ISSN: 2348 - 2117

International Journal of Engineering Technology and Computer Research (IJETCR)
Available Online at www.ijetcr.org
Volume 2; Issue 6; Page No. 160-170

Optimization of Machining Parameters for Maximum Material Removal Rate in Turning of AISI 52100 Steel by Using Response Surface Methodology

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ABSTRACT

Metal machining has been a very important process in Production. Machining Conditions play a vital role in estimating the performance of machining operations. It have long been recognized that the machining conditions, such as cutting speed, feed and depth of cut affect the performance of the operation in great extent. These parameters must be selected to optimize the quality of machining operations. It can be achieved by mathematical modeling of performance as a function of machining conditions using design of experiments (DOE).

Model adequacy tests were conducted using ANOVA table and the effects of various parameters were investigated and presented in the form of contour plots and 3D surface graphs. Numerical optimization was carried out considering all the input parameters within range so as to minimize the surface roughness indicators and maximize the material removal rate.

The optimal values for material removal rate obtained are cutting speed 260.00 m/min, feed 0.50 mm/rev, depth of cut 0.50 mm. The findings of this study would be beneficial to manufacturing industries where MRR plays a very important role.

Key Words: DESIGN EXPERT, RSM, FEED, DOC, SPEED

1. INTRODUCTION:

The Material removal rate of the machined workpiece is greatly influenced by the cutting tool properties, machining parameters, workpiece properties and cutting phenomenon. Machining parameters such as speed, feed and depth of cut play a vital role during machining. These have a major effect on the quantity of production, cost of production and production rate hence their care full selection assumes significance. The selected machining parameters should yield desired quality on the machined surface while utilizing the machining resources such as machine tool and cutting tool to the fullest extent possible, consistent with the constraints on these resources.

Turning is one of the commonest among these methods. Turning is the process of machining external cylindrical and conical surfaces (Nalbant et al. 2006). In this process the work material will held in the chuck of a lathe and rotated. The tool is held rigidly in a tool post and moved at a constant rate along the axis of the bar, cutting away a layer of metal to form a profile.

The aim of present work is to develop surface roughness indicators and material removal rate (MRR) prediction models using response surface methodology (RSM) based on face centered design (FCD). An attempt has also been to analyses the effect of machining conditions on surface roughness indicators and material removal rate during turning of AISI 52100 steel with carbide inserts.

The RSM has been used in the present work due to following advantages:

1. Numbers of trials required for experimentation are reduced.
2. Optimum value of the machining parameters can be determined.
3. Assessment of experimental error and pure error can be made.

1. LITERATURE REVIEW

Nian et al., 1999 used Taguchi method to optimize multiple performance characteristics including tool life, cutting force and surface finish in turning of S45C steel bars by using tungsten carbide tool. The orthogonal array, multi-response signal-to-noise ratio and analysis of variance have been employed to study the performance characteristics in turning operations. Three cutting parameters namely, cutting speed, feed rate and depth of cut were optimized for maximum tool life, minimum cutting force and maximum surface finish. It has been found that the Taguchi method provides a simple, systematic and efficient methodology for the optimization of the cutting parameters.

Ghani et al., 2003 experimentally investigated the effect of speed, feed and depth of cut on tool life, surface finish and vibration during turning of nodular cast iron using ceramic tool. Numbers of cutting test have been conducted to verify the change in surface finish of the workpiece due to increased tool wear. Also, the effects of vibration on the flank wear in the direction of main cutting force and radial cutting force have been investigated. The results revealed that the tool life of the alumina ceramic inserts has been found unsatisfactory. On the other hand, Variation in surface finish with the progression of the flank wear under all cutting conditions has been found almost constant.

Kirby et al., 2005 used L_9 orthogonal array based Taguchi parameter design to optimize the surface roughness of aluminium workpieces in turning operation. The spindle speed, feed rate, depth of cut and tool nose radius were considered as control parameters. Varying room temperature and more than one insert of the same specification have been treated as noise factors. A confirmation runs have been conducted to verify the results. The results indicated the effectiveness of the method in determining the best turning parameters for the optimal surface roughness

Gaitonde et al., 2007 utilized Taguchi's L9 orthogonal technique with the utility concept for minimization of surface roughness and specific cutting force in turning of brass using K10 carbide tool. The quantity of lubricant, cutting speed and feed rate has been considered as process parameters. The analysis of means (ANOM) and analysis of variance (ANOVA) on multi-response signal-to-noise (S/N) ratio have been employed for obtaining the optimal parameter levels and identifying the level of importance of the process parameters. Results revealed that feed rate is the most dominant parameter that's affecting the surface roughness followed by minimum quantity of lubricant and cutting speed.

Syung Lan, et al., 2009 used Taguchi methodology to investigate the effect of cutting parameters (cutting speed, depth of cut, feed rate and tool nose radius) on MRR during turning. Additionally, nine fuzzy control rules using triangle membership function with respective to five linguistic grades for the MRR is constructed. The results show that proposed fuzzy Taguchi deduction methodology improves MRR.

Sahoo and Sahoo, 2011 developed surface roughness prediction models in turning of D2 steel using TiN coated carbide insert. The prediction model has been developed in terms of cutting speed, feed and depth of cut using L27 orthogonal array base Taguchi parameter design and response surface methodology. The influence of the machining parameters on the surface finish has also been investigated. The result reveals that feed has been found most significant parameter followed by the depth of cut. The effect of cutting speed has been found insignificant.

Kumar et al., 2013 analyzed the effects of machining parameters (speed, depth of cut, feed and nose radius) on surface roughness and MRR. In addition to this, an attempt has also been made to optimize the machining parameters to obtain minimum surface roughness and maximum MRR using multi attribute decision making approach (MADM).

2. EXPERIMENTAL DETAILS

The main parameters affecting MRR are cutting speed, depth of cut and feed (Arbizu and Perez, 2003). These three are the primary parameters in any basic machining operation. Other factors such as kind of material and type of tool have a large influence, of course, but these three are the ones the operator can change by adjusting the controls at the time of machining.

On the basis of above discussion cutting speed, depth of cut and feed have been considered as a process parameters in the present research.

3.1 Design of experiments

The process parameter is tabulated in table 3.1 and complete design layouts for experiments on AISI 52100 steel are summarized in table 3.2. The design layout table shows total 20 experimental combinations of cutting speed, feed and depth of cut. The twenty set of experiments constitute 2^3factorial points, six centre points and six star points.

To avoid premature cutting-tool failures the range of process parameters have been selected by considering the several factors like type of machining operation, type of material, cutting range specified by the cutting tool manufacturers, range given in the handbook and from the reported work.

Table 3.1 Process parameters and their levels for the turning of AISI 52100 steel

Factors	Symbol	Levels		
		-1	0	+1
Cutting speed (m/min)	A	140	200	260
Feed (mm/rev)	B	0.20	0.35	0.50
Depth of cut (mm)	C	0.20	0.35	0.50

Table 3.2 Experimental design layout for the turning of AISI 52100 steel

Std	Run	A:Cutting speed (m/min)	B: Feed (mm/rev.)	C: Depth of cut (mm)
12	1	200	0.50	0.35
10	2	260	0.35	0.35
3	3	140	0.50	0.20
15	4	200	0.35	0.35
2	5	260	0.20	0.20
19	6	200	0.35	0.35
5	7	140	0.20	0.50
18	8	200	0.35	0.35
4	9	260	0.50	0.20
9	10	140	0.35	0.35
7	11	140	0.50	0.50
6	12	260	0.20	0.50
16	13	200	0.35	0.35
20	14	200	0.35	0.35
13	15	200	0.35	0.20
14	16	200	0.35	0.50
1	17	140	0.20	0.20
8	18	260	0.50	0.50
11	19	200	0.20	0.35
17	20	200	0.35	0.35

3.2 EQUIPMENTS USED IN EXPERIMENT AND MEASUREMENT

The experimental details include the machine tool, cutting inserts, work piece material, chemical composition, coolant and the measurement of surface roughness indicators system.

3.2.1 Machine tool for turning

The CNC becomes very common in factories and are capable to enhance product quality as well as productivity (Kaladhar et al.2011, Lan 2009, Galanis et al.2010).

Keeping in view the above, all the turning experiments on the AISI 52100 steel have been carried out on **HYUNDAI HIT 8S** model no.**MS 1630s**. The CNC machining centre equipped with continuously variable spindle speed up to 6000 rpm and 7.5HP motor drive was used for experimentation. A pictorial view of CNC lathe is given in figure 3.1. Technical specifications of the CNC turning centre are summarized in table 3.3.

Fig. 3.1 CNC lathe used for the turning purpose (Rajasthan Udyog Ltd., Jodhpur)

Table 3.3 Technical specification of the CNC turning centre

Model	**HYUNDAI 8S**MODEL NO:**MS 1630s**
Control:	SIEMENS 840C
Chuck Diameter:	152 mm
Maximum Turning Diameter:	160 mm
Maximum Turning Length:	285 mm
Swing Over Bed:	300 mm
Swing Over Cross Slide:	300 mm
Spindle Speed:	6000 rpm

3.2.2 Cutting inserts for turning

Coated carbide tools are known to perform better than uncoated carbide tools when turning steel (Thomas et al., 1997; Yang and Tarng 1999). On the basis of this reason, commercially used carbide coated carbide Inserts for turning steel was used in this research for turning. The cutting inserts used for experimentation was WNMG 089404 MF-2 with grade TP2500 manufactured by Seco tools. The pictorial view of cutting insert is shown in fig 3.2.

Fig 3.2 (Cutting Insert) WNMG 089404 MF-2 TP2500

2.2.3 observation for MRR

Table 3.6 Measured surface roughness indicators and MRR in turning of AISI 52100 steel

Std	Run	MRR (mm^3/Sec)
12	1	1800
10	2	1817.1
3	3	1080.02
15	4	1730.93
2	5	875.013
19	6	1615.78
5	7	1528.88
18	8	1615.78
4	9	1050
9	10	1383.92
Std	**Run**	**MRR (mm^3/Sec)**
7	11	2606.2
6	12	2171.83
16	13	1525.78
20	14	1525.78
13	15	895.32
14	16	2275.48
1	17	636.26
8	18	3057.75
11	19	1215.12
17	20	1585.78

3.2.7 Calculation of MRR

Material removal rate can be calculate by using of this formula-

$$\frac{\frac{\pi}{4}(D_i^2 - D_f^2) \times L}{t}$$

Here D_i – (Diameter before machining or Initial Diameter)

D_f – (Diameter after machining or Final Diameter)

L – (Machining length)

t – (Time taken in machining for given length)

For calculation of material removal rate, machining time and initial diameter has been already taken for all runs before machining.

3. RESULTS AND DISCUSSIONS

After the examination of Fit Summary, output revealed that the two level factorial interaction models is statistically significant for material removal rate and therefore it will be used for further analysis.

4.1 Mathematical model for material removal rate

The regression model for material removal rate in terms of coded factors is shown as follows:

$$MRR = 1599.64 + 173.64 * A + 316.69 * B + 710.35 * C - 57.52 * A * B + 110.72 * A * C + 168.06 * B * C$$

(4.13)

While, the regression model for material removal rate in terms of actual factors is shown as follow:

$$MRR = -46.82 + 0.8251 * Cutting\ speed + 775.211 * Feed - 339.071 * Depth\ of\ cut - 6.391 * Cutting\ speed * Feed + 12.302 * Cutting\ speed * Depth\ of\ cut + 7469.405 * Feed * Depth\ of\ cut \quad (4.14)$$

4.2 ANOVA analysis for material removal rate

The ANOVA analysis was carried out for a significance level of α = 0.05, i.e. for a confidence level of 95%. The ANOVA test for material removal rate is summarized in Table 4.7.

It shows that the value of "Prob. > *F*" for model is 0.0001 which is less than 0.05, that indicates the model is significant, In the same manner, The value of "Prob. > *F*" for main effect of cutting speed, feed and depth of cut, and two-level factorial interaction of speed and feed, feed and depth of cut, and speed and depth of cut (because of factorial interaction model) are less than 0.05 so these terms are significant model terms. The value of "Prob. > *F*" for lack-of-fit is 0.7113 which is greater than 0.05 that's indicate that lack of fit is insignificant. The non-significant Lack of Fit is desirable The R^2 value is equal to 0.9912 or close to 1, which is desirable. The adjusted R^2 value is equal to 0.9871. The result shows that the adjusted R^2 value is very close to the ordinary R^2 value. Adequate precision value is equal to 59.981; a ratio greater than 4 is desirable which indicates adequate model discrimination.

Table 4.7 ANOVA table for quadratic model (Material removal rate, *MRR*)

Source	Sum of Squares	Degree of freedom	Mean Square	F Value	p-value Prob > F	
Model	6700928	6	1116821	243.87	0.0001	S
A-Cutting speed	301513	1	301513	65.84	0.0001	S
B-feed	1002905	1	1002905	219	0.0001	S
C-depth of cut	5046010	1	5046010	1101.87	0.0001	S
AB	26469.9	1	26469.9	5.78	0.0318	S
AC	98072.9	1	98072.9	21.42	0.0005	S
BC	225957.7	1	225957.7	49.34	0.0001	S
Residual	59533.7	13	4579.52			
Lack of Fit	30673.6	8	3834.2	0.66	0.7113	**NS**
Pure error	28860.10	5	5772.02			
Core total	6760461	19				

Std. Dev.	67.67	R-Squared	0.9912
Mean	1599.64	Adj R-Squared	0.9871
C.V. %	4.23	Pred R-Squared	0.9756
PRESS	164682.5	Adeq Precision	59.981

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4.3 Percentage contribution of significant parameters

The percentage contribution of the significant terms on average surface roughness in quadratic model is shown in figure 4.1. The figure shows that the depth of cut is the dominant factor affecting the material removal rate among all machining parameters with 75.30 % contribution, followed by the feed and cutting speed with contribution of 14.97 %, and 4.50% respectively.

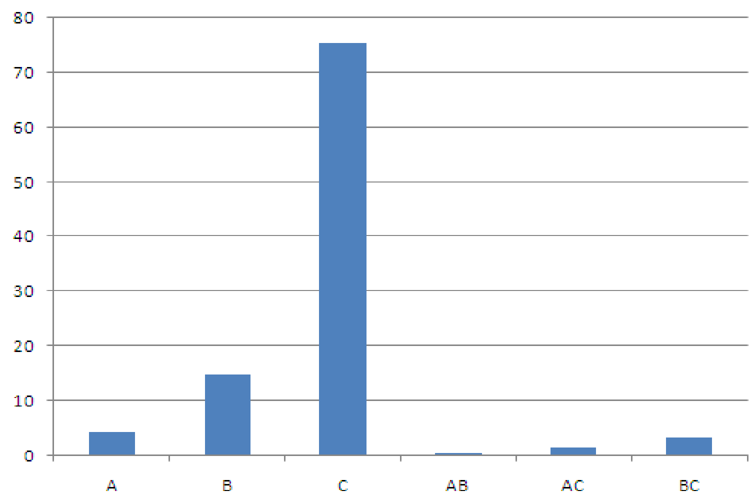


Fig.4.1 Bar chart for percentage contribution for material removal rate

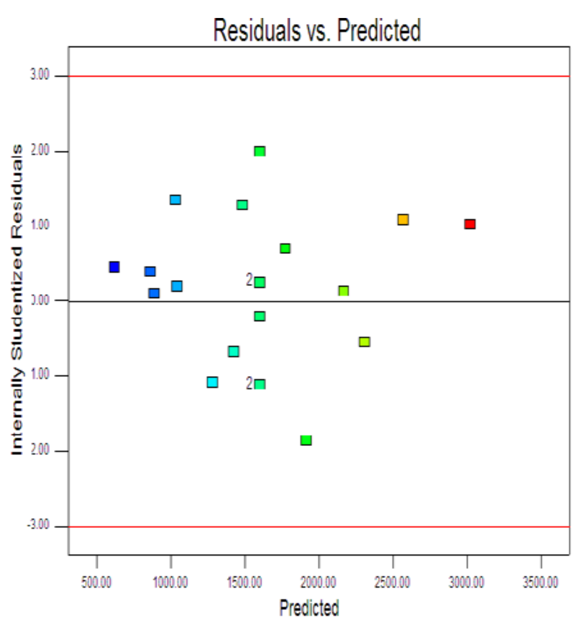
A: cutting speed, B: feed, C: depth of cut

4.4 Diagnosis of assumptions of ANOVA for MRR

It was previously that analysis of variance (ANOVA) is commonly used to perform test for (1) significance of the regression model, (2) significance on individual model coefficients, and (3) lack of fit of model. This analysis is based on two assumptions: (1) the variables are normally distributed and (2) homogeneity of variance. Significant violation of either assumption can increase the chances of error.

The normal probability plot of the residuals is shown in Fig.4.2. The normal probability plot indicates whether the residuals follow a normal distribution or not, if the residuals follow a normal distribution majority of points will follow a straight line except some moderate scatter even with normal data. The figure displays that the residuals generally fall on a straight line plying that the errors are distributed normally.

Fig.4.3 represents residuals versus the predicted response plot for Material removal rate. It tests the assumption of constant variance. The plot should be a random scatter. The figure shows that there is no obvious pattern and it shows unusual structure. This implies that there is no reason to suspect any violation of the independence or constant variance assumption.



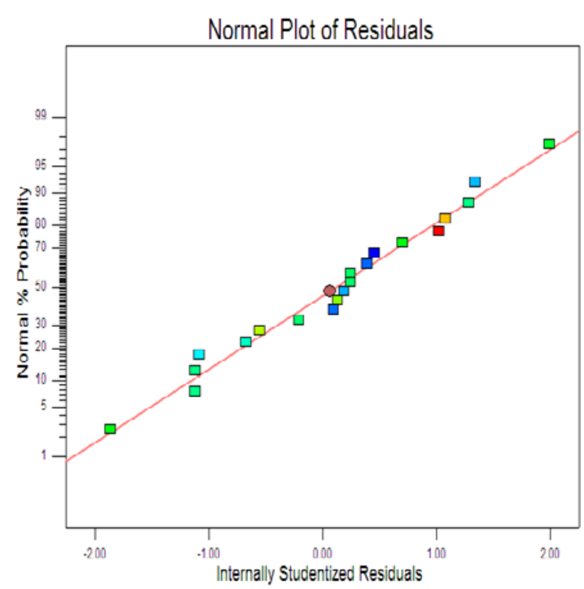


Fig.4.2 Normal probability of the residuals plot for material removal rate

Fig.4.3 Residual verses predicted value plot for material removal rate

4.5. Effect of cutting parameters on material removal rate

Influence of cutting parameters on material removal rate is shown in figure 4.4. It shows as cutting speed, feed and depth of cut increases the material removal rate also increases because at higher feed rate and at higher cutting speed, the tool traverses the work piece too speedily resulting, increase in material removal rate.

Fig 4.4 (a) shows effect of cutting speed on Material removal rate at constant feed 0.35 mm/rev and constant depth of cut 0.35mm, fig. 4.4 (b) shows effect of feed on material removal rate at constant cutting speed 200 m/min and constant depth of cut 0.35mm and fig. 4.4 (c) shows effect of feed on material removal rate at constant cutting speed 200 m/min and constant cutting feed 0.35m

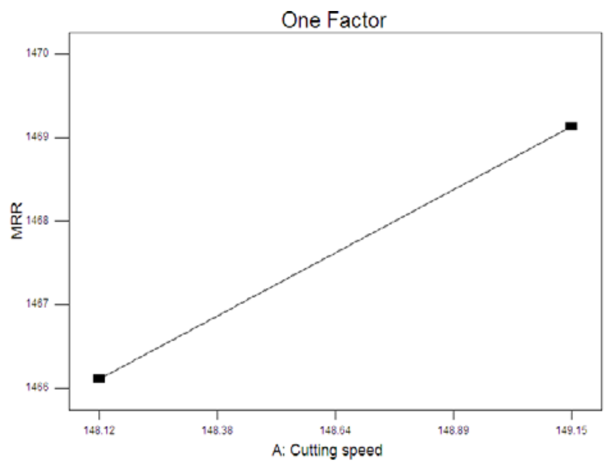


Fig. 4.4 (a) Effect of cutting speed on Material removal rate at constant feed 0.35 mm/rev and constant depth of cut 0.35mm

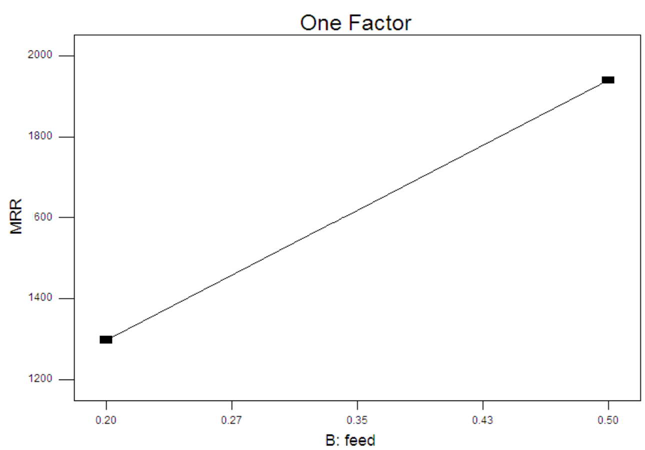


Fig. 4.4 (b) Effect of feed on material removal rate at constant cutting speed 200 m/min and constant depth of cut 0.35mm

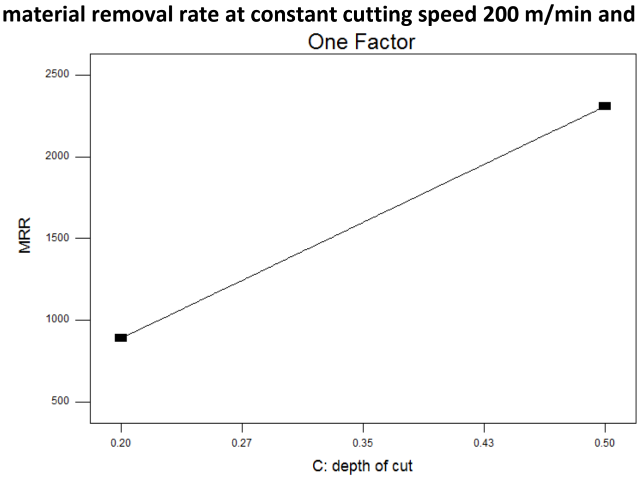


Fig. 4.4 (c) Effect of feed on material removal rate at constant cutting speed 200 m/min and constant cutting feed 0.35mm

Fig.4.4 Effect of cutting parameters on material removal rate

The 3D surface graphs for material removal rate is shown in Fig.4.5. According to the 3 D plots, the material removal rate is significantly maximized, when the feed is set to the high level (0.50 mm/rev.), cutting speed at high level (260 m/min) and depth of cut also at high level (0.50 mm).

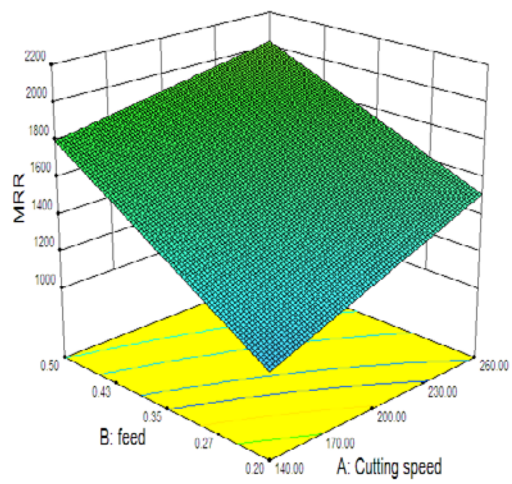


Fig 4.5 (a) 3D Surface graphs for material removal rate b/w feed and speed

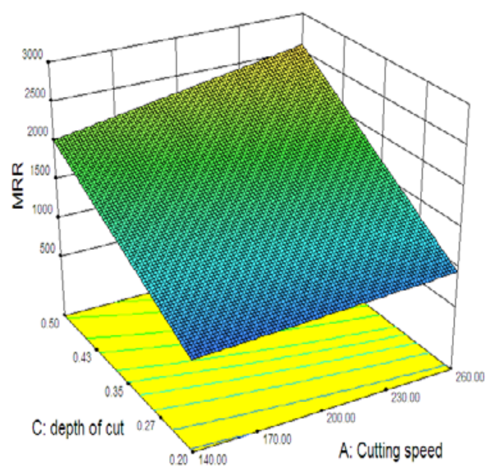


Fig 4.5 (b) 3D Surface graphs for material removal rate b/w depth of cut and speed

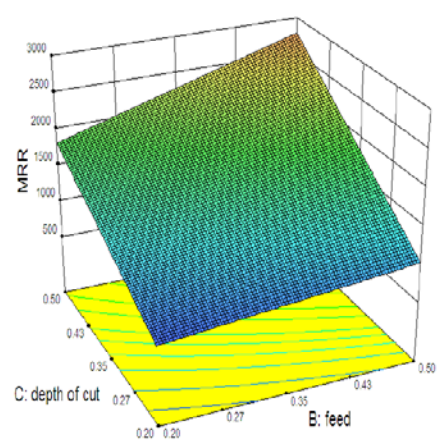


Fig 4.5 (c) 3D Surface graphs for material removal rate b/w depth of cut and feed

Fig- 4.5 3D Surface graphs for material removal rate

Figure 4.6 represents the cube plot which shows the three factor interaction, among feed, cutting speed and depth of cut. According to the plot, the material removal rate is significantly maximized (MRR =3021.58 m/min) when the feed is set to the high level (0.50 mm/rev), speed at high level (260 m/min) and the depth of cut at high level (0.50 mm).

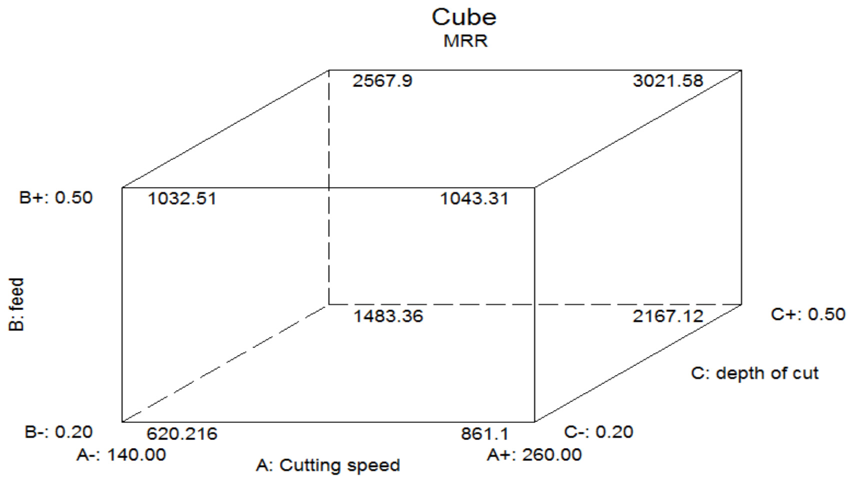


Fig. 4.6 Cube plot for material removal rate

4. OPTIMIZATION OF CUTTING CONDITION

In the present work, The constraints used during the optimization process for material removal rate are summarized in Table 5.1 the optimal solutions for for material removal rate are reported in table 5.2.

Table 5.1 Constraints for optimization of cutting conditions for material removal rate

Name	Goal	Lower limit	Upper limit
A: Cutting speed	is in range	140	260
B: Feed rate	is in range	0.2	0.5
C: Depth of cut	Is in range	0.2	0.5
MRR	Maximize	636.26	3057.75

Table 5.4 Optimization results for material removal rate

No.	Cutting speed (m/min)	Feed (mm/rev.)	depth of cut (mm)	MRR	Desirability	
1	260	0.50	0.50	3021.58	0.985	Selected
2	256.66	0.50	0.50	3008.95	0.980	
3	260	0.49	0.50	3003.62	0.978	

5. CONFORMATION EXPERIMENTS

Statistically developed mathematical models MRR models have been found 0.9864, 0.9626, 0.9630 and 0.9912 respectively which indicates the model ability for making predictions. This conclusion must be further supported through the confirmation runs. A set of three confirmation runs have been performed to verify the prediction ability of the developed material removal rate models. The values of material removal rate obtained by confirmation run and those predicted through the model are compared in table 6.1. The percentage error between the experimental and the predicted values of roughness indicators and material removal rate are found to be less than 5% per cent. In other words, all the experimental values are within the 95 per cent prediction interval, which clearly demonstrates the accuracy of the models developed in this work.

Table 6.1 Plan of confirmation experiments and results for material removal rate

S.	Cutting	Feed	depth	Experimental	Predicted	Error %
1	260	0.50	0.50	3168	3021.58	4.62
2	256.66	0.50	0.50	3125	3008.95	3.71
3	260	0.49	0.50	3154	3003.62	4.77

6. CONCLUSION AND FUTURE SCOPE

The objective of the present work is to optimize the machining parameters for minimum surface roughness indicators and maximum material removal rate during turning of AISI 52100 steel using RSM based on the face centered design. In addition to this an attempt has also been made to investigate the effect of turning parameters on surface roughness indicators and on material removal rate.

7.1 CONCLUSION

The important conclusions drawn from the present work are summarized as follows:

1. The results of ANOVA and the confirmation runs verify that the developed mathematical models for surface roughness indicators shows excellent fit and provide predicted values of surface roughness that are close to the experimental values, within 95 per cent confidence level.
2. The percentage error between the predicted and experimental values of the response factor during the confirmation experiments are found within 5 per cent.
3. The model can be used for direct evaluation of surface roughness indicators and material removal rate under various combinations of machining parameters during turning of AISI 52100 steel.
4. Out of three parameters, depth of cut seems to be the most significant and influential machining parameter that affect the material removal rate (MRR) followed by feed.
5. All the three parameters have significant effect on the material removal rate.
6. The 3D plots clearly show that material removal rate increases with increasing the depth of cut, feed as well as the cutting speed.
7. Percentage contribution of parameters on material removal rate C (depth of cut) = 75.30%, B (feed) = 14.97% and A (cutting speed) = 4.50 % have been found, which clearly indicate that depth of cut is the dominant factor affecting the material removal rate.
8. The maximum material removal rate MRR (3021.58m/min) have been obtained at cutting speed 260 m/ min, feed 0.50 mm/rev and depth of cut 0.50mm.

7.2 FUTURE SCOPE

In this study, mathematical modeling and optimization has been attempted for surface roughness parameters. The work can be extended to consider more response variables like cutting forces, tool wear etc. Also, more machining parameters such as coolant concentration, tool angles etc can be introduced to have a better insight in to the process.

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