Experimental Investigation and Optimization of Milling Parameters in the Machining of Carbon Fiber Reinforced Polymer Composite Material using PCD Tool

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Abstract

Due to superior mechanical properties with lower weight compared to metals, there is an extended use of Carbon Fiber Reinforced Polymer (CFRP) and hence requires efficient machining solutions. For high quality surface roughness and to remove excess material, milling is one of the most practical machining techniques. Optimization of end milling parameters with multiple performance characteristics is done by a combination of Grey Relational Analysis and Taguchi design with L18 orthogonal array. Milling operation is performed on a vertical milling machine. The four input parameters considered for this investigation are milling strategy, feed rate, spindle speed and depth of cut. Machining force and delamination factor are selected as output performance parameters. It is observed that the largest value of GRG is for up milling, spindle speed of 1000rpm; feed rate of 70mm/min and depth of cut 0.2mm. Depth of cut and feed rate are found to the two most dominating factors
Keywords: Carbon Fiber Reinforced Polymer (CFRP), Milling, Optimization, Grey Relational Analysis, Taguchi Design, Machining Force, Delamination, Feed Rate, Depth Of Cut

I. INTRODUCTION

There is high utilization of Carbon fiber reinforced polymer (CFRP) due to its properties such as very high strength-to-weight ratio, fatigue resistance and excellent damage tolerance in the fields of construction, aerospace, automobiles & robotics. Challenges with machining CFRP material is that the various layers of the structure can cause delamination, splintering and fraying. The performance of milling is determined by surface quality which plays a vital role. Superior surface quality can result in improved fatigue strength, corrosion resistance and creep life. Milling is done when highly accurate and quality finished products are required. The parameters which influence the machining are cutting speed, spindle speed, depth of cut and feed rate.

The machinability is mainly influenced by the mechanical properties of the CFRP which is determined by the type of fiber, the matrix material, the fiber volume content, the fiber orientation and the manufacturing process. Due to the inhomogeneous and anisotropic material properties machining of CFRP comes along with certain difficulties like fiber pull-out, delamination and decomposition of matrix material which leads to a degradation of the surface quality and the material properties (Pecat, Rentsch & Brinksmeier, 2012). Various modes of fiber breakage in different tool-work configurations determine the magnitude of the cutting force required. Tool wear is slightly more serious when cutting parallel to the fibers, an overall assessment considering burrs, surface roughness and cutting force indicates that 0” cutting, i.e., cutting parallel to the fiber axis, is recommended for milling of unidirectional fiber-reinforced plastics (Hocheng, Puw & Huang, 1993). The need to optimize the cutting parameters is increasing as the demand for specific surface roughness increases. Surface roughness has a greater influence on performance of mechanical pieces, dimensional precision, production cost and to achieve the desired surface finish there is necessity to understand the kinetics of machining processes which affect the performance of cutting tools and material removal mechanism (Paulo Davim & Pedro Reis, 2005). Fiber orientation is an important factor which decides the surface finish of machined products. The surface finish obtained is smooth when milling operation is done in 0degree to +45degree to the fiber orientation. The resultant forces measured while machining of CFRPs with different fiber orientation suggest that the cutting mechanism is different for each fiber orientation (Pecat, Rentsch & Brinksmeier, 2012). Feed rate is the cutting parameter that present the highest statistical and physical influence on surface roughness (94.1 and 77.5%), and on delamination factor (83.9 and 85.9%), for both end mills, respectively (Paulo Davim & Pedro Reis, 2005). Presented results confirmed feed rate as a factor with strongest influence on the normal cutting force, in a way that increasing in feed rate results in increasing of cutting force and deterioration of profile accuracy. The cutting speed has no much effect on the normal cutting force. From the machining results, it can be asserted that medium cutting speed and low feed are the optimal cutting conditions for robotic trimming of CFRP laminate (Slamani, Gauthier & Chatelain, 2014).

II. EXPERIMENTAL PROCEDURE

A. Work Material and Cutting Tool:

The work material shown in Figure 1 selected for this experiment is 3K Bi-directional carbon Fibre/Epoxy composite. The epoxy-carbon fibre reinforcement is of woven fabric form, having following specifications. Type of weave: plain, weight: 200 gm/m2 and of 0.2 mm thickness. The resin used is Resin Araldite® LY 556 (Viscosity at 25 °C (ISO 9371B) 10000 - 12000 [Mpa-s] and Density at 25 °C (ISO 1675)1.15 - 1.20 [g/cm3]) and hardener HY 951 added 10% by weight. The work specimens are rectangular in shape, 150 mm long, 50 mm width and 5 mm thickness consisting of 22 layers of fabric hot pressed together. It has good dimensional stability and very good mechanical properties (Table 1)

Tool wear was an important factor while choosing the cutting tool for milling operation as it would give a better surface finish and also have a longer tool life. Polycrystalline diamond (PCD) tools are most suited for machining of fibre reinforced composites. The cutting tool used is polycrystalline diamond (PCD) end mill and is shown in Figure 2 below with two flutes and 10mm diameter.

Fig. 1: Work Piece

Table – 1
Material Properties

Key characteristics of 3K Bi-Directional Carbon Fiber	
Density	*1.8g/cc*
Filament Diameter	*7 μm*
Tensile strength	*3450 Mpa*
Tensile Modulus	*230 Gpa*
Percentage Elongation *Tensile strength (Laminate)*	*1.5%* *429 Mpa* *39 Mpa*

Fig. 2: Cutting Tool

B. Plan of Experiments:

The experiments were planned using Taguchi's design of experiments (DOE). The nonlinear relationship among the process parameters, if it exists, can only be revealed if more than two levels of the parameters are considered (Byrne & Taguchi, 1987). Thus, each selected parameter is analyzed at three levels. In the present study, three factors at three levels and one factor at two levels were selected and assignment of the corresponding levels using Taguchi's L18 orthogonal array (OA) for four factors at three levels for experimentation. The orthogonal array consists of 8 columns and 18 rows. The factors are assigned to column no, 1, 2, 3 and 6 respectively. Each trial was repeated once and also the trials were carried out in random order. The selected cutting parameters and their assigned values of levels (Table 2). Each and every step of this conducted experiment is shown as a flow chart in Figure 3

Table - 2
Factor and Levels (L-1, L-2, L-3) For Milling Process

Symbol	*Cutting parameter*	*L-1*	*L-2*	*L-3*
A	*Type of milling*	*Down*	*Up*	*-*
B	*Spindle Speed (rpm)*	*800*	*1000*	*1200*
C	*Feed Rate (mm/min)*	*70*	*120*	*170*
D	*Depth of cut (mm)*	*0.2*	*0.4*	*0.6*

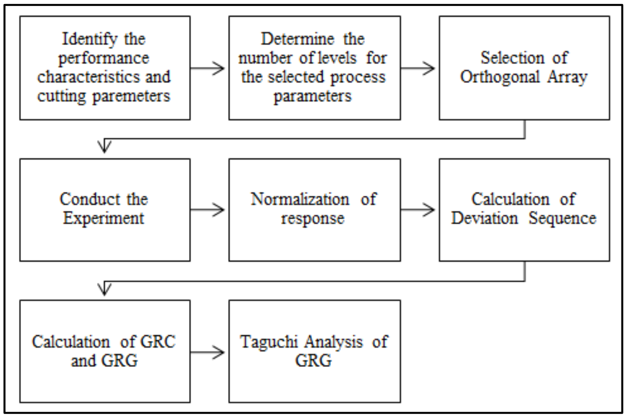

Fig. 3: Study Methodology

C. Machine Tools Setup:

The milling set up is shown in Figure 4 Vertical HAAS(USA), Model TM-2CNC machine center with the following technical specifications: Axes travel – 1016 x 406 x 406 mm(x, y, z), Spindle speed – 4000 rpm direct speed, Direct speed – Belt drive and Horse power 7.5 KW is utilized for edge milling experiments. Kistler piezoelectric dynamometer of type-5233A with built-in charge amplifier up to 10KN and a least count of 1mN.

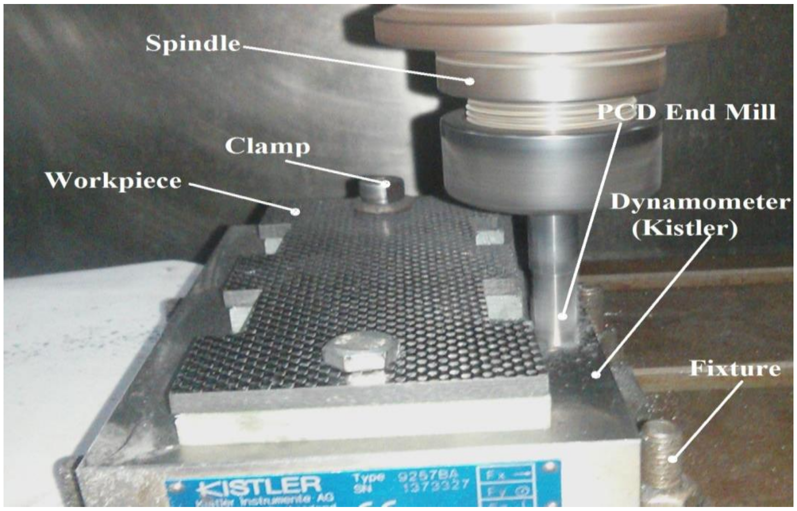

Fig. 4: Experimentation Setup

D. Data Acquisition:

Acquisition of data was accomplished using S-surf software by connecting this profiler to computer. Kistler Dynoware type-2825A software was utilized for data acquisition by connecting the dynamometer to the computer. Figure 5 shows the dynamometer control module which was used to take the reading of cutting forces. Also a sample of cutting forces graph is shown in Figure 6. The delamination measurements were done using Mitutoyo PJ-A3000 profile projector shown in Figure 7. Data acquisition was accomplished by transferring the data which was stored in the memory card to the computer. Figure 8 shows a sample delamination profile.

Fig. 5: Dynamometer Control Module

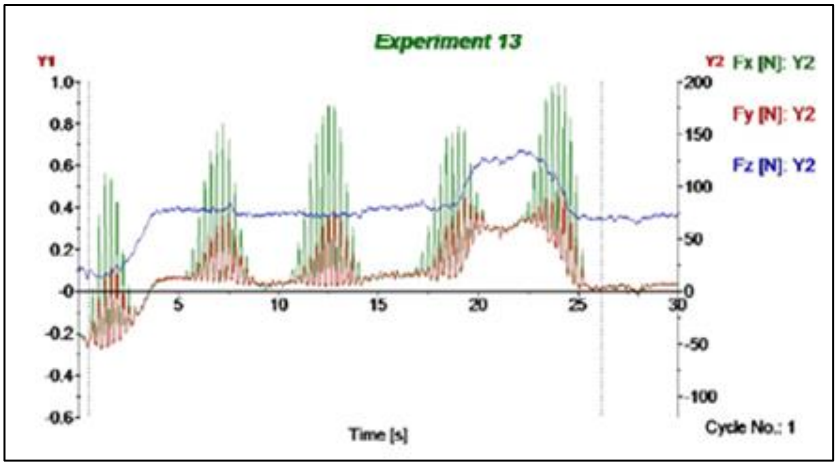

Fig. 6: Sample Graph of Cutting Forces

Fig. 7: Profile Projector Setup

Fig. 8: Sample Delamination Profile

III. GREY-TAGUCHI OPTIMISATION

In grey relational analysis, the data pre-processing is the first step performed to normalize the random grey data with different measurement units to transform them to dimensionless parameters. Thus, data pre-processing converts the original sequences to a set of comparable sequences. Different methods are employed to pre-process grey data depending upon the quality characteristics of the original data (Deng J.L. 1989).

Table - 3
Experimental Plan with Resultant Machining Force and Delamination Factor Response

Expt. No	A Milling Strategy		B Spindle Speed		C Feed Rate		D Depth of Cut		F (N)	DF
	Actual	Coded	Actual	Coded	Actual	Coded	Actual	Coded		
1	DM	1	800	1	70	1	0.2	1	260.629	1.028
2	DM	1	800	1	120	2	0.4	2	254.258	1.090
3	DM	1	800	1	170	3	0.6	3	243.741	1.031
4	DM	1	1000	2	70	1	0.4	2	241.809	1.030
5	DM	1	1000	2	120	2	0.6	3	252.171	1.046
6	DM	1	1000	2	170	3	0.2	1	221.532	1.122
7	DM	1	1200	3	70	1	0.6	3	246.545	1.030
8	DM	1	1200	3	120	2	0.2	1	216.964	1.080
9	DM	1	1200	3	170	3	0.4	2	231.624	1.103
10	UM	2	800	1	70	1	0.4	2	255.287	1.075
11	UM	2	800	1	120	2	0.6	3	271.808	1.066
12	UM	2	800	1	170	3	0.2	1	285.511	1.018
13	UM	2	1000	2	70	1	0.2	1	258.411	1.016
14	UM	2	1000	2	120	2	0.4	2	311.721	1.040
15	UM	2	1000	2	170	3	0.6	3	272.496	1.060
16	UM	2	1200	3	70	1	0.6	3	257.864	1.059
17	UM	2	1200	3	120	2	0.2	1	246.98	1.085
18	UM	2	1200	3	170	3	0.4	2	247.812	1.060

The original reference sequence and pre-processed data (comparability sequence) are represented by $x_0^{(0)}(k)$, and $x_i^o(k), i = 1,2,\ldots..m; k = 1,2,\ldots.n$ respectively, where, **m** is the number of experiments and **n** is the total number of observations of data.

If the original data has the quality characteristic as 'smaller the better', then original data is pre-processed as 'smaller the best'

$$x_i^*(k) = \frac{max x_i^o(k) - x_i^o(k)}{max x_i^o(k) - min x_i^o(k)} \qquad (1)$$

Next step is the calculation of deviation sequence, $\Delta oi(k)$from the reference sequence of pre-processes data $x_i^*(k)$and the comparability sequence $x_i^*(k)$.The grey relational coefficient is calculated from the deviation sequence using the following relation:

$$\gamma\left(x_o^*(k), x_i^*(k)\right) = \frac{\Delta min + \xi\Delta max}{\Delta oi(k) + \xi\Delta max} \qquad (2)$$

Where, $\Delta oi(k)$ is the deviation sequence of the reference sequence $x_o^*(k)$and comparability sequence $x_i^*(k)$

$$\Delta oi(k) = \left|x_o^*(k) - x_i^*(k)\right| \qquad (3)$$

ξ is the distinguishing coefficient $\xi \in [0,1]$ The distinguishing coefficient (ξ)value is chosen to be 0.5**.**

The grey relational grade $\gamma(x_o^*, x_i^*)$ represents the degree of correlation between the reference and comparability sequences. Additionally, grey relational coefficients are averaged to obtain the grey relational grade. Grey relational coefficients and grey relational grade are calculated and listed in the table 4.

Using Taguchi analysis and experimental setup he discussed methods and responses to decrease surface roughness. His paper titled "Optimization of machining parameters in turning GFRP composites using a carbide (K10) cutting tool based on the Taguchi Method with Fuzzy logics" is one of the first attempts at converting a multi-performance characteristic into a single multi-response performance index (MRPI). (Palanikumar, Karunamoorthy & Karthikeyan, 2006) in "Multiple Performance Optimization of Machining Parameters on the Machining of GFRP Composites Using Carbide (K10) Tool "using Taguchi analysis by L27 orthogonal array machining parameters like work piece fiber orientation, cutting speed, feed rate, depth of cut and machining time were optimized and results proved that machining process can be improved effectively by using this approach. Grey theory supplies solution to a problem where the data is incomplete and discrete. Hence it is effective when applied to machining which has multiple inputs and based on uncertainty. (Huang and Lin, 2002) applied the grey relational analysis to design the die-sinking electric discharge machining parameters. Fung studied the grey relational analysis to obtain the optimal parameters

Table - 4
Calculated GRC and GRG

Expt. Run	*Normalization*		*Deviation Sequence*		*Grey Relational Coefficient*		*GRG*	*Rank*
	F(N)	*DF*	*F(N)*	*DF*	*F(N)*	*DF*		
1	*0.539*	*0.884*	*0.461*	*0.116*	*0.520*	*0.812*	*0.666*	*7*
2	*0.606*	*0.299*	*0.394*	*0.701*	*0.560*	*0.416*	*0.488*	*18*
3	*0.717*	*0.861*	*0.283*	*0.139*	*0.639*	*0.782*	*0.711*	*4*
4	*0.738*	*0.869*	*0.262*	*0.131*	*0.656*	*0.792*	*0.724*	*3*
5	*0.629*	*0.721*	*0.371*	*0.279*	*0.574*	*0.642*	*0.608*	*9*
6	*0.952*	*0.000*	*0.048*	*1.000*	*0.912*	*0.333*	*0.623*	*8*
7	*0.688*	*0.871*	*0.312*	*0.129*	*0.616*	*0.795*	*0.706*	*5*
8	*1.000*	*0.395*	*0.000*	*0.605*	*1.000*	*0.452*	*0.726*	*2*
9	*0.845*	*0.182*	*0.155*	*0.818*	*0.764*	*0.379*	*0.572*	*11*
10	*0.596*	*0.439*	*0.404*	*0.561*	*0.553*	*0.471*	*0.512*	*15*
11	*0.421*	*0.528*	*0.579*	*0.472*	*0.464*	*0.514*	*0.489*	*17*
12	*0.277*	*0.978*	*0.723*	*0.022*	*0.409*	*0.958*	*0.683*	*6*
13	*0.563*	*1.000*	*0.437*	*0.000*	*0.533*	*1.000*	*0.767*	*1*
14	*0.000*	*0.778*	*1.000*	*0.222*	*0.333*	*0.692*	*0.513*	*14*
15	*0.414*	*0.587*	*0.586*	*0.413*	*0.460*	*0.548*	*0.504*	*16*
16	*0.568*	*0.596*	*0.432*	*0.404*	*0.537*	*0.553*	*0.545*	*12*
17	*0.683*	*0.349*	*0.317*	*0.651*	*0.612*	*0.434*	*0.523*	*13*
18	*0.675*	*0.581*	*0.325*	*0.419*	*0.606*	*0.544*	*0.575*	*10*

IV. Result and Discussion

From Table 4, it is found that for experiment no 13, machining parameter setting is the optimal parameter setting for attaining multiple performances, simultaneously among 18 experiments. However, the relative importance among the achieving parameters for the multiple performance characteristics still needed to be analyzed so that the optimal combinations of the milling parameter levels could be determined more clearly.

For analyzing the results, mean analysis was used and is presented as response table (See table 5).

Table - 5
Responses Table for Means

	Level1 111	*Level2 2*	*Level3 3*	*Delta*	*Rank*
A	*0.6470*	*0.5679*	-	*0.0791*	*3*
B	*0.5915*	*0.623*	*0.6078*	*0.0315*	*4*
C	*0.6532*	*0.5579*	*0.6112*	*0.0954*	*2*
D	*0.6647*	*0.5639*	*0.5937*	*0.1009*	*1*

The procedure for the response table is to group the GRCs by factor levels and then average them. The optimal level of the milling parameters is the level with the greatest GRG value. Based on the results obtained from Table 5, the optimal parameters achieved are milling type at level 1, spindle speed at level 2, feed rate at level 1 and depth of cut at level 1 for achieving least delamination and resultant machining force. The optimal solution A1B2C1D1 found in this study is only the near optimal solution. A response graph is shown in Figure 9.

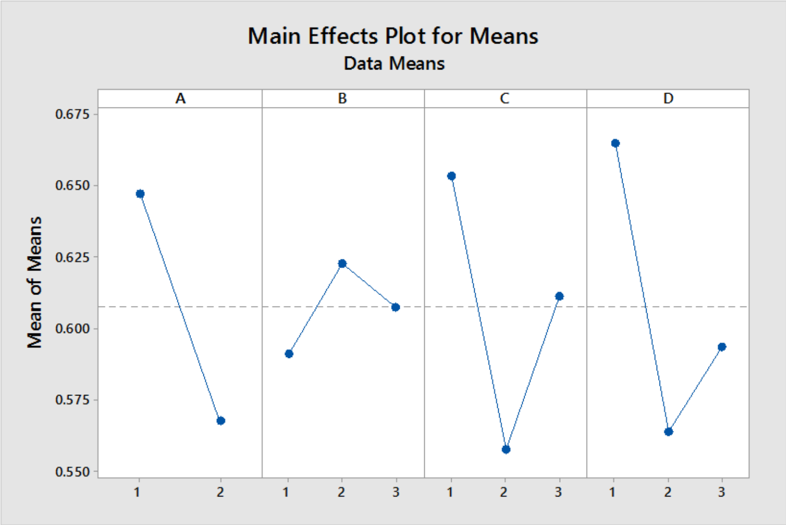

Fig. 9: Response Graph for GRG

V. Conclusion

In this study, GRA has been developed towards optimizing the resultant machining force and delamination factor in edge milling of carbon fiber reinforced epoxy composites. The basic idea of Grey Relational Analysis is to find a Grey Relational Grade, which can be used for the optimization conversion from a multi objective case to a single objective case. GRG is also used to estimate the parameter effects on the overall performance response. By this way, a multi-response optimization problem has been converted to an equivalent single objective optimization problem, which has been further solved by Taguchi philosophy.

Experiments revealed that from the delamination point of view, the most appropriate optimal parameter in case of edge milling are up milling, spindle speed at 1000 rpm, feed rate at 70 mm/min and depth of cut at 0.2mm.

Depths of cut and feed rate have the most dominant roles in influencing the delamination. Also, a minimum value of delamination has been obtained for the up milling area.

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