

MULTI-OBJECTIVE OPTIMIZATION OF CUTTING PARAMETERS FOR SURFACE ROUGHNESS AND METAL REMOVAL RATE IN SURFACE GRINDING USING RESPONSE SURFACE METHODOLOGY

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ABSTRACT

Surface grinding is the most common process used in the manufacturing sector to produce smooth finish on flat surfaces. Surface quality and metal removal rate are the two important performance characteristics to be considered in the grinding process. The economics of the machining process is affected by several factors such as abrasive wheel grade, wheel speed, depth of cut, table speed and material properties. In this work, empirical models are developed for surface roughness and metal removal rate by considering wheel speed, table speed and depth of cut as control factors using response surface methodology. In this paper, Response surface methodology (RSM) has been applied to determine the optimum machining parameters leading to minimum surface roughness and maximum metal removal rate in Surface grinding process operation on EN24 steel. The second order mathematical models in terms of machining parameters were developed for metal removal rate (MRR) and Surface roughness on the basis of experimental results. The model selected for optimization has been validated with F-test. The adequacy of the models is tested on output responses have been established with analysis of variance (ANNOVA). An attempt has also been made to optimize cutting parameters using multi-objective characteristics for the developed prediction models using Response surface methodology (RSM)

KEYWORDS: Surface grinding, MRR, Surface roughness, RSM, Optimization.

I. INTRODUCTION

Grinding is a complex machining process with lot of interactive parameters, which depend upon the grinding type and requirements of products. The surface quality produced in surface grinding is influenced by various parameters given as follows .(i) Wheel parameters: abrasives, grain size, grade, structure, binder, shape and dimension, etc.(ii) Work piece parameters: fracture mode, mechanical properties, and chemical composition, etc.(iii) Process parameters: wheel speed, depth of cut, table speed, and dressing condition, etc.(iv) Machine parameters: static and dynamic characteristics, spindle system, and table system, etc.[1] surface roughness is an performance index to meet the technical standards and customer satisfaction this performance index depends on various machining parameters. The selection of proper combination of machining parameters yields the desired surface finish and metal removal rate [2] the proper combination of machining parameters is an important task as it determines the optimal values of surface roughness and metal removal rate. It is necessary to develop mathematical models to predicate the influence of the operating conditions [3].

In the present work mathematical models has been developed to predicate the surface roughness and metal removal rate with the help of Response surface methodology, Design of experiments [30]. The Response surface methodology (RSM) is a practical, accurate and easy for implementation. The study of most important variables effecting the quality characteristics and a plan for conducting such experiments is called design of experiments(DOE) [31].The experimental data is used to develop

mathematical models for second order models using regression methods. Analysis of variance is employed to verify the validity of the model. RSM optimization procedure has been employed to optimize the output responses, surface roughness and metal removal rate subjected to grinding parameters namely wheel speed, table speed and depth of cut using multi objective function model.

II. METHODOLOGY

In this work, experimental results were used for modeling using Response surface methodology, is a practical, accurate and easy for implementation. The experimental data was used to build first order and second order mathematical models by using regression analysis method. This developed mathematical models were optimized by using the RSM optimization procedure for the output responses by imposing lower and upper limit for the input machining parameters namely table speed, wheel speed, and depth of cut.

2.1 Design of Experiments (DOE)

The study of most important variables affecting quality characteristics and a plan for conducting such experiments is called the Design of Experiments. G.Taguchi (1959) of Japan, by developing the associated concept of linear graph, was able to devise numerous variants based on the OA design, which can easily be applied by an engineer or a scientist without acquiring advanced statistical knowledge for working out the design and analysis of even complicated experiments (Ross J. Philip, 1989). These methods have the advantage of being highly flexible and readily enable allocation of different levels of factors, even when these levels are not the same in number for all the factors studied [5]. The beauty of these methods lies in cutting to the bare minimum the size of experimentation. At the same time yielding results with high precision, thus, by a mere 27 experiments, we may be able to evaluate all the main effects. The Design layout in Taguchi's Method explained below:

1. List down the Response, Factors and levels along with the desired interactions.
2. Find the Degrees of Freedom for each factor and for each interaction.
3. Compute the Total Degrees of Freedom (TDF).
4. The minimum number of trials (MNE) is equal to total degrees of freedom Plus one (+1).
5. Choose the nearest orthogonal array series like: L4, L8, L16 or L9, L27, etc.
6. Draw the required Linear Graph (LG).
7. Number the linear Graph by starting with the Number 1 for factor A and Number 2 for factor B. Then check whether any interaction exists. If not, proceed with the Number 3 for factor C. If there is an interaction, check with the interaction Table, which Column is to be allotted to the interaction? Then Proceed with the next number for the next factor.
8. Complete the numbering as described until the following is achieved. All the factors and interactions are numbered. There is no repetition of numbers. The interaction numbers are as per the Interaction table. The numbers used do not exceed the number of columns permitted for the orthogonal array table.
9. Write the column numbers against each factor. That is the Design Assignment. Rewrite the OA Table with only those columns represented by factors and all the rows as per the OA Table. Replace the 1, 2 & 3 in the Table with the Physical value of the level from the Factors and Levels identified. This completes the Design Layout.

2.2 Response Surface Methodology (RSM)

Response Surface Methodology is combination of mathematical and statistical technique [30-31], used develop the mathematical model for analysis and optimization. By conducting experiment trails and applying the regression analysis, the output responses can be expressed in terms of input machining parameters namely table speed, depth of cut and wheel speed. The major steps in Response Surface Methodology are

1. Identification of predominate factors which influences the surface roughness, Metal removal rate.
2. Developing the experimental design matrix, conducting the experiments as per the above design matrix.

3. Developing the mathematical model.
4. Determination of constant coefficients of the developed model.
5. Testing the significance of the coefficients.
6. Adequacy test for the developed model by using analysis of variance (ANNOVA).
7. Analyzing the effect of input machining parameters on output responses, surface roughness and metal removal rate

III. MATHEMATICAL FORMULATION

The first order and second order Mathematical models were developed using multiple regression analysis for both the output responses namely surface roughness and metal removal rate. Multiple regression analysis [17-22] is a statistical technique, practical, easy to use and accurate. The aim of developing the mathematical models is to relate the output responses with the input machining parameters and there by optimization of the machining process. By using these models, optimization problem can be solved by using Taghis optimization procedure as multi objective function model. The mathematical models can be represented by

$$Y = f(V, N, d) \quad (1)$$

Where Y is the output grinding response, V, N, d are the table speed, wheel speed, depth of cut respectively

In this work the following mathematical models were formulated.

$$\text{Metal removal rate, } MRR = K_1 V^{a_1} N^{b_1} d^{c_1} e \quad (2)$$

$$\text{Surface roughness, } Ra = K_2 V^{a_2} N^{b_2} d^{c_2} e \quad (3)$$

To determine the above constants and exponents, this mathematical model have to be linearised by performing the logarithmic transformation which as follows

$$\ln MRR = \ln k_1 + a_1 \ln V + b_1 \ln N + c_1 \ln d \quad (4)$$

$$\ln Ra = \ln k_2 + a_2 \ln V + b_2 \ln N + c_2 \ln d \quad (5)$$

The constant and exponents can be determined by the method of least squares. The first order and second order linear models, develop from the above functional relationship using the least square regression analysis can be represented as follows

$$Y_1 = Y - e = b_0 x_0 + b_1 x_1 + b_2 x_2 + b_3 x_3 \quad (6)$$

Where Y_1 is first order output response of metal removal rate, Y is the measured metal removal rate, x_1, x_2, x_3 are the logarithmic transformations of table speed, wheel speed, depth of cut, respectively.

The second order polynomial of output response will be given as

$$Y_2 = Y - e = b_0 x_0 + b_1 x_1 + b_2 x_2 + b_3 x_3 + b_{12} x_1 x_2 + b_{13} x_1 x_3 + b_{23} x_2 x_3 + b_{11} x_1^2 + b_{22} x_2^2 + b_{33} x_3^2 \quad (7)$$

Where Y_2 is second order output response of metal removal rate Y is the measured metal removal rate, $b_0, b_1, b_2, b_3, b_{12}, b_{13}, b_{23}, b_{11}, b_{22}, b_{33}$ are estimated by the method of lest squares. The validity of this mathematical model will be tested using F test, Chi-Square test before going for optimization.

IV. EXPERIMENTAL DETAILS

A set of experiments were conducted on surface grinding machine to determine effect of machining parameters namely table speed(m/min),wheel speed(RPM),depth of cut(mm) on output responses namely surface roughness and metal removal rate. The machining conditions were listed in table 1.Three levels and three factors used to design the orthogonal array by using design of experiments(DOE) and relevant ranges of parameters as shown in Table 2.Grinding wheel used for the present work is the aluminum oxide abrasives with vitrified bond, WA 60K5V is used. The selected L_{27} orthogonal array to conduct the experiments is shown in the Table 3 along with the output responses, MRR and surface roughness. MRR was calculated as the ratio of volume of material removed from the work piece to the machining time. The surface roughness, Ra was measured in perpendicular to the cutting direction using with Surface Roughness tester SJ-201 at 0.8mm cutoff value. An average of six measurements was taken at six different places to record the output response, surface roughness. These results will be further used to analyze the effect of input machining parameters on output responses with the help of RSM and design expert software.

Table 1 Machining conditions

- (a) Work piece material: EN 24 steel
- (b) Chemical composition: Carbon 0.35-0.45/ Silicon 0.10-0.35/ Manganese 0.45-0.70/ Nickel 1.30-1.80 / Chromium 0.90-1.40/ Moly 0.20-0.35/ Sulphur 0.050 (max)/ Phosphorous 0.050(max) and balance Fe
- (c) Work piece dimensions: 155mm x 38mm x 38mm
- (d) Physical properties: Hardness-201BHN, Density-7.85 gm/cc,
Tensile Strength-620 Mpa
- (e) Grinding wheel: Aluminum oxide abrasives with vitrified bond wheel WA 60K5V
- (f) Grinding wheel size :250 mm ODX25 mm widthx76.2 mm ID

Table 2 Levels of independent control factors

S.No	Control Factor	Symbol	Levels of factors			Unit
			-1	0	+1	
1	Wheel speed	N	1250	1650	2050	RPM
2	Table speed	V	7.5	10	12.5	m/min
3	Depth of cut	d	5	10	15	μm

Table 3 Experimental observations

Trail no	Wheelspeed (N)(RPM)	Table speed (V)(m/min)	Depth of cut (d)(μm)	Surface Roughness (Ra)(μm)	Metal Removal rate (gm/min)
1	1250	7.50	5	1.034	5.510
2	1250	7.50	10	1.440	10.28
3	1250	7.50	15	1.624	15.505
4	1250	10.0	5	1.324	7.350
5	1250	10.0	10	1.591	13.28
6	1250	10.0	15	1.721	22.07
7	1250	12.5	5	1.38	9.190
8	1250	12.5	10	1.679	16.89
9	1250	12.5	15	1.940	26.09
10	1650	7.50	5	1.180	6.260
11	1650	7.50	10	1.56	13.13
12	1650	7.50	15	1.684	17.68
13	1650	10.0	5	1.490	11.63
14	1650	10.0	10	1.641	15.61
15	1650	10.0	15	1.716	21.17
16	1650	12.5	5	1.501	12.42
17	1650	12.5	10	1.697	18.17
18	1650	12.5	15	1.826	25.87
19	2050	7.50	5	1.361	7.760
20	2050	7.50	10	1.582	13.21
21	2050	7.50	15	1.703	19.40
22	2050	10.0	5	1.460	10.35
23	2050	10.0	10	1.632	15.16
24	2050	10.0	15	1.805	24.16
25	2050	12.5	5	1.513	12.64

26	2050	12.5	10	1.734	22.44
27	2050	12.5	15	2.072	30.44

V. DEVELOPMENT OF EMPIRICAL MODELS

In the present study, Empirical models of second order for the output responses, Surface roughness (Ra), Metal removal rate (MRR) in terms of input machining parameters in actual factors were developed by using the RSM [23-27]. The developed models are further used for optimization of the machining process. To determine the regression coefficients of the developed model, the Statistical analysis software, MINITAB, 16V is used. The second order models were developed for output responses due to lower predictability of the first order model to the present problem. The following equations were obtained in terms of uncoded factors

$$R_a = -0.4485 + 0.0005N + 0.1236V + 0.0975d - 0.0022V^2 - 0.0017d^2 - 0.00002NV - 0.000013Nd + 0.000053Vd \quad (8)$$

$$MRR = -0.9022 + 0.0023N - 0.3760V - 0.20041d - 0.000001N^2 + 0.0118V^2 + 0.0203d^2 + 0.00036NV + 0.00007Nd + 0.1006Vd \quad (9)$$

Analysis of variance (ANNOVA) is employed to test the significance of the developed models. The multiple regression coefficients of the second order model for surface roughness and metal removal rate were found 0.9325 and 0.9781 respectively. The R^2 values are very high, close to one, it indicates that the second order models were adequate to represent the machining process. The "Pred R-Squared" of 0.8027 is in reasonable agreement with the "Adj R-Squared" of 0.8967 in case of surface roughness. The "Pred R-Squared" of 0.9498 is in reasonable agreement with the "Adj R-Squared" of 0.9666 in case of MRR. Similarly, The Model F-value of 26.09 for surface roughness and The Model F-value of 84.51 for metal removal rate implies the model is significant. There is only a 0.01% chance that a "Model F-Value" this large could occur due to noise. The analysis of variance (ANNOVA) of response surface quadratic model for surface roughness and metal removal rate were shown in Table 4 and Table 5 respectively. Adeq Precision" measures the signal to noise ratio. A ratio greater than 4 is desirable. S/N ratio of 18.415 & 32.54 for surface roughness and MRR indicates an adequate signal. This model can be used to navigate the design space. The P value for both the models is lower than 0.05 (at 95% confidence level) indicates that the both the models were considered to be statistically significant. The normal probability plots of residuals for Ra and metal removal rate are shown in the fig 1 and fig 2 respectively. From these plots, it can be concluding that the residuals lies on a straight line which implies that the errors are distributed normally and the developed regression models are well fitted with the observed values. The Plot of Predicted versus actual response for surface roughness and MRR are shown in the fig 3 and fig 4 respectively and show that the models are adequate without any violation of independence or constant assumption.

Table 4 ANOVA for Response Surface Quadratic Model of Ra

Source	Sum of Squares	df	Mean Square	F Value	p-value
Model	1.18	9	0.13	26.09	0.0001
N	0.071	1	0.071	14.09	0.0016
V	0.26	1	0.26	52.24	< 0.0001
d	0.82	1	0.82	163.66	< 0.0001
NV	4.332E-003	1	4.332E-003	0.86	0.3662
Nd	7.550E-003	1	7.550E-003	1.50	0.2371
Vd	5.333E-006	1	5.333E-006	1.061E-003	0.9744
N^2	4.603E-007	1	4.630E-007	9.211E-005	0.9925
V^2	1.157E-003	1	1.157E-003	0.23	0.6374

d ²	0.011	1	0.011	2.23	0.1537
Residual	0.085	17	5.026E-003		
Cor.Total	1.27	26			
Std.Dev.	0.071		R-Squared	0.9325	
Mean	1.59		Adj R-Squared	0.8967	
C.V	4.46		Pred R-Squared	0.8027	
PRESS	0.25		Adeq Precision	18.415	

Table 5 ANOVA for Response Surface Quadratic Model of MRR

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob>F
Model	1098.50	9	122.06	84.51	< 0.0001
N	48.00	1	48	33.24	< 0.0001
V	237.73	1	237.73	164.61	< 0.0001
d	790.36	1	790.36	547.25	< 0.0001
NV	1.52	1	1.52	1.05	0.3189
Nd	0.22	1	0.22	0.15	0.6994
Vd	18.99	1	18.99	13.15	0.0021
N ²	0.086	1	0.086	0.060	0.8101
V ²	0.033	1	0.033	0.023	0.8825
d ²	1.55	1	1.55	1.07	0.3144
Residual	24.55	17	1.44		
Cor.Total	1123.05	26			
Std.Dev.		1.2		R-Squared	0.9781
Mean		15.69		Adj R-Squared	0.9666
C.V		7.66		Pred R-Squared	0.9498
PRESS		56.37		Adeq Precision	32.524

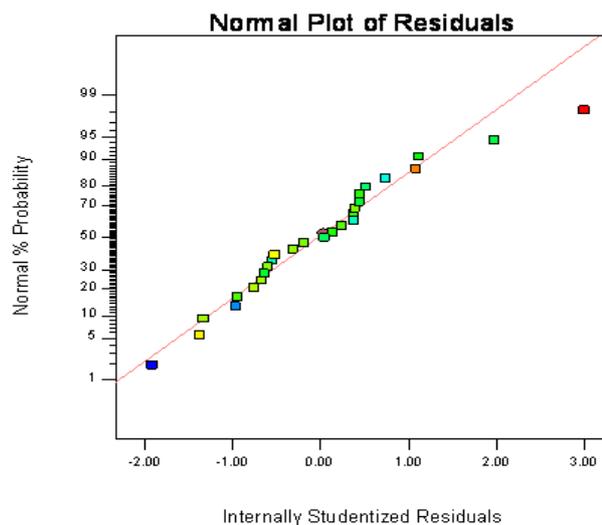


Figure 1. Normal probability plot of residuals for Ra

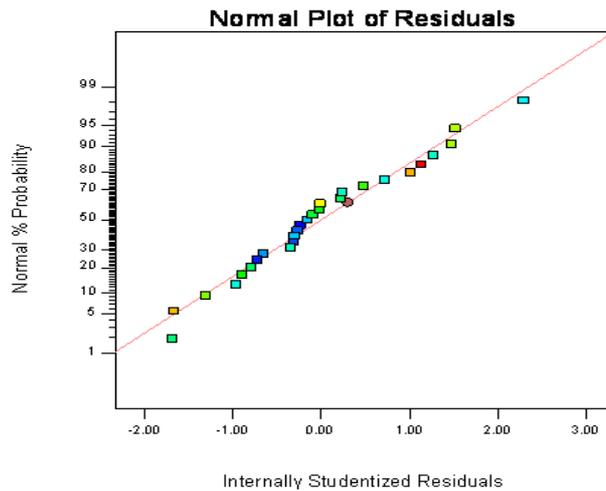


Figure 2. Normal probability plot of residuals for MRR

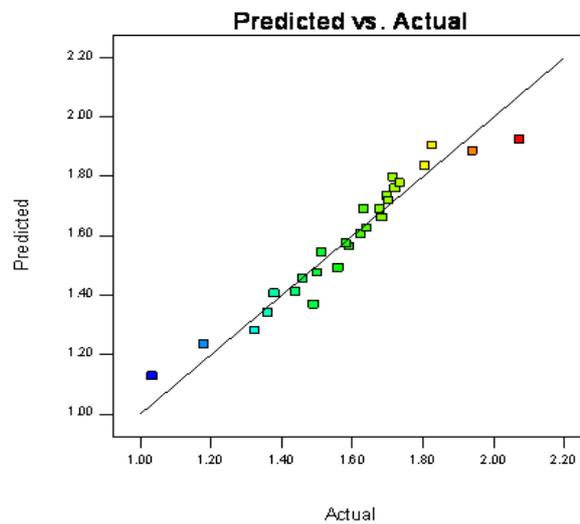


Figure 3. Comparison of Predicted and actual values for Ra

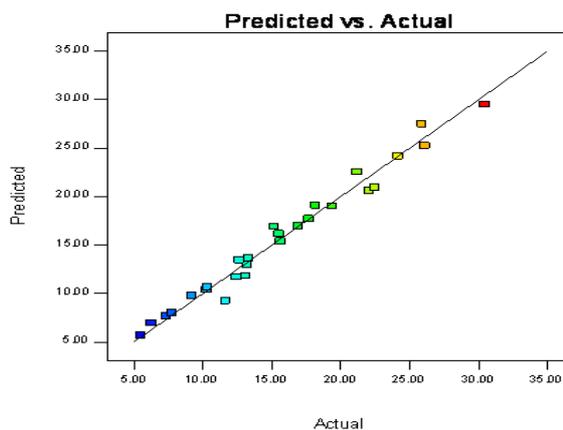


Figure 4. Comparison of Predicted and actual values for MRR

VI. INTERPRETATION OF DEVELOPED MODELS

The detailed main effects and interaction effects for both the outputs are discussed in the following sections. It should be noted that if a particular parameter does not influence the output during the course of evaluation, it gets eliminated.

6.1 Effect of process parameters on surface roughness (Ra)

6.1.1 Direct effects

The direct effect of process parameters on output response, surface roughness is shown in figs 5 to 7. From Fig. 5, it is observed that increase in wheel speed tends to improve the finish. With carbide tools particularly, slow speed is not at all desirable since it means wastage of time and money and tools wear out faster. Fig. 6 shows the effect of table speed on roughness. As the table speed increases, finish gets poorest because the tool marks show on the work piece. The effect of depth of cut on surface roughness is shown in Fig. 7. It is noted from Fig. 7, that the increase in depth of cut makes the finish poor. Hence smaller values of table speed and depth of cut and larger value of wheel speed must be selected in order to achieve better surface roughness during the process.

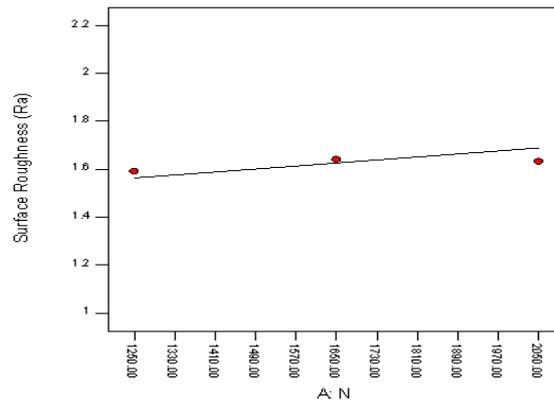


Figure 5. Direct effect of wheel speed on Ra

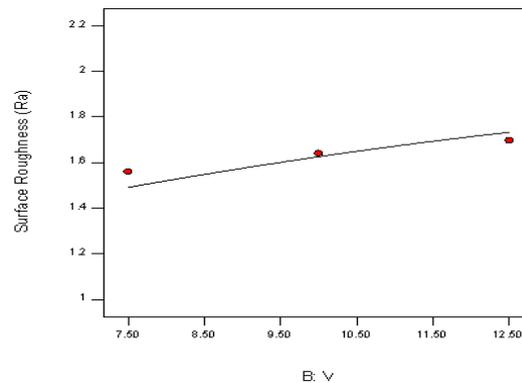


Figure 6. Direct effect of table speed on Ra

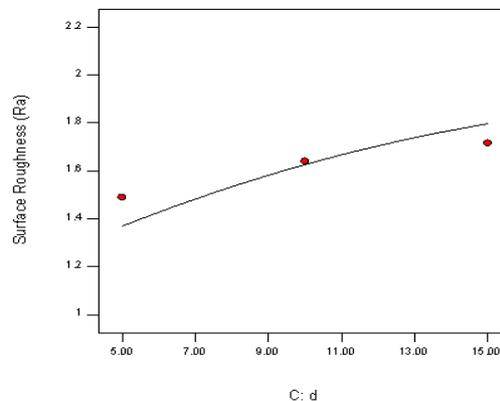


Figure 7. Direct effect of depth of cut on Ra

6.1.2 Interaction effects

The three dimensional surface plots for the surface roughness are shown in figs 8-10. In each of these graphs, two cutting parameters are varied while the third parameter is held as its mid value. From fig 8, it is observed that best surface roughness was obtained at the lowest depth of cut and low wheel speed combination. The surface roughness results also indicate a poor surface finish for a lower depth of cut at a lower wheel speed. This behavior is due to the plugging action of the tool on the work piece surface at lower depth of cut. It is seen from these graphs that there is significant amount of curvature indicating non –linearity in the variation. From fig 9, it is observed that best surface roughness is obtained at low depth of cut and low table speed. The 3d surface graph of Ra at constant depth of cut of 10 microns is shown in fig 10. From these graphs it is observed that there is switching of the curvature effect. It indicates that the reversal in behavior depending on the combination of the machining parameters. It also points towards significant contribution from the interaction of the machining parameters.

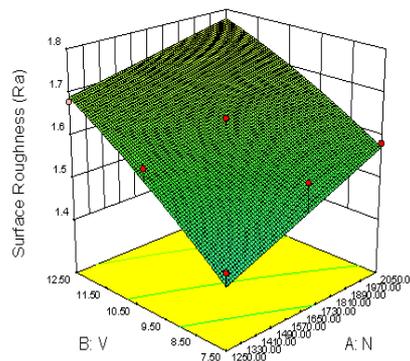


Figure 8. Interaction effect of wheel speed and depth of cut on Ra

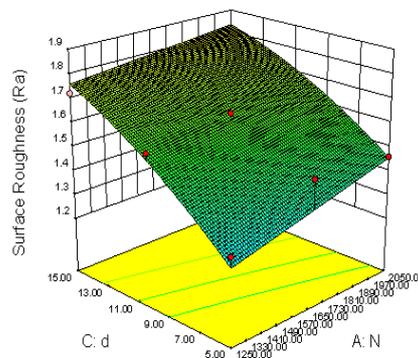


Figure 9. Interaction effect of depth of cut speed and table speed on Ra.

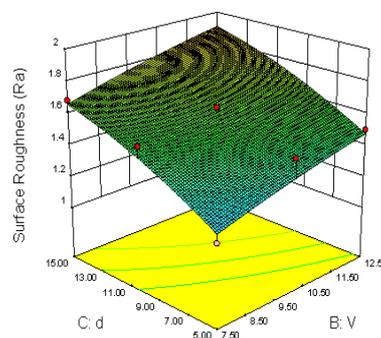


Figure 10. Interaction effect of wheel speed and table speed on Ra.

6.2 Effect of Process parameters on MRR

6.2.1 Direct effects

The direct effect of process parameters on output response, surface roughness is shown in Figs 11 to 13. From Fig. 11, it is observed that increase in wheel speed tends to increase the MRR; where as the other two machining parameters are kept at its mid value. It is observed from the direct effects, depth of cut plays more vital role on MRR than other two parameters. Material removal rate in machining process is an important factor because of its vital effect on the industrial economy. Increasing the table speed, wheel speed and depth of cut leads to an increase in the amount of Material removal rate. But the most influential factors are table speed, and depth of cut. The highest value of MRR is obtained at the extreme range of the input parameters in all the interaction plots. Also the MRR increases gradually with the depth of cut.

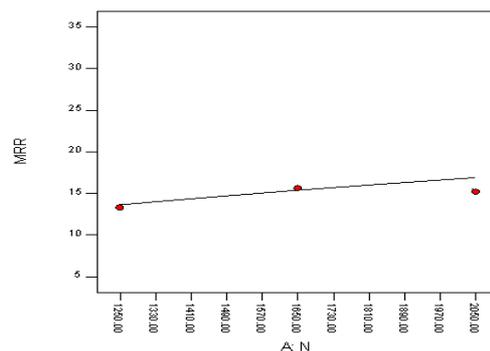


Figure 11. Direct effect of wheel speed on MRR

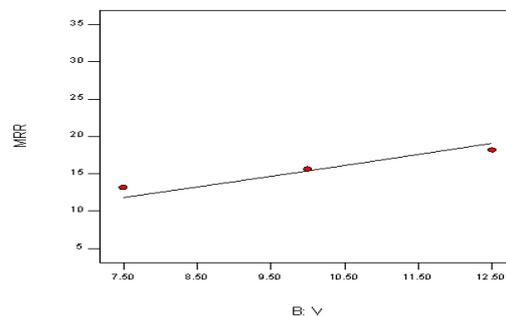


Figure 12. Direct effect of Table speed on MRR

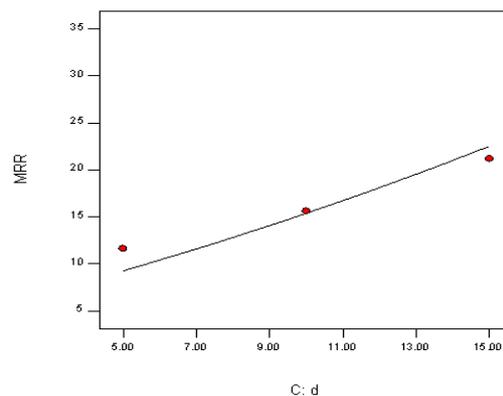


Figure 13. Direct effect of depth of cut on MRR

6.2.2 Interaction effects

The 3D surface graphs for metal removal rate are shown in the fig 14 to 16 and shows that the graphs are curvilinear profile as the empirical model developed is quadratic. In each of these graphs, two cutting parameters are varied while the third parameter is held as its mid value. From fig 14, it is

observed that best surface roughness was obtained at the lowest depth of cut and low wheel speed combination. The surface roughness results also indicate a poor surface finish for a lower depth of cut at a lower wheel speed. This behavior is due to the plugging action of the tool on the work piece surface at lower depth of cut. It is seen from these graphs that there is significant amount of curvature indicating non –linearity in the variation. From these graphs it is observed that there is switching of the curvature effect. It indicates that the reversal in behavior depending on the combination of the machining parameters. It also points towards significant contribution from the interaction of the machining parameters.

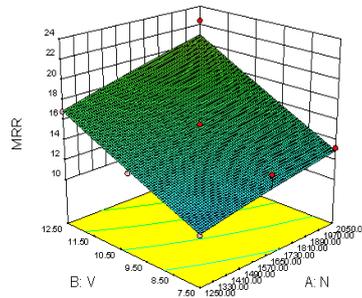


Figure 14. Interaction effect of wheel speed and table speed on MRR

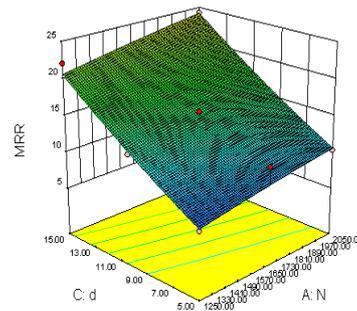


Figure 15. Interaction effect of wheel speed and depth of cut on MRR

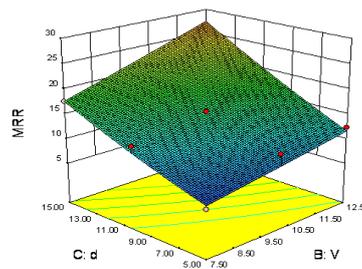


Figure 16. Interaction effect of table speed and depth of cut on MRR

VII. FORMULATION OF THE PROBLEM

In the process of optimization, the aim is to maximize the MRR and minimize the surface roughness (R_a), which forms the multi objective optimisation problem and these two are conflicting in nature [24]. The optimization problem for MRR and surface roughness (R_a) with feasible limits of control variables are represented in the equations (9) and (10) respectively after eliminating the insignificant terms.

Minimize

$$R_a = -0.4485 + 0.0005N + 0.1236V + 0.0975d - 0.0022V^2 - 0.0017d^2 - 0.00002NV - 0.000013Nd + 0.000053Vd \quad (10)$$

Maximize

$$MRR = -0.9022 + 0.0023N - 0.3760V - 0.20041d - 0.000001N^2 + 0.0118V^2 + 0.020d^2 + 0.00036NV + 0.00007Nd + 0.1006Vd \quad (11)$$

Subjected to

$$1250 \text{ RPM} \leq N \leq 2050 \text{ RPM}$$

$$7.5 \text{ m/min} \leq V \leq 12.5 \text{ m/min}$$

$$5 \mu\text{m} \leq d \leq 15 \mu\text{m}$$

Once the optimization problem is formulated, then it is solved using a Response surface optimisation.

VIII. OPTIMIZATION OF THE PROBLEM

Optimization of machining parameters increases the utility for machining economics, a response surface optimization is attempted using Minitab software for individual machining parameters in surface grinding. Table 6 shows the RSM optimization results for the surface roughness and MRR parameters in surface grinding. It also includes the results from confirmation experiments conducted with the optimum conditions.

Table 6 RSM optimization for output responses

Parameter	Objective Function	Optimum combination			Predicted response	Expected Value	% of error
		N	V	d			
Ra	Min	1250	7.5	5	1.128	1.034	8.3
MRR	Max	2050	12.5	15	29.48	30.44	3.25

IX. RESULTS

The optimum results for the output responses namely surface roughness and Metal removal rate in terms of machining parameters namely wheel speed, table speed and depth of cut on EN 24 steel on CNC surface grinding machine using Minitab software were determined and presented in Table 6. The confirmation experiments were conducted and there is a good agreement between predicted and experimental values. It is found that the error in prediction of the optimum conditions is about 3 to 8%. Thus the response optimization predicts the optimum conditions fairly well.

X. Conclusions

In this study an experimental investigation performed to evaluate the surface roughness and MRR parameters of EN 24 steel in surface grinding operation has been presented. A plan of experiments has been prepared in order to test the influence of cutting speed, feed rate and depth of cut on the output parameters. The obtained data have been statistically processed using response surface method. The empirical models of output parameters are established and tested through the analysis of variance to validate the adequacy of the models. It is found that the surface roughness and MRR parameters greatly depend on work piece materials. A response surface optimization is attempted using Minitab software for output responses in surface grinding.

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