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Experimental Investigation on Delamination in Nanocomposite Drilling

This article addresses the influence of cutting parameters on drilling-induced delamination of woven glass fiber-epoxy composites reinforced with functionalized multi-walled carbon nanotubes (MWCNTs). The input parameters include feed rate, cutting speed, drill size, and wt. % carbon nanotubes present in nanocomposite laminates. Experiments were conducted based on Taguchi L_{16} orthogonal array and analysis of variance was conducted to determine the significance of each parameter. The results indicate that the main effects of nano content, feed rate, and spindle speed are significant, while the effect of drill diameter is negligible. Furthermore, the optimum drilling conditions for minimum delamination were determined according to the Taguchi's S/N ratio analysis.

Keywords: Nanocomposites, Multi-walled carbon nanotubes, Drilling process, Delamination, Taguchi, Analysis of variance.

1. INTRODUCTION

Polymers, particularly fibre reinforced composites, are regarded as potential candidate materials for various industrial applications due to their distinctive physical and mechanical properties [1-8]. Recently, the development of nanomaterials has become a new subject in material science. Nanoparticles, in general, are considered as attractive potential fillers to improve the mechanical properties of polymers. In addition, depending on the applied type of filler, nanoparticles can effect the electrical and thermal properties of the final nanocomposite. As an example, carbon nanotube composites found early commercial success particularly in the automobile industry since they are observed to have high stiffness, high strength, and low density [9-11].

Composites are usually fabricated to near net shapes by autoclave molding, compression molding or filament winding. However, as a structural material, secondary machining operations, such as drilling, are required to assemble and join composite materials to other structures. Nevertheless, drilling of composites is considerably more difficult than drilling of conventional metals and their alloys. Drilling process in composites is difficult and challenging due to the anisotropy, inhomogeneity and abrasive nature of these materials. Similarly to impact induced-damage [12-14], the drilling process on composites results in deteriorations such as matrix cracking, fiber breakage, fiber pull-out and delamination. Delamination is found to be as the most serious concern because in addition to reducing the structural integrity of the laminate, it also results in poor assembly tolerance and has the potential for long-term performance deterioration [15-17].

When drilling, delamination is caused by the low interlinear bond strength of the laminate and high drilling forces. Two forms of delamination called 'peel-up' at the drill entrance and 'push-out' at the exit side of the laminate are shown schematically in Figure 1. Peel-up happens as the drill goes into the laminate. After the cutting edge of the drill comes into contact with the plate, the drilling force acting in the peripheral direction is the driving force for delamination. It causes a peeling force in the axial direction through the slope of the drill flute, which results in separation of the layers from each other at the top, forming a delamination zone. The peeling force is a function of tool geometry and friction between the tool and the workpiece. Push-out is the delamination mechanism occurring as the drill approaches the back side of the laminate, where the uncut thickness is small and the resistance to deformation reduces. Gradually, the applied load goes beyond the interlaminar bond strength and delamination happens. This occurs before the laminate is completely penetrated by the tool. A different drill geometry and drilling conditions can decrease the delamination by lowering the thrust force. In practice, it has been shown that the delamination associated with push-out is more severe than the one associated with peel-up [17-22].

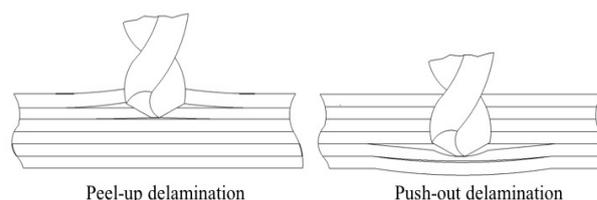


Figure 1. Peel-up and push-out mechanisms in the delamination of fiber reinforced composite materials.

The propagation of delamination and the size of the damage are influenced by the drilling thrust force developed during the process. High thrust force results from the use of improper drilling parameters, improper tool geometry and the nature of the material being drilled.

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Hence, the proper choice of these governing parameters allows free-delamination drilling [23-27]. Several empirical studies have been performed to understand the effects of drilling parameters on drilling thrust force and associated delamination. Almost all researchers reported that feed rate makes the largest contribution to delamination and thrust force and both increase with feed rate at any cutting speeds [28-37]. The effect of cutting speed is contradictory, since increasing this parameter was reported beneficial in references [38-40], while it did affect negatively delamination in references [41-44]. Tsao and Hocheng observed that a drill with a small diameter produces lower thrust force and consequently less delamination when drilling CFRP laminates [44,45]. In addition to cutting parameters, drilling induced delamination is highly influenced by the properties of the constituent materials, fiber, resin and nanoparticles. Ponnuel *et al.* [46,47] investigated the influence of the presence of multi-walled carbon nanotubes in the epoxy/glass fabric composites on the drilling characteristics of these materials. The results show the incorporation of multi-walled carbon nanotubes significantly improves the drilled hole quality at all cutting speeds and feed rates at the entrance and exit side.

Drilling-induced delamination affects the mechanical properties of composite materials and limits their use in high-performance applications. In this paper, we aim to investigate the influence of drilling parameters (feed rate, cutting speed and drill diameter) as well as nano content (wt.% of MWCNTs) on delamination of E-glass-epoxy/MWCNT laminates. The Taguchi design of experiments and analysis of variance are used to analyze the drilling characteristics of these materials.

2. EXPERIMENTAL PROCEDURE

2.1 Material Preparation

The polymer used in this study consists of an epoxy polymer based on bisphenol-A resin, cycloaliphatic amine curing agent, and multi-walled carbon nanotubes functionalized using carboxyl groups (-COOH). These nanotubes had a diameter of 10 nm, an average length of several microns and carbon purity of > 95%. The functionalized MWCNTs at four different weight percentages including 0, 0.1, 0.5 and 1 wt. % and epoxy resin were mixed together in a mechanical stirrer for 3 h.

To prevent agglomeration, the mixture was then placed in an ultrasound bath at 150 kW/cm² intensity and 5 μm amplitude for half an hour. Cycloaliphatic amine curing agent was added to the mixture and mixed for 1 h and then placed in a vacuum oven to remove entrapped air bubbles. E-glass woven fabrics were also used as reinforcement. E-glass/epoxy nanocomposites were manufactured using vacuum assisted hand lay-up technique. Twelve layers of E-glass fabric were used to fabricate all specimens. Curing was carried out in an autoclave at 60°C at a pressure of 1 MPa. The fabricated composite plate had an average thickness of 2.6±0.1 mm and fiber volume fraction of 55%. Finally, test samples of 20×150 mm dimensions were cut using waterjet cutting machine.

2.2 Drilling tests

Drilling experiments were conducted on a Deckel FP4M vertical machine using standard high-speed steel twist drills with the constant geometry as given in Table 1. To facilitate the performing of the drilling experiments, an appropriate experimental setup was used as shown in Figure 2. The experiments were replicated twice, in dry condition, to circumvent the possible experimental errors. The thrust force was measured using Kistler 9255B piezoelectric dynamometer. The drilled specimens were scanned with a digital scanner and the images of the drilled holes were fed to SolidWorks software. Then, the diameter of the damaged zone and damaged area of the drilled holes were measured.

Table 1. Specification of the drill bits used in the experiments.

Family	Standard	Tool material	Nominal Diameter	Point angle	Helix angle	Flutes	Flute length
2462-Guhring	Din 340	HSS	5-6	130	30	2	87

* All lengths are in mm and all angles are in degree.



Figure 2. Experimental setup for drilling tests.

2.3 Design of Experiments: Taguchi Method

In a full factorial design, all possible combinations for a given set of factors and levels are examined. Most engineering experimental plans involve the consideration of a large number of factors and levels, which results in a huge number of experiments. In order to decrease the number of these experiments to an acceptable and practical level, only a small set from them is selected. This method, selecting a limited number of experiments, is known as fractional factorial design. Fractional factorial designs provide quite good information on the main effects and some information about interaction effects [48]. Taguchi method is a highly fractional factorial design which provides more complete interaction information than it is the case for typical fractional factorial designs. The Taguchi method uses *S/N* ratio instead of the mean value to measure the quality characteristics deviating from the desired values. From the quality point of view, there are three possible categories to evaluate the characteristics. They are “smaller is better”, “nominal is better”, and “larger is better”. The calculation of the *S/N* ratio for each

experiment is shown below for the case of a specific target value of the performance characteristic. In the equations below, M_i is the mean value, V_i is the variance, and y_i is the value of the performance characteristic for a given experiment [49].

$$SN_i = 10 \log \frac{M_i^2}{v_i^2} \quad (1)$$

where:

$$M_i = \frac{1}{N_i} \sum_{j=1}^{N_i} y_{i,j} \quad (2)$$

$$V_i^2 = \frac{1}{N_i-1} \sum_{j=1}^{N_i} (y_{i,j} - M_i)^2 \quad (3)$$

where i is the experiment number; j is the trial number; N_i is the number of trials for experiment i .

For the case of minimizing the thrust, the following definition of the S/N ratio should be used:

$$SN_i = -10 \log \left(\sum_{j=1}^{N_i} \frac{y_j^2}{N_i} \right) \quad (4)$$

And for the case of maximizing the residual tensile strength, the following definition of the S/N ratio should be used:

$$SN_i = -10 \log \left(\frac{1}{N_i} \sum_{j=1}^{N_i} \frac{1}{y_j^2} \right) \quad (5)$$

In this investigation, four parameters, namely, nano content, feed rate, cutting speed and drill diameter were selected and the range of the parameters was determined based on our preliminary studies [50]. Nano-content and feed rate were investigated at four levels, while two levels were chosen for cutting speed and drill diameter as shown in Table 2. For the plan of experiments, Taguchi method based on L_{16} orthogonal array was used. Moreover, analysis of variance (ANOVA) was employed to identify the level of importance of the input parameters on the performance characteristics. In this study, Minitab statistical analysis software and MATLAB were employed for all designs, plots, and analyses to perform the Taguchi and ANOVA analysis.

Table 2. Assignment of the levels to the parameters.

Parameters	Symbol	Units	Level 1	Level 2	Level 3	Level 4
Nano content	A	%	0	0.1	0.5	1
Feed rate	B	mm/rev	0.04	0.06	0.08	0.1
Cutting speed	C	rpm	315	630	-	-
Drill size	D	mm	4	5	-	-

3. RESULTS AND DISCUSSION

After performing drilling experiments, damage inspection is necessary for the assessment of machining damage. The visualization and assessment of delamination, however, is a difficult and challenging task since the damage is internal. Optical microscopy and image

analysis are often used for measuring the extent of delamination size [51]. A delamination factor was defined in [52] as the ratio of the maximum diameter of damage zone on the surface of workpiece to the hole diameter. Figure 3 shows a schematic explaining the delamination factor.

$$F_d = \frac{d_{\max}}{d} \quad (6)$$

Davim *et al.* [53] proposed the adjusted delamination factor F_{da} to evaluate the delamination zone by digital image processing. The advantage of this approach is that it incorporates the novel approach of area function. Adjusted delamination factor gives better results of measurement compared with delamination factor proposed by Chen. The equation of the adjusted delamination factor is expressed as follows:

$$F_{da} = \alpha \frac{d_{\max}}{d} + \beta \frac{A_{\max}}{A} \quad (7)$$

$$F_{da} = F_d + \frac{A_d}{A} (F_d^2 - F_d) \quad (8)$$

$$\beta = \frac{A_d}{A_{nom} - A_{\max}} \quad \alpha = 1 - \beta \quad (9)$$

where d is the nominal diameter of the hole, A is the area related to the nominal hole, A_{\max} is the area related to the maximum diameter of the delamination zone (d_{\max}), and A_d is the delaminated area.

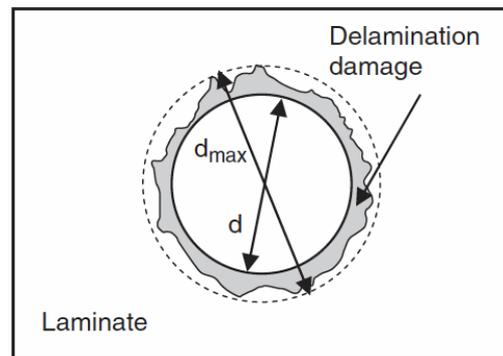


Figure 3. Schematic representation of the delamination factor [54].

The L_{16} orthogonal array layout and measured experimental results of adjusted delamination factor (F_{da}) are shown in Table 3.

The main purpose of the analysis of variance is to analyze which process parameters significantly affect the response. The analysis of variance for adjusted delamination factor is shown in Table 4. In addition, in order to find the contribution of each parameter to the response, a Pareto chart is used. Pareto chart is a type of bar chart in which the horizontal axis shows categories of interest, rather than a continuous scale. By ordering the bars from largest to smallest, a Pareto chart helps to find which of the parameters significantly affect the response. A cumulative percentage line can help to assess the added contribution of each category. Pareto charts are helpful to focus improvement efforts on areas where the largest gains can be made. Pareto chart for process factors is shown in Figure 4.

Table 3. The L16 orthogonal array layout and measured experimental results.

Trial no.	Input parameters				F_{da}		
	Nano Content (wt. %)	Feed Rate (mm/rev)	Cutting Speed (rpm)	Drill Size (mm)	R_1	R_2	S/N
1	0	0.04	315	4	1.17	1.17	-1.364
2	0	0.06	315	4	1.6	1.59	-4.055
3	0	0.08	630	5	1.61	1.55	-3.975
4	0	0.1	630	5	1.81	2.32	-6.364
5	0.1	0.04	315	5	1.09	1.08	-0.709
6	0.1	0.06	315	5	1.37	1.35	-2.671
7	0.1	0.08	630	4	1.15	1.15	-1.214
8	0.1	0.1	630	4	1.62	1.65	-4.271
9	0.5	0.04	630	4	1.08	1.08	-0.668
10	0.5	0.06	630	4	1.09	1.1	-0.788
11	0.5	0.08	315	5	1.71	1.69	-4.609
12	0.5	0.1	315	5	2.21	2.25	-6.966
13	1	0.04	630	5	1.11	1.12	-0.946
14	1	0.06	630	5	1.13	1.15	-1.138
15	1	0.08	315	4	2.33	2.4	-7.478
16	1	0.1	315	4	2.52	2.55	-8.08

Table 4. ANOVA table for delamination factor.

Source	Sum Sq.	d. f.	Mean Sq.	F	Prob>F	P (%)
Nano-content	0.95178	3	0.31726	12.25	0.0001	12.6
Feed rate	4.78217	3	0.59406	61.55	0	62.8
Cutting speed	1.26405	1	0.26405	48.81	0	16.6
Drill size	0.01531	1	0.01531	0.59	0.4497	0.2
Error	0.59564	23	0.0259			7.8
Total	7.60895	31				100

According to the results of Table 3 and Figure 4, adjusted delamination factor is significantly affected by feed rate (62.8%) followed by cutting speed (16.6%) and nano content (12.6 %); while the effect of drill diameter is negligible (0.2%). The error term in the table and figure shows the influence of all factors not included in the experiments, their interactions, and effects of experimental error.

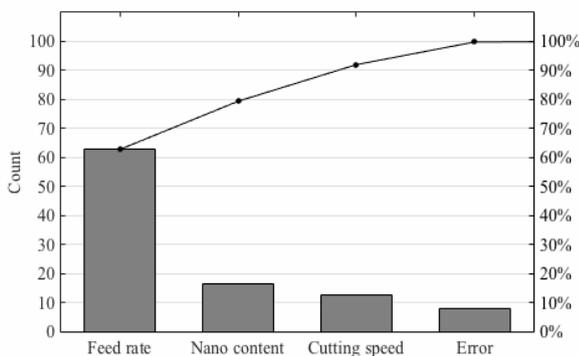


Figure 4. Pareto chart of process parameters.

The use of both analysis of variance technique and Taguchi's S/N ratio analysis makes it less cumbersome to analyze the results. The obtained values of S/N ratios are given in Table 5 and plotted in Figure 5. From Figure 5, the feed rate and then the cutting speed and nano content have a great influence on delamination. Conversely, delamination is only slightly influenced by

the drill diameter. The area of delamination is enlarged with increasing feed rate and decreasing cutting speed. This is mainly attributed to the higher impact of the cutting edges which leads to the increase in the drilling thrust force. Higher thrust force, in turn, leads to more delamination propagation. Moreover, it can be observed that the nano content has a positive effect on delamination factor at the beginning and then its effect changes to negative. According to the figure, the optimum process parameters are as nano content at level 2 (0.1 wt. %), feed rate at level 1 (0.04 mm/rev), cutting speed at level 2 (630 rpm) and drill diameter at level 2 (5 mm).

Table 5. Response table for signal to noise ratios of adjusted delamination factor.

Symbol	Process parameters	Level 1	Level 2	Level 3	Level 4	Max-Min	Rank
A	Nano content	-42.17	-39.55	-38.98	-42.59	3.61	2
B	Feed rate	-36.33	-38.86	-42.40	-45.70	9.37	1
C	Cutting speed	-42.33	-39.32			3.01	3
D	Drill size	-40.74	-40.91			0.17	4

Interaction effects are important in reaching a more general conclusion in parametric studies. To understand the interaction between factors, the graph of the average responses at each treatment combination is shown in Figure 6. The significant interaction is indicated by the lack

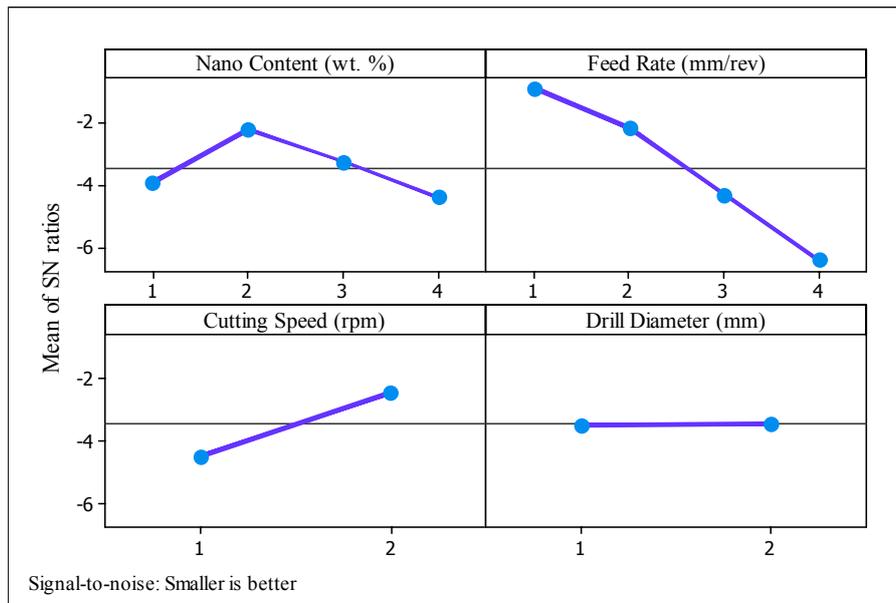


Figure 5. Response table for signal to noise ratios.

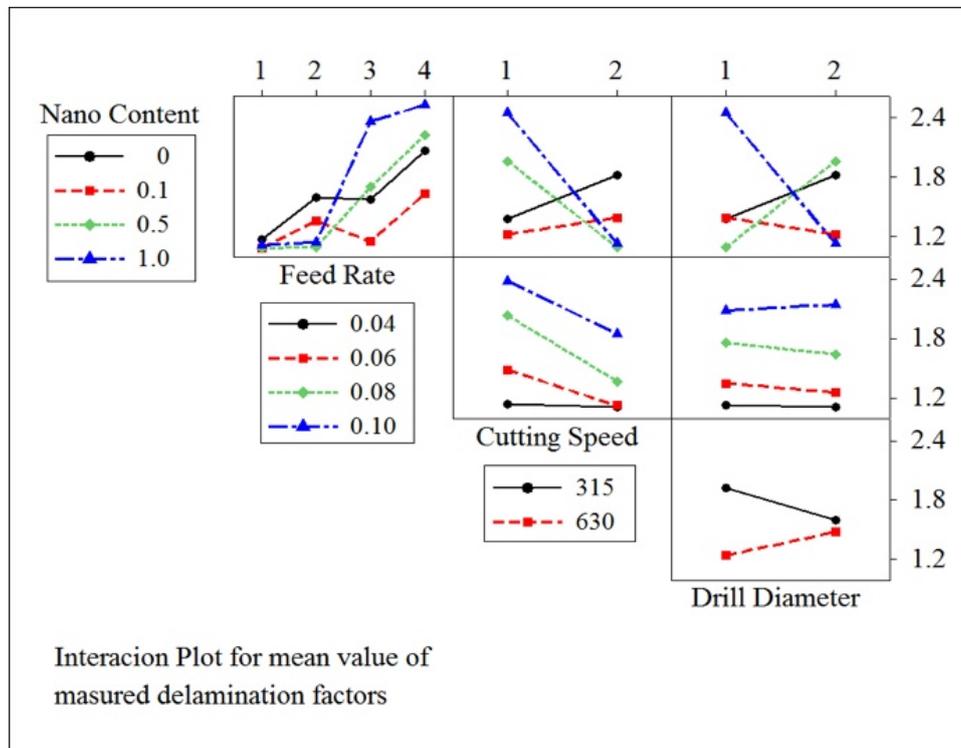


Figure 6. The interaction plots for mean values of measured delamination factors.

of parallelism of the lines. From Figure 6, the drill diameter shows significant interactions with the cutting speed and nano content. Furthermore, a significant interaction between cutting speed and feed rate can be seen. There is also a fairly small interaction between feed rate and nano content, as shown by the quite similar shape of the curves.

4. CONCLUSIONS

In the current paper, the effect of drilling parameters on drilling-induced delamination of woven glass fiber-epoxy composites reinforced with functionalized multi-walled carbon nanotubes (MWCNTs) was investigated. Four parameters, i.e., nano content, feed rate, spindle

speed and drill diameter, based on the Taguchi L_{16} orthogonal array, were studied. The results are summarized as follows:

- The main effects of nano content, feed rate and spindle speed are significant, while the effect of drill diameter is negligible based on analysis of variance.
- The feed rate is the parameter that has the greatest influence on the delamination factor (62.8%).
- The area of delamination increases with increasing feed rate and decreasing spindle speed according to the Taguchi's S/N ratio analysis.
- The nano content has a positive effect on delamination factor at the beginning and then its effect changes to negative

- Optimum drilling conditions for minimum delamination are as nano content at level 2 (0.1 wt. %), feed rate at level 1 (0.04 mm/rev), spindle speed at level 2 (630 rpm) and drill diameter at level 2 (5 mm)
- The drill diameter shows significant interactions with the spindle speed and nano content. Furthermore, the results show a significant interaction between feed rate and spindle speed.

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**ЕКСПЕРИМЕНТАЛНО ИСТРАЖИВАЊЕ
ДЕЛАМИНАЦИЈЕ ТОКОМ БУШЕЊА
НАНОКОМПОЗИТА**

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Овој рад представља утицај параметара резања на деламинацију насталу бушењем тканог стаклено-епоксидног композита ојачаним функционализованим вишезидним угљеничним нано-цевима (MWCNTs). Улазни параметри укључују корак резања, брзину резања, величину бургије и проценат угљичних нанопреци присутних у нано-композитним ламинатима. Експерименти су спроведени на основу Taguchi L16 ортогоналног поља и извршена је анализа варијанте за одређивање значаја сваког параметра. Резултати указују на то да су главни нано ефекти, корак резања и брзина вретена значајни, док је ефекат пречника бургије занемарљив. Осим тога, утврђени су оптимални услови бушења за минималну деламинацију у складу са анализом односа S/N Taguchi-a.