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Multi-objective Optimisation of Machining Fibre Reinforced Composites

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Abstract: Since the inception of their wide use in the 1960s, advanced composite materials such as Fibre Reinforced Polymer (FRP) composites have seen an exponential growth in application for various engineering fields. FRP composites are normally produced near to net-shape, yet they are often subjected to final machining processes in order to meet the required geometric features and dimensional accuracies. Hence, this paper describes the use of Taguchi orthogonal array coupled with the Grey relational analysis to facilitate the optimisation of multiple machinability characteristics during end milling of Glass Fibre Reinforced Polymer (GFRP) composites. Based on the results of Taguchi experiments, the Grey relational grade was determined from the Grey analysis to solve the multiple machinability characteristics of tool life, machining forces and surface roughness. The results suggested that feed rate have the most significant influence on the multiple machinability characteristics. Confirmation test revealed that the Taguchi-Grey analysis can be effectively used to determine the multiple machinability characteristics and consequently improve the end milling of GFRP composites.

Key words: GFRP composites, machining, end milling, Taguchi method, multi-objective optimisation, Grey analysis

INTRODUCTION

Composite materials such as Fibre Reinforced Polymer Composites (FRPs) have been used in diverse engineering applications which include automotive, aerospace as well as in the marine industries. Several distinct and appealing properties of the FRPs, such as high specific strength, fracture toughness, light weight, excellent corrosion and thermal resistance, make these composites desirable for the aforesaid applications. With the widespread usage of FRPs, machining of them into the required net-shape and to meet the desired dimensional precisions has become essential. Furthermore, in conjunction with advances in the design techniques, intricately shaped composite products or components can only inevitably be attained through machining processes.

FRPs such as glass fibre reinforced composites constitutes of fibre reinforcements, are in-homogeneously bonded with the polymer matrix. Hence, achieving the required machining surface quality becomes a challenge with such material composition. This is due to the fact that during machining the fibres take a proportion of the load to promote a series of fibre fractures and matrix material failures (Bhattacharrya *et al*., 1993). These phenomena would results into irregular or rough machining surface. Another major concern while machining of FRPs is the deterioration of tool sharpness due to abrasive actions of the fibres reinforcements. Hence, this renders poor machinability of the material due to the increase of machining/tool forces and deterioration of surface finishes.

Consequently, a number of scientific studies on FRPs machining, have progressed since initiated in the late 1970s by Everstine and Rogers (1971). Indeed, a considerable number of empirical and analytical studies have recently contributed toward the scientific findings on FRPs machining, some of which are discussed hereafter. Palanikumar *et al*. (2006a-c, 2008), for instance, have reported a number of experimental investigations in optimizing the machining parameters for minimum surface roughness during turning operation of GFRP composites. In their studies, feed rate was found to be the dominant factor in influencing the machinability performance.

Meanwhile, in view of FRPs being a poor conductor, Bhattacharrya *et al*. (1993) have shown a significant tool life during turning of Kevlar composites. This was achieved by reducing the cutting zone temperature through application of liquid nitrogen. According to the authors, the magnitude of tool wear was substantially low and may not indicate any failures. Hence, suggestion was made that the surface roughness might become the governing criteria to indicate the rejection of cutting tool during turning of Kevlar composites under cryogenic conditions. As a matter of fact, the electron microscopic studies of machined surface have conspicuously revealed the deterioration of surface roughness with increasing number of long exposed fibres protruding from the machined surface (Bhattacharrya *et al*., 1993).

Of all machining processes for FRPs, little work other than that presented herein has reported on comprehensive study on milling this composite material. Earliest study was reported by Hocheng *et al*. (1993) and Hocheng and Puw (1993), in which they investigated the machinability of uni-directional carbon fibre reinforced composites using single square carbide insert. Later on, Davim *et al*. (2004) and Davim and Reis (2005) performed the milling of woven type Glass Fibre Reinforced Plastic (GFRP) composites using carbide tool in milling operation. The authors asserted that feed rate was the dominant factor to affect the surface roughness, delamination damage and dimensional precision. In a recent study, Azmi *et al*. (2012) confirmed this result through end milling tests of uni-directional GFRP composites using Taguchi Design of Experiment with three different machining parameters which are spindle speed, feed rate and depth of cut.

Summarizing on the available literature on milling of FRPs, one would also find very limited studies on multiple optimisation of surface finishes, machining forces and most importantly tool life. Hence, it is imperative to determine the global optimal milling parameters in order to achieve maximisation of tool life while minimising surface roughness and machining forces for the practical machining of GFRP composites. In this study, optimisation of machining parameters during end milling GFRP have been performed using Taguchi experimental design coupled with Grey relational analysis. The results reported in this paper indicate that the multi objective optimisation of machinability characteristics during end milling of GFRP composites has been significantly improved.

MATERIALS AND METHODS

In the present work, a series of machining tests were carried out on a Centroid 1050A vertical milling machine (8000 RPM maximum spindle speed and 28 kW power) to investigate the machinability of GFRP composites during end milling. It is to note here that machining experiments were performed under dry cutting conditions. Meanwhile, the work materials, having the size of 210×135×6±0.5 mm, were made of glass fibre reinforced epoxy matrix. In this experiment, the end milling cutter chosen was the four flutes uncoated tungsten carbide (WC) with 12 mm diameter, 30° helix angle, 9° primary relief angle, 25 mm flute length and 75 mm overall length. Details of workpiece fabrication, data acquisition equipment, Taguchi experimental matrix and Grey relational analysis are subsequently discussed as follow.

Workpiece fabrication: The composite materials for the end milling experiments were fabricated using 16 layers of uni-directional E-Glass fibres as the reinforcement while epoxy resins as the matrix material. The fibreglass-epoxy laminates were fabricated using the vacuum assisted resin transfer/infusion moulding (VARTM). This process gives better advantages than the traditional wet hand lay-up in term of the final quality of the laminates produced (higher volume fraction and reduced voids) as well as having a safer and cleaner fabrication environment. During the fabrication, the E-Glass fibre mats (EU450-1270, supplied by High Modulus (NZ) were initially cut into the size of 300×300 mm and then laid-up on a glass mould for fabrication. Prior to infusion, the epoxy resins (R300) and hardener (R310) supplied by Nuplex FGI were prepared at a mixed ratio of 4:1. Those infused panels were then cut into required dimensions using water-cooled diamond saw cutter. Figure 1 illustrates the resin infusion process during composite laminate fabrication.

Force data acquisition: The machining forces in the X direction (feed), Y direction (cutting) and Z direction (thrust) generated during machining were acquired using a 3 axis Kistler® piezoelectric dynamometer (Model: 9265B), Fig. 2. Force signals from dynamometer were fed into Kistler® charge amplifier (Model: 5001), in which they were digitised and sampled at an appropriate rate using PC with LabVIEW software. Prior to machining experiments, the dynamometer was calibrated with quasi-static loading on the Instron machine to ensure data accuracy. The GFRP composites laminate was fixed on top of the dynamometer using cap screws, as depicted in Fig. 2, as to alleviate any effect of displacement or vibrations.

Surface roughness measurement: The commonly used Centre Line Average, R_a was employed for the surface roughness measurement using the Taylor Hobson Surtronic-3 (with setting of 5 mm traverse length and 0.8 mm cut-off value). The measurements were made along the feed direction of the milled surface using a 'diamond stylus variable reluctance type' pick-up of 5 μm radius. The reported R_a value is the average of five measurements for each machining conditions which were repeated three times.

Tool wear measurement and tool life criteria: Tool wear measurement in machining experiment is crucial so that

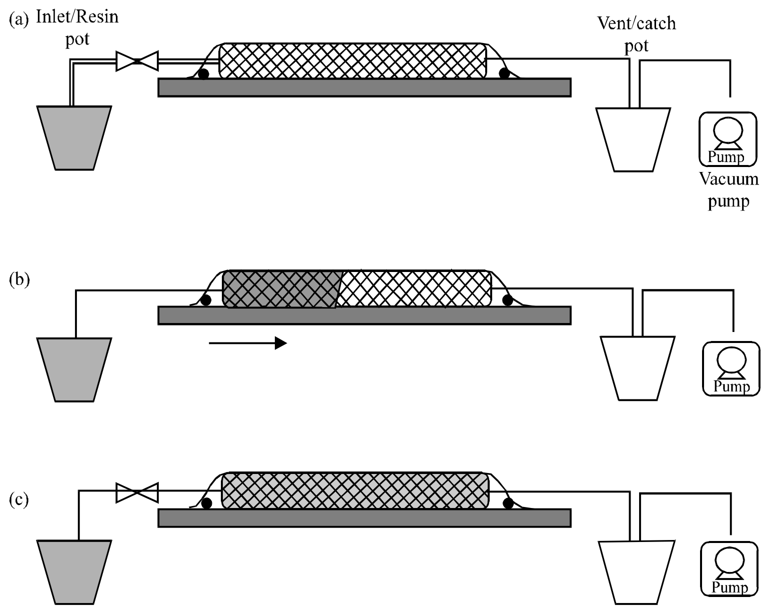

Fig. 1: Composite fabrication, (a) Pre-filling stage, (b) Filling stage and (c) Post filling stage using resin infusion

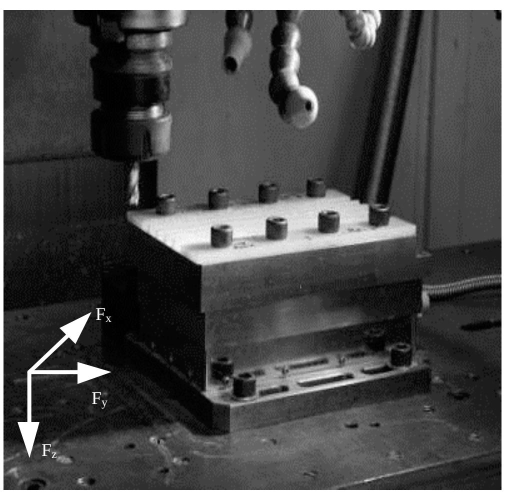

Fig. 2: Kistler dynamometer for force data acquisition

accurate timing of tool replacement or tool re-sharpened can be performed. In this study, the length of flank wear land on the side/peripheral cutting edges of the end mill tool were measured under the optical stereo microscope (Model: Leica MZ16) which was equipped with a digital camera. The microscope was set at 115×magnification in order to capture images of the wear land on the cutting tool. Wear measurement was undertaken at predetermined intervals during the end milling tests. Figure 3 displays the schematic diagram for tool wear measurement on the flank face of the end mill tool. Tool wear criteria for this experiment were based on either:

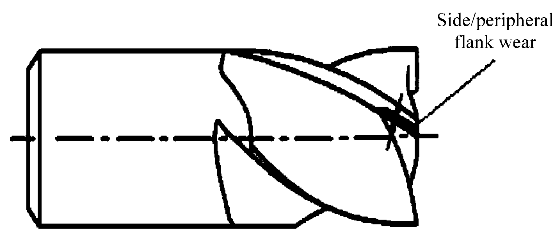

Fig. 3: Flank wear measurement on cutting tool

- Uniform maximum flank wear of 0.2 mm on any of the tooth, or
- An overall wear of 0.3 mm (average on all four tooth), or
- Excessive edge and nose deformation/ rounding on more than 2 cutting tooth

Consequently, the total machining time was recorded as the useful cutting Tool Life (TL), for subsequent machinability assessment and analysis.

Taguchi experimental matrix: The experiments for this work were planned according to Taguchi design of Experiment, in which a special design of orthogonal array was arranged in order to study the entire experimental factors with a minimum number of experiments. In Taguchi's orthogonal array, each combination of factors will have a balance, which means that, within a column of an array; each factor will have an equal number of levels or will appear in a same number of times (Park, 1996).

Table 1: Taguchi L_9 experimental layout

	Machining factor and level		
Experiment No.	A	B	C
1	1	1	1
2	1	2	2
3	1	3	3
4	2	1	3
5	2	2	1
6	2	3	2
7	3	1	2
8	3	2	3
9	3	3	1

For the current set of experiments, three end milling parameters have been chosen namely, the feed rate (A), spindle speed (B) and depth of cut (C). Each of the factors was set at three levels, which count into two-degree of freedoms. Based on the degree of freedom for each factor, the L_9 orthogonal array was chosen. The experimental parameters and their levels are arranged according to this array for this current study (Table 1).

Meanwhile, the basis of Taguchi analysis is to determine the optimum level of each experimental factor and the relative significance of those factors on the targeted experimental response. This can be achieved by using the concept of signal to noise (S/N) ratio and the statistical Analysis of Variance (ANOVA). With respect to the S/N ratio, Taguchi has classifies S/N ratio into three categories or objectives such as "the smaller the better", "the larger the better" and "nominal the best" types (Park, 1996). The optimum level for a factor is the level that results in the highest value of S/N ratio in the experimental region.

Grey relational analysis: The use of S/N ratio is often complicated when each targeted experimental responses have different S/N ratio objectives. One experimental response may correspond to "the higher the better" S/N ratio while the other may lead to "the lower the better" S/N ratio. In this case, there is a need to re-evaluate the multiple performance characteristics into a single performance characteristic. This can be achieved by employing the Grey relational analysis. In this analysis the different dimension system for each experimental response is converted into non-dimensional Grey relational grade of 0-1 for the re-evaluation.

The Grey relational analysis theory was initialised by Deng which makes use of quantitative analysis to handle uncertainty in experimental results through grey system (Deng, 1989). Followings are the summarized steps in the Grey relational analysis for multiple performance optimizations, while the details can be found (Tsao, 2009; Lin, 2004; Hsiao *et al*., 2007; Murugesan and Balamurugan, 2012; Kumar and Balachandar, 2012):

- Linear normalisation of the experimental results between the values of 0 to 1 (data preprocessing) due to different measurement units of the results. It is based on the following expressions:

$$\chi_{ij} = \frac{y_{ij} - \min_i y_{ij}}{\max_i y_{ij} - \min_i y_{ij}} \quad (1)$$

For "the lower the better" or:

$$\chi_{ij} = \frac{\max_i y_{ij} - y_{ij}}{\max_i y_{ij} - \min_i y_{ij}} \quad (2)$$

For "the higher the better".

Where, χ_{ij} is the normalised value, y_{ij} is the ith experimental results in the jth experiment:

- Calculating the Grey relational coefficient to express the relationship between the ideal and actual normalized experimental results. The grey relational coefficient can be calculated as shown in Eq. 3:

$$\xi_{ij} = \frac{\min_i \min_j \left|x_i^o - x_{ij}\right| + \zeta \max_i \max_j \left|x_i^o - x_{ij}\right|}{\left|x_i^o - x_{ij}\right| + \zeta \max_i \max_j \left|x_i^o - x_{ij}\right|} \quad (3)$$

where, x^o_i is the ideal normalized result for the ith performance characteristics. ζ is the distinguishing coefficient which is set between 0 and 1:

- Calculating the Grey relational grade by averaging the Grey relational coefficients
- Selection of optimal levels for the process parameters using statistical methods
- Verifying the optimal parameters through the confirmation experiment

RESULTS AND DISCUSSION

Results of experiments: The results of targeted experimental responses, which include machining forces, surface roughness and tool life, are displayed in Table 2. All measurement for these experimental responses was performed using the equipment discussed earlier. It is to note that the average values of each measurement were taken for the subsequent Taguchi and Grey analyses. As apparent, experiment number 1 gives the lowest value of machining force, F_m, whereas, experiment number 8 resulted in the highest machining force of 90.87 N. In contrast, the minimum surface roughness R_a value of 1.80 μm has been observed under

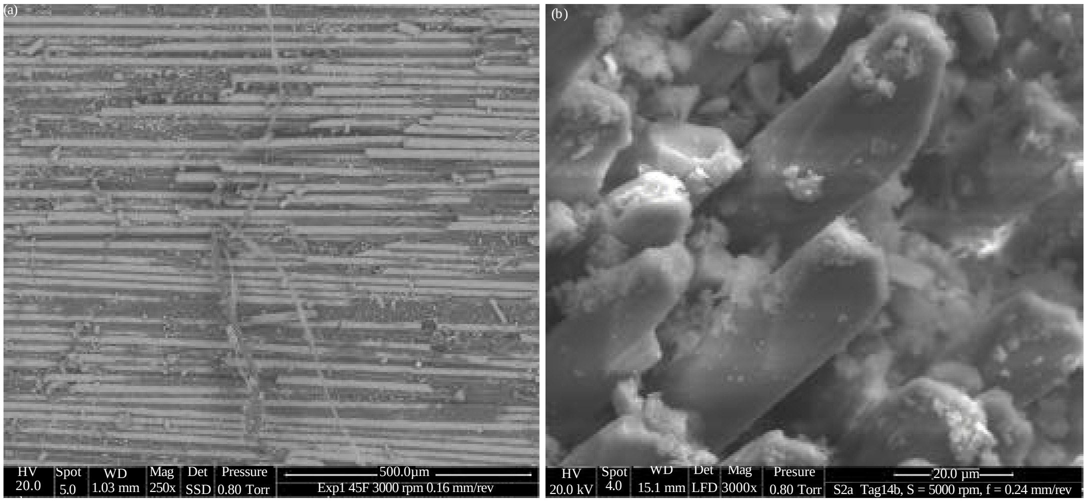

Fig. 4(a-b): Evidence of interfacial and brittle fractures of, (a) fibres and (b) epoxy matrix after cutting

Table 2: Experimental results from Taguchi experiment for machining forces (F_m), surface roughness (R_a) and tool life (TL)

	Experimental results		
Experiment No.	F_m (N)	R_a (µm)	TL (sec)
1	20.68	2.12	940
2	30.52	2.09	701
3	38.16	1.80	642
4	66.70	2.69	576
5	29.35	2.19	443
6	44.07	2.39	313
7	66.41	2.58	272
8	90.87	2.42	140
9	42.88	2.41	188

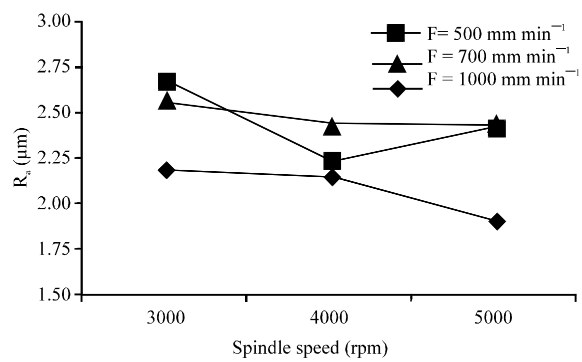

Fig. 5: Effect of changing spindle speed and feed rate (F) on surface roughness (R_a)

the experimental combination of lowest feed rate, highest spindle speed and highest depth of cut. On the other hand, longest tool life of 940 sec can be achieved under the first experimental combinations.

It is well known that cutting mechanisms of GFRP composites are mainly characterised by buckling, bending failures, brittle and interfacial fractures of fibre reinforcement and epoxy matrix (Bhattacharrya *et al*., 1993; Palanikumar *et al*., 2006a; Hocheng *et al*., 1993). These mechanisms are clearly depicted in the Scanning Electron Microscopic (SEM) images (Fig. 4). The process is further augmented with elevated machining conditions.

Individual experimental results showed that the surface quality is largely influenced by feed rate (Fig. 5). In fact, similar to that of metal machining, the magnitude of surface roughness, R_a deteriorates with the increase of feed rate. On the other hand, it is evident from Fig. 5 that the increase in spindle speed exhibits a marginal improvement on surface roughness.

These findings are consistent with the results of Davim *et al*. (2004) and Davim and Reis (2005) during milling of fibre reinforced composites. As highlighted in Azmi *et al*. (2012), feed rate influences the mechanisms of chip formation, which will largely determine the value of R_a. In addition, deterioration in surface roughness at higher feed rate is attributed to the increase strain rate on the composite material which promotes excessive fractures on glass fibres and epoxy matrix (Azmi *et al*., 2012).

As far as the machining forces are concerned, the value of the resultant force, F_m was determined based on the following equation:

$$F_m = \sqrt{F_x^2 + F_y^2 + F_z^2} \quad (4)$$

where, F_m is the resultant force, F_x is the feed force (x direction), F_y is the cutting force (y direction) and F_z is thrust force (z direction) respectively (Fig. 2).

The results showed that combinations of feed rate and depth of cut accounted for the increase of resultant

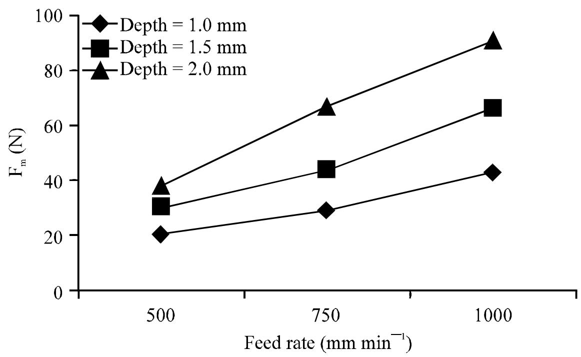

Fig. 6: Effect of changing feed rate and depth on cut on resultant force (F_m)

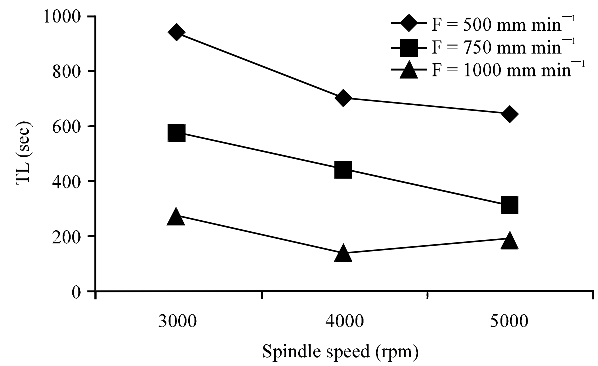

Fig. 7: Effect of changing feed rate (F) and spindle speed on tool life (TL)

machining force magnitude, F_m (Fig. 6). This is attributed by the fact that feed rate and depth of cut governed the undeformed chip thickness during the cutting process. In contrary to this study, Davim *et al.* (2004) reported that only feed rate has significant influence on the magnitude of machining force during end milling of FRPs. It is to vital to highlight that the increase in cutting speed during machining accelerates the brittle fracture of polymer matrix, hence, requiring less force to shear the material. This explains the fact that the effect of spindle speed is trivial as found in the current study.

Finally, it is evident that combination of spindle speed and feed rate play the pivotal role to determine the useful life of cutting tool during end milling GFRP (Fig. 7). This result is expected as it can be explained by the theory of metal cutting. From the result, depth of cut displays marginal effect on the tool wear or life. Nevertheless, the increase in depth of cut allows more direct contact of fibre reinforcement on the tool flank face to accelerate the abrasive wear.

It is imperative to highlight here that, due to contradictory effects of each machinability output, globally optimised situation for enhancement of end milling GFRP composites would be difficult using the traditional Taguchi analysis. Hence, this paper proposed the Grey relational analysis as a solution for the optimum setting of experimental combinations of the multiple objectives or response of GFRP machinability investigated in this study. Details of the Grey relational analysis and the results are discussed in the following section.

Results of grey relational analysis: Results of data pre-processing and Grey relational grade from the Grey analysis explained earlier are shown in Table 3. The highest value of the Grey relational grade is preferred for optimum condition as it corresponds closer to ideally normalized or optimized value.

Table 3: Results of Grey relational analyses for machining forces (F_m), surface roughness (R_a) and tool life (TL)

	Data pre-processing			Grey relational	
Experiment No.	F_m (N)	R_a (μm)	TL (sec)	Grade	Rank
Ideal sequence	1.000	1.000	1.000	-	-
1	1.000	0.505	1.000	0.834	1
2	0.860	0.902	0.701	0.748	2
3	0.751	1.000	0.627	0.747	3
4	0.344	0.558	0.544	0.496	7
5	0.876	0.660	0.378	0.614	4
6	0.667	0.726	0.216	0.545	5
7	0.348	0.000	0.165	0.381	8
8	0.000	0.256	0.000	0.356	9
9	0.684	0.579	0.060	0.501	6

Table 4: Response table for the Grey relational grade

	Grey relational grade			
Factor	Level 1	Level 2	Level 3	Max-Min
A	0.759	0.499	0.404	0.355
B	0.560	0.542	0.560	0.018
C	0.638	0.512	0.513	0.126

From this Table 3, it is apparent that experiment number 1, which is at $A_1B_1C_1$, has the highest Grey relational grade of 0.834. Nevertheless, the relative effect and significance among the experimental factors were also calculated to determine the optimal combinations of the factors more accurately. This was performed using response graph and statistical Analysis of Variance (ANOVA).

Statistical analyses: In order to understand the effect of experimental factors on the machinability characteristics, response table and response graph were developed. Table 4, illustrate the changes in the average values of Grey relational grade due to the experimental factors. It provides the basis for optimal setting of the experimental factors level by choosing the highest value of the Grey relational grade for each factor.

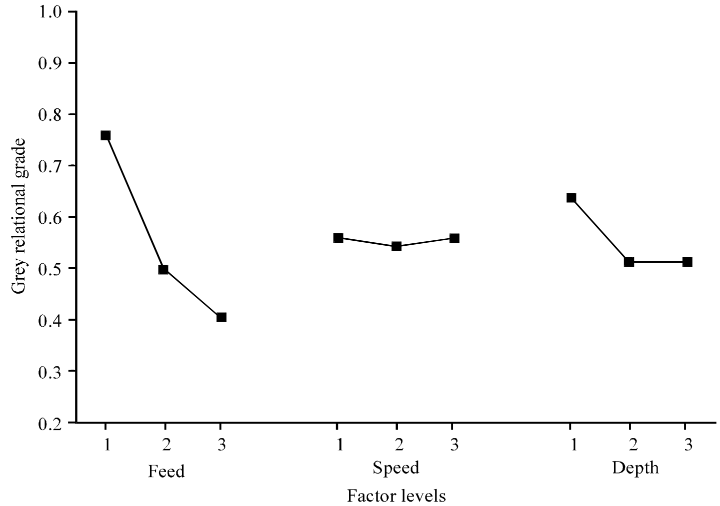

Fig. 8: Response graph for the Grey relational grade

On the other hand, the average of these Grey relational grades is also illustrated in term of response graph (Fig. 8). From these results, it can be concluded that the optimal setting to achieve highest Grey relational grade for this experiment is when feed rate, spindle speed and depth of cut are set at $F_1S_3D_1$. The Max-Min values showed that the feed rate is the most significant factor for the multiple machinability characteristics of end milling GFRP composites. This is further confirmed by performing the statistical Analysis of Variance (ANOVA).

The purpose of ANOVA is to determine which machining parameters that significantly affect 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 machining parameters and their respective error variance. The f-test, is performed to statistically evaluate the relative significant of each machining factor, in which feed rate was found to be the most significant factor for this experiment (Table 5).

Table 5, the f-value for this factor is 67.73, which is higher than the corresponding F-ratio value of 6.94 ($F_{0.05, 2,4}$) from the Fisher Table. In term of percentage of contribution of each factor, feed rate has the highest value which is at 84.39%, followed by depth of cut, 13.12%. The changing of spindle speed has the least effect on the Grey relational grade, which has been confirmed through the ANOVA results. It is considered as insignificant factor as it failed the test of significance at 95% confidence level.

Confirmation test: Once the optimal level of the end milling parameters has been identified, the next step is to confirm and verify the improvement that can be achieved from the Grey relational analysis. The confirmation test was performed at the optimum condition determined from the Grey analysis. On the other hand, the predicted values for all machinability characteristics at the optimum condition were obtained from the following equation:

$$\hat{\alpha} = \alpha_m + \sum_{i=1}^{q} (\alpha_i - \alpha_m) \quad (5)$$

where, α_m is the total mean and α_i is the mean at optimal level of each machinability characteristics, respectively, while q is the number of the machining parameters. Table 6 shows the results of this confirmation experiment and predicted values under optimal cutting parameters in comparison to the initial cutting factor.

Table 5: Analysis of variance of Grey relational grade

Factor	df	SS	MS	F-test	$F_{ratio(2,4)}$	Contr (%)
A	2	0.2025	0.1013	67.73	6.94	84.39
B	(2)	0.0006	(Pooled)			
C	2	0.0315	0.0157	10.53	6.94	13.12
Error	4	0.0060	0.0015			2.49
Total	8	0.2400				100.00

Table 6: Result of the confirmation experiment for each machinability characteristics and the Grey relational grade

		Optimal conditions	
	Initial	Prediction	Experiment
Level	F1S2D2	F1S3D1	F1S3D1
F_m (N)	30.52	23.75	24.16
R_a (μm)	2.09	2.52	2.42
TL (sec)	701	729	874
Grey relational grade	0.676	0.845	0.865

Improvement grey relational grade = (Between initial cutting and exp.) = 0.189

As depicted, resultant force is reduced from 30.52-24.16 N, surface roughness is increased from 2.09-2.42 μm and tool life is increased from 701-874 sec. Moreover, the Grey relational grade is also improved from 0.676-0.855. Thus, through this study, it is clearly shown that the multiple machinability characteristics during end milling of GFRP composites were further improved through Grey relational analysis.

CONCLUSIONS

This study has presented the experimental investigation of end milling GFRP composites using Taguchi-Grey analysis. The objective is to solve the optimisation of end milling parameters with multiple machinability characteristics namely low machining forces and surface roughness as well as longer tool life. The results of Grey and statistical analyses suggested that feed rate is the governing factor that affects the multiple machinability characteristics. It has been found that the optimal combination of the machining parameters is when feed rate at level 1, spindle speed at level 3 and depth of cut at level 1 ($A_1B_3C_1$). Optimisation of these parameters have simultaneously considered the minimisation of surface roughness and machining forces while maximizing the tool useful life. Confirmation test also shown that the machining forces, surface roughness and tool life were significantly improved using the Taguchi method coupled with the Grey analysis.

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