Surface Roughness Prediction Model for Grinding of Composite Laminate Using Factorial Design

P. Chockalingam, C. K. Kok, T. R. Vijayaram

***Abstract*—**Glass fiber reinforced polymer (GFRP) laminates have been widely used because of their unique mechanical and physical properties such as high specific strength, stiffness and corrosive resistance. Accordingly, the demand for precise grinding of composites has been increasing enormously. Grinding is the one of the obligatory methods for fabricating products with composite materials and it is usually the final operation in the assembly of structural laminates. In this experimental study, an attempt has been made to develop an empirical model to predict the surface roughness of ground GFRP composite laminate with respect to the influencing grinding parameters by factorial design approach of design of experiments (DOE). The significance of grinding parameters and their three factor interaction effects on grinding of GFRP composite have been analyzed in detail. An empirical equation has been developed to attain minimum surface roughness in GFRP laminate grinding.

***Keywords*—**GFRP Laminates, Grinding, Surface Roughness, Factorial Design.

I. Introduction

CORROSIVE resistance, lightweight, high specific stiffness and strength are among the properties that make GFRP composite laminates suitable materials for a wide range of applications in aeronautical, automotive, and marine fields. The growing applications of composites expand the opportunity of machining processes such as cutting, drilling, milling, grinding, etc. The machining of composite laminates is different from that of metal working in many respects. Grinding is one of the most important operations to remove unwanted material in order to achieve the desired geometry, whose complex characteristics determine the technological output and quality [1]. Grinding is particularly needed to acquire high dimensional accuracy and surface finish [2].

Unlike metal, the machining of fiber reinforced polymer composite is different due not only to its inhomogeneity, but also the constituent fiber and matrix properties [3]. Fiber reinforcement in GFRP composites will affect their grindability of the material. Therefore, a precise machining conditions need to be performed to ensure the desired surface roughness. Selection of process parameters is important in grinding to achieve high quality surfaces. The quality of the work is influenced by cutting conditions, machining processes, tool geometries, tool wear, and work piece materials [4]. For these reasons there have been research and developments with the objective of optimizing the cutting conditions to obtain a better productivity in grinding process. It is necessary to understand the relationship among various controllable parameters and to identify the important parameters that influence the surface quality of grinding.

Surface roughness has received serious attentions for many years. Surface finish is a main consideration in the assembly of mechanical components and is also an indicator of manufacturing processes exactness. It is an important design feature in many situations such as parts subject to fatigue loads, precision fits, fastener holes and aesthetic requirements. Tawakali et al. [5] reported that, surface roughness increases with increasing feed and decreases at higher cutting speeds. Even though many factors affect the surface condition of a ground part, grinding parameters such as depth of cut, feed rate and speed have a considerable influence on the surface roughness for a particular machine and material. The surface roughness increases with increasing feed rate and fiber orientation, and less influence by depth of cut in composite machining process [6].

To understand the effects of grinding parameters on surface quality, one common approach is to develop an empirical model using design of experiment. Design of experiments can be used to systematically investigate the process variability that influences product quality. Noordin et al. [7] used a face centered, central composite design involving three parameters to investigate the performance of coated carbide tool on surface roughness and tangential force. Palanikumar et al. [8] predicted tool wear on the machining of GFRP composite using regression analysis and analysis of variance (ANOVA). Anand et al. [9] reported that the grinding force components changes from plowing to steady state grinding at higher wheel speeds so surface roughness. This paper discusses the application of the factorial design approach to develop an empirical model to predict the surface roughness for GFRP composite laminate.

II. Experimental Details

The independently controllable machining parameters [1]-[11] that have greater influences on surface roughness in the grinding of composite are (i) Speed (x_1), (ii) Feed (x_2), and (iii) Depth of cut (x_3). Consequently in this study, based on the machine and tool specifications the lower and upper limits of these factors are fixed. The following are the steps involved in the experimental investigation.

i. Develop an experimental plan using factorial approach
ii. Conduct experiments randomly as per design matrix

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iii. Record the response, surface roughness and analyze the response using ANOVA
iv. Develop the empirical model
v. Check the adequacy of the model developed
vi. Present the result

The design of experiment has a major effect on the number of experiments needed. The experiment conducted was based on a two level full factorial design. The grinding parameters and their levels chosen are summarized in Table I.

TABLE I
CONTROL VARIABLE AND THEIR LEVELS

Parameter	Levels					
	Original values			Coded values		
	Low	Middle	High	Low	Middle	High
Speed, x_1, (rpm)	4000	5500	7000	-1	0	1
Feed, x_2, (mm/min)	1000	1250	1500	-1	0	1
Depth of cut, x_3, (mm)	0.2	0.25	0.3	-1	0	1

A. Workpiece Material

The composite laminate material adapted in this study was the one fabricated by hand lay-up technique using chopped strand mat 450 g/m^2 glass fiber and reinforced polyester, (R-glass fiber and orthophalic unsaturated polyester) with the addition of methyl ketone peroxide as catalyst [12]. Specimens of size of 50mm x 15mm x 10mm in size were cut from a plate of 250mm x 250mm x 10mm and grinding was performed on the 50mm x 10mm face. The properties of laminate are given in Table II.

TABLE II
PROPERTIES OF COMPOSITE LAMINATES

Tensile strength	80-90 MPa
Tensile modulus	1.55 – 1.65 GPa
Density	1600 kg/m^3
Hardness	53-56 B

B. Machine, Grinding Wheel and Measuring Instrument

Grinding was performed in a Mazak CNC machining centre according to the experimental design. The experiments were carried out randomly from design values to avoid systematic errors. Aluminum oxide profile mounted wheel, PA46QV, 25mm diameter x 32mm length x 6mm mandrel was used in this experiment. The design matrix and corresponding response are given in Table III. The common profile surface roughness parameter, arithmetic mean value (Ra) is considered in this study. Surface roughness of the ground surface was measured in perpendicular direction to grinding run with the help of Mahr's Perthometer S2 PGK. The resolution of the equipment is ±25µm and repeatability is 5%. For each response, an average of three readings was tabulated. Fig. 1 shows the experimental setup.

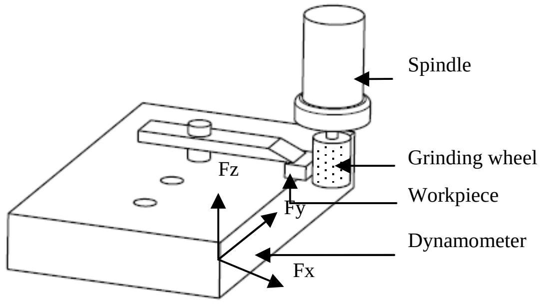

Fig. 1 Experimental setup

TABLE III
DESIGN TABLE AND CORRESPONDING RESPONSE

Run	Coded			Original value			Ra Surface roughness
	x_1 Speed	x_2 Feed	x_3 Depth of cut	Speed	Feed	Depth of cut	
	rpm	mm/min	mm	rpm	mm/min	mm	µm
1	-1	-1	-1	4000	1000	0.2	1.482
2	1	-1	-1	7000	1000	0.2	2.149
3	-1	1	-1	4000	1500	0.2	1.480
4	1	1	-1	7000	1500	0.2	3.525
5	-1	-1	1	4000	1000	0.3	3.490
6	1	-1	1	7000	1000	0.3	2.764
7	-1	1	1	4000	1500	0.3	2.585
8	1	1	1	7000	1500	0.3	1.720
9	0	0	0	5500	1250	0.25	1.780
10	0	0	0	5500	1250	0.25	2.020
11	0	0	0	5500	1250	0.25	1.820
12	0	0	0	5500	1250	0.25	1.852

III. MATHEMATICAL MODEL

The surface roughness, the response function of the GFRP composite laminate, is represented as ''y'', and expressed as $y = f(x_1, x_2, x_3)$. The model selected is polynomial [13], which includes the effects of main and interaction effect of all three factors and given as:

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_1 x_2 + \beta_5 x_1 x_3 + \beta_6 x_2 x_3 + \beta_7 x_1 x_2 x_3 + \text{error}, \quad (1)$$

where, β_0 is the average response value and $\beta_1, \beta_2, \ldots, \beta_7$ are the coefficients that depends on main effects and interaction effects. This model is important type of model for statistical models and for exploration of data sets.

To evaluate the significance of main and interaction effects, an analysis of variance (ANOVA) was carried out using Minitab 15 software with a confidence level of 95%, and the test results presented in Table IV. In the ANOVA, regression was used to derive an empirical model, which was fitted for surface roughness response from the coefficient values from Table V. The capability of the empirical model was verified by using the coefficient of determination, R^2. The calculated value of 97.82% shows the excellent correlation between experimental and predicted values. The model developed is significant.

TABLE IV
ANALYSIS OF VARIANCE FOR SURFACE ROUGHNESS, RA

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Main Effects	3	0.6606	0.6606	0.2202	19.78	0.018
2-Way Interactions	3	3.8866	3.8866	1.2955	116.34	0.001
3-Way Interactions	1	0.2876	0.2876	0.2876	25.83	0.015
Curvature	1	0.7529	0.7529	0.75296	67.61	0.004
Residual Error	3	0.0334	0.0334	0.0111		
Pure Error	3	0.0334	0.0334	0.0111		
Total	11	5.6213				

TABLE V
ESTIMATED EFFECTS AND COEFFICIENT FOR SURFACE ROUGHNESS

Term	Effect	Coef	Se Coef	T	P
Constant		2.3994	0.03731	64.31	0.000
Speed	0.2802	0.1401	0.03731	3.76	0.033
Feed	-0.1437	-0.0719	0.03731	-1.93	0.150
Depth of Cut	0.4808	0.2404	0.03731	6.44	0.008
Speed*Feed	0.3098	0.1549	0.03731	4.15	0.025
Speed*Depth of Cut	-1.0758	-0.5379	0.03731	-14.42	0.001
Feed*Depth of Cut	-0.8307	-0.4154	0.03731	-11.13	0.002
Speed*Feed*Depth	-0.3792	-0.1896	0.03731	-5.08	0.015
Ct Pt		-0.5314	0.06462	-8.22	0.004

S = 0.105527; R-Sq = 99.41%; R-Sq(adj) = 97.82%

Regression results from the ANOVA indicate the direction, size, and statistical significance of the relationship between a parameter and response in the following manner:-

i. The sign of each coefficient indicates the direction of the relationship.
ii. The coefficients represent the mean change in the response for one unit of change in the predictor while holding other parameter in the model constant.
iii. The p-value for each coefficient tests the null hypothesis that the coefficient is equal to zero (no effect). Therefore, low p-values suggest the predictor is a meaningful addition to your model.

The derived equation, which can be used to predict new observations, was given as

$$Ra = 2.40 + 0.14x_1 - 0.07x_2 + 0.24x_3 + 0.15x_1 * x_2 - 0.53x_1 * x_3 - 0.41\, x_2 * x_3 - 0.19\, x_1 * x_2 * x_3 \quad (2)$$

A. Verification of the Developed Model

Fig. 2 shows that normal probability plot of residuals. All the residuals plotted evenly both side and generally fall on straight line implying the errors are distributed normally.

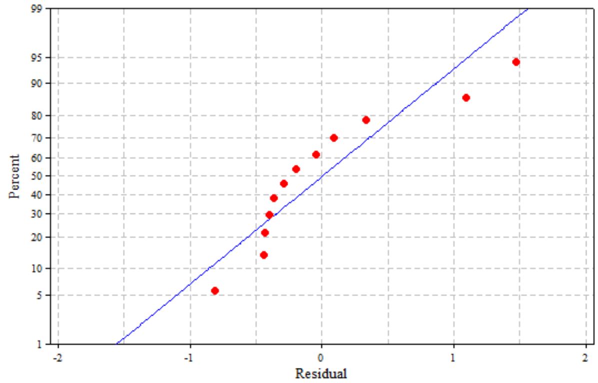

Fig. 2 Normal Probability plot of residuals

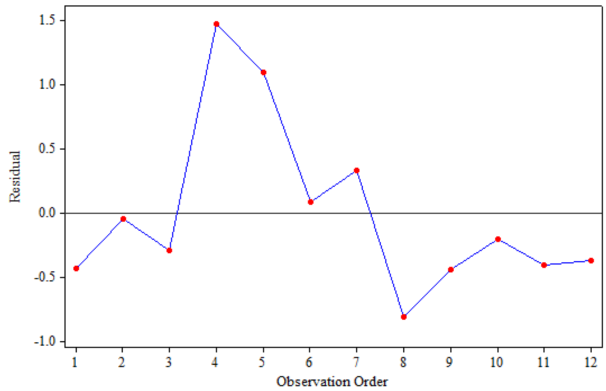

Fig. 3 Residual verses Observation Order

Fig. 3 shows the residuals verses the observation order. From the figure, it is evident that there are no runs of positive and negative residuals indicating a lack of independence randomness. The plot shows that the residuals are distributed evenly in both positive and negative along the run, and therefore the data based on which the model derived is said to be in control.

Fig. 4 indicates the residuals versus fitted values, which shows only the maximum variation of -1 to 1.5 µm in surface roughness between observed and fitted values. This plot does not reveal any obvious pattern; indicating good fit and equal variance. Hence the fitted model is adequate.

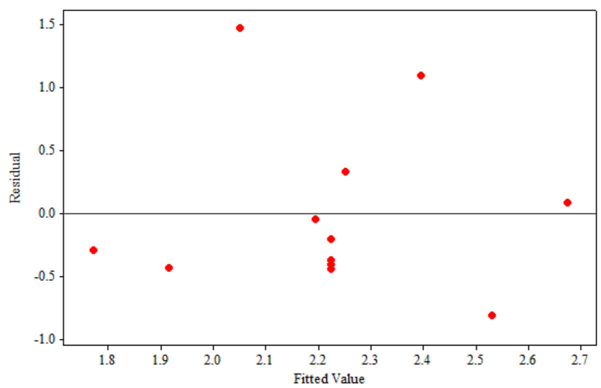

Fig. 4 Residual Verses Fitted Value

IV. Discussion

Surface roughness is an important parameter in the evaluation of machining performance. Even though many factors may affect surface roughness, grinding parameters such as cutting speed, feed rate and depth of cut are proven to have significant influence for a given machine tool and work piece. It is worth noting that the techniques and methodologies required for processing composite materials are substantially different from those for metals. The mechanism of material removal in GFRP composites is a combination of plastic deformation, shearing and bending rupture.

In relating surface roughness to the grinding parameters empirically, it is assumed that a direct correlation exists between surface roughness and the equivalent chip thickness, such as suggested by Malkin [14] in (3)

$$R_a = C_3 h_{eq}^{x}, \qquad (3)$$

where R_a is the average roughness, and C_3 and x are coefficients. According to this equation the depth of cut and feed have the same effect on roughness.

However, in GFRP laminate grinding, the surface roughness depends on the machining parameters and not solely on the equivalent chip thickness. This is evident from the following observations. At constant feed and depth of cut, as speed was increased, material removal should have reduced due to the reduction in equivalent chip thickness (42%). However, it is observed that grains sliding and rubbing led to higher surface roughness. Similarly, when holding the speed constant, in cases of where feed and depth of cut were increased, increase in equivalent chip thickness (33%) by increased cutting action of abrasive grains has led instead to a reduction in surface roughness. This observation agrees with A Di Ilio et al. [15] findings for metal matrix composite grinding. Therefore, the method for evaluating the influence of grinding parameters on surface roughness of GFRP composites could be significantly different from that of metals.

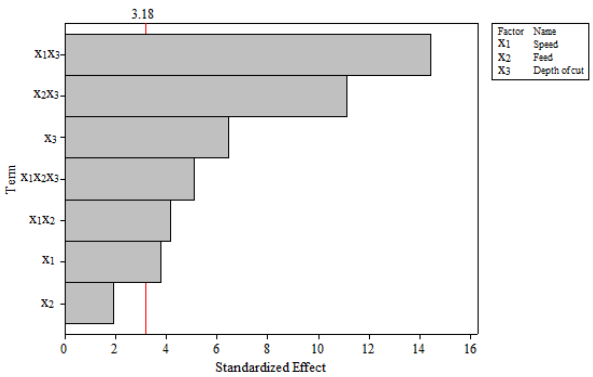

Fig. 5 Pareto Chart

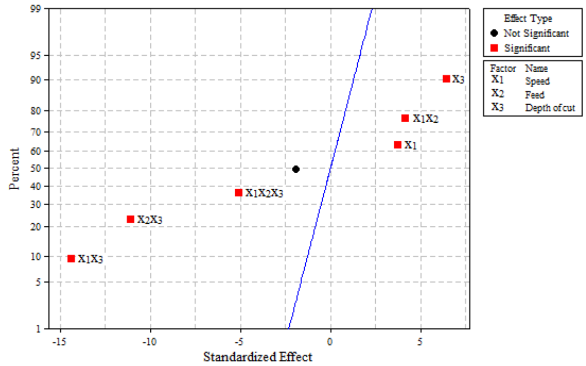

Fig. 6 Effect Plot of Standardized Effect

The effects of different parameters can be analyzed by using a standardized Pareto chart and a normal probability plot. Fig. 5 shows the Pareto chart of the standardized effects. The Pareto chart displays the absolute value of the effects, and draws a reference line on the chart. Any effect that extends past this line is potentially important. Fig. 6 shows the effect plot of the standardized effects. The effects that are negligible are normally distributed, with a mean zero and a variance r^2. Based on Figs. 5 and 6, it can be concluded that the factors that are considered to be significant at 95% confidence level are depth of cut (x_3), speed (x_1) and all the interactions between speed, feed and depth of cut.

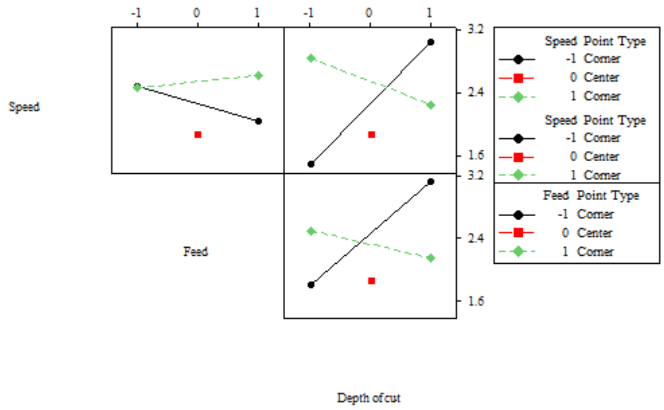

Fig. 7 Interaction Effect Plots

Fig. 7 shows the interaction effect plot for the identified significant parameters. At low speed, increasing feed led to lower surface roughness due to increased cutting action and chip thickness. On the other hand, increasing depth of cut at low speed tends to increase surface roughness due to grain ploughing.

At higher speed, surface roughness increased steeply with increasing feed at lower depth of cut due to increased sliding of grains. On the contrary, at higher speed and higher depth of cuts, surface roughness decreased with increasing feed due to more ploughing and cutting.

At high feed and high speed, increasing depth of cut, reduced surface roughness, again due to more cutting than ploughing and sliding. But at low speed and lower the feed, increasing the depth of cut increased the surface roughness significantly. In summary, surface roughness of ground GFRP laminates depends on the machining parameters combinations.

V. CONCLUSION

By means of design of experiment, an empirical model relating grinding parameters and the surface roughness of chop-strand-mat GFRP laminate work piece was developed. . From this study, we can conclude that the most significant factors which influence the grinding surface roughness model are depth of cut, speed and also the interactions of speed, feed and depth of cut. The developed model is effective for the design space studied. It is observed that GFRP laminate grinding is very different from metal grinding and that its surface roughness does not depend solely on equivalent chip thickness alone but it on the combination of machining parameters.

REFERENCES

[1] P. Krajnik, P Kopac, J. *et al*., Design of grinding factors based on response surface methodology. J. Mat. Processing Tech, 162-163 (2005) 629-636.
[2] Hu, N.S, Zhang, L.C. Some observations in grinding unidirectional carbon fibre reinforced plastics. J. Mat. Processing Tech. 152 (2004) 333-338.
[3] Palanikumar, K., Karunamoorthy, L., Karthikeyan, R. Assessment of factors influencing surface roughness on the machining of glass fibre-reinforced polymer composites. Materials and Design 27 (2006) 862–871
[4] Mohan, N.S., Ramachandra, A., Kulkarni, S.M. Influence of process parameters on cutting force and torque during drilling of GFPR composites. Composite Structures: 71 (2005) 407-413.
[5] Intermittent grinding of ceramic matrix composites (CMCs) utilizing a developed segmented wheel. Taghi Tawakoli, Bahman Azarhoushang. International Journal of Machine Tools & Manufacture 51 (2011) 112–119.
[6] Hu, N.S., Zhang, L.C. A study on the Grindability of multidirectional carbon fibre reinforced plastics. J. Mat. Processing Tech. 140 (2003) 152-156.
[7] M.Y. Noordin , V.C. Venkatesh, V.C., Sharif, S., Elting, S., Abdullah, A. Application of response surface methodology in describing the performance of coated carbide tools when turning AISI 1045 steel. Journal of Materials Processing Technology 145 (2004) 46–58
[8] Palanikumar, K., Paulo Davim, J.. Mathematical model to predict tool wear on the machining of glass fibre reinforced plastic composites. Materials & Design.2007:2008-2014.
[9] B. Anand Ronald, L. Vijayaraghavan, R. Krishnamurthy. Studies on the influence of grinding wheel bond material on the grindability of metal matrix composites. Materials and Design 30 (2009) 679–686.
[10] Di Ilio, A., Paoletti, A,. Tagliaferri, V., and Veniali, F. An experimental study on grinding of silicon carbide reinforced Aluminium alloys. Int. J. Mach. Tools Manufact. Vol 36, No.6 673-685, 1996.
[11] Venu Gopala Rao, G., Mahajan, P., Bhatnagar, N. Micro-mechanial modelling of FRP composites- Cutting force analysis. Composite Science and Tech. 67 (2007) 579-593.
[12] El_Tayeb, N.S.M., Yousif, B.F., Yap T.C. Tribological studies of polyester reinforced with CSM 450 R glass fibre sliding against smooth stainless steel counterface. Wear 261 (2006) 443-452.
[13] Montgomery, D.C. *Design and Analysis of Experiments*, 5th ed., Wiley, New York, 2001.
[14] Malkin S (1989) Grinding Technology—Theory Applications of Machining with Abrasives. Ellis Horwood Limited, West Sussex.
[15] Di Ilio, A. Paoletti, D. D'Addona. Characterization and modeling of the grinding process of metal matrix composites. CIRP Annals - Manufacturing Technology 58 (2009) 291–294.