, Vol.5 No. 3

[13] Phadke M.S, Quality Engineering Using robust Design (Prentice Hall, Englewood, Cliffs, NJ, 1989).