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Influence of Multi-Walled Carbon Nanotubes on Circularity of Drilled Holes In Epoxy/Glass Fabric Polymeric Composite

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Abstract

This paper investigates the influence of the multi walled carbon nanotubes (MWCNTs) on the circularity of drilled hole in epoxy/glass fabric polymer composite. Two specimen of neat epoxy and MWCNTs filled glass fabric hybrid polymeric nanocomposite materials were prepared and drilling tests were conducted with HSS twist drill of diameter 6mm. Shape of the damaged area around the drilled holes at the entrance and exit sides were measured and analysed in terms of circularity for all the cutting speed and feed rate combinations in the designed space. Grey relational analysis showed that the reinforcement with MWCNTs has greatly improved the circularity of the drilled holes in epoxy/ glass fabric polymer composite. Analysis of grey relational grades indicates that the MWCNTs reinforcement and the feed rate are influential factors on circularity. Based on the mean grey relational grades, optimal cutting conditions were observed with level 1 and level 1 of cutting speed and feed rate respectively.

Keywords: carbon nanotubes;drilling;circularity;optimsation;grey relational analysis.

Nomenclature

A	Material
B	Cutting speed (m/min)
C	Feed rate (mm/rev)
C_y	Circularity
P	Perimeter of damaged area around drilled hole

A_d	Damaged area around drilled hole
n	Number of observations
DF	Degree of freedom
SS	Sum of squares
MS	Mean square
F	Ratio of MS of a variable to Error MS
P	Percentage of contribution
a	95% confidence level
R^2	Proportion of explained variability in the ANOVA model

Introduction

Composite material is a combination of two or more inherently different materials, with properties that exceed the constituent materials. Fiber reinforced plastics are used for wide range of applications including automobile and aerospace industries due to their superior mechanical performance. In spite of their superior mechanical properties, these fiber reinforced composite materials are needed to be machined as they are to be usually assembled in complex structures [1]. Though these materials can be produced to a near-net shape, still drilling of holes is necessary for the assembly of complex products [2]. During drilling an inter-ply failure phenomenon called delamination is normally induced [3]. Quality of drilled hole is measured in terms of surface delamination, fiber/resin pullout and inadequate surface roughness of the hole wall [4]. Luis Miguel P. Durao et al. [1] studied the influence of feed rate on circularity and concluded that the increase in feed rate will decrease the circularity. The authors [1] also related the circularity to the shape of damaged area around the drilled hole.

Influence of drilling parameters (cutting speed and feed rate) on the required cutting forces, torques and delamination that occurs at drill entrance and exit in drilling composites has been extensively studied [5,6]. The feed rate, cutting speed, and material thickness are the parameters which influence the delamination in drilling of GFRP composites. The influence of carbon nanotube (CNT) morphology and diameter on the processing and properties of CNT-reinforced aluminium composites is shown by A.M.K. Esawi et al. [7].

For optimisation of process parameters, grey relational analysis has been used. The grey relational analysis is predominantly used for multi objective characteristic problems. It also provides an efficient solution to the uncertainty, multiple inputs and discrete data problem like machining [8]. Tosun [9] used grey relational analysis in optimizing the drilling parameters. Chin-Phin Fung [10] studied the grey relational analysis to obtain the optimal parameters for moulding process. Chorng-Jyh Tzeng et al. demonstrated the use of grey relational analysis in optimising multi objective characteristics of turning operations [11]. The main objective of this paper is to investigate the influence of MWCNTs on the shape of the damaged area around the drilled hole when drilling a GFRP composite at various cutting speed and feed rate combinations.

Fabrication of Specimen

An ultrasonic vibrator was used to sonicate, calculated amount of MWCNTs (0.3% by weight) in ethanol for one hour at 40 KHz to minimise agglomeration. The MWCNTs are less than 8 nm in diameter and 20-30 µm in length. MWCNTs are purchased from "Chengdu Organic Chemicals Co Ltd., China". Mixture of MWCNTs and ethanol were then added to the epoxy resin and sonicated for another one hour. The mixture was mechanically stirred at 80°C for one hour to remove ethanol. The specimen was fabricated by laying up five layers of E-glass coarse plain weave fabric. Each layer was coated with 0.3% by weight of MWCNTs filled epoxy Araldite LY556 with hardener HY951 in the ratio 10:1. The layup was done between steel templates and aluminium sheets on both sides. Silicone was used as a releasing agent between aluminium sheets. The setup was pressurised in a compression moulding unit at a pressure of 2.4 MPa for 24 hours. The fabricated hybrid nanocomposite laminate was approximately 2.8mm thick and had approximately 40% volume fraction of glass fiber and 60% volume fraction of epoxy matrix filled with 0.3% by weight of MWCNTs. Neat epoxy composite was also fabricated with approximately 40% volume fraction of glass fiber and 60% volume fraction of epoxy matrix. The experimental details are shown in table 1. The chosen four level design for the cutting parameters is shown in table 2.

Experimental Setup

Factorial design based experiments were conducted to investigate the damage area around the drilled holes by measuring circularity. Circularity is given as a function of perimeter, P, of the damaged area around the drilled hole and the damaged area around drilled hole, A_d, as follows:

$$C_y = 4\pi \frac{A_d}{P^2} \tag{1}$$

The scanned images were used to analyse the damage around the hole. A 600 dpi scanner was used for scanning. The entrance and exit sides of the drilled holes were analysed using Image J 1.46v public domain software. With proper threshold, the circularity was measured using Image J 1.46v software at the entrance and exit sides for all the drilled holes. Grey relational theory based analysis provides an excellent methodology to optimise the cutting conditions for the above problem. Grey relational analysis is a measure of the absolute value of the data difference between sequences. The following steps are carried out for the optimisation process:

1. Calculation of circularity at the entrance and exit sides.
2. Normalisation of circularity values.
3. Calculation of deviation sequences.
4. Calculation of grey relational coefficients and grey relational grades.
5. Selection of optimal levels.

Table 1: Experimental Details

Specimen	a) 0.3% by weight MWCNTs filled epoxy/glass fabric nanocomposite; Volume fraction of glass fiber mat (5 layers) =0.40; Volume fraction of MWCNTs filled epoxy matrix=0.60. b) Neat epoxy /glass fabric composite; Volume fraction of glass fiber mat (5 layers) =0.40; Volume fraction of epoxy matrix=0.60.
Cutting tool	HSS twist drill with point angle 118°
Diameter of cutting tool	6 (mm)
Cutting conditions	Cutting speed : 9.426, 14.139, 18.852, 23.565 (m/min) Feed rate : 0.04, 0.06, 0.08, 0.1 (mm/rev)
Environment	Dry

Table 2: Factors and levels

Symbol	Factor	Level 1	Level 2	Level 3	Level 4
A	Material	Neat epoxy	MWCNTs filled epoxy	-	-
B	Cutting speed (m/min)	9.426	14.139	18.852	23.565
C	Feed rate (mm/rev)	0.04	0.06	0.08	0.1

In Grey relational analysis data pre-processing is performed to normalise the random grey data. The original reference sequence and pre-processed data are given by $x_0^{(0)}$(k) and $x_i^{(0)}$(k), i = 1,2 m and k = 1,2 n respectively. Where m is the number of experiments and n, is the total number of observations. Since the original data has the quality characteristics as ‘larger the better’ the original data are pre-processed using the following equation:

$$x_i^*(k) = \frac{x_i^{(0)}(k) - \min x_i^{(0)}(k)}{\max x_i^{(0)}(k) - \min x_i^{(0)}(k)} \quad (2)$$

Deviation sequence $\Delta_{oi}(k)$ is given by the equation:

$$\Delta_{oi}(k) = \left| x_0^*(k) - x_i^*(k) \right| \quad (3)$$

$$\Delta \max = \max_{\forall j \in i} \max_{\forall k} \left| x_0^*(k) - x_i^*(k) \right| \quad (4)$$

$$\Delta \min = \min_{\forall j \in i} \min_{\forall k} \left| x_0^*(k) - x_i^*(k) \right| \quad (5)$$

The grey relational coefficient is calculated using the following relation:

$$\gamma(x_0^*(k), x_i^*(k)) = \frac{\Delta_{\min} + \xi\Delta_{\max}}{\Delta_{oi}(k) + \xi\Delta_{\max}} \tag{6}$$

ξ is the distinguishing coefficient, mostly given with a value of 0.5. Grey relational grade is the weighed sum of grey relational coefficients of various factors (circularity at the entrance and exit sides) considered, and is given as follows:

$$\gamma(x_0^*, x_i^*) = \sum_{k=1}^{n} \beta_k \gamma((x_0^*(k), x_i^*(k)), \text{ where } \sum_{k=1}^{n} \beta_k = 1 \tag{7}$$

Since all the factors are given with equal weights, β_k is taken as 0.5.

Table 3: Plan of experiments and the summary of circularity and grey relational grades

Experiment No	**Test specimen**	**Cutting speed**	**Feed rate**	**Circularity**				**Grey relational grades**			**Rank**
				Entrance side		**Exit side**					
				Set1	**Set2**	**Set1**	**Set2**	**Set1**	**Set2**	**Average**	
1	1	1	1	0.85	0.88	0.93	0.8	0.655	0.473	0.564	14
2	1	1	2	0.85	0.89	0.89	0.81	0.597	0.493	0.545	17
3	1	1	3	0.82	0.87	0.84	0.79	0.519	0.455	0.487	26
4	1	1	4	0.83	0.88	0.81	0.86	0.503	0.532	0.518	21
5	1	2	1	0.88	0.89	0.8	0.84	0.546	0.521	0.534	19
6	1	2	2	0.77	0.88	0.66	0.8	0.384	0.473	0.429	32
7	1	2	3	0.85	0.89	0.77	0.8	0.495	0.485	0.49	24
8	1	2	4	0.84	0.89	0.83	0.84	0.527	0.521	0.524	20
9	1	3	1	0.89	0.93	0.85	0.9	0.599	0.665	0.632	11
10	1	3	2	0.83	0.88	0.85	0.88	0.537	0.558	0.548	16
11	1	3	3	0.81	0.92	0.87	0.86	0.54	0.588	0.564	15
12	1	3	4	0.81	0.87	0.77	0.82	0.461	0.479	0.47	30
13	1	4	1	0.9	0.94	0.85	0.88	0.613	0.653	0.633	10
14	1	4	2	0.9	0.8	0.81	0.83	0.579	0.433	0.506	22
15	1	4	3	0.84	0.78	0.84	0.85	0.536	0.442	0.489	25
16	1	4	4	0.83	0.8	0.82	0.72	0.511	0.358	0.435	31
17	2	1	1	0.9	0.92	0.98	0.85	0.822	0.576	0.699	7
18	2	1	2	0.93	0.99	0.96	0.96	0.822	1	0.911	1
19	2	1	3	0.92	0.91	0.93	0.76	0.745	0.486	0.616	12
20	2	1	4	0.9	0.93	0.84	0.91	0.603	0.683	0.643	9
21	2	2	1	0.96	0.99	0.96	0.84	0.889	0.765	0.827	2
22	2	2	2	0.92	0.97	0.8	0.94	0.604	0.856	0.73	5
23	2	2	3	0.84	0.8	0.91	0.69	0.615	0.345	0.48	27
24	2	2	4	0.93	0.87	0.92	0.89	0.747	0.563	0.655	8
25	2	3	1	0.98	0.97	0.9	0.9	0.847	0.767	0.807	3
26	2	3	2	0.96	0.94	0.92	0.89	0.815	0.669	0.742	4
27	2	3	3	0.92	0.91	0.83	0.83	0.626	0.539	0.583	13
28	2	3	4	0.87	0.84	0.78	0.84	0.521	0.471	0.496	23
29	2	4	1	0.91	0.98	0.9	0.85	0.684	0.732	0.708	6
30	2	4	2	0.83	0.89	0.78	0.79	0.483	0.477	0.48	28
31	2	4	3	0.69	0.89	0.8	0.85	0.417	0.532	0.475	29
32	2	4	4	0.91	0.93	0.62	0.83	0.504	0.573	0.539	18

Table 4: Analysis of variance for grades

SYMBOL	DF	SS	MS	F_{test}	F_{table} 95% [a]	P (%)
A	1	0.255	0.255	30.93	4.149	21.7
B	3	0.072	0.024	2.93	2.901	6.13
C	3	0.243	0.081	9.83	2.901	20.68
A*B	3	0.062	0.020	2.51	2.901	5.28
A*C	3	0.075	0.025	3.02	2.901	6.38
B*C	9	0.128	0.014	1.72	2.188	10.89
A*B*C	9	0.072	0.008	0.97	2.188	6.13
Error	32	0.264	0.008			22.47
Total	63	1.175				100

Results and Discussions

Grey Relational Analysis

In grey relational analysis, higher grey relational grade value corresponds to optimal performance. The grades shown in the table 3 are ranked. From the ranks given in table 3, it can be observed that the experiment number 18 made on MWCNT filled epoxy laminate produced highest grade of 0.911 at cutting speed of 9.426 m/min and feed rate of 0.06 mm/rev. Whereas, the worst performance, with a grey relational grade of 0.429 at the cutting speed of 18.852 m/min and feed rate of 0.06 mm/rev, was observed in the experiment number 6 of neat epoxy laminate.

Analysis of Variance (ANOVA)

To investigate the significance of process parameters, the grey relational grades were analysed using the analysis of variance approach. From table 4, it is observed that the influence of multiwalled carbon nanotubes is significant in the design space with a contribution of 21.7%. Feed rate also significantly affects the circularity with a contribution of 20.68%. The R^2 value of 77.47% shows that the model explains about 77.47 % of total variations. From the analysis of variance and from the ranks of the grey relational grades it is evident that the presence of MWCNTs improves the circularity of the drilled holes. From figure 1, the optimal cutting conditions for circularity is obtained at cutting speed at level 1 (9.426 m/min) and feed rate at level 1 (0.04 mm/rev) with MWCNTs filled epoxy laminate. The average grey relational grade in MWCNTs filled epoxy laminate is 0.6493, which is 24.19% more than the average grey relational grade of 0.5228 achieved in neat epoxy laminate. F_{table} values were reported in [12].

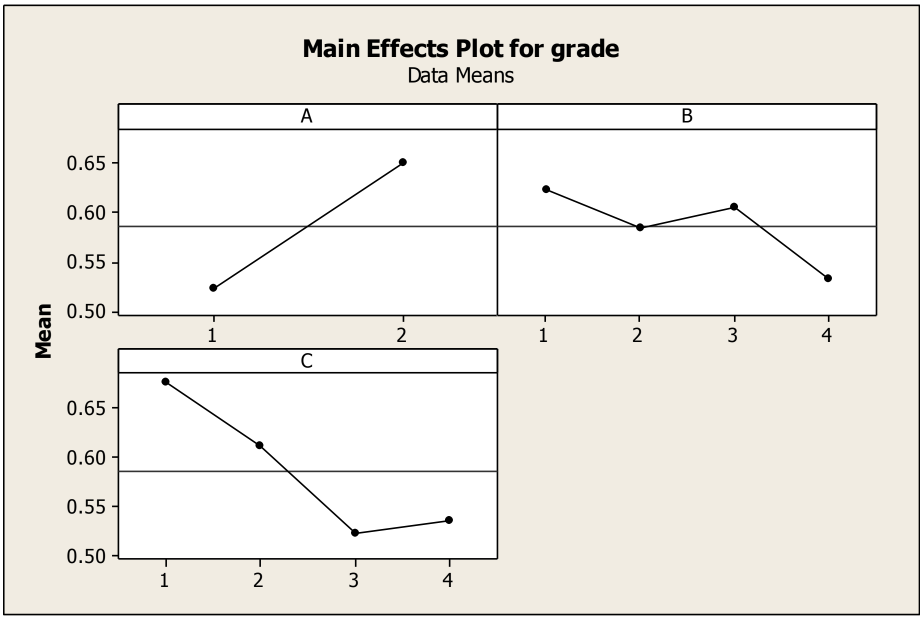

Figure 1: Main Effects Plot For Mean Grades

Conclusions

This study investigated the effect of the presence of MWCNTs on the circularity of the drilled holes in epoxy/ glass fabric composite. Grey relational analysis approach was used to find the optimal cutting conditions when the circularity at the entry and exit sides was considered simultaneously. Grey relational analysis based optimisation indicated that overall improvement in the circularity due to the addition of MWCNTs is around 24.19%. Average grey relational grade of MWCNTs filled and neat epoxy composite are 0.6493 and 0.5228 respectively. Optimal cutting speed and feed rate are 9.426 (m/min) and 0.04 (mm/rev) respectively.

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