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PREDICTION OF SURFACE ROUGHNESS IN END MILLING OPERATION OF DUPLEX STAINLESS STEEL USING RESPONSE SURFACE METHODOLOGY

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Abstract

Response surface methodology has been used to study the effects of the machining parameters such as spindle speed, feed rate and axial depth of cut on surface roughness of duplex stainless steel in end milling operation. Dry milling experiments were conducted with three levels of spindle speed, feed rate and axial depth of cut. A mathematical model has been developed to predict the surface roughness in terms of the machining parameters using Box-Behnken design response surface methodology. The adequacy of the model was verified using analysis of variance. The prediction equation shows that the feed rate is the most important factor that influences the surface roughness followed by axial depth of cut and spindle speed. The validity of the model was verified by conducting the confirmation experiment.

Keywords: Duplex stainless steel, Surface roughness, End milling, Response surface methodology, Box-Behnken design.

1. Introduction

Stainless steels are excellent corrosion resistance materials. They possess high mechanical properties, wide range of strength levels and good formability with aesthetically pleasing appearance. Duplex stainless steels (DSS) are chromium-nickel-molybdenum alloys that are balanced to contain a mixture of austenite and ferrite. The DSS alloys offer two important advantages over austenitic stainless steel alloys, namely greater resistance to chloride stress corrosion cracking resistance and higher mechanical properties. DSS also have better toughness and ductility, compared

Nomenclatures

A	First factor - Spindle speed in rpm
Adeq.Precision	Adequate Precision
Adj.R^2	Adjusted *R* squared
B	Second factor - Feed rate in mm/min
C	Third factor - Axial depth of cut in mm
Cor.total	Totals of all information corrected for the mean
d.f.	Degree of freedom
F	A statistical parameter
Prob.>F	Probability you would expect to get the stated *F* value
Pre.R^2	Predicted *R* squared
Ra	Arithmetic mean surface roughness
R^2	Coefficient of determination

Greek Symbols

σ	Stdandard Deviation
ε	Error term

Abbreviations

BBD	Box-Behnken Design
CV	Coefficient of variation
MS	Mean square
PRESS	Predicted residual error sum of square
SS	Sum of square

with ferritic stainless steels. The properties of DSSs are achieved with overall lower alloy content than similar-performing super-austenitic grades, making their use cost-effective for many applications [1]. DSSs are extensively being used in many industrial sectors like chemical and petrochemical, offshore, desalination, oil and gas industry, pollution control equipment, chemical tankers, pressure vessels, storage tanks, machinery in the pulp and paper industry, marine industry and also in civil engineering applications [1-4]. The machinability of stainless steel alloy is generally considered to be poor due to low thermal conductivity, more built up edge (BUE) formation tendency and high work hardening rate [5-7]. Hence machining stainless steel presents a major challenge for the machine tool industries.

Sai et al. [4] investigated the residual stresses, microstructure, surface roughness and micro hardness of carbon steels and DSS materials during milling operations. They found that high cutting speed with less feed rate improved the quality of the machining surface. The surface quality was reduced at lower cutting speed due to formation of BUE. The active wear and failure mechanism of hot isostatic pressed (HIPed) P/M Duplok 27 and conventionally produced stainless steel ASTM A81901A during drilling operation was investigated by Paro et al. [8]. In P/M produced DSS there are more hard oxide particles causing machining difficulties from the wear point of view. High strength and work hardening rate also cause difficulties from the machining point of view. The machinabilty of Duplok 27 and ASTM A81901A stainless steel were affected by the formation of BUE. Similarly, Selvaraj et al. [9] investigated the influence of cutting speed, feed rate and bulk texture on surface roughness of ASTM A 995 grade 4A and 5A

DSSs using coated carbide cutting tools in dry turning operation. With increasing cutting speed, surface roughness values decreased until a minimum value and then increased. Better surface finish was noticed at lower feed rate than in higher feed rate. Grade 4A yielded better surface finish at all cutting speeds and feed rates employed than in grade 5A which was attributed to the presence of partial fiber texture in the austenite phase of 4A work piece material. In another work, Krolczyk et al. [10] used response surface methodology (RSM) method to predict surface roughness of DSS in dry turning process. They found that feed rate was the main influencing factor on the surface roughness.

Response surface methodology is a collection of statistical and mathematical methods that are useful for modelling the relationship between the input process parameters and the output response [11]. Two types of RSM are used for experimentation. They are Rotational central composite design (RCCD) and Box-Behnken design (BBD). BBD is normally used when performing non sequential experiments. That is, performing the experiments only once [12, 13]. BBD has the advantage of requiring fewer experiments than RCCD and full factorial design. The various steps of RSM are as follows [13, 14]:

1. Identifying the important influencing factors for the response;
2. Developing the experimental design matrix;
3. Conducting the experiments as per the design matrix;
4. Measuring and recording the response;
5. Developing the mathematical prediction model;
6. Checking the adequacy of the model by analysis of variance method;
7. Analysing the effect of different parameters on the response.

Many researchers have been applied the RSM model to study the effects of various input parameters on surface roughness of different processes such as milling, turning, drilling, electrical discharge machining, flow forming and foam cup moulding, etc.

Mansour et al. [15] developed a mathematical model for the surface roughness using RSM in face milling of EN32 (160 BHN). They reported that an increase in either the feed or the axial depth of cut increases the surface roughness, where as an increase in the cutting speed decreases the surface roughness. Similarly, Wang et al. [16] analysed the influence of cutting condition and tool geometry on surface roughness when slot end milling of Al 2014-T6. They developed a surface roughness model for both dry cutting and coolant conditions using RSM. The significant factors affecting dry cut model were the cutting speed, feed, concavity and relief angles, while for the coolant model, they were feed and concavity angles. They found that surface roughness increases with the increase of feed, concavity and relief angles. Hossein et al. [17] developed first and second order cutting force equations using the RSM to study the effects of input parameters (cutting speed, feed rate, radial depth and axial depth of cut) on cutting force in end milling process. They reported that the most influential parameter was feed rate followed by axial depth, and radial depth of cut, and finally, the cutting speed. Sakthivel et al. [18] developed a mathematical model using RSM to predict the acceleration amplitude of vibration in terms of machining parameters such as helix angle of cutting tool, spindle speed, feed rate, and axial and radial depth of cut. They found that the helix angle, feed rate and axial depth of cut had a significant effect on acceleration amplitude. Similarly, Premnath et al. [19] developed RSM model to predict surface roughness during face milling of hybrid composites. They reported that cutting speed was the major factor influencing the surface roughness followed by feed and weight factor of Al_2O_3. The interaction of cutting speed and feed rate had greater influence compared to other interactions on surface roughness.

Palanikumar [14] attempted to model the surface roughness through RSM in turning glass fiber reinforced plastics composites. They reported that the surface roughness was decreased with the increase of cutting speed and depth of cut while it was increased with the increase of feed rate and fibre orientation angle. Babu et al. [13] developed an empirical second order model for predicting the surface roughness in dry turning EN 24 alloy steel using RSM. The cutting parameters, cutting speed, feed rate, and depth of cut were analysed and optimised using BBD. Their results reveal that the cutting speed has significant role in producing least surface roughness followed by feed rate and depth of cut. Ramesh et al. [20] studied the effect of cutting parameters on surface roughness in turning of titanium alloys using RSM. Their results reveal that the feed rate was the most influential factor which affects the surface roughness. The order of importance was feed rate, followed by depth of cut and cutting speed. Makadia et al. [21] studied the effect of feed rate, tool nose radius, cutting speed and depth of cut on the surface roughness of AISI 410 steel using RSM in turning. Their results reveal that surface roughness increases with the increase in the feed rate and decreases with the increase in the nose radius. Similarly, Davidson et al. [22] studied the effects of the flow-forming parameters such as speed of the mandrel, longitudinal feed, and amount of coolant used on the surface roughness of flow-formed AA 6061 alloy tube using RSM. Gu et al. [23] used BBD to determine the influence of machining parameters on the performance of electro discharge machining (EDM) of Ti6Al4V with a bundled electrode. Wu et al. [24] applied BBD to the optimisation of process parameters in foam cup moulding. They reported that this approach was scientific, reasonable, quick and efficient to optimise the process parameters

Overall study of various literatures cited above reveals that in case of alloy metals irrespective of machining process the cutting parameters that are influential with respect to surface roughness are cutting speed, feed rate and depth of cut. It is also observed that very limited research work has been carried out in machining of conventionally produced nitrogen alloyed DSS and more specifically in the end milling process. Hence, in the present study, an attempt has been made to develop a surface roughness prediction model in terms of the machining parameters such as spindle speed, feed rate and axial depth of cut in end milling process of nitrogen alloyed DSS using RSM. The mathematical model is used to study the effect of each parameter on the surface roughness.

2. Experimental Work

The machining experiments were carried out in a HMT FN1U semi automatic milling machine. The milling machine is equipped with 2.2 kW spindle motor and 0.75 kW feed motor. End milling operations were performed with a 20 mm diameter end mill cutter (TE90AX 220-09-L). TiCN coated tungsten carbide inserts (AXMT 0903 08 PER-EML TT8020) were used in the experiment. The end mill cutter has provision to fix two tool inserts. But only one insert is fixed for machining in the present work. For each experiment new tool insert is used. All the experiments were carried out with new tool inserts. Each experiment was carried out for a cutting length of 100 mm. The surface roughness parameter, arithmetic mean surface roughness (*Ra*) was measured using a TIME TR100 portable surface roughness tester. The tool insert and end mill cutter used in this experiment are shown in Figs. 1 and 2, respectively. The experiments were conducted without the application of cutting fluid (dry machining).

Fig. 1. AXMT 0903 08 PER-EML TT8020 tool insert.

Fig. 2. TE90AX 220-09-L end mill cutter.

The workpiece materials used for the experiments are ASTM A 995 grade 4A cast DSS. The dimensions of the work piece are 120 × 100 × 30 mm. The chemical composition and mechanical properties are given in Tables 1 and 2, respectively.

Table 1. Chemical composition of ASTM A 995 GRADE - 4A DSS (Wt %).

C	Si	Mn	S	P	Cr	Ni	Mo	Cu	N	Fe
0.028	0.65	0.71	0.006	0.027	22.16	5.66	3.33	0.14	0.24	Bal

Table 2. Mechanical properties of ASTM A 995 GRADE - 4A DSS.

Tensile Strength (MPa)	Yield Strength (MPa)	Elongation (%)	Hardness (BHN)
732	595	30.2	212

The three machining parameters selected for this study are *A*, first factor - spindle speed in rpm, *B,* second factor - feed rate in mm/min and *C*, third factor - axial depth of cut in mm. The machining parameters levels are selected based on the preliminary trial tests and recommendations given by tool and workpiece manufacturers. The machining parameters considered and their levels are shown in Table 3.

Table 3. Machining parameters and their level.

S.No	Factor	Low	High
1	Spindle speed (rpm)	500	1000
2	Feed rate (mm/min)	40	100
3	Depth of cut (mm)	0.4	1.2

3. Mathematical Model for Surface Roughness

3.1. Experimental design matrix

The BBD consists of 17 sets of experimental conditions. The experimental design allowed the estimation of the linear, quadratic and interactive effects of the process parameters on the surface roughness. The experiments were conducted as per the design matrix. The experimental results of surface roughness are given in Table 4.

Table 4. Experimental layout for the Box-Behnken design.

Run No.	Spindle speed (rpm)	Feed rate (mm/min)	Depth of cut (mm)	Surface roughness, *Ra* (μm)
1	500	70	0.40	0.74
2	750	100	0.40	0.87
3	750	40	1.20	0.72
4	1000	70	1.20	0.8
5	1000	40	0.80	0.6
6	500	40	0.80	0.72
7	500	70	1.20	0.92
8	750	70	0.80	0.69
9	750	100	1.20	0.99
10	1000	100	0.80	0.83
11	1000	70	0.40	0.59
12	750	40	0.40	0.55
13	750	70	0.80	0.69
14	500	100	0.80	0.98
15	750	70	0.80	0.71
16	750	70	0.80	0.67
17	750	70	0.80	0.69

3.2. Mathematical model

RSM quantifies the relationship between the measured response and the input factors. In this case, a non-linear relationship exists between the surface roughness and the input factors, namely spindle speed, feed rate and axial depth of cut. The quadratic equation representing the response surface for the factors is given in Eq. (1).

$$R_a = b_0 + b_1A + b_2B + b_3C + b_{11}A^2 + b_{22}B^2 + b_{33}C^2 + b_{12}AB + b_{13}AC + b_{23}BC + \varepsilon \quad (1)$$

Where, b_0 is constant, coefficients b_1, b_2 and b_3 are linear terms, coefficients b_{11}, b_{22} and b_{33} are second order terms, coefficients b_{12}, b_{13} and b_{23} are the interaction terms and ε is error term.

Statistical software Design Expert 7 Trial developed by Stat-Ease Inc was used to determine these coefficients. The mathematical model was developed in coded values for *Ra* is given in Eq. 2.

$$Ra = 0.69 - 0.068A + 0.14B + 0.085C - 0.0075AB + 0.0075AC - 0.012BC + 0.036A^2 + 0.056B^2 + 0.036C^2 \quad (2)$$

Where, *A*- spindle speed in rpm, *B*-feed rate in mm/min, c-depth of cut in mm and *Ra*- surface roughness parameter in µm. The mathematical model given in Eq. 2 can be used to predict the surface roughness by substituting the coded values of the respective process parameters.

4. Results and Discussion

4.1. Analysis of variance

The Analysis of variance (ANOVA) is commonly used to summarise the test for significance of the regression model and test for significant on individual model coefficients. The model summary statistics is shown in Table 5. From Table 5, coefficient of determination, adjusted *R* squared and predicted *R* squared values are higher for quadratic model. So, this model was suggested for further analysis.

Table 5. Model summary statistics.

Source	σ	R^2	Adj. R^2	Pred. R^2	PRESS	
Linear	0.049	0.8842	0.8575	0.8256	0.047	
2FI	0.055	0.8881	0.8210	0.7081	0.079	
Quadratic	0.022	0.9878	0.9722	0.8481	0.041	Suggested

Table 6 shows the ANOVA table for the response surface quadratic model for surface roughness. The Model F-value of 63.21implies the model is significant.

Table 6. ANOVA table for response surface model for surface roughness.

Source	S.S	d.f.	M.S.	*F* Value	Prob > *F*
Model	0.27	9	0.030	63.21	< 0.0001
A	0.036	1	0.036	77.32	< 0.0001
B	0.15	1	0.15	309.27	< 0.0001
C	0.058	1	0.058	122.61	< 0.0001
AB	2.250E-004	1	2.250E-004	0.48	0.5119
AC	2.250E-004	1	2.250E-004	0.48	0.5119
BC	6.250E-004	1	6.250E-004	1.33	0.2874
A^2	5.533E-003	1	5.533E-003	11.74	0.0110
B^2	0.013	1	0.013	28.26	0.0011
C^2	5.533E-003	1	5.533E-003	11.74	0.0110
Residual	3.300E-003	7	4.714E-004		
Cor Total	0.27	16			

There is only a 0.01% chance that a "Model *F*-Value" this large could occur due to noise. Values of *"Prob. > F"* less than 0.05 indicate model terms are significant. From Table 6, it can be observed that the linear model terms (*A, B* and *C*) and quadratic model terms (A^2, B^2 and C^2) are significant. There are not many insignificant model terms noticed in this analysis and hence there is no need for model reduction and improvement of the model.

Table 7 shows the regression statistics. The co-efficient of determination is high, close to 1, which is desirable. The " *Pre.*R^2" of 0.8481is in reasonable agreement with the " *Adj.*R^2 " of 0.9722. *"Adeq. Precision"* measures the signal to noise ratio. A ratio greater than 4 is desirable. In this case the ratio of 26.572 indicates an adequate signal. This model can be used to navigate the design space.

Table 7. Regression statistics.

Parameters	Values
σ	0.022
Mean	0.75
CV	2.89
PRESS	0.041
R^2	0.9878
Adj. R^2	0.9722
Pre. R^2	0.8481
Adeq. Precision	26.572

The adequacy of the model has also been investigated by the examination of residuals [11]. The residuals are examined using the normal probability plots of the residuals and the plot of the residuals versus the predicted response. The normal probability plots of the residuals and the plots of the residuals versus the predicted responses for the *Ra* values are shown in Figs. 3 and 4, respectively. Figure 3 revealed that the residuals generally fall on a straight line implying that the errors are distributed normally. Also Fig. 4 revealed that they have no obvious pattern and unusual structure. This implies that the model proposed is adequate and there is no reason to suspect any violation of the independence or constant variance assumptions [22, 25].

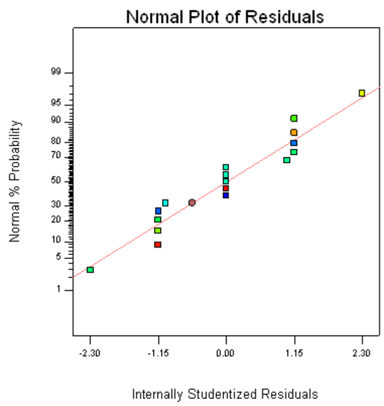

Fig. 3. Normal probability plot of residuals for surface roughness, *Ra*.

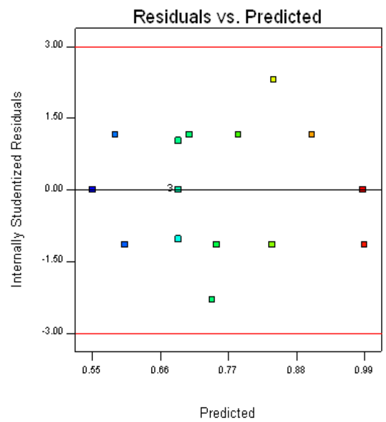

Fig. 4. Plot of residuals vs. predicted surface roughness, *Ra*.

4.2. Main effect of spindle speed on surface roughness

Figure 5 represents the main effect of spindle speed on surface roughness. From Fig. 5, it can be observed that the surface roughness decreases as the spindle speed is increased from 500 to 1000 rpm. At higher spindle speed, BUE formation tendency is decreased, more heat is carried away by the chip and less heat is dissipated to the workpiece. Hence, the surface roughness is decreased. The spindle speed should be kept at high level (1000 rpm) to achieve minimum surface roughness.

4.3. Main effect of feed rate on surface roughness

Figure 6 represents the main effect of feed rate on surface roughness. From Fig. 6, it is observed that surface roughness decreases with decrease in feed rate. Hence, the feed rate should be kept at low level (40 mm/min) to achieve better surface finish. Increase in feed rate increases the area of contact between tool and workpiece. It increases the cutting forces and promotes higher values of surface roughness on the workpiece surface.

4.4. Main effect of axial depth of cut on surface roughness

Figure 7 represents the main effect of axial depth of cut on surface roughness. From Fig. 7, it is observed that the surface roughness increases as the axial depth of cut is increased from 0.4 mm to 1.2 mm. The increase in depth of cut increases chip cross-sectional area and volume of material removal. Due to these cutting force and chatter are increased. Hence, the surface roughness is increased. The depth of cut should be kept at low level (0.4 mm) to achieve minimum surface roughness.

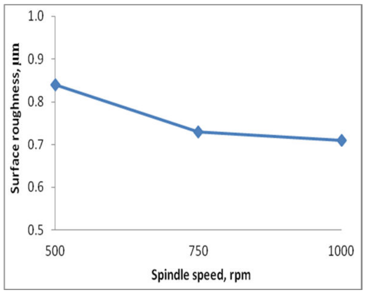

Fig. 5. Main effect of spindle speed on surface roughness, *Ra*.

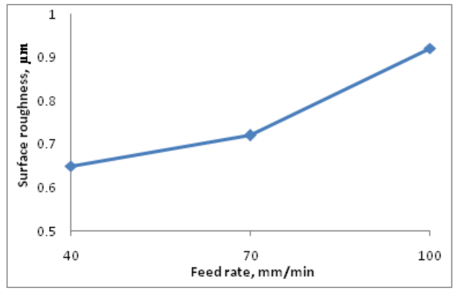

Fig. 6. Main effect of feed rate on surface roughness, *Ra*.

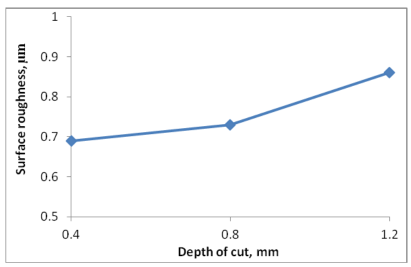

Fig. 7. Main effect of depth of cut on surface roughness, *Ra*.

4.5. Interaction effect of spindle speed and feed rate on surface roughness

Figure 8 shows the 3D surface graph for the surface roughness, as the spindle speed and the feed rate varies and the axial depth of cut kept at 0.8 mm. From Fig. 8, the surface roughness decreases for all the three feed rates as the spindle speed is increased from 500 to 1000 rpm. This decreasing trend is not changed in all three levels of feed rate. Hence the interaction effect of spindle speed and feed rate is less significant. From the response surface plot, it is noted that the surface roughness reaches a maximum of 0.99 µm when the spindle speed is at 500 rpm and the feed rate is at 100 mm/min. It reaches a minimum of 0.59 µm when the spindle speed is at 1000 rpm and the feed rate is at 40 mm/min. High level spindle speed combined with low level feed rate gives optimum surface roughness.

4.6. Interaction effect of spindle speed and depth of cut on surface roughness

Figure 9 shows the 3D surface graph for the surface roughness, as the spindle speed and the depth of cut varies and the feed rate kept at 70 mm/min. From Fig. 9, the surface roughness decreases for all the three depth of cut as the spindle speed is increased from 500 to 1000 rpm. This decreasing trend is not changed in all three levels of depth of cut. Hence the interaction effect of spindle speed and depth of cut is less significant. From the response surface plot, it is noted that the surface roughness reaches a maximum of 0.91 µm when the spindle speed is at 500 rpm and the depth of cut is at 1.2 mm. It reaches a minimum of 0.60 µm when the spindle speed is at 1000 rpm and the depth of cut is at 0.4 mm. High level spindle speed combined with low level depth of cut gives optimum surface roughness.

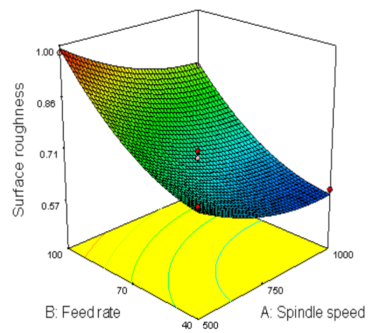

Fig. 8. 3D surface graph for the *Ra* at *C* = 0.8 mm, as *A* and *B* varies.

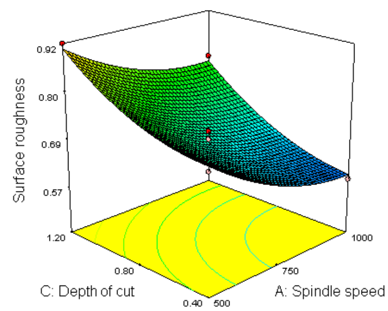

Fig. 9. 3D surface graph for the *Ra* at *B* = 70 mm/min, as *A* and *C* varies.

4.7. Interaction effect of feed rate and depth of cut on surface roughness

Figure 10 shows the 3D surface graph for the surface roughness, as the feed rate and the depth of cut varies and the spindle speed kept at 750 rpm. From Fig. 10, the surface roughness increases for all the three depth of cut as the feed rate is increased from 40 to 100 mm/min. This increasing trend is not changed in all three levels of depth of cut. Hence the interaction effect of feed rate and depth of cut is less significant. From the response surface plot, it is noted that the surface roughness reaches a maximum of 0.99 µm when the feed rate is at 100 mm/min and the depth of cut is at 1.2 mm. It reaches a minimum of 0.55 µm when the feed rate is at 40 mm/min and the depth of cut is at 0.4 mm. Low level feed rate combined with low level depth of cut gives optimum surface roughness.

4.8. Optimal cutting conditions

Figure 11 shows the cube surface roughness plot for different combinations of spindle speed, feed rate and axial depth of cut. From Fig. 11, it can be observed that the optimal surface roughness of 0.52 µm is obtained when the spindle speed is kept at high level (1000 rpm), the feed rate at low level (40 mm/min) and the axial depth of cut at low level (0.4 mm).

5. Confirmation Test

In order to verify the accuracy of the model developed, confirmation tests were performed. The validations of the experimental results are shown in Table 8.

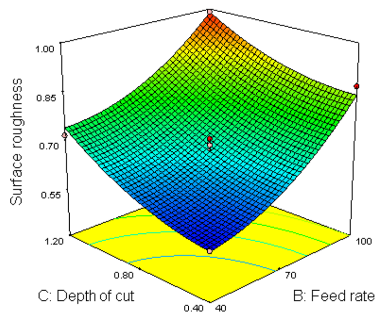

Fig. 10. 3D surface graph for the *Ra* at *A* = 750 rpm, as *B* and *C* varies.

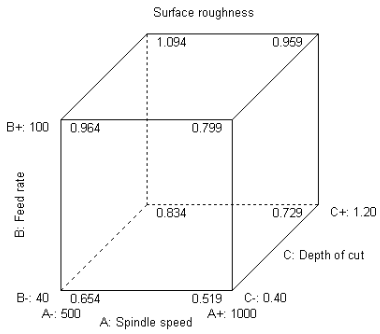

Fig. 11. Cube *Ra* plot.

Table 8. Results of confirmation test.

S. No.	Spindle Speed, rpm	Feed Rate, mm/min	Depth of cut, mm	Surface roughness, *Ra* (μm) Experimental	Surface roughness, *Ra* (μm) Predicted	% Error
1	1000	40	0.4	0.54	0.52	3.70
2	750	70	1.0	0.72	0.74	-2.78
3	500	40	0.4	0.67	0.65	2.98
4	1000	100	1.2	1.01	0.96	4.95

The test condition for the confirmation test was so chosen that they be within the range of the levels defined previously. The predicted value and the experimental value were compared and the percentage error was calculated. The error percentage is within the range of -3 to 5%. So the response equation for the surface roughness evolved through RSM can be used successfully to predict the surface roughness values for any combination of the spindle speed, feed rate, and the axial depth of cut values within the range of the experimentation conducted. This model is valid only for the assumed test conditions and within the specified volatility of machining parameters.

6. Conclusions

In this paper, the experiments were conducted to predict the surface roughness of DSS in end milling process for various input parameters namely the spindle speed, feed rate, and the axial depth of cut. The following conclusions were arrived based on the experimental investigation.

- The investigation presented a Box-Behnken Design response surface methodology to develop a second-order quadratic model to predict surface roughness in terms of spindle speed, feed rate and axial depth of cut.
- The main effects of spindle speed, feed rate and depth of cut are more significant. However, the interaction effects of spindle speed and feed rate, spindle speed and depth of cut and feed rate and depth of cut are less significant.

- The optimal surface roughness of 0.52 μm was obtained when the spindle speed was kept at high level (1000 rpm), the feed rate at low level (40 mm/min) and the axial depth of cut at low level (0.4 mm).
- The predicted results are compared with results from confirmation tests and the error is within the range of -3 to 5%.

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