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December 29, 2020

A Novel Approach for Optimization of Machining Characteristics of Polymer Nanocomposites

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Abstract— Glass fiber polymer composites possess a broad spectrum of applications in spacecraft, automotive, marine, and sports components. Due to enhanced features, this material replacing the conventional engineering materials and their alloys. Its machining behavior requires more attention for proper utilization and makes them cost-effective. Some critical issues such as fiber pull out, matrix debonding, resin pulls out, etc., due to their anisotropic and abrasive nature. It can be overcome by machining performance optimization using hybrid modules. This article describes an experimental investigation on machining (Milling) of multiwall carbon nanotube (MWCNT) doped epoxy /GFRP composites and effect of process parameters viz. spindle speed (S), feed rate (F), depth of cut (D), MWCNT weight % (R%) on machining performances such as MRR, cutting force (Fc), and Surface roughness (Ra) has been examined. Taguchi based L_9 orthogonal array was employed to execute the machining. A relatively advanced combined approach of Data Envelopment Analysis based Ranking (DEAR) and Taguchi was used to tackling critical issues of multiple conflicting responses. The optimal condition of the DEAR-Taguchi approach found at S2450F85D0.6R2%. It has been validated through a confirmatory test, which shows satisfactory improvement in machining performance. This enhancement is highly required for a cost-effective machining environment.

Keywords— Milling, Optimization, DEAR, GFRP, MWCNT, Taguchi

1. INTRODUCTION

For the last three decades, glass fiber successfully used in polymer composites. It becomes an alternative in the polymer manufacturing sector to full fill the use of multifunctional materials. It consists of high endurance limit, high resistance to corrosion, high rigidity density ratio, and low thermal expansion coefficients. A small product such as a golf shaft, bicycle parts and aircraft interior, etc., especially GFRP, was preferred [1, 2]. In the 90s, carbon nanotubes (CNTs) were introduced to enrich the epoxy composites' mechanical aspects as the best possible fillers [3, 4]. SWCNTs (single wall) and MWCNTs (multi-walling) depend on the number of tubes. CNTs' epoxy-based nano polymer composites are useful additives to modify epoxy structures to increase flexural modulus and bending strength [5, 6]. The proper utilization of any material is not feasible without understanding its machining and machinability aspects. The primary machining process such as drilling, milling, turning, etc. used in the manufacturing system to complete the product design. The manufacturing sector is changing rapidly to fulfill customers' desire in terms of durability, lightweight, shiny appearances, and other aesthetic requirements [7, 8]. At these conditions, polymers (plastics) play a key role in maintaining the developed components' quality and productivity. In polymers materials, the glass fiber reinforced composites are widely used in manufacturing sectors due to availability and cost-effectiveness [9]. But there are some limitations in macro composites like aspect ratio, dispersion of fillers, matrix, and reinforcement bonding, etc. Nanocomposites' developments overcome these issues by doping/mixing nanomaterials like CNT (SW/MW) and glass fiber into the epoxy matrix [10, 11].

2. BACKGROUND AND PROBLEM FORMULATION

MWCNT reinforced epoxy materials possess enhanced mechanical and chemical properties to manufacture components in aircraft, biomedical, sensors, optical devices, etc., [12-14]. Various eminent scholars explored their work for machining GFRP/CFRP/KFRP composites, but very limited information on machining of CNT doped GFRP nanocomposites is available. In this series, Kishore Kumar et al. [15] conducted experimental research using CFRP and CNT doping. The epoxy resins were modified by 0.1%, 0.2%, 0.3% and 0.4% of MWCNTs weight percent introduced to study the consequences of CNTs fillers. GFRP samples improved by 0.3% MWCNTs have higher tensile strength (242.22 MPa) and flexural strength (332.53 MPa) relative to neat GFRPs. The results proved that MWCNTs play a major role in improving material properties such as tensile, failure strain and durability. Dinesh Kumar Rathore et al. [16] investigated elevated glass fiber/epoxy composite MWCNT temperature durability. Flexural tests at room temperature tests demonstrated that the addition of 0.1% MWCNT for yielded maximum strength in all CNT modified composite systems (+ 32.8% over GE control) and modulus (+ 11.5% over GE control). MWCNT – GE composites have led to an accelerated decline in mechanical efficiency while the temperature compared with GE composites has increased. The viscoelastic behavior of all composites over a temperature range has been studied through dynamic mechanical, thermal analysis (DMTA). Rahulreddy Chennareddy et al. [17] doped the MWCNTs scattered in the epoxy matrix to produce the GFRP resistance for UV-positive composite was studied. Direct voltage tests of 0.25% wt.% GFRP, 0.5% wt.% and 1.0% wt.% of MWCNTs show good UV-resistance and stability. Microstructural analysis shows that MWCNTs can be able to prevent UV degradation of the polymer backbone caused by UV radiation in the GFRP. Scanning microscopy of the electron (SEM) images revealed that MWCNTs can handle UV-radiated microcracking and therefore improve GFRP resistance to UV degradation. Mahmoud R. et al. performed [18], bending test and laminate bending strength of plastic reinforced carbon fiber joint. During the test, the specimen received two acoustic emission sensors (AE) to monitor the progress of the fracture. Increased bending strength and joint consistency were demonstrated by the laminated reinforced joints and some overlapping joints. The maximum increase for the laminated joint of 5 layers was 24% and the multichambered joint of 6 layers was 58%. J. Paulo Davim et al. (Paulo Davim & Mata, 2007) done experimental work on composite milling and output considered was delamination related to the material characteristics and cutting parameters that have been conducted. A. I. Azmi et al. [19] examined a milling analysis of glass fiber composites using uncoated carbide method. The experiments were performed to test GFRP machinability in terms of tool wear, service life, machining efficiency, and machining powers. The cutting speed was recognized as the primary parameter to influence tool life with fiber orientation and feed rate. During final milling tests, the machining force differences were monitored constantly due largely to the rise in tool wear and fiber orientation [20-22].

The prior state of the art confirmed that MWCNT doped epoxy and Carbon fiber in the epoxy matrix possess a wide array of applications due to enhanced mechanical characteristics. The ample work is available on machining GFRP composites using various cutting tools and optimization modules. But the existing data shows that very limited work is offered on parametric appraisal and machinability estimation of MWCNT modified glass fiber composites. This paper explores the machining behavior and parametric study during the milling operation. This work will value added to understand the effects of varying process parameters, namely, spindle speed, feed rate and wt.% of MWCNT on milling characteristics viz, MRR, surface roughness and cutting force. For optimization, a relatively advanced hybridization approach of the DEAR and Taguchi concept is proposed. Integrated DEAR-Taguchi converted multiple responses transformed into a single objective function. Then, the DEAR-Taguchi hybrid module was utilized to acquire a feasible ranking order overall index of machining characteristics. The outcomes of the confirmatory test will justify the feasibility of the proposed hybrid method. This work can overcome the drawback and limitations of the existing optimization approach.

3. EXPERIMENTATION

3.1 Materials and Fabrication method

During fabrication of MWCNT doped epoxy/GFRP composites, 200 GSM Plain Woven Glass Fabrics and Epoxy Resin-520 was used supplied by M/s. procured from M/s. Nanoscience technology company 468, Shihani road Nand Gram Meerut Road Ghaziabad -201001 Uttar Pradesh India. The reinforcement for MWCNT into epoxy composites was varied at three distinct weight percentages (1, 2, 3 wt.%). The experiments were done on a vertical CNC (Fig. 1) Milling machine setup (Model No. BMV35 TC20) at three discrete levels (Table 1) of machine parameters like Spindle Speed (S), feed rate (F), depth of cut (D) and wt. % of Multiwall carbon nanotube (MWCNT) with solid carbide of 8 mm diameter milling tool. Taguchi L9 array was used to perform the experimentation and corresponding observed data are mentioned in Table 2. The attached milling dynamometer measured the cutting force and for evaluation of surface roughness, a Surtronic S100 surface tester was used.

Table 1. Process Parameters

Parameters	Nomenclature	Level 1	Level 2	Level 3

Spindle Speed	S	850	1650	2450
Feed Rate	F	85	165	245
Depth of cut	D	0.6	1.2	1.8
MWCNT	R%	1	2	3

Fig. 1. Machining (Milling) for MWCNT doped epoxy and Glass fiber in polymer composites

Table 2. Taguchi L9 OA observe data and corresponding S/N ratio

S. No	Process parameter				Observed Data		
	S	F	D	R%	MRR (mm^3/sec)	F_c (N)	R_a (µm)
1	850	85	0.6	1	0.0612	13.34	3.46
2	850	165	1.2	2	0.3107	17.46	3.11
3	850	245	1.8	3	0.9121	17.16	3.42
4	1650	85	1.2	3	0.2347	9.87	2.55
5	1650	165	1.8	1	0.6880	30.01	3.85
6	1650	245	0.6	2	0.1950	17.95	2.88
7	2450	85	1.8	2	0.2581	9.02	3.26
8	2450	165	0.6	3	0.1645	11.56	2.76
9	2450	245	1.2	1	0.3973	24.52	4.75

4. PARAMETRIC OPTIMIZATION

Taguchi based DEAR hybrid method employed to optimize the parameters and their effect on responses simultaneously. The present studies aim to maximize MRR, minimizing surface roughness and cutting force during milling of MWCNT/GFRP composites.

4.1 Taguchi Approach

Taguchi based L_9 orthogonal array is a combination of all possible sets for a test. This effective technique is used to scrutinize the influence of the machine parameter through the minimum experiments' order. Taguchi method is used for the statistical scale for the single response used for computing the signal to noise ratio (S/N ratio) [23, 24]. In this case, the MRR was considered as a maximization function, i.e., higher the better using the expression:

Higher the Better (HB)

$$(S/N)_{ij} = -10\log\left(\frac{1}{n}\sum_{j=1}^{n}\frac{1}{X_{ij}^2}\right) \quad (1)$$

The cutting force (Fc) and surface roughness (Ra) values correspond to the minimization function, i.e., Lower the better (LB) using the expression:

$$(S/N)_{ij} = -10\log\left(\frac{1}{n}\sum_{j=1}^{n}X_{ij}^2\right) \quad (2)$$

Where $(S/N)_{ij}$ is S/N ratio, X_{ij}^2 is measured significance data of the i^{th} experimentation at the j^{th} assessment.

4.2 Data Envelopment Analysis Based Ranking (DEAR)

A set of observed responses are recorded into a ratio in this method. To achieve the optimal condition of the process parameters, it can be regarded as a multi-response performance index (MRPI) value [25]. The following steps are used for Ranking Methodology (DEAR) based on data design analysis:

- Calculation of weights(w) of each response

$$MRR = \frac{\text{MRR}}{\sum \text{MRR}} \tag{3}$$

$$R_a = \frac{(\frac{1}{Ra})}{\sum(\frac{1}{Ra})} \tag{4}$$

$$F_c = \frac{(\frac{1}{Fc})}{\sum(\frac{1}{Fc})} \tag{5}$$

- Transform the data into weighted response

$$P = W_{MRR} \times \text{MRR} \tag{6}$$

$$Q = W_{Ra} \times Ra \tag{7}$$

$$R = W_{Fc} \times Fc \tag{8}$$

- Finally calculate the MRPI and allotted ranking.
- $$MRPI = \frac{P}{Q+R} \tag{9}$$

5. RESULT AND DISCUSSION

For milling of GFRP Doped MWCNT composite, varying constraints were used, and observed data were recorded through measuring methods and equipment. The weight of each milling characteristic was calculated using the DEAR methodology under different process parameter combinations. The consolidated MRPI for all factors at all levels is shown in Table 1. The experimental work results have been studied to determine the machining process as a higher material removal rate and minimum surface roughness, cutting force. The machining performance has been converted into the S/N ratio to eliminate the machining process's uncorrelated factor (Table 3). Then normalized the machining response's value into a specified quantity (weightage matrix) as depicted in Table 3. After calculating normalized data of each response, calculate the weight assign for every response characteristic using Eqs. 3-5. The weight assigns to each response using (Eqs. 6-8) the simple multiplication method. Finally, MRPI values calculated for each process response corresponding to each experiment response. The maximum value of MRPI can be regarded as the optimal value of each process parameter's process variables. The higher value of the MRPI, which corresponds to input parameter was selected as the optimal machining condition based on the OA setting. Table 4 demonstrates (Fig. 2) that spindle speed (2450 rpm), feed rate (85 mm/rev), depth of cut (0.6 mm) and wt.% of MWCNT (3%) are noticed as the optimum parameters based on DEAR-Taguchi predicted set. Tables 4 shows the higher MRPI value obtained as 2.732374 and its corresponding rank.

Table 3. Corresponding S/N ratio and weightage matrix

	S/N ratio			Weightage matrix	
MRR (dB)	F_c (dB)	R_a (dB)	W_{MRR}	W_{Fc}	W_{Ra}
-26.6958	9.3790	12.1413	0.2177	0.0877	0.1132
-12.584	10.3053	9.8035	0.1026	0.1087	0.1030
-3.22998	9.4800	9.9541	0.0263	0.1070	0.1119
-15.0206	12.0298	14.7581	0.1225	0.0722	0.0882
-5.67906	8.4513	5.0991	0.0463	0.2090	0.1256
-16.6301	10.9727	9.5631	0.1356	0.1114	0.0967
-14.1951	9.8962	15.5403	0.1157	0.0685	0.1072
-18.1075	11.3424	13.3853	0.1477	0.0796	0.0936
-10.4485	6.6267	6.8540	0.0852	0.1555	0.1602

Table 4. MRPI and corresponding rank

	Transform data into weightage matrix		MRPI	Rank
P	Q	R		

-5.8133	1.0617	1.0658	2.7323	1
-1.2917	1.0617	1.0658	0.6071	6
-0.0851	1.0617	1.0658	0.04	9
-1.8404	1.0617	1.0658	0.8650	4
-0.2630	1.0617	1.0658	0.1236	8
-2.2559	1.0617	1.0658	1.0603	3
-1.6436	1.0617	1.0658	0.7725	5
-2.6746	1.0617	1.0658	1.2571	2
-0.8905	1.0617	1.0658	0.4185	7

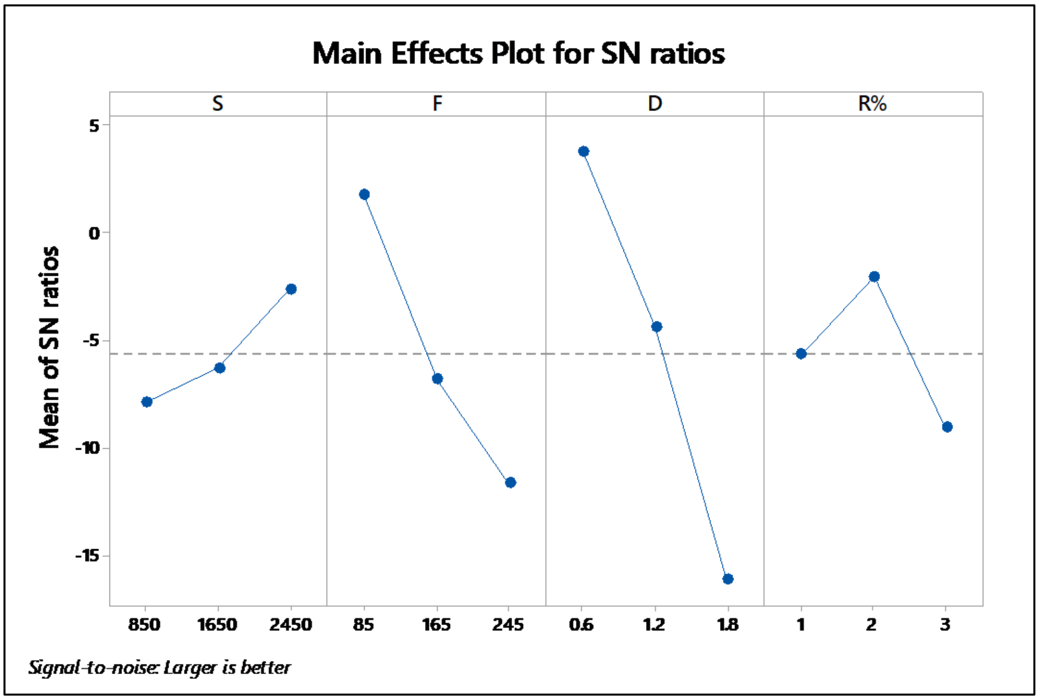

Fig. 2. S/N ratio for MRPI

The optimal setting during machining (milling) of MWCNT doped epoxy and Glass fiber in polymer composites are found as S-2450 rpm, F-85 mm/min and R-2 % with improvement in milling characteristics, namely MRR, surface roughness, and cutting force found as -26.6958 to -28.805dB, 9.379079 to 12.05dB and 12.14136 to16.5dB respectively. It is observed that higher spindle speed reduces the thrust force and reduces the value of thrust force corresponds to good surface finishing. The machined component's surface plays an important role when a material is subjected to creep and fatigue loading, close fits, precision, fastener holes, riveting and other aesthetic demands of manufacturing processes [26, 27]. The results inferred that an increase in higher spindle speed, in this case, increases the temperature between the machining interface, which softens the polymeric material of the machining zone, which gives a lower value of thrust force with improved surface finishing [28, 29].

5.1 ANOVA Test

ANOVA for MRPI reveals that feed rate and cutting depth are important factors (p values < 0.05 at a confidence level of 95%). The values were calculated as a contribution percentage based on a cumulative square value number; the depth of cut exerts the highest Effect on MRPI (54.42 percent), followed by a feed rate (26.14 percent). The significance of ANOVA is shown in Table 5, the closer to the unit value of R^2 (87.33% or 0.8733). The validation has been taken, as shown in Fig. 3 to expect the correctness of the model. It makes easier to understand the predicting model accuracy during trials. The initial validation process involves data subset into a graphical display. The data are direct and there is not much deviation, i.e., the test model's projected result is found as satisfactory [30, 31].

Table 5. Analysis of Variance

Source	DF	Seq SS	Contribution	P-Value

Regression	4	4.5259	87.33%	0.044
S	1	0.1446	2.79%	0.401
F	1	1.3547	26.14%	0.045
D	1	2.8203	54.42%	0.014
R%	1	0.2063	3.98%	0.325
Error	4	0.6568	12.67%	
Total	8	5.1826	100.00%	

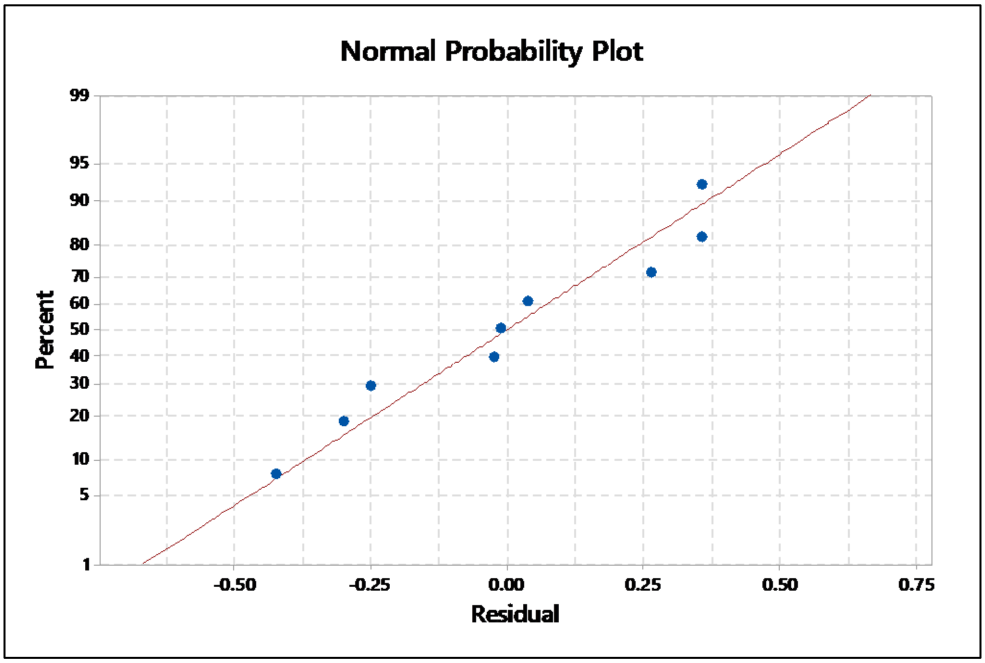

Fig. 3. Normal probability plot for MRPI

The process parameter's main effects are depicted in Table 6, used to evaluate the importance of performance measures of input process variables in every process. The plots showed that the depth of cut has the most critical effect on the removal rate and surface roughness. The depth of cut is having the highest value of 1.6833, which is the highest affecting parameters trail by feed rate 1.4567, which is the physical influence of process performance.

The lowest surface roughness can be achieved with spindle speed and minimum feed rate. With the lowest feed rate, the surface roughness gradually decreases along with an increase in spindle speed and remains merely unaltered of spindle speed 2450 rpm [32].

Table 6. Response Table for Means

Level	S	F	D	R%
1	1.1265	1.4567	1.6833	1.0915
2	0.6830	0.6626	0.6302	0.8133
3	0.8161	0.5063	0.3121	0.7207
Delta	0.4435	0.9503	1.3712	0.3708
Rank	3	2	1	4

5.2 Confirmatory

The optimum combination for parameters is found as S2450F85D0.6R2%. Table 7 shows the outcomes of the confirmatory test. It can be noted that the DEAR-Taguchi hybrid approach considerably enhances the experimental value of surface roughness, cutting forces, and MRR. The desired improvement in the milling characteristics shows the application potential of the proposed module.

Table 7. Confirmatory test result

		Optimal condition DEAR-Taguchi	
Response	OA	Predicted	Confirmatory
Setting	S1F1D1R1	S4F1D1R2	S4F1D1R2
MRR	-26.6958 dB		-28.805 dB
Fc	9.379079 dB		12.05dB
Ra	12.14136 dB		16.5dB

6. CONCLUSION

This article demonstrates the milling investigation of the MWCNT/glass fiber modified polymer composites using SiC cutting tools. The influence of process parameters on the MRR, cutting forces, and surface finish was analyzed using the DEAR and Taguchi theory approach. The outcome of this study can be concluded as:

- The DEAR based Taguchi module effectively aggregated the conflicting milling characteristics into the objective function (MRPI), which is not feasible by the traditional Taguchi concept.
- DEAR is a relatively advanced optimization method in combination with the Taguchi concept, which gives an optimal condition of S2450F85D0.6R2%.
- The ANOVA analysis highlighted that the depth of cut and cutting force process parameters was considered for the influential parameter with 54.42% and 26.14%, respectively.
- The increase in speed improves the surface roughness values and the weight percentage of MWCNT plays a crucial role in obtaining the enhanced milling characteristics.
- The outcome of the confirmatory test shows a satisfactory improvement in milling characteristics for the desired machining environment. It can be forwarded to the plastic manufacturer for the control of productivity and quality indices.

The integrated approach of DEAR based Taguchi method for machining of composites can be used for other multi-criteria case studies. It is a generalized optimization module that given satisfactory outcomes during milling of MWCNT doped GFRP composites. It can be adapted for other machining operations such as Turning, Drilling, etc. The other parameters, such as different types of tools, materials removal mechanisms, tooltip temperature, cutting condition, etc. can be explored better in the future to comprehend MWCNT/GFRP composites' machining behavior.

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