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Grey relational analysis to determine the optimum process parameters in turning of GFRP composites

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ABSTRACT

Glass fiber reinforced polymer composites are finding its increased applications in variety of engineering applications such as aerospace, automobile, electronics and other industries. The main objective of this study is to optimize the process parameters with multiple machinability characteristics. The performance characteristics considered were surface roughness (R_a), Cutting force (F_z) and cutting power (P). Optimal combination of process parameters can then be determined by Taguchi method using the grey relational grade as performance index. The process parameters considered were cutting speed, feed, depth of cut and fiber orientation angle (work piece). Experiments are planned according to Taguchi's L_{25} orthogonal array in the design of experiments and were carried out on an all geared lathe using carbide (K20) cutting tool insert. The experimental results reveal that the feed is the most significant process parameter on the multiple machinability characteristics, this proposed method can be effectively used to improve the machining characteristics of GFRP composites.

Introduction

In recent years, fiber reinforced plastics (FRPs) are continuously replacing the traditional engineering materials because of their superior advantage over other engineering materials. The advantages include high strength to weight ratio, high fracture toughness, and excellent corrosion and thermal resistance. The glass fiber reinforced plastic (GFRP) composites are being extensively used in various fields like Aerospace, Automobile, Chemical industries, Off shore power plants, Refinery, Oil and Gas, Pulp and paper, Waste and waste water etc,. The application filed of FRP composites, expands the opportunity of machining such as cutting off, drilling, milling, turning etc, has increased for its fabrication. However, the users of FRP have faced difficulties to machine it, because knowledge and experience acquired for conventional materials cannot be applied to such new materials, of which machinability is completely different from that of conventional materials. However the users of FRP composites are facing difficulties to machine it, because of delamination, fiber pull out, short tool life, matrix debonding, burning and formation of powder like chips. However, the weakness of composite material lies in their susceptibility to machining damage when subjected to improper machining conditions. To minimize the damage in machining, it is important to monitor process variables such as cutting speed, feed, depth of cut etc,. In most applications, traditional metal cutting machine tools and techniques are still being used to machine the FRP composites. But machining of FRP composites is different from that of conventional materials because of its inhomogeneity [1]. Most of the studies on the machining of GFRP composites have been concentrated on the mechanism of tool wear and surface roughness. However for the practical machining of GFRP composites, it is necessary to determine the optimal machining parameters to achieve high quality, which provides a preliminary basis for survival in today's dynamic market conditions. Previously, the Taguchi method was used to analyze the optimal process parameters of a single quality characteristic [2]. The Taguchi method primarily uses engineering judgment to decide optimal factor levels for multi-responses, which increases uncerataniy during the decision making process [3]. This problem was solved by the grey system theory introduced by Deng [4]. Chen et al [5] have proposed the integration of grey relational analysis and the Taguchi method to solve multiple quality characteristics. This method transforms multiple quality characteristics into single grey relational grade. By comparing the computed grey relational grades the array of optimal set of process parameters are determined Lin [6] has proposed the use of grey relational grade to the machining parameter optimization of the EDM process. Hossein Hasani et.al [7] have applied the grey relational analysis to determine the optimum process parameters for open-end spinning yarn, from the experimental results they concluded that rotor speed has [the most significant effect on the multiple performance characteristics. Lin and Lin [8] used orthogonal array along with grey relational analysis for optimization of EDM process with multiple characteristics such as material removal rate, surface roughness and electrode wear ratio. The machining parameters taken up for the experimental work were work piece polarity, pulse on time, duty factor, open discharge voltage, discharge current and dielectric fluid. Wang [9] has developed a novel procedure for optimizing dynamic multi responses using the combination of principle component analysis and grey relational analysis. PCA determines the correlation among the multiple quality characteristics for uncorrelated components and those are applied to multiple criteria evaluation of the grey relational model. Chou [10] proposed a grey fuzzy control scheme for controlling the turning process to achieve a constant cutting force under different conditions. Grey fuzzy controller contains grey predictor and

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fuzzy logic controller. They applied Taguchi-genetic methodology to grey predictor as well as fuzzy controller for searching the optimal cutting parameters. Pawade and Joshi [11] in their new effective approach, Taguchi and grey relational analysis were used. Their experimental work was to optimize the high speed turning of Inconel 718 with multiple performance measures such as cutting force and surface roughness. Chen et al. [12] have attempted to determine optimal parameters in CO2 laser cutting of 6 mm thick poly methyl methacrylate (PMMA) using grey relational analysis method. The input laser parameters taken up for this study were gas flow rate, pulse repetition frequency, cutting speed and focus position and the response parameters were optical transmittance ratio and work piece surface roughness. The parameters that had higher influence are assisted gas flow rate and beam focus depth.

The objective of this investigation is to find the significant parameters affecting the machining performances by integrating the Grey relational analysis and statistical method. And also, to determine the optimal combination of process parameters to minimize the surface roughness (R_a), Cutting force (F_z) and Cutting power in turning of GFRP composite tubes of different fiber orientation angles range from 30^o to 90^o in steps of 15^o.

Materials, Experimental set-up and Measurements

The Composite tubes of different fiber orientation angles (30^o~ 90^o) used in this investigation were produced by the filament winding process, whose outer diameter is 60mm and inner diameter 30mm and length 500mm. Filament winding is an effective process to manufacture composite tubes and this process gives very high directional strength and precise alignment of fibers. The photo graphs of the GFRP tubes are shown in Figure 1. The experiments were planned using Taguchi's orthogonal array in the design of experiments. The experiments were conducted according to L_{25} orthogonal array on an all geared lathe with Carbide (K20) 120408 sandvick make cutting tool insert. The ISO specifications of the tool holder used for the turning operation is a WIDAX tool holder PC LNR 2020 K12. The independently controlled process parameters considered in this investigation were cutting speed, feed, depth of cut and fiber orientation angle. The considered factors are multilevel variables and their outcome effects are not linearly related, so it is decided to use five levels for each factor. The material specifications and process parameters and their levels are given in Table 1-2. The output responses considered in this investigation were surface roughness (R_a), cutting force (F_z), and cutting power (P). In machining, the cutting force is measured by using KISTLER quarts 3-component dynamometer. The dynamometer is calibrated for the cutting force in the range from 0 to 1000N. To get the accuracy in machining the cutting force (F_z) is measured for three times and the average cutting force has been taken for the analysis.

Table 1. Material Specifications

Fiber: E-GLASS R099 1200 P556	
Manufacturer	Saint Gobain Vetrotex India ltd
R-009	Multi filament Roving
1200	Linear density Tex
P556	Sizing reference for vetrotex
Resin: Epoxy	
Manufacturer:	CIBA GEIGY
Product	ARALDITE MY 740 IN 110KG Q2.
Hardener	HT972

The average surface roughness (R_a), which is mostly used in industrial applications. The surface roughness tester (FORM TALY SURF) was used in this investigation. The cutting power (P) is the criterion for design and selection of any machine tool. Power consumption in the machining operation may be used for monitoring the tool condition. The cutting power is the product of main cutting force (F_z) and the cutting velocity (V) and is given by the equation 1.

$$\text{Cutting power (P)} = \frac{F_z * V}{60} \text{ Watts} \quad (1)$$

The photo graph of the original experimental setup is shown in Figure 2.

Figure 1. Photo graph of the GFRP Tubes

Table 2. Process parameters and their levels

Process parameters With units	Notation	Variable	Levels 1	2	3	4	5
Speed, m/min	V	x_1	40	60	95	145	225
Feed, mm/rev	f	x_2	0.048	0.096	0.143	0.191	0.238
Depth of cut, mm	d	x_3	0.25	0.5	0.75	1.0	1.25
Fiber orientation angle, deg	Φ	x_4	30	45	60	75	90

Figure: 2 Photo graph of the original Experimental setup

The objective of this investigation is to present an effective method to find the significant process parameters affecting the machining performance by integrating Grey relational analysis and statistical method. Furthermore, it is feasible to obtain the optimal setting of process parameters to obtain minimum surface roughness (R_a), minimum cutting force (F_z) and minimum cutting power (P) using Grey relational analysis.

Table 3. Experimental Runs and Responses

Exp. No.	Cutting speed (V) m/min	Feed (f) mm/rev	Depth of cut (d) mm	Fiber orientation angle (Φ)deg.	Measured Responses		Calculated Response
					Surface roughness (R_a), μm	Cutting Force (F_z), N	Cutting power (P), W
1	40	0.048	0.25	30	3.0692	356.98	237.98
2	40	0.096	0.5	45	3.4644	425.64	283.76
3	40	0.143	0.75	60	3.9152	469.33	312.88
4	40	0.191	1.0	75	4.2531	549.82	366.54
5	40	0.238	1.25	90	4.5328	625.64	417.09
6	60	0.048	0.5	60	3.4107	376.15	376.15
7	60	0.096	0.75	75	3.5924	455.68	455.68
8	60	0.143	1.0	90	3.874	475.04	475.04
9	60	0.191	1.25	30	3.7309	441.8	441.8
10	60	0.238	.25	45	4.0493	442.34	442.34
11	95	0.048	0.75	90	2.9894	418.16	662.08
12	95	0.096	1.0	30	2.5413	345.04	546.31
13	95	0.143	1.25	45	3.435	425.64	673.93
14	95	0.191	0.25	60	3.9476	411.38	651.35
15	95	0.238	0.5	75	4.1033	451.82	715.38
16	145	0.048	1.0	45	2.2689	322.51	779.4
17	145	0.096	1.25	60	2.8318	358.13	865.48
18	145	0.143	0.25	75	3.4736	402.83	973.5
19	145	0.191	0.5	90	3.5746	467.44	1129.64
20	145	0.238	0.75	30	3.0566	426.17	1029.91
21	225	0.048	1.25	75	2.64	335.18	1256.92
22	225	0.096	0.25	90	3.5843	418.16	1568.1
23	225	0.143	0.5	30	3.1469	358.72	1345.2
24	225	0.191	0.75	45	3.2861	353.64	1326.15
25	225	0.238	1.0	60	3.331	415.04	1556.4

The experimental data along with measured and calculated responses are shown in Table 3.

Grey Relational Analysis

The Grey Relational Analysis (GRA) integrated with Taguchi method represents a new approach for the optimization. The grey theory is based on the random uncertainty of small samples which developed into an evaluation technique to solve certain problems of system that are complex and having incomplete information. A system for which the relevant information is completely known is 'White' system, while a system for which the relevant information is completely unknown is a 'Black' system. If any system between these limits is a 'Grey' system having poor or limited information [13]. Grey Relational Analysis (GRA) a normalization evaluation technique is extended to solve the complicated multi-performance characterization effectively.

Data- Preprocessing

Preprocessing or grey relational generation of collected dat involves normalization by dividing the data in original series by their average [14]. In this investigation the data to be normalized are surface roughness (R_a), cutting force (F_z) and cutting power (P). If these machining responses carry different units of measurement, the grey relational analysis may leads to incorrect results, therefore they need to be brought under the same units i.e., dimensionless. It is the transformation of original sequence series to a comparable series [15]. So, the experimental values are normalized between the range 0 to 1. In this investigation for processing the machining characteristics viz., surface roughness (R_a), cutting force (F_z) and cutting power (P) Lowe-the better criterion used and is given by the equation 2.

$$x_i(K) = \frac{Max\,Y_i(K) - Y_i\,(K)}{Max\,Y_i\,(K) - Min\,Y_i\,(K)} \qquad (2)$$

Where x_i (K) is the value after the grey relational generation, *Min* Y_i (K) is the smallest value of Y_i (K) for the K_{th} response, and *Max* Y_i(K) is the largest value of Yi(K) for the K_{th} response. After the data processing it is necessary to calculate the grey relational coefficient, which is obtained by using the equation 3.

$$\xi_i = \frac{\Delta_{min} - \Delta_{max}}{\Delta_{oi}\,(K) - \zeta\,\Delta_{max}} \qquad (3)$$

Where

$\Delta_{oi}\,(k) = \|x_0\ (k) - x_i\ (k)\|$ is the difference of absolute value between x_0 (k) and x_i (k), ζ= Distinguishing coefficient (0 ~ 1), ζ= 0.5 commonly used, Δ_{min}= minimum value of the deviational sequence, Δ_{max}= maximum value of the deviational sequence. After calculating the grey relational coefficient, the grade of grey relation could be found using the following relation (4).

$$\gamma_i = \frac{1}{n}\sum_{k=1}^{n} \zeta_i\ (k) \qquad (4)$$

Where γ_i is the grey relational grade for $k_{i\ th}$ experiment, n is the number of machining responses. Base on the grey relational grade, the optimum process parameters have to be identified. Grade of grey relations shows the relationship between the sequences and the effect of comparability sequence and the reference sequence. When both the sequences are equal, then the grey relational grade will be equal to 1. The higher value of the grey relational grade means that the corresponding process parameters are closer to optimal [3]. In other words, optimization of the complicated multiple process responses is converted into optimization of a single grey relational grade.

Results and Discussions

Glass fiber reinforce polymer composite material are widely used in variety of engineering applications. In fiber reinforced composites, fibers carry bulk of the load and matrix serves as a medium to transfer the load to the fibers. In machining of FRP composites, fiber delamination, fiber fracture and fiber pull-out are the major problem. During machining, tool under goes severe wear due to abrasive phase present in the material. During the turning of GFRP composites, the cutting force developed should be kept minimum. The increase in the cutting force tends to tool wear and the wear on tool produces rough surface finish. In this investigation, lower the values of average surface roughness (R_a), cutting force (F_z) and the cutting power (P) were the desirable targets. Therefore, the data sequences have the smaller-the better characteristic. The values of average surface roughness, cutting force and cutting power are set to be reference sequence. The data processing of each performance characteristics were calculated using equation (2) and are shown in Table 4. The grey relational coefficients and grey relational grades for each performance characteristic are calculated using equation (3) and (4) and are shown in Table 5.

Table 4. Data-processing of each performance characteristic

Exp No.	Surface roughness (R_a)	Cutting Force (F_z)	Cutting power (P)
1	0.6464	0.8862	1
2	0.4719	0.6597	0.9655
3	0.2728	0.5156	0.9436
4	0.1235	0.2501	0.9033
5	0	0	0.8653
6	0.4956	0.8230	0.8961
7	0.4153	0.5606	0.8363
8	0.2910	0.4968	0.8217
9	0.3542	0.6064	0.8467
10	0.2135	0.6046	0.846
11	0.6817	0.6844	0.6811
12	0.8796	0.9256	0.7681
13	0.4849	0.6597	0.6722
14	0.2584	0.7068	0.6892
15	0.1897	0.5734	0.6410
16	1	1	0.5929
17	0.7513	0.8824	0.5282
18	0.4678	0.7350	0.4470
19	0.4232	0.5218	0.3296
20	0.6520	0.6580	0.4046
21	0.8360	0.9582	0.2339
22	0.4189	0.6844	0
23	0.6121	0.8805	0.1675
24	0.550687	0.897305	0.1819
25	0.530854	0.694751	0.0087

From the Table 5, it is inferred that experiment number 16, which is at V4 f_1 d_3 Φ_2 has the highest grey relational grade of 0.8504. Nevertheless, the relative effect and significance among the experimental factors were also calculated to determine the optimal combination of the process parameters more accurately. This was performed using response graph and statistical Analysis of Variance (ANOVA).

Statistical Analysis: In order to assess the effect of process parameters on the machinability characteristics, the response table and response graph were developed. Table 6, shows the changes in the average values of Grey relational grade at each level of process parameters selected. It proves the basis for optimal setting of the process parameter levels by choosing the highest value of the Grey relational grade.

Table 5. Grey relational coefficients and grey relational grades for each Performance characteristic

Exp No.	Surface roughness (R_a)	Cutting Force (F_z)	Cutting power (P)	Grey Relational Grade
1	0.5857	0.8145	1	0.8001
2	0.4864	0.5950	0.9354	0.6722
3	0.4074	0.5079	0.8986	0.6046
4	0.363	0.4000	0.8379	0.5337
5	0.3333	0.3333	0.7877	0.4848
6	0.4978	0.7385	0.8279	0.6881
7	0.4609	0.5322	0.7533	0.5821
8	0.4135	0.4984	0.7371	0.5497
9	0.4363	0.5595	0.7653	0.5870
10	0.3886	0.5584	0.7645	0.5705
11	0.6110	0.6130	0.6105	0.6115
12	0.8059	0.8704	0.6831	0.7865
13	0.4925	0.5950	0.6040	0.5638
14	0.4027	0.6303	0.6166	0.5499
15	0.3815	0.5396	0.5820	0.5010
16	1	1	0.5512	0.8504
17	0.6678	0.8095	0.5145	0.6639
18	0.4844	0.6535	0.4748	0.5376
19	0.4643	0.5111	0.4272	0.4675
20	0.5896	0.5938	0.4564	0.5466
21	0.7530	0.9228	0.3949	0.6902
22	0.4624	0.6130	0.3333	0.4696
23	0.5631	0.8071	0.3752	0.5818
24	0.5266	0.8296	0.3793	0.5785
25	0.5159	0.6208	0.3352	0.4906

Table. 6 Response table for GRG

Levels	V	f	d	Φ
1	**0.6191**	**0.7281**	0.5855	**0.6604**
2	0.5955	0.6349	0.5821	0.6471
3	0.6025	0.5675	0.5847	0.5994
4	0.6132	0.5433	**0.6422**	0.5689
5	0.5621	0.5184	0.5979	0.5166
Rank	4	1	3	2

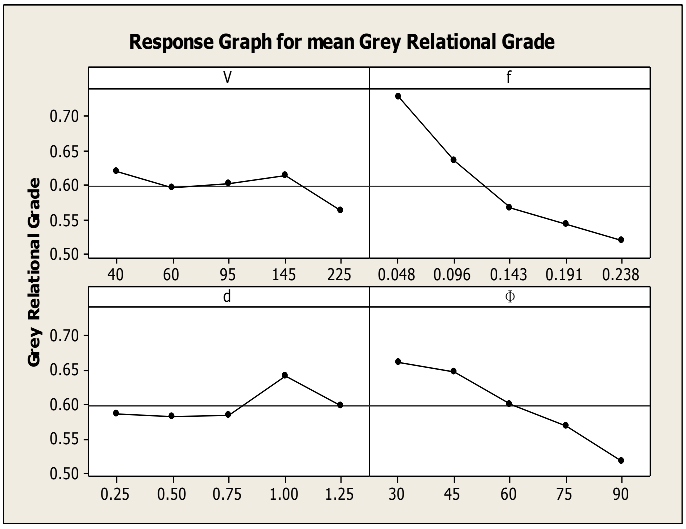

Figure 3. Response Graph for the Grey relational grade

The grater the values of grey relational grades gives the low surface roughness (R_a), low cutting force (F_z) and Low cutting power (P). With the help of response Table 6 and response Graph 3, the optimal process parameter combination has been determined as V_1, f_1, d_4 and Φ_1. The rank (Max-MinValue) showed that the feed is the most significant parameters for the multiple machinability characteristics of turning GFRP composites. This is further confirmed by performing the statistical Analysis of Variance (ANOVA).

The purpose of ANOVA is to determine which process parameter that significantly affects the machinability characteristics. This can be achieved by measuring the sum of squared deviations from the total mean of the Grey relational grade for each process parameter and their error variance. The F-test is performed to evaluate statistically the relative significant of each process parameter.

Table 7. Analysis of Variance for GRG

Factor	df	SS	MS	F	% Contr
V	4	0.0099	0.00247	1.09	3.928
f	4	0.1424	0.0356	15.67	56.37
d	4	0.0127	0.00317	1.40	5.02
Φ	4	0.0688	0.01721	7.58	27.29
Error	8	0.01817	0.00227		7.208
Total	24	0.25206			

From the Table 7, it is asserted that, the feed the most significant process parameter, which has the highest percentage of contribution 56.37% followed by fiber orientation angle, depth of cut and Cutting speed.

Conclusions

The objective of this investigation is to optimization of turning parameters with multiple machinability characteristics namely low surface roughness (R_a), low cutting force (F_z) and Low cutting power (P) using Taguchi-Grey relational analysis. The higher the grey relational grade is close to the optimal. The results of the Grey and statistical analysis have suggested that the feed is the most significant parameter that affect the multiple machining characteristics. From the response table of average grey relational grade, it is found to be largest values of GRG for the cutting speed of 40 m/min, feed rate of 0.048 mm/rev, depth of cut 1.0 mm and the Fiber orientation angle 30^0. The optimal combination of these parameters simultaneously minimizes the multiple machining characteristics Viz., Surface roughness, cutting force and cutting power. The order of the influential process parameters based on the Taguchi response table in sequence is feed rate (f), fiber orientation angle (Φ), depth of cut (d) and the cutting speed (V).

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