Methodology for assessment of factors influencing surface roughness on the drilling of carbon fiber-reinforced composites

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Abstract

In the present work, the effects of machining parameters on surface roughness during high-speed drilling of carbon fiber reinforced plastic (CFRP) composite are presented. The machining experiments are carried out on lathe using two levels of factors. The factors considered were: % volume fraction of carbon fiber, cutting speed, drill diameter and feed rate. A procedure has been developed to assess and optimize the chosen factors to attain minimum surface roughness by incorporating: (i) response table and effect graph, (ii) normal probability plot (iii) analysis of variance (ANOVA) technique. From the test results, we observe that the technique used is convenient to predict the main effects and interaction effects of different influential combinations of machining parameters. Feed rate is the factor, which has greater influence on surface roughness followed by % volume fraction of fiber and drill diameter. The interaction between all parameters has more influence on surface roughness, followed by (drill diameter and feed rate) and (% volume fraction of fiber and drill diameter) comparing with other interactions on the machining of $CFRP_S$ composites.

الخلاصة

يتناول البحث الحالي تأثير متغيرات التشغيل على خشونة السطح عند تثقيب البلاستك المقوى بألياف الكاربون وباستخدام برايم من فولاذ السرعات العالية HSS . التجارب نفذت على ماكنة الخراطة باستخدام مستويين من العوامل. متغيرات التشغيل التي درست هي الكسر الحجمي لألياف الكاربون ، سرعة القطع ، قطر البريمة ومعدل التغذية. أجريت خطوات تدريجية لتخمين ونمذجة العوامل المختارة للحصول على اقل خشونة ممكنة بواسطة (i) جدول الاستجابة ورسم التأثير (ii) مخطط التوزيع الطبيعي للاحتمالية (iii) تحليل التباين بواسطة تقنية ANOVA . لوحظ من النتائج أن التقنية المستخدمة ملائمة للتنبؤ بتأثير العوامل الرئيسية والعوامل المتفاعلة لمتغيرات التشغيل . معدل التغذية هو العامل الرئيسي المؤثر على خشونة السطح من بين العوامل المختارة متبوعا" بالكسر الحجمي لليف ومن ثم قطر البريمة. كذلك لوحظ إن التفاعل بين كل متغيرات التشغيل يكون له تأثير كبير على خشونة السطح متبوعا" بـــ (قطر البريمة ومعدل التغذية) ومن ثم (الكسر الحجمي لليف و قطر البريمة) مقارنة بعوامل التشغيل المتفاعلة الأخرى.

KEYWORDS: drilling; CFRP composites; Surface roughness; Response table; Effect graph; ANOVA; Normal probability plot

Nomenclature

CFRP	carbon fiber-reinforced plastic	V_f	Volume fraction in %
V_c	Cutting speed in m/min	W_f	Fiber mass in Kg
f	Feed rate in mm/rev	ρ_f	Fiber density in Kg/m^3
d	Drill diameter in mm	ρ_m	Matrix density in Kg/m^3
Ψ	Mass fraction in %	W_c	Composites mass in Kg
W_m	Matrix mass in Kg	HSS	high speed steel
β_o	average response value	Ra	Surface roughness value in μm
$\beta_1, \beta_2, \beta_3$………… $\beta 15$	co-efficients that depends on main effects and interaction effects.		

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1. Introduction

Composites by definition are materials which comprise two or more constituents resulting in a product with superior properties compared to the individual elements. The general structure of composites typically involves a bulk phase known as the matrix, and a stronger and harder interspersed phase known as the reinforcement. The latter can be in the form of particles, fibers (continuous or discontinuous), wires, etc. and are commonly made from glass, ceramics, carbide, carbon, aramid, etc. [Callister, 2000], while the former is either a polymer, ceramic or metal [Abrao et al., 2007]. Today fiber-reinforced plastics (FRPs) have an important place in the field of engineering materials[Palanikuma and Davim,2009].They are important materials for structural components owing to their excellent properties such as high specific strength, high specific stiffness, high damping, low thermal expansion, good dimensional stability and an unusual combination of properties not obtainable with metal alloys[Arul et al., 2006]. Examples of their use can be found in aerospace, aeronautical, automotive, railway or nautical construction industries [Durãoa et al., 2007] .

Machining of fiber - reinforced composite differs significantly from machining of conventional metals and alloys, owing to the behavior of matrix material, reinforcement and diverse properties of fiber, matrix and orientation of fiber and volume fraction of fibers [Naveen et al., 2009]. Generally, FRP composites has two phases of materials, namely, harder reinforcement and softer matrix, due to which they exhibit varying mechanical properties. The mechanism of material removal is also different from that of single-phased material, such as metals[Aravindan et al., 2008]. A typical FRP component is molded to near-net shape and subsequently finish machined to meet geometric tolerance and surface finish requirements. Achieving an acceptable surface quality with conventional methods of machining has been found extremely difficult due to the anisotropic and heterogeneous nature of these materials. Excessive tool wear is prevalent and frequently induces fiber pullout and surface ply delamination in the component part [Bagci and Işık, 2006]. This limitation has provided both academic and industrial motivation for research on the application of traditional methods of machining to reinforced polymers.

There have been many studies in the machining of FRPs. [Wang and Zhang, 2003] investigated the machinability of epoxy composites reinforced by unidirectional carbon fiber materials when subjected to orthogonal cutting and found that the subsurface damage and its mechanisms of a machined component are greatly influenced by fiber orientation. [Khasbaba 2004] investigated the influence of drilling and material variables on thrust force, torque, and delamination of GFRP composites experimentally. He implied that the presence of sand filler in continuous-winding composites not only raised the values of cutting forces and push-out delamination but also increased their values with increasing cutting speed.[Hocheng *et al.*, 2005] present a review on the major scenes towards delamination-free drilling of composite materials. they aspects of the mathematical analysis, the effects of special drill bits, pilot hole and back-up plate and the feasible use of non-traditional machining.[Palanikumar et al 2006] have attempted to assess the influence of machining parameters on surface roughness in machining GFRP composites. It concludes that the feed rate has more influence on surface roughness and it is followed by cutting speed.[Durãoa et al., 2007] have studied the effect of drilling parameters on composite plates damage with three cutting speeds, three feed rates and three tool geometries are compared. Conclusions show the influence of an adequate selection of tool and cutting parameters in delamination reduction.[Karnik et al. 2008] investigated entry delamination when drilling woven CFRP 2.5mm thick using 5mm carbide twin lipped drills over a range of cutting speeds (63–630 m/min) and feed rates (1000–9000 mm/min) with different drill point angles. Their findings showed that the entry delamination factor was sensitive to all process parameters examined however, a combination of high cutting speed, low feed rate and small point angle reduced entry effects. [Naveen et al. 2009] used the Taguchi L18 orthogonal array to find the optimal cutting parameters in turning GFRP pipes. Based on composite desirability value, the optimum levels of parameters have been identified, and significant contribution of parameters is determined by analysis of variance. Confirmation test is also

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conducted to validate the test result. It is clearly shown that the multi-responses in the machining process are improved through this approach. Thus, the application of desirability function analysis in Taguchi technique proves to be an effective tool for optimizing the machining parameters of GFRP pipes.[Islam et al., 2010] have studied the effect of laminate configuration and feed rate on cutting performance when twist drilling 1.5mm diameter holes in 3mm thick CFRP laminate using tungsten carbide (WC) stepped drills. The control variables considered were prepreg type (3 types) and form (unidirectional (UD) and woven), together with drill feed rate (0.2 and 0.4 mm/rev). A full factorial experimental design was used involving 12 tests. Response variables included the number of drilled holes (wear criterion VBmax≤100_m), thrust force and torque, together with entry and exit delamination (conventional and adjusted delamination factor values calculated) and hole diameter. Best results were obtained with woven MTM44-1/HTS oven cured material (3750 holes) while the effect of prepreg form on tool life was evident only when operating at the higher level of feed rate. Thrust forces were typically under 125N with torque values generally below 65Nmm over the range of operating parameters employed. Finally, the delamination factor (Fd) measured at hole entry and exit ranged between ~1.2–1.8 and 1.0–2.1 respectively.[Krishnamoorthy et al., 2011] used the artificial neural network (ANN) for the prediction of delamination factor at the exit plane of the CFRP material in drilling operation. It is found that ANN model predicts the delamination for any given set of machining parameters with maximum error of 0.81% and minimum error of 0.03%. Thus an ANN model is highly suitable for the prediction of delamination in CFRP materials.

From the literature it is found that the machining of FRP is an important area of research, but only very few studies have been carried out on optimization of surface roughness while machining of fiber reinforced plastics composite. Hence, the main objective of the present work is to optimize surface roughness while machining CFRP$_s$.

2. Scheme of investigation

In order to investigate the influence of machining parameters on the surface roughness (Ra) four principal machining parameters such as the cutting speed (V_c), feed rate (f), drill diameter (d), and volume fraction (V_f) were taken. In this study, these machining parameters were chosen as the independent input variables. The desired responses was the surface roughness (Ra) which are assumed to be affected by the above four principal machining parameters, the present investigation has been planned in the following steps:

(i) identifying the important factors, which influence the surface roughness on the machining of CFRP composites;
(ii) finding the upper and lower limits of the factors identified;
(iii) developing the experimental design matrix using design of experiments;
(iv) conducting the experiments as per the design matrix;
(v) assessing the factors and its effects using response table and effect graph;
(vi) assessing the real or chance effect of factors using normal probability plot;
(vii) analyzing the results using ANOVA;
(viii) optimizing the chosen factor levels to attain minimum surface roughness

2.1. Identifying the important factors

The machining parameters identified are: (i) cutting speed; (A), (ii) workpiece (volume fraction of fiber) (B); (iii) drill diameter (C); (iv) feed rate (D). Out of the four parameters considered, volume fraction of fibre has been specially applied to fiber-reinforced composite materials.

2.2. Finding the upper and lower limits of the factors identified

For finding the upper and lower limits of the machining parameters, a detailed analysis has been carried out. The limits identified are discussed below :

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(i) The surface roughness decreases with increase of cutting speed and vice versa [El-Sonbaty et al., 2004]. But the higher cutting speed was found to cause a higher interface temperature and severe tool wear and hence the cutting speed has been set at low level and is between 75 and 150 m/min.

(ii) The increase in volume fraction decreases the surface roughness. However, with increase in volume fraction, the rate of decrease in roughness is reduced due to the chip fracture extending to work piece, which produce force fluctuations and ridge formation due to machine tool and vibration [Srinivasa et al., 2008]. For the present study, the % volume fraction of SiC particles is fixed between 10% and 20%.

(iii) The increase in drill diameter, results in high normal pressure and seizure on the rake face and promotes the built up edge (BUE) formation. Hence, the surface roughness increases with increase of drill diameter[Ramkumar et al., 2004]. The drill diameter considered in this work is between 6 and 8 mm.

(iv) The increase in feed rate increase the surface roughness. With increase in feed rate plastic deformation decreased and the scale formed resulted in increased roughness . The increase in feed rate also increase the chatter and it produces incomplete machining at a faster traverse, which leads to more tool wear[Isik and Ekici, 2010]. The feed rate selected is between 0.10 and 0.30 mm/rev.

2.3. Developing the experimental design matrix using design of experiments

All possible combinations of levels are included so that there are 2^n (where n refers to the number of factors, i.e., $2^4 = 16$) trials in the experiment. The notations, units and their levels chosen are summarized in Table 1. For easy recording and processing of experimental data, the parameters levels are coded as +1 and −1.

2.4. Conducting the experiments

Woven CFRP composites of 10 mm thickness (4 Layers) were prepared by lay-up technique. The matrix was epoxy with a standard grade of CY223 and hardener HY956 manufactured by Ciba-Giegy/Germany. Carbon fiber were used as reinforcement in the composites manufactured by Grazer/ Germany. Curing was done at room temperature for about 24 hours. The nominal volume fraction of fiber is 40% .It can be calculated by using the following expression **[Deborah, 2010]**:

$$V_f = \frac{1}{1+\frac{1-\Psi}{\Psi}\frac{\rho f}{\rho m}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

$$\Psi = \frac{W_f}{W_c} \times 100\% \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

the fiber properties listed in table 2. The specimens were cut to a size of 30×30 mm.

A Harrison/England medium duty lathe with 2.2 KW spindle power was used to perform the experiments. The drill tool used were manufactured by Guhring with (6 and 8 mm) diameter and four flute. and also made from high speed steel HSS wth a clearance angle of 12°, rake angle 6°, and Point angle were privately sharpened with 118°. All machining tests were carried out without coolant. The average surface roughness (*R*a) in the direction of the tool movement was measured in five different places of the machined surface using a surface roughness tester, Taylor Hobson measuring instrument. surface mean roughness (*R*a) in microns value of the five locations was considered for the particular trial. The machining operations were carried out as per the condition given by the design matrix at random to avoid systematic errors. The design matrix and the corresponding responses are given in Table 3.

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3. Assessing the factors and its effects

Assessing the factors and its effects on surface roughness of $CFRP_s$ composite machining process has been carried out through: (i) response table and effect graph, (ii) normal probability plot; (iii) analysis of variance (ANOVA) technique.

3.1. Response table and effect graph

Response tables are used to simplify the calculations needed to analyze the experimental data. In response table, the effect of a factor on a response variable is the change in the response when the factor goes from its low level to its high level. The complete response table for a two level, 16 run full factorial experimental design is shown in Table 4. If the effect of a factor is greater than zero, the average response is higher for the higher level of the factor than for the low level. However, if the estimated effect is less than zero, it indicates that the average response is higher at low level of the factor than at high level. If the effect for a factor is very small, then it is probably because of random variation than a 'real' factor effect. The graphical display [Ravi et al.,2004] such as effect graph can be used, in conjunction with a response table, to identify appropriate settings for machining parameters to minimize the surface roughness. The effect of main and interaction factors derived from the response table for composite machining process is plotted in Fig. 1. From figure, it is inferred that larger the vertical line, the larger the change in surface roughness of $CFRP_S$, when going from level -1 to level +1 for a factor. It will be pointed out that the statistical significance of a factor is directly related to the length of the vertical line.

3.2. Normal probability plot

In effect graph, it is found that some of the factor effects are larger than the other, but it is not clear, whether these results are 'real' or 'chance'. To identify the 'real' effects, normal probability plot are used and is shown in Fig. 2. Normal plot is a graphical technique based on ''Central limit theorem''. The procedure for constructing the normal probability plot is given elsewhere [Lochner and Mater ,1990]. The calculations required for constructing the graph is shown in Table 5. As per the normal probability plot, points which are close to a line fitted to the middle group of points represent estimated factors which do not demonstrate any significant effect on the response variable. On the other hand, the points appear to be far away from the straight line are likely to represent the 'real' factor effects on the surface roughness. In Fig.2, A, B, C, D and their interactions ABCD, CD, AC, BC and ACD are quite away from the straight line and are considered to be significant.

3.3. Analysis of variance

The normal probability plot has the disadvantage of not providing a clear criterion for what values for estimated effects indicate significant factor or interaction effects. In addition, how do we measure amount of departure from the straight line pattern. ANOVA meets this need by how much an estimate must differ from zero in order to be judged "statistically significant". The ANOVA result is presented in Table 6. This analysis has been carried out for a level of significance of 5%, i.e., for a level of confidence of 95%. From the ANOVA results, it is concluded that the factors *A*, *B*, *C*, *D* and their interactions *AC*, *BC* and *CD* have significant effect on surface roughness and *AB*, *AD,BD* have no effect at 95% confidence level. As the interaction effect of *AC*, *BC* and *CD* seems to be significant to the surface roughness.

4. Mathematical model

From the analysis of effect graph, response table, and interaction graphs, the optimal machining parameters for the CFRP composite machining process is achieved for the minimum value of surface roughness. The optimal conditions arrived are:

(i) Cutting speed at high level (150 m/min)
(ii) % Volume fraction of carbon fiber at high level (20%)
(iii) Drill diameter at low level (6 mm)

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(iv) Feed rate at low level (0.10 mm/rev)
Based on the above optimum conditions, the response function can be expressed as:

$$Y = f\,(\mathrm{A, B, C, D}) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(3)$$

The model chosen includes the effects of main and interaction effect of all factors . The model selected is polynomial and is expressed as follows:

$$Ra = \beta_o + \beta_1(A) + \beta_2(B) + \beta_3(C) + \beta_4(D) + \beta_5(AB) + \beta_6(AC) + \beta_7(AD) + \beta_8(BC) + \beta_9(BD) + \beta_{10}(CD) + \beta_{11}(ABC) + \beta_{12}(ABD) + \beta_{13}(ACD) + \beta_{14}(BCD) + \beta_{15}(ABCD) \quad \ldots\ldots\ldots\ldots\ldots\ldots(4)$$

In engineering problems, the higher order interactions (three factor interactions and four factor interactions) are practically insignificant and hence not considered. After omitting three factor and four factor interactions, the model is written as:

$$Ra = \beta_o + \beta_1(A) + \beta_2(B) + \beta_3(C) + \beta_4(D) + \beta_5(AB) + \beta_6(AC) + \beta_7(AD) + \beta_8(BC) + \beta_9(BD) + \beta_{10}(CD) \quad \ldots\ldots\ldots\ldots\ldots\ldots(5)$$

$$Ra = 2.088 + (2.012-2.088) + (2.213-2.088) + (1.978-2.088) + (1.961-2.088) + (2.201-2.088) + (2.017-2.088) + (2.412-2.088)$$
$$Ra = 2.481\ \mu\mathrm{m}$$

The above result reveals that the minimum surface roughness on the machining of CFRP_S composites within the range of factor under investigation is 2.481µm. The validity of the optimization procedure has been checked through confirmation experiments. Table 7 shows the results of the confirmation experiment using optimal machining parameters. The confirmation experiments have been repeated for 3 times and the average surface roughness is taken for comparison. As shown in table, the surface roughness reduced from 2.42 to 1.92µm. It is clear that the surface roughness is considerably improved through this study.

5. Discussion

Surface roughness plays an important role in many areas and is a factor of great importance in the evaluation of machining accuracy. Although many factors affect the surface condition of a machined part, machining parameters such as cutting speed, feed rate and drill diameter have a significant influence on the surface roughness for a given machine tool and work piece set-up.

From the available literature, it has been known that the mechanism of cutting in FRP is due to the combination of plastic deformation, shearing and bending rupture. The above mechanism depends on flexibility, orientation and toughness of the fibers [Santhanakrishnan et al., 1989].

The cutting speed plays an important role in deciding the surface roughness. At high cutting speeds, the surface roughness decreases. At low speeds, the BUE is formed and also the chip fracture readily producing the rough surface. As the speed increase, the BUE vanishes, chip fracture decreases, and hence the roughness decreases.

The increase in drill diameter, results in high normal pressure and seizure on the rake face and promotes the BUE formation. Hence, the surface roughness increases along with increase in drill diameter. The increase in feed rate, increases the surface roughness linearly up to 0.3 mm/rev. At feed rates between 0.15 and 0.3 mm/rev, the BUE forms readily and is accomplished by feed marks resulting in increased roughness.

The results shown prove that the surface roughness of CFRP_S composite is highly influenced by the feed rate, cutting speed and % volume fraction of carbon fiber in the work piece. The drill

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diameter also plays a significant role on composite machining process in deciding the surface roughness.

The interaction between machining parameters also play a prominent role in machining of $CFRP_S$ composites. In the present study, only three interactions between parameters namely cutting speed and drill diameter (AC), % volume fraction of fiber and drill diameter (BC) and drill diameter and feed rate (CD) have significant effects. From the ANOVA analysis, it is found that feed rate is the most significant parameters than other parameters. Among the interactions, the interaction between drill diameter and feed rate is more significant factor than other interactions. Furthermore, the surface roughness reduces as the cutting speed increases or % volume fraction of carbon fiber of the work piece increases. But the surface roughness increases with the increase of feed rate and drill diameter.

6. Conclusion

Using experimental design, the machining parameters, which are having influence on surface roughness on the machining of $CFRP_S$ composites, have been assessed.

(1) The technique used is convenient to predict the main effects and interaction effects of different influential combinations of machining parameters.

(2) Feed rate is the factor, which has greater influence on surface roughness, followed by % volume fraction of fiber and drill diameter .

(3) The interaction between all parameters has more influence on surface roughness, followed by (drill diameter and feed rate) and (% volume fraction of fiber and drill diameter) comparing with other interactions on the machining of $CFRP_S$ composites.

(4) The parameters considered in the experiments are optimized to attain minimum surface roughness using effect graph, response table, normal probability plot, and analysis of variance (ANOVA) technique.

(5) The optimization procedure can be used to predict the surface roughness for drilling of $CFRP_S$ composites within the ranges of variable studied. However, the validity of the procedure is limited to the range of factors considered for the experimentation.

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Table 1 - Control parameters and their levels

Exp. No	Parameter	Notation	Unit	Levels			
				Actual factors		Coded factors	
				Low	High	Low	High
1	Cutting speed	A	m/min.	75	150	-1	+1
2	Volume fraction	B	%	10	20	-1	+1
3	Drill diameter	C	mm	6	8	-1	+1
4	Feed rate	D	mm/rev.	0.1	0.3	-1	+1

Table 2 – Fiber properties

Fiber	Density $Kg.m^{-3}$	Tensile strength MPa	Modulus of elasticity GPa	Elongation % at break	Diameter μm	Thermal conductivity W/mk
Carbon	1750	5000	240	2.3	15	17

Table 3 – Design matrix and corresponding output response

Exp. No	Coded factors				Actual factors				Response variable Ra, μm
	A	B	C	D	A	B	C	D	
1	-1	-1	-1	-1	75	10	6	0.1	2.42
2	+1	-1	-1	-1	150	10	6	0.1	1.39
3	-1	+1	-1	-1	75	20	6	0.1	2.24
4	+1	+1	-1	-1	150	20	6	0.1	1.92
5	-1	-1	+1	-1	75	10	8	0.1	1.63
6	+1	-1	+1	-1	150	10	8	0.1	1.92
7	-1	+1	+1	-1	75	20	8	0.1	2.14
8	+1	+1	+1	-1	150	20	8	0.1	2.03
9	-1	-1	-1	+1	75	10	6	0.3	1.76
10	+1	-1	-1	+1	150	10	6	0.3	2.03
11	-1	+1	-1	+1	75	20	6	0.3	2.25
12	+1	+1	-1	+1	150	20	6	0.3	1.82
13	-1	-1	+1	+1	75	10	8	0.3	2.54
14	+1	-1	+1	+1	150	10	8	0.3	2.01
15	-1	+1	+1	+1	75	20	8	0.3	2.33
16	+1	+1	+1	+1	150	20	8	0.3	2.98

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Table 4- Response table for surface roughness

S. No	Ra µm	A		B		C		D		AB		AC		AD	
		-1	+1	-1	+1	-1	+1	-1	+1	-1	+1	-1	+1	-1	+1
1	2.42	2.42		2.42		2.42		2.42			2.42		2.42		2.42
2	1.39		1.39	1.39		1.39		1.39		1.39		1.39		1.39	
3	2.24	2.24			2.24	2.24		2.24		2.24			2.24		2.24
4	1.92		1.92		1.92	1.92		1.92			1.92	1.92		1.92	
5	1.63	1.63		1.63			1.63	1.63			1.63	1.63		1.63	
6	1.92		1.92	1.92			1.92	1.92		1.92			1.92		1.92
7	2.14	2.14			2.14		2.14	2.14		2.14		2.14		2.14	
8	2.03		2.03		2.03		2.03	2.03			2.03		2.03		2.03
9	1.76	1.76		1.76		1.76			1.76		1.76		1.76		1.76
10	2.03		2.03	2.03		2.03			2.03	2.03		2.03		2.03	
11	2.25	2.25			2.25	2.25			2.25	2.25			2.25		2.25
12	1.82		1.82		1.82	1.82			1.82		1.82	1.82		1.82	
13	2.54	2.54		2.54			2.54		2.54		2.54	2.54		2.54	
14	2.01		2.01	2.01			2.01		2.01	2.01			2.01		2.01
15	2.33	2.33			2.33		2.33		2.33	2.33		2.33		2.33	
16	2.98		2.98		2.98		2.98		2.98		2.98		2.98		2.98
Average	2.088	2.163	2.012	1.962	2.213	1.978	2.197	1.961	2.215	2.038	2.137	1.975	2.201	1.975	2.201
Effect		-0.151		0.251		0.219		0.254		0.099		0.226		0.141	

Followed to above table

S. No	BC		BD		CD		ABC		ABD		ACD		BCD		ABCD	
	-1	+1	-1	+1	-1	+1	-1	+1	-1	+1	-1	+1	-1	+1	-1	+1
1		2.42		2.42		2.42	2.42		2.42		2.42		2.42			2.42
2		1.39		1.39		1.39		1.39		1.39		1.39	1.39		1.39	1.39
3	2.24		2.24			2.24		2.24		2.24	2.24			2.24	2.24	2.24
4	1.92		1.92			1.92	1.92		1.92			1.92		1.92		
5	1.63			1.63	1.63			1.63	1.63			1.63		1.63	1.63	1.63
6	1.92			1.92	1.92		1.92			1.92	1.92			1.92		
7		2.14	2.14		2.14		2.14			2.14		2.14	2.14			
8		2.03	2.03		2.03			2.03	2.03		2.03		2.03		2.03	
9		1.76	1.76		1.76		1.76			1.76		1.76		1.76	1.76	
10		2.03	2.03		2.03			2.03	2.03		2.03			2.03		2.03
11	2.25			2.25	2.25			2.25	2.25			2.25	2.25			2.25
12	1.82			1.82	1.82		1.82			1.82	1.82		1.82		1.82	
13	2.54		2.54			2.54		2.54		2.54	2.54		2.54			2.54
14	2.01		2.01			2.01	2.01		2.01			2.01	2.01		2.01	
15		2.33		2.33		2.33	2.33		2.33		2.33			2.33	2.33	
16		2.98		2.98		2.98		2.98		2.98		2.98		2.98		2.98
Average	2.412	2.135	2.083	2.092	1.947	2.228	2.04	2.136	2.077	2.098	2.166	2.01	2.075	2.101	1.901	2.185
Effect	-0.277		0.009		0.281		0.096		0.021		-0.156		0.026		0.284	

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Table 5 - Calculation for normal probability plot

Factor	Estimated effects (E)	Rank order (i)	Probability (P_i =100(i-0.5)/15)
BC	-0.277	1	3.33
ACD	-0.156	2	10
A	-0.151	3	16.67
BD	0.009	4	23.33
ABD	0.021	5	30
BCD	0.026	6	36.67
ABC	0.096	7	43.33
AB	0.099	8	50
AD	0.141	9	56.67
C	0.219	10	63.33
AC	0.226	11	70
B	0.251	12	76.67
D	0.254	13	83.33
CD	0.281	14	90
ABCD	0.284	15	96.67

Table 6 - ANOVA test results

S. No	Factors	Estimated effects (E)	Effects squared (E^2)	Degree of freedom	Mean square
1	A	-0.151	0.022801	1	0.022801
2	B	0.251	0.063001	1	0.063001
3	C	0.219	0.047961	1	0.047961
4	D	0.254	0.064516	1	0.064516
5	AB	0.099	0.009801	1	0.009801
6	AC	0.226	0.051076	1	0.051076
7	AD	0.141	0.019881	1	0.019881
8	BC	-0.277	0.076729	1	0.076729
9	BD	0.009	0.000081	1	0.000081
10	CD	0.281	0.078961	1	0.078961
Error			0.16468	5	0.032936

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Table 7 – Results of the confirmation trials and their comparison with the results

	Initial level	Optimal machining parameters for Ra	
		Prediction	Experimental
Setting levels	A(-1)B(-1)C(-1)D(-1)	A(+1)B(+1)C(-1)D(-1)	A(+1)B(+1)C(-1)D(-1)
Ra (µm)	2.42	2.481	1.92
Improvement in surface roughness = 0.5 µm			

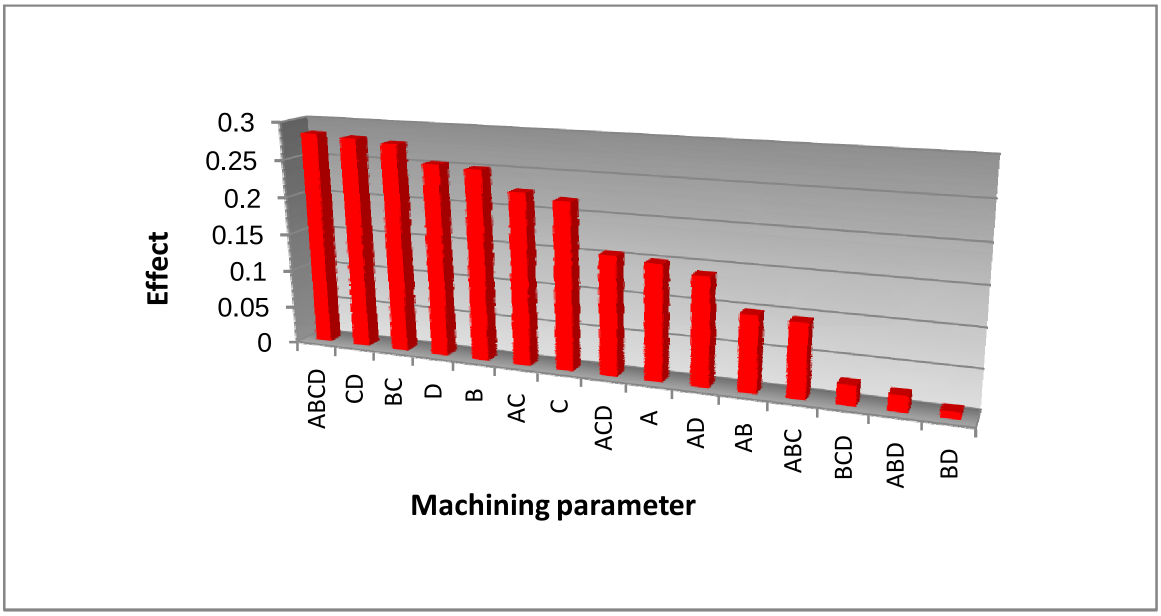

Fig. 1 Effect graph

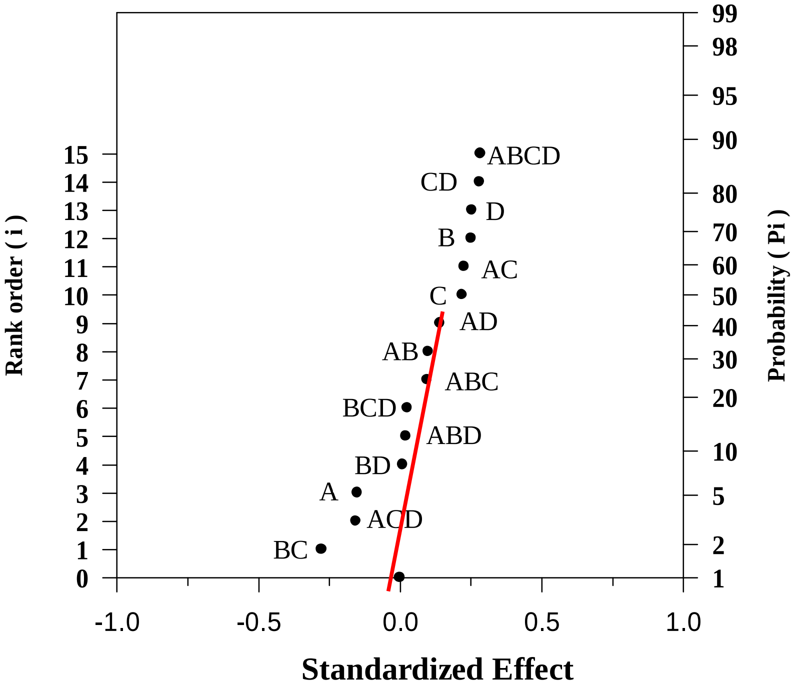

Fig. 2 Normal probability plot

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