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Effects of Addition of Glass Fibers and SiC Particles on the Mechanical and Machinability Behaviours of Areca Fine Fiber-Reinforced Phenol Formaldehyde Composite

Athijayamani AYYANAR*, Prabhu MUTHUSAMY, Sidhardhan SUSAIYAPPAN*****

**Department of Mechanical Engineering, GCE, Bodi-625 582, Tamilnadu, India, E-mail: athimania@gmail.com (Corresponding Author)*

***Department of Mechanical Engineering, SMRECCET, Thanjavur, Tamilnadu, India.*

****Department of Civil Engineering, GCE, Tirunelveli, Tamilnadu, India.*

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1. Introduction

Currently, a great deal of the studies on natural cellulose/synthetic fiber reinforced polymer hybrid composites has been carried out by much number of researchers because of natural cellulose fibers offer poor in properties, mostly in mechanical, compared to synthetic fibers. Even though the biodegradability of these types of hybrid composites is compromised by synthetic fibers, it is remunerated by the enhancement in their physical and mechanical properties. Therefore, in recent years, the research on natural fiber/synthetic fiber hybrid composites has been significantly increased. In these hybrid composites, natural cellulose fibers are mostly hybridized with glass fibers [1 – 5]. Hybridization of natural and synthetic particles as fillers, with the fiber-reinforced polymer composites has been just beginning to build their purpose in the field of engineering and technology. With the purpose of obtaining the preferred material properties for a scrupulous application, many numbers of researchers have been carrying out their research to know how the material property changes to the particle content as filler, under various conditions [6, 7].

With the arrival of fiber-reinforced polymer hybrid composite materials and their extensive use in aerospace, automotive and structural applications, it has become necessary to carry out the secondary manufacturing process like drilling. Drilling operations are used to produce the holes on the parts and components made from the fiber-reinforced polymer hybrid composites and to facilitate bolting or riveting to the main load bearing parts and components. Drilling of fiber-reinforced polymer hybrid composites was affected by some of the factors, which affect the drilling process, like process parameters (cutting speed, feed rate, depth of cut, and point angle) and material parameters (size of the fibers and particles, orientation) or combination of both parameters. The effects of drilling process parameters on the responses obtained during drilling of fiber-reinforced polymer composites are studied by several researchers [8, 9].

In the present study, the AFF/GF/PF hybrid composites are prepared by the rule of mixture method using hand lay-up technique and their mechanical properties are evaluated based on the weight percentages of both the fibers. Then, the AFF/GF/PF hybrid composite with the highest mechanical properties is again hybridized with SiC particles in three different weight percentages (3, 6 and 9%). Finally, drilling operations are carried out on the AFF/GF/SiC/PF hybrid composite, which having maximum mechanical properties, to understand the effects of drilling process parameters (cutting speed, feed rate, and drill diameter) on the responses (drilling induced thrust force and torque) obtained during drilling operations. A non-linear regression technique is used to predict the response values with combination of process parameters. The predicted thrust force and torque values are validated and compared with the experimental results to find out the quality and accuracy of the predicted models. An attempt is taken on this composite material to understand their mechanical and machinability behaviors with the aim of finding their usages in the industrial and commercial applications.

2. Experimental details

2.1. Materials

For the preparation of composite plates, Areca Fine Fibers (AFFs), Glass Fibers (GFs) and silicon carbide (SiC) particles are used with the Phenol formaldehyde (PF) resin matrix. The AFFs are procured from M/s Alphonse Fiber industry in Nagercoil, Tamilnadu, India. The non-woven GFs and SiC are purchased from GVR Enterprise, Madurai, Tamilnadu, India. A resole-type PF resin (M/s Windson Chemical Private Limited, Gujarat, India) was also obtained with an acidic catalyst (hydrochloric acid) and cross-linking agent (divinylbenzene). All reinforcements are used as received, the condition without any treatments. The typical properties of fibers and resin used in the present study are given in Tables 1 and 2.

2.2. Preparation of composites

In the present study, two different types of hybrid composites are prepared with the help of hand lay-up technique, i.e., AFF/GF/PF and AFF/GF/SiC/PF, at room temperature. During the preparation of the AFF/GF/PF hybrid composites by the rule of mixture method, the fiber weight percentage was kept as constant of 40%. The SiC particles are incorporated into the range of 3, 6, and 9% in weight for the preparation of the AFF/GF/SiC/PF hybrid composites. The PF resin matrix with the acidic catalyst (hydrochloric acid) and cross-linking agent (divinylbenzene) was prepared in the ratio of 2:1.5:100. First, the PF resin was mixed with the fibers thoroughly using a mechanical stirrer for 30 minutes. Then, the acidic catalyst and cross-linking agent is mixed with the PF and fiber mixture and they are stirred again for 15 minutes. Finally, the mould is closed and allowed to cure at room temperature for 48 hours.

2.3. Mechanical testing

After the preparation of composite plate, composite specimens are cut from the plate as per ASTM standards and tested for its characterization based on the mechanical properties, such as tensile, flexural and impact. The flexural and tensile testing is carried out using an FIE universal testing machine according to ASTM D 790-10 and ASTM D 638–10, respectively at a crosshead speed of 2 mm/min and humidity of 50%. All the tests are carried out in the room temperature. Totally five specimens are tested for each property and their average values with 95% of confidence intervals are recorded and used for the analysis.

2.4. Drilling of composite specimens

For an assembly operation, the secondary manufacturing processes are required for parts or components made from fiber-reinforced polymer composites. In this study, an attempt is taken to understand the process parameters that influence the drilling induced thrust force and torque during drilling of 20AFF/20GF/6SiC/PF hybrid composites. The 20AFF/20GF/6SiC/PF hybrid composite gives better mechanical properties compared to the other composites, therefore, they have selected for the machinability study. The influence of various drilling process parameters, such as cutting speed, feed rate and tool diameter on drilling induced thrust force and torque is examined in the drilling of 20AFF/20GF/6SiC/PF hybrid composite composites. Drilling operations are carried out based on the experimental design of Taguchi's L_{27} orthogonal array using carbide drill bits. Table 3 gives the level of drilling process parameters used in this study.

Table 1

The typical properties of the AFFs and GFs used in the present study [10]

Properties	Areca fine fiber	Glass fiber
Diameter, mm	0.285-0.89	0.003-0.020
Length, m	0.18-0.40	-
Density, g/cm^3	1.05-1.25	2.54
Ultimate stress, MPa	89.5-118.67	1950-2050
Elongation at break,%	11-12.5	4.5-4.9

Table 2

The typical properties of PF resin used in the present study [10]

Specific gravity	1.12-1.16
Polar surface area, Å^2	9.23
Flash point, ºC	72.5
Boiling point ºC	181.8
Composition	Carbon-Carbon
Elongation at break,%	2
Density, g/cm^3	1.3

Table 3

Level of drilling process parameters used in this study

Parameter / Level	1	2	3
Cutting speed, rpm	300	600	900
Feed rate, mm/rev	0.1	0.2	0.3
Drill diameter, mm	6	9	12

2.5. Experimental setup for drilling operation

In the present study, the drilling operations are carried out on a MTAB CNC milling machine in which a multi component Piezo Electric Drill Tool Dynamometer is attached to record the responses (thrust force and torque). The Schematic diagram of drilling setup is presented in Fig. 1. The drilling operations on the composite specimens are performed using a carbide drill bit with three different process parameters, such as cutting speed, feed rate, and drill diameter.

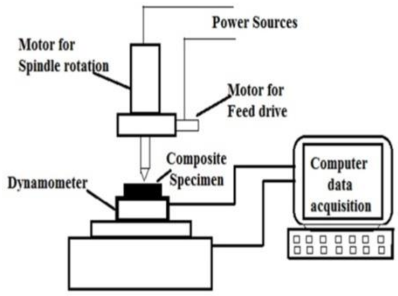


Fig. 1 Schematic diagram of drilling operation set-up for 20AFF/20GF/6SiC/PF hybrid composite

3. Results and discussion

3.1. Effects of addition of GFs on the mechanical properties of AFF/PF composites

Fig. 2 shows the tensile strength and modulus of the AFF/GF/PF hybrid composites prepared by the rule of mixture method. The tensile strength and modulus values of hybrid composites decreased with the increase of the AFF content. The AFFs are more hydrophilic in nature due to higher cellulose and hemi-cellulose content, whereas the PF is hydrophobic in nature. The compatibility of AFFs with the PF is light when comparing the compatibility of the GFs and PF. Therefore, the interaction between the AFFs and PF was not well, which leads to the lower tensile strength and modulus. The tensile strength and modulus of the 20AFF/20GF hybrid composite is slightly lower than the 0AFF/40GF composite. It assumed that the hybrid composites with 20AFF/20GF exhibit better tensile strength and modulus due to better interfacial bonding between the fiber and the matrix compared with the other hybrid composites. The better interfacial bonding leads to the effective distribution of the applied load (stress) among the fibers, resulting in better tensile strength and modulus values. The 20AFF/20GF hybrid composite is 3.6% lower than the 0AFF/40GF composite in tensile strength.

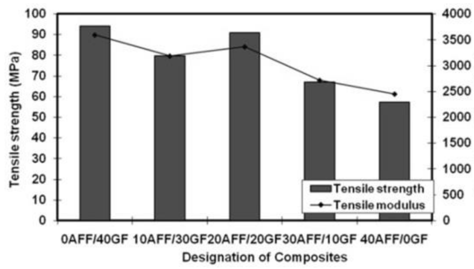


Fig. 2 Variations of tensile strength of AFF/PF composites based on the weight percentage of GFs

The influence of the AFFs and GFs content on the flexural strength and modulus of the PF composites is shown in Fig. 3. From Fig. 3, it is observed that the flexural strength and modulus of the composites also decreases with increase in AFFs content. This is because of poor adhesion between the AFFs and the matrix. The poor adhesion between the fiber and the matrix cannot transfer the stress (applied load) to the adjacent fibers and the matrix, which leads to the lower strength of the composites. The maximum flexural strength and modulus values are observed for 0AFF/40GF composite and it is followed by 20AFF/20GF hybrid composite. When comparing the 20AFF/20GF hybrid composite with the 0AFF/40GF composite, there was 7.6% of reduction in flexural strength value.

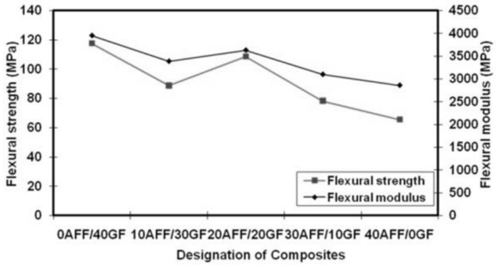


Fig. 3 Variations of flexural strength of AFF/PF composites based on the weight percentage of GFs

The results revealed that the 20AFF/20GF/PF hybrid composites give better tensile and flexural properties than the 30AFF/10GF/PF and 40AFF/0GF/PF composites and it is followed by the 10AFF/30GF/PF hybrid composite. The 20AFF/20GF/PF hybrid composites show the slightly lower tensile and flexural properties than the 0AFF/40GF/PF composites.

3.2. Effects of addition of SiC on the mechanical properties of AFF/GF/PF hybrid composites

From the above results, the 20AFF/20GF/PF hybrid composite was taken for further investigation. The SiC particles in three different weight percentages (3, 6, and 9%) are incorporated with the 20AFF/20GF/PF composite to evaluate their mechanical properties. Because of the particles are acting as a bridge during stress transfer from the matrix to the fiber in the fiber-reinforced polymer composites when the load is applied. They also improve the mechanical interlocking and adhesion between the fiber and the matrix.

Experimental results for tensile test of AFF/GF/SiC/PF hybrid composite are presented in the Fig. 4. It is observed that the tensile properties of the composites increase with the increase of the addition of SiC particles up to 6% and then dropped. This is because of a strong adhesion between the fiber, particle and the matrix during addition of 6% of SiC particles. When adding 9% of SiC particles, the brittleness of the composite specimens is increased due to insufficient resin matrix to wet the fibers and particles. Therefore, the AFF/GF/SiC/PF hybrid composite specimens containing 9% of SiC particles fail quickly in brittle nature. The tensile strength of hybrid composite containing 6% of SiC particles is 4.06% higher than the hybrid composite prepared with the 3% of SiC particles. In the hybrid composite containing 3% of SiC particles, the particle distribution within the composite is poor, therefore, the particles cannot help to transfer the applied load from the matrix to fiber. It leads to the lower mechanical properties. The tensile strength of 20AFF/20GF/3SiC/PF and 20AFF/20GF/9SiC/PF hybrid composites is almost same. The maximum tensile modulus value was also observed in the hybrid composite containing 6% of SiC particles. It is 5.48% and 3.36% higher than the hybrid composites containing 3 and 9% of SiC particles.

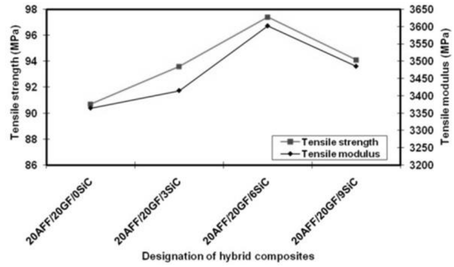


Fig. 4 Variations of tensile strength of AFF/GF/PF hybrid composites based on the weight percentage of SiC particles

The effects of weight percentage of SiC particles on the flexural strength and modulus of the AFF/GF/SiC/PF hybrid composites are shown in Fig. 5. It is noticeable that the addition of 6% of SiC particles is having a significant effect on flexural strength and modulus. The flexural strength of AFF/GF/SiC/PF hybrid composite is increased up to 6% SiC content and then decreased with the increase in content of SiC (9%). A strong adhesion between the fiber, particle and matrix is obtained during addition of 6% of SiC particles, whereas a weak adhesion is obtained between the fiber, particle, and matrix during addition of 9% of SiC particles due to lack of wettability. The flexural modulus shows the high value during addition of 6% of SiC particles, which is 5.01% and 4.3% higher than the hybrid composite having 3 and 9% of SiC particles, respectively.

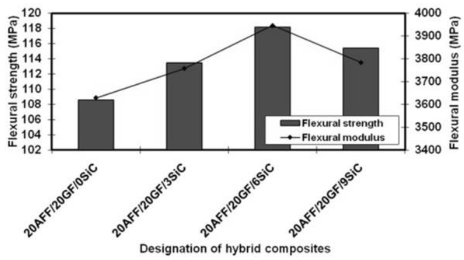
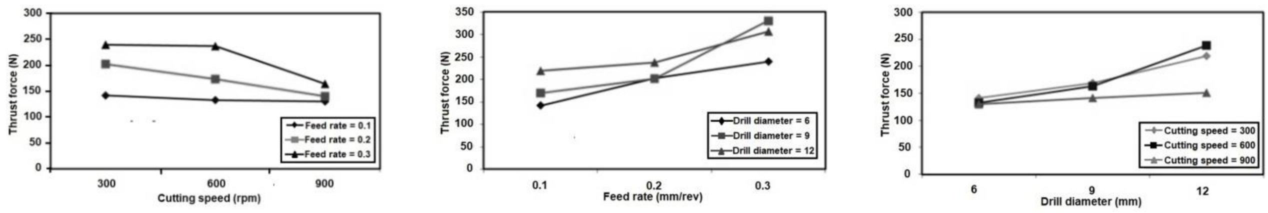


Fig. 5 Variations of flexural strength of AFF/GF/PF hybrid composites based on the weight percentage of SiC particles

Furthermore, the AFF/GF/SiC/PF hybrid composites exhibited the highest values of tensile and flexural properties after addition of the 6% of SiC particles. Therefore, it is proved that the addition of 6% of SiC particles enhanced interfacial adhesion and interaction between the fibers (AFFs and GFs), particles (SiC) and the resin matrix (PF), thus improving the tensile and flexural properties.

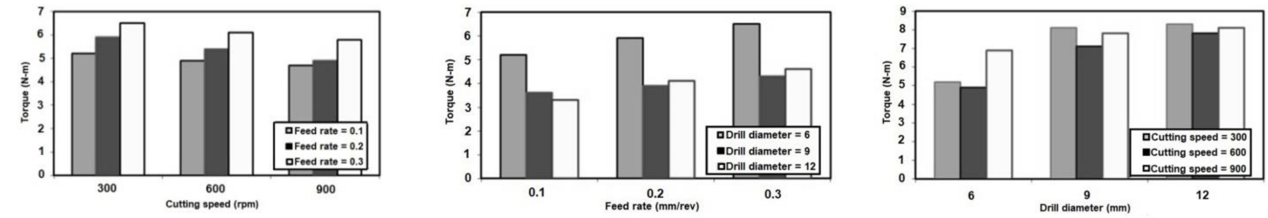
3.3. Influence of the drilling process parameters on thrust force and torque

Experimental results obtained in drilling of 20AFF/20GF/6SiC/PF hybrid composite are also presented in Figs. 6, a-c and 7, a-c. The influence of the drilling process parameters on thrust force obtained during drilling of 20AFF/20GF/6SiC/PF hybrid composite is shown in Fig. 6, a. From the Fig. 6, a, it is observed that the thrust force decreases with the increase of cutting speed. The value of thrust force at 900 rpm is lower than the 300 and 600 rpm during drilling of 20AFF/20GF/6SiC/PF hybrid composite. The effect of the feed rate on the thrust force during drilling of 20AFF/20GF/6SiC/PF hybrid composite is given in Fig. 6, b. It can be seen that the thrust force increases with increase in feed rate. The feed rate plays an imperative role on the thrust force during drilling of 20AFF/20GF/6SiC/PF hybrid composite. The experimental results showed that the thrust force is increased by increasing the feed rate. The value of thrust force is the minimum at a lower feed rate, and maximum at a higher feed rate. This is because of while increasing the feed rate, the load on the drill bit used in the operation increases, consecutively, increases the thrust force. The effects of the drill diameter on the thrust force with respect to the cutting speed are illustrated in Fig. 6, c. A similar trend is observed on the thrust force by the drill diameter like as feed rate. During drilling operation, the value of thrust force increases with the increase of the drill diameter. This may be due to the increase of contact area between the tool and the composite specimen and also consequent increase in applied load. When increasing the drill diameter during drilling of hybrid composite the contact area between the drill bit and the specimen is also increasing, which is increasing the load applied during drilling operations.



a b c

Fig. 6 Effects of: a) cutting speed; b) feed rate; c) drill diameter on the drilling induced thrust force in the drilling of 20AFF/20GF/6SiC/PF hybrid composites



a b c

Fig. 7 Effects of: a) cutting speed; b) feed rate; c) drill diameter on the drilling induced torque in the 20AFF/20GF/6SiC/PF hybrid composites

In manufacturing and assembly industries, the joining of parts and components prepared from the fiber-reinforced polymer composites are crucial because of the non-homogeneity of fiber-reinforced polymer composites. Therefore, the effective joining is crucial in those composites. The most of the effective joining can be performed by using proper drilled holes. But, the developed thrust force and torque during drilling operations creates some common problems like matrix cracking, fiber breakage de-bonding of fibers from the matrix, fiber pullout, thermal degradation, and delamination [11].

The torque developed in drilling operation of fiber-reinforced polymer composites are also an imperative concern. The controlling and monitoring of torque in drilling is needed for the manufacturing and assembly industries. Figs. 7, a-c shows the experimental torque values obtained during drilling of the 20AFF/20GF/6SiC/PF hybrid composite. The drilling induced torque will mainly depend on the manufacturing conditions employed, such as the parameters used, machine and material conditions. The results show that the cutting speed has a significant effect on torque when drilling at high feed values. In high feed value, the torque decreases with increase of cutting speed. During machining, the feed rate and drill diameter affect the torque value of 20AFF/20GF/6SiC/PF hybrid composite. The torque value increases with increase in feed rate based on the drill diameter. When increasing the drill diameter, the torque value also increased. It is observed that the cutting speed is most significant process parameters during drilling of the 20AFF/20GF/6SiC/PF hybrid composite, followed by feed rate. From the above results, it can be observed that thrust force and torque increase with the feed rate and drill diameter.

3.4. Statistical models for thrust force and torque

In this paper, multi-variable non-linear regression method has been used to predict the response values (thrust force and torque) statistically based on the combination of process parameters (cutting speed, feed rate, and drill diameter). The multi variable non-linear regression method can be employed to get the relation between input process parameters and response variables and the input parameters. Several statistical prediction softwares are available to obtain the non-linear equation for the machining process. Among these, the Statistical Package for Social Sciences (SPSS) was used to predict and compare the responses of mechanical and machining process for all types of materials from the last few decades. The prediction model for a machining process having three different process parameters is in the form as given below:

$$Y = k \times A^x \times B^y \times C^z, \qquad (1)$$

where: *Y* is the response of the machining operation; *A*, *B*, and *C* are the process parameters of machining operation; the *k*, *x*, *y* and *z* are constant parameters.

In this study, the SPSS with version of 26 was used to carry out the prediction process by multi-variable non-linear regression method. The quality and accuracy of the predicted model are checked by the coefficient of determination (R^2). The non-linear models for the thrust force and torque values are represented as follows:

$$Thrust\ Force = k \times Cutting\ speed^x \times Feed\ rate^y \times \times Drill\ diameter^z, \qquad (2)$$

$$Torque = k \times Cutting\ speed^x \times Feed\ rate^y \times \times Drill\ diameter^z. \qquad (3)$$

After the prediction process using an estimation method of Levenberg-Marquardt in SPSS, the values of constant parameters for the thrust force and torque are obtained in 95% of confidence intervals and represented in the non-linear form as follows:

$$Thrust\ Force = 105.418 \times CS^{0.096} \times FR^{0.797} \times DD^{-0.148}, \qquad (4)$$

$$Torque = 0.808 \times CS^{-0.197} \times FR^{0.677} \times DD^{0.036}, \qquad (5)$$

where: *CS* is cutting speed in rpm; *FR* is feed rate in mm/rev; *DD* is the drill diameter in mm. The values of coefficient determination for thrust force and torque are found to be 0.828 and 0.780 respectively.

A validation and comparison study was carried out among the experimental results and predicted results. For validation and comparison study, 10 experiments from 27 combinations were selected with experimental thrust force and torque values, as given in Table 4. Table 5 gives comparison of the experimental and predicted thrust force values and also their error% with average absolute error percentage. Moreover, the comparison of experimental and predicted torque values and also their error% with average absolute error percentage are given in Table 6.

Table 4

Experimental process parameters and their response values for validation

Sl.No	*CS*, rpm	*FR*, mm/rev	*DD*, mm	Thrust force, N	Torque, N-m
1	300	0.3	12	294.2	6.46
2	600	0.1	6	125.8	4.90
3	600	0.1	9	191.5	7.31
4	600	0.1	12	246.6	7.63
5	600	0.2	6	136.2	5.15
6	600	0.2	9	160.5	6.27
7	600	0.2	12	251.5	7.99
8	600	0.3	6	143.8	3.80
9	600	0.3	9	211.4	5.46
10	600	0.3	12	253.5	7.54

CS = Cutting speed; *FR* = Feed rate; *DD* = Drill diameter

The average absolute error percentage between the experimental thrust force values and the predicted thrust force values is 7.5%, as given in Table 5. Similarly, the average absolute error between the experimental torque values and the predicted torque values is 0.07%. The average absolute values of both the thrust force and torque values are between the percentages of 0 to 10. Therefore, it is observed clearly that the models created for thrust force and torque using non-linear regression method can be used to predict the response values with minimum error percentage. It is proved that the predicted response values are found to be a good agreement with the experimental result values.

Table 5

Comparison of experimental and predicted thrust force values

Sl. No	Experimental Thrust force	Predicted Thrust force	Error%
1	294.2	293.2	0.93
2	125.8	137.2	-11.38
3	191.5	189.5	1.93
4	246.6	238.4	8.27
5	136.2	146.6	-10.37
6	160.5	202.5	-41.97
7	251.5	254. 7	-3.18
8	143.8	152.4	-8.61
9	211.4	210.5	0.87
10	253.5	264.7	-11.27
Average absolute error percentage			7.5

Table 6

Comparison of experimental and predicted torque values

Sl. No	Experimental torque	Predicted torque	Error%
1	6.46	6.76	-0.30
2	4.90	5.39	-0.49
3	7.31	7.09	0.22
4	7.63	8.61	-0.98
5	5.15	4.70	0.45
6	6.27	6.18	0.09
7	7.99	7.51	0.48
8	3.80	4.34	-0.54
9	5.46	5.71	-0.25
10	7.54	6.94	0.60
Average absolute error percentage			0.07

4. Conclusions

A performance study was carried out on the AFF/GF/SiC/PF hybrid composites in three stages based on the content of fibers and particles to understand their behaviors during the mechanical and machining process. Mechanical and machinability studies of composite materials can almost decide their usage in the industrial and commercial applications. The variations in mechanical properties of AFF/PF composites by the incorporation of GFs as per the rule of mixture were evaluated as a function of fiber contents in the first stage. From the results, it is observed that the 20AFF/20GF/PF hybrid composites give better mechanical properties than the other hybrid composites. In the second stage, the effects of addition of SiC particles on the mechanical properties of the 20AFF/20GF/PF were observed based on the weight percentage of SiC particles. The results revealed that the 20AFF/20GF/PF hybrid composites exhib-

ited the highest values of mechanical properties after addition of the 6% of SiC particles. The addition of 6% of SiC particles enhanced interfacial adhesion and interaction in the 20AFF/20GF/PF hybrid composites. The effects of process parameters on the drilling induced thrust force and torque obtained during drilling of 20AFF/20GF/6SiC/PF hybrid composite were studied in the third stage based on the level of process parameters. The cutting speed was most significant process parameters during drilling of the 20AFF/20GF/6SiC/PF hybrid composite, followed by feed rate and drill diameter. The drilling induced thrust force and torque increases with the feed rate and drill diameter.
The predicted models developed for thrust force and torque values using non-linear regression method were found to be a good agreement with the experimental thrust force and torque.

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A. Athijayamani, M. Prabhu, S. Sidhardhan

EFFECTS OF ADDITION OF GLASS FIBERS AND SIC PARTICLES ON THE MECHANICAL AND MACHINABILITY BEHAVIOURS OF ARECA FINE FIBER-REINFORCED PHENOL FORMALDEHYDE COMPOSITE

S u m m a r y

In the present experimental study the effects of addition of Glass Fibers (GFs) and Silicon Carbide (SiC) particles on the mechanical and machinability behaviors of Areca Fine Fiber (AFF)-reinforced Phenol Formaldehyde (PF) composites were evaluated in three stages. Composites were prepared by hand lay-up technique at room temperature. From the first stage, it is observed that the 20AFF/20GF/PF hybrid composites give better mechanical properties than the other hybrid composites followed by the 10AFF/30GF/PF hybrid composite. The results of second stage revealed that the AFF/GF/SiC/PF hybrid composites exhibited the highest values of mechanical properties after addition of the 6% of SiC particles. From third stage, it is observed that the cutting speed is most significant process parameter during drilling of the 20AFF/20GF/6SiC/PF hybrid composite, followed by feed rate. Moreover, a non-linear regression method was used to predict the response values (thrust force and torque) and found to be a good agreement with the experimental result values.

Keywords: natural cellulose fibers, glass fibers, silicon carbide particles, mechanical properties, drilling.

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