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To cite this article: K Balasubramanian *et al* 2016 *IOP Conf. Ser.: Mater. Sci. Eng.* **152** 012051

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Machining analysis of natural fibre reinforced composites using fuzzy logic

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Abstract. In this work, a new composite plate with natural jute fibre as the reinforcement fibres and isophthalic polyester as the resin was manufactured and subjected to a series of end milling operation by changing three input factors namely speed, feed rate and depth of cut. During each operation, the output responses namely thrust force and torque were measured. The responses were analyzed using Taguchi method to examine the relation between the input factors and output responses, and also to know the most influencing factors on the responses. The data was also analyzed using fuzzy rule model for prediction of responses for a range of input factors. The results showed that all three factors chosen have significant effect on the responses. The fuzzy model data in comparison with the experimental values shows only a marginal error and hence the prediction was highly satisfactory.

1. Introduction

Composite materials are man-made materials, which are manufactured with the aim of replacing the conventional materials by overcoming their disadvantages. A composite material has two constituents in its structure, namely the matrix and reinforcements. Composite materials are broadly classified into three types according to their matrices: polymer matrix composites (PMC), metal matrix composites (MMC) and ceramic matrix composites (CMC). Among these composites, fibre reinforced plastics are widely used as structural elements in aircraft, marine, civil and commercial sectors. Fibre reinforced plastics replaces conventional materials in all these applications due to their tailor-made properties. Fibre reinforced plastics are made of synthetic fibres like glass, carbon, Kevlar, etc. Though they have several advantages including high strength, stiffness, fatigue life and wear resistance, they also have disadvantages like high density, high cost, and poor recycling and bio-degradable properties.

In order to overcome these disadvantages, the natural fibres taken from the plants and animals are being used as reinforcements in recent few years as alternatives to the synthetic fibres. Bio-fibres like jute, sisal, vetiver, hemp and bamboo are abundantly available at reasonable cost. These fibres, when used as reinforcements in composites, provide very good mechanical properties and they are free from environmental hazards. When the natural composites are used as structural components, they involve several machining operations like drilling, slotting, surface finishing, etc. Hence machining associated damage and failure analysis in natural composites will help the composite industries to appropriately select optimum conditions for machining and also optimum proportion of composite constituents for



improved machinability. Fibre reinforced plastics have found wide applications in the field of aircraft, automotive and shipping industries owing to their better mechanical and also electrical properties. The machining of such composites attracts the researchers because of non-homogeneous internal structure. Failure of fibre reinforced composites during machining depends on improper selection of fibre, resin, fibre orientation and number of layers.

2. Literature survey

Davim *et al.* [1] reported that feed rate majorly affects the surface roughness during milling of glass fibre reinforced composites. They also demonstrated that delamination factor and surface roughness depends on feed and cutting speed during the milling process of carbon fibre reinforced composites [2]. Farahnakian *et al.* [3] made investigations on polyamide added with Nano clay and concluded that feed and speed are the major factors influencing the surface roughness. Davim *et al.* [4] studied the machining aspects of milling on medium density fibre boards and reported that feed and speed have more influence on surface roughness. Litak *et al.* [5] performed a multi scale entropy analysis on carbon fibre reinforced composites.

Rentsch *et al.* [6] performed finite element modeling on cutting of carbon fibre reinforced plastics with a disc milling cutter and reported that the calculated and experimental results of the material removal mechanism were almost the same but the cutting forces in comparison with experimental data were not satisfactory. Schule *et al.* [7], in their experiments involving spiral and wobble milling on short glass fibre reinforced composites with polyester resin, illustrated that the direction of the processing forces is directed to the center of the work piece in both methods and wobble milling is not sensitive to tool wear with respect to the process force direction. Prakash *et al.* [8] conducted a series of drilling experiments on medium density fibre boards and reported that delamination factor is influenced by both speed and feed, and the speed-feed combination is also influential. Isik *et al.* [9] reported, after a series of drilling experiments on glass fibre reinforced composites plate, that the delamination factor is higher at high feed rate and it is also increasing with the number of lutes and at high point angle. Singh *et al.* [10] performed finite element analysis on drilling of composites reinforced with glass fibre and concluded that thrust is predominantly affected by the point angle and feed. Similarly, the thrust force and damage increases with increasing feed rate while performing drilling experiments on glass fibre reinforced composites [11, 12]. Similar works have been carried out by different authors [13-16] on carbon and glass fibre reinforced composites and they reported the variation of responses like thrust, torque, delamination factor with machining parameters. During turning of a composite rod, the tool wear is found to be less at low cutting speed and cubic boron nitride tool shows the better overall performance than ceramic and tungsten carbide tools. Also, the surface quality decreases as the depth of cut increases [17, 18].

Applications of composite materials are increasing and the introduction of such new materials will enhance performance and life of the components. Hence there is always a need of machining operations for industries on composite materials. Analysis of various machining parameters reduces unnecessary experimentation and helps the end users to select optimum machining conditions. In the present work, a new composite plate made of isophthalic polyester as the matrix and natural jute as the fibre is manufactured by hand layup technique. Then, a series of 27 milling experiments were performed during which the thrust force and torque were varied. Experimental results were analyzed using the Taguchi method from which the significance of each factor on the measured responses was studied. After that, the data were analyzed using fuzzy logic for prediction of responses. Finally, the fuzzy predicted values were compared with the experimental values and the percentage of error was calculated.

3. Experimental procedure

3.1. Method and materials

Composite materials used in this study were manufactured by hand layup technique with isophthalic polyester as the resin and woven natural jute as the fibre in the ratio 1:1 by weight. The experiments were performed on a 15 mm thick and 20 mm x 20 mm square composite plate consisting of 10 fibre layers. The tool utilized was the 7 mm, 4-fluted end mill made of high speed steel. A vertical milling machine with 3HP main motor, 2HP feed motor and spindle speed range of 80 rpm to 2720 rpm was

used for conducting the experiments. The output readings of thrust and torque were taken from the dynamometer.

3.2. Plan of experiments

The experiments were designed and analyzed using Taguchi's L_{27} (3^3) orthogonal array. The three levels of cutting speed, feed and depth of cut are shown in Table 1 and the combinations of input factors during all experimental trials and the measured responses are listed in Table 2.

Table 1. Assignment of levels to the machining factors

Level	Speed, N (rpm)	Feed f, (mm/rev)	Depth of cut, d (mm)
1	210	0.04	1.0
2	660	0.08	1.5
3	1750	0.15	2.0

Table 2. Experimental design and measured responses

Exp. No	Speed, N (rpm)	Feed, f (mm/rev)	Depth of Cut, d (mm)	Thrust Force	Torque
1	210	0.04	1.0	31.88	2.55
2	210	0.04	1.5	39.53	3.43
3	210	0.04	2.0	51.21	4.12
4	210	0.08	1.0	45.62	4.32
5	210	0.08	1.5	52.48	3.53
6	210	0.08	2.0	60.04	6.18
7	210	0.15	1.0	57.78	4.41
8	210	0.15	1.5	61.41	5.49
9	210	0.15	2.0	70.83	6.67
10	660	0.04	1.0	36.20	2.35
11	660	0.04	1.5	42.58	3.53
12	660	0.04	2.0	54.54	4.61
13	660	0.08	1.0	30.71	3.83
14	660	0.08	1.5	53.46	4.41
15	660	0.08	2.0	45.81	5.40
16	660	0.15	1.0	32.77	3.63
17	660	0.15	1.5	46.70	4.41
18	660	0.15	2.0	48.66	5.69
19	1750	0.04	1.0	15.40	1.28
20	1750	0.04	1.5	24.92	2.35
21	1750	0.04	2.0	26.19	3.14
22	1750	0.08	1.0	27.27	2.06
23	1750	0.08	1.5	16.19	3.34
24	1750	0.08	2.0	32.96	4.41
25	1750	0.15	1.0	28.15	3.43
26	1750	0.15	1.5	14.22	4.51
27	1750	0.15	2.0	29.04	5.10

4. Results and discussion

From the ANOVA table for the thrust force (see Table 3), the most of the influencing factors were identified as speed, depth of cut and speed- feed combinations, which all had p-value less than 0.05. In the meantime, from the ANOVA table for the torque (see Table 4), the most influencing factors were identified as speed, feed rate and depth of cut, which all had p-value less than 0.05.

Table 3. ANOVA table for thrust force

Source	Sum of squares	Degrees of freedom	Mean square	F value	P value
Model	5691.22	18	316.18	10.25	0.0011 Significant
A-Speed	3830.02	2	1915.01	62.08	< 0.0001
B-Feed	255.53	2	127.77	4.14	0.0583
C-Depth of Cut	724.72	2	362.36	11.75	0.0042
AB	523.20	4	130.80	4.24	0.0392
AC	307.53	4	76.88	2.49	0.1265
BC	50.22	4	12.56	0.41	0.7991
Residual	246.79	8	30.85		
Total	5938.00	26			

Table 4. ANOVA table for torque

Source	Sum of squares	Degrees of freedom	Mean square	F value	P value
Model	41.52	18	2.31	15.54	0.0002 Significant
A-Speed	7.37	2	3.68	24.81	0.0004
B-Feed	14.53	2	7.27	48.95	<0.0001
C-Depth of Cut	17.12	2	8.56	57.67	<0.0001
AB	1.39	4	0.35	2.34	0.1424
AC	0.53	4	0.13	0.89	0.5127
BC	0.58	4	0.14	0.97	0.4737
Residual	1.19	8	0.15		
Total	42.70	26			

Figure 1 depicts the plots for the main effects for thrust force. It is evident that the thrust force decreases as speed increases but increases with the increase in feed rate and depth of cut. Referring to Figure 2, the thrust force increases for low speed-feed combination but remains almost the same for the medium and high speed-feed combinations. Also, it was observed that the thrust force shows an increasing trend for all combinations of speed-depth of cut and at all combinations of feed-depth of cut. On the other hand, plots for the main effects for torque are illustrated in Figure 3. The torque decreases when speed increases but increases when feed rate and depth of cut are increased. The plots for the main effects for torque are rather similar to those for the thrust force. The interaction plot in Figure 4 reveals that the torque increases as the speed-feed combination increases. Similar trend was observed for two combinations factors like speed-depth of cut and for feed rate-depth of cut.

5. Fuzzy rule modeling

The fuzzy logic is used to evaluate the behavior of any system that has no analytical or numerical functions. It has high capability of understanding the more complex systems. The first stage of fuzzy is to develop the membership functions for algorithm development. In this work, the fuzzy rule was employed using the MATLAB software. The membership functions were developed by taking the appropriate range of the selected value of the factors. A triangular membership function was adopted in which three values: low, medium and high, were taken for the input and output parameters. The membership functions of the output responses are presented in Figure 5 and Figure 6.

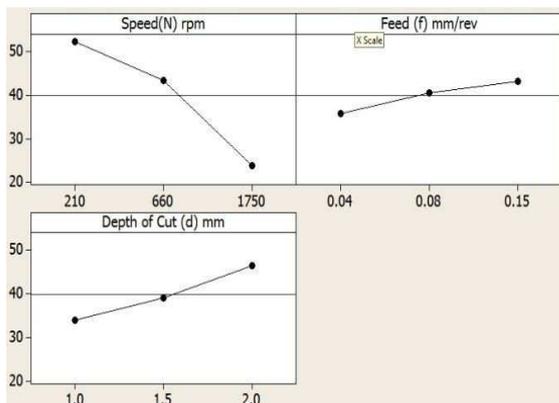


Figure 1. Plots of the main effects for thrust force

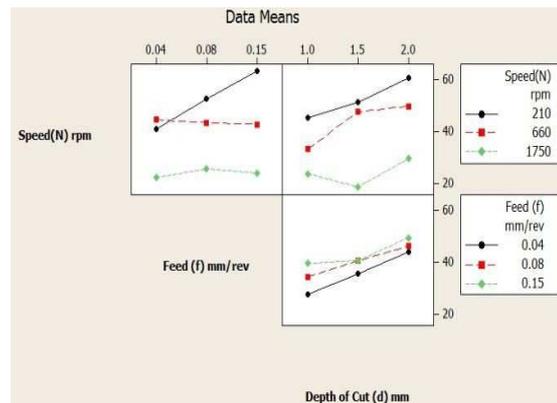


Figure 2. Plots of the interactions for thrust force

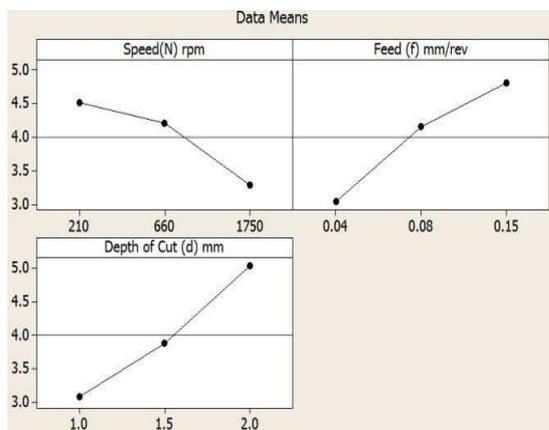


Figure 3. Plots of the main effects for torque

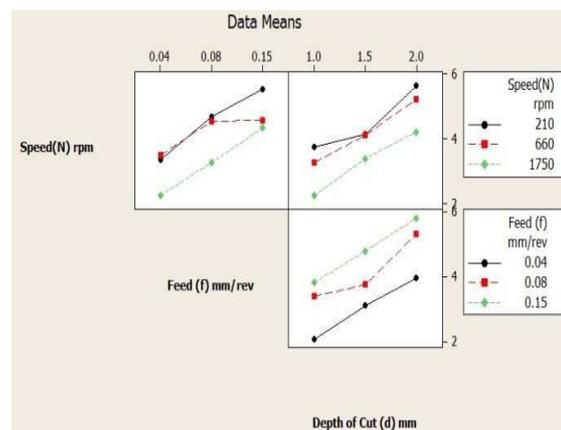


Figure 4. Plots of the interactions for torque

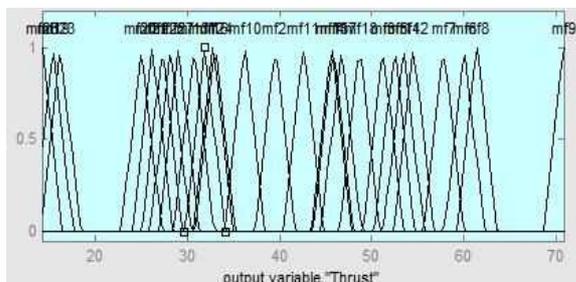


Figure 5. Membership function for thrust force

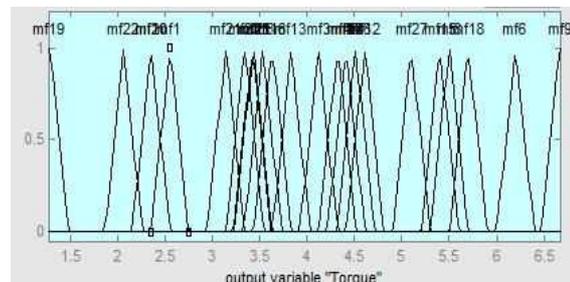


Figure 6. Membership function for torque

The next stage of fuzzy is the de-fuzzification process. This reduces the membership vector into a scalar quantity, presumably to the most representative value. Fuzzy logic works by considering a series of IF-THEN statements containing inputs and outputs. In this study, the inputs x_1 , x_2 and x_3 were assigned to cutting speed, feed rate and depth of cut, respectively, while the outputs y_1 and y_2 were assigned to thrust force and torque, respectively. The experimental values and the corresponding fuzzy predicted ones are shown in Table 5. Note that the parameters' setting for each experimental run can be referred back to Table 2. From these values, the percentage error between the experimental ones and fuzzy predictions were calculated. The average percentage error for thrust and torque were found to be 0.77% and 1.22%, respectively.

Table 5. Consolidated table of experimental and fuzzy predicted values

Exp. No	Experimental Thrust	Predicted Thrust	Thrust % Error	Experimental Torque	Predicted Torque	Torque % Error
1	31.88	32.14	-0.82	2.55	2.32	9.02
2	39.53	38.55	2.48	3.43	3.39	1.17
3	51.21	50.68	1.03	4.12	4.20	-1.94
4	45.62	45.03	1.29	4.32	4.26	1.39
5	52.48	52.59	-0.21	3.53	3.52	0.28
6	60.04	60.71	-1.12	6.18	6.25	-1.13
7	57.78	57.97	-0.33	4.41	4.51	-2.26
8	61.41	60.22	1.94	5.49	5.53	-0.73
9	70.83	70.30	0.75	6.67	6.62	0.75
10	36.20	34.90	3.59	2.35	2.40	-2.13
11	42.58	41.70	2.07	3.53	3.51	0.57
12	54.54	53.60	1.72	4.61	4.47	3.04
13	30.71	30.12	1.92	3.83	3.55	7.31
14	53.46	53.20	0.49	4.41	4.15	5.90
15	45.81	47.12	-2.86	5.40	5.21	3.52
16	32.77	33.11	-1.04	3.63	3.52	3.03
17	46.70	45.89	1.73	4.41	4.38	0.68
18	48.66	48.45	0.43	5.69	5.87	-3.16
19	15.40	15.50	-0.65	1.28	1.21	5.47
20	24.92	25.00	-0.32	2.35	2.15	8.51
21	26.19	25.73	1.76	3.14	3.11	0.96
22	27.27	26.92	1.28	2.06	2.10	-1.94
23	16.19	15.98	1.30	3.34	3.29	1.50
24	32.96	33.12	-0.49	4.41	4.52	-2.49
25	28.15	27.56	2.10	3.43	3.51	-2.33
26	14.22	13.83	2.74	4.51	4.59	-1.77
27	29.04	29.00	0.14	5.10	5.11	-0.20

6. Conclusion

From the above discussions on the effects and characteristics of thrust force and torque on the natural fibre reinforced composites, the following conclusions can be drawn. Firstly, speed and depth of cut were found to be the most influencing factors for thrust force whereas speed, feed and depth of cut are the predominant factors for torque. In addition, both thrust force and torque closely behave similar as the main and predominant effects. As speed increases, both responses decrease. However, the thrust force and torque are increased when feed and depth of cut are increased. Furthermore, high speed, high feed and medium depth of cut are the optimum machining conditions while considering the thrust force factor. Meanwhile, high speed, low feed and low depth of cut are the optimum condition for torque. Moreover, thrust force and torque were modeled using fuzzy rule and the models were closely correlated with the experimental data with an average error of 0.77% and 1.22%, respectively. Hence, the fuzzy modeling of thrust and torque can be taken to be highly satisfactory. Also, fuzzy modeling

helps to accurately predict the responses for any values of cutting speed, feed rate and depth of cut combinations within a specific range of values.

Acknowledgment

The authors would like to acknowledge Universiti Putra Malaysia for supporting this research under GP-IPB 9441503.

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