6

EXPERIMENTAL DESIGN ANALYSIS AND RESPONSE SURFACE METHODOLOGY

6.1 Introduction

The 3^k Factorial Design is a factorial arrangement with *k* factors, each at three levels. Factors and interactions will be denoted by capital letters. We will refer to the three levels of the factors as low, intermediate, and high. Several dissimilar notations may be used to represent these factor levels; one choice is to represent the factor levels by the digits 0 (low), 1 (intermediate), and 2 (high). Each treatment combination in the 3^k design will be denoted by *k* digits, where the first digit indicates the level of factor *A*, the second digit indicates the level of factor B,…, and the *k*th digit indicates the level of factor *K*. For example, in a 3^2 design, 00 denotes the treatment combination corresponding to A and B both at the low level, and 01 denotes the treatment combination corresponding to A at the low level and B at the intermediate level. Figures 6.1 and 6.2 show the geometry of the 3^2 and the 3^3 design, respectively, using this notation.

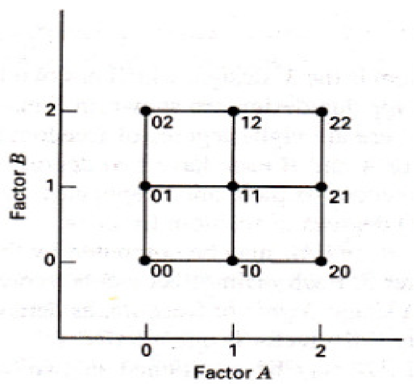

Fig. 6.1 3^2 Design

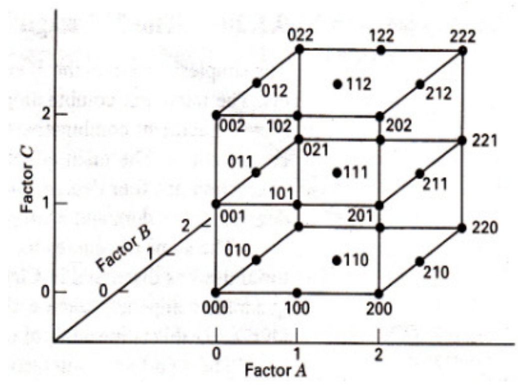

Fig. 6.2 3^3 Design

This scheme of notation could have been used for the 2^k designs presented previously, with 0 and 1 used in place of the ±1s, respectively. In the 2^k design, we desire the ±1 notation because it facilitates the geometric view of the design and because it is directly related to regression modeling, blocking, and the construction of fractional factorials.

In the 3^k system of designs, when the factors are quantitative, we often represent the low, intermediate, and high levels by -1, 0, and +1, respectively. This facilitates fitting a regression model relating the response to the factor levels. For example, consider the 3^2 design in Figure 6.1, and let x_1 represent factor A and x_2 represent factor B. A regression model relating the response y to x_1 and x_2 that is supported by this design is

$$y = \beta_o + \beta_1 x_1 + \beta_1 x_1 + \beta_{12} x_1 x_2 + \beta_{11} x_1^2 + \beta_{22} x_2^2 + \epsilon \quad (6.1)$$

Notice that the addition of a third factor level allows the connection between the response and design factors to be modeled as a quadratic.

The 3^k design is absolutely a likely preference by an experimenter who is corrected about curvature in the response function. However, two points need to be considered:

1. The 3^k design is not the well-organized way to model a quadratic relationship; the response surface designs are more alternatives.
2. The 2^k design augmented with center points is an excellent way to obtain an indication of curvature. It allows one to keep the size and of the design low and simultaneously obtain some protection against curvature. Then, if curvature is important, the two-level design can be augmented with axial runs to obtain a central composite design. This sequential strategy of testing is far more efficient than running a 3^k factorial design with quantitative factors.

6.1.1 The General 3^k Design

The scheme used in the 3^2 and 3^3 designs can be readily extended to the case of k factors, each at three levels, that is, to a 3^k factorial design. The usual digital notation is employed for the treatment combinations, so 0120 represent a treatment combination in 3^4 design with A and D at the low levels, B at the intermediate level, and C at the high level. There are 3^k treatment combinations, with 3^k -1 degrees of freedom between them. These treatment combinations allow sums of squares to be determined for k main effects, each with two degrees of freedom; $\binom{k}{2}$ two-factor interactions, each with four degrees of freedom;…; and one k-factor interaction with 2^k degrees of freedom. In general, an h-factor interaction has 2^k degrees of freedom. If there are n replicates, there are $n3^k - 1$ total degrees of freedom and $3^k(n - 1)$ degrees of freedom for error.

Sums of squares for effects and connections are computed by the usual methods for factorial design. Typically, three-factor and higher interactions are not broken down any further. However, any h-factor interaction has 2^{h-1} orthogonal two-degrees-of-freedom components. For case, the four-factor, interaction ABCD has $2^{4-1} = 8$ orthogonal two-degrees-of-freedom components, denoted by $ABCD^2$, ABC^2D, AB^2CD, ABCD, ABC^2D^2, AB^2C^2D, AB^2CD^2, and $AB^2C^2D^2$. In writing these components, note that the only exponent allowed on the first letter is 1. If the exponent on the first letter is not 1, then the entire expression must be squared and the exponents reduced modulus 3. To demonstrate this, consider

$$A^2BCD = (A^2BCD)^2 = A^4B^2C^2D^2 = AB^2C^2D^2$$

These interaction components have no physical interpretation, but they are useful in constructing more complex designs.

The size of the design increases rapidly with k. For example, a 3^3 design has 27 treatment combinations per replication, a 3^4 design has 81, a 3^5 design has 243, and so on. Therefore, only a single replicate of the 3^k design is frequently considered, and higher order interactions are combined to provide an estimate of error. As an illustration, if three-factor and higher interactions are negligible, then a single replicate of the 3^3 design provides 8 degrees of freedom for error, and a single replicate of the 3^4 design provides 48 degrees of freedom for error. There are still large designs for $k \geq 3$ factors and, consequently, not too useful.

6.2 Response Surface Methodology

Response surface methodology or RSM is a set of mathematical and statistical techniques valuable for the modeling and analysis of problems in which a response of interest is inclined by several variables and the objective is to optimize this response. For example, suppose that a mechanical engineer wishes to find the levels of feed (x_1) and depth of cut (x_2) that maximize the yield (y) of a process. The process yield is a function of the levels of feed and depth of cut, say

$$y = f(x_1, x_2) + \in \quad (6.2)$$

where ∈ represents the noise or error observed in the response y. If we give the expected response by $E(y) = f(x_1, x_2) = \eta$, then the surface represented by

$$\eta = f(x_1, x_2)$$

is called a response surface.

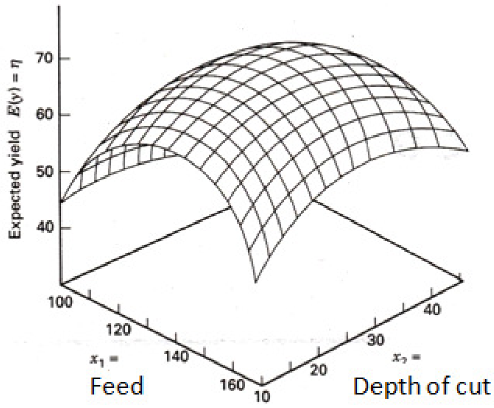

Fig. 6.3 3 D Response surface showing the expected Yield (η) as a function of feed (x_1) and depth of cut (x_2)

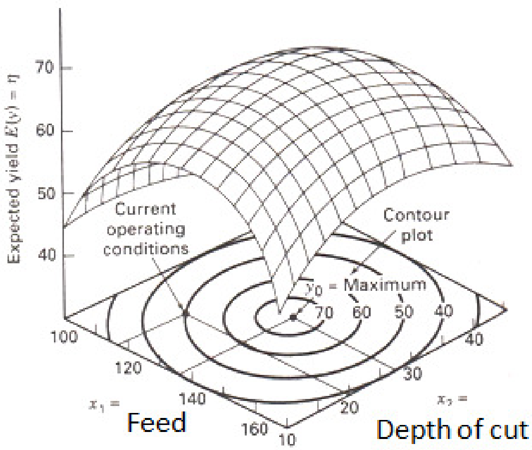

Fig. 6.4 A contour plot of a response surface

We usually symbolize the response surface graphically, such as in Figure 6.3, where η is plotted versus the levels of x_1 and x_2. To help picture the shape of a response surface, we plot the contours of the surface as shown in Figure 6.4. In the contour plot, lines of constant response are drawn in the x_1, x_2 plane. Each contour corresponds to a particular height of the response surface.

In most RSM problems, the form of the correlation between the response and the independent variables is unknown. Thus the first step in RSM is to find a appropriate approximation for the true functional relationship between y and the set of independent variables is employed. Usually a low-order polynomial in some region on the independent variables is employed. If the response is well modeled by a linear function of the independent variables, then the approximating function is the first-order model

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_k x_k + \in \tag{6.3}$$

If there is curving in the system, then a polynomial of higher degree must be used, such as the second-order model

$$y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \sum_{i<j}\sum \beta_{ij} x_i x_j + \in \tag{6.4}$$

Almost all RSM problems use one or both of these models. Of course, it is unlikely that a polynomial model will be a reasonable approximation of the true functional relationship over the entire space of the autonomous variables, but for a relatively small region they usually work quite well.

The method of least squares is used to estimate the parameters in the approximating polynomials. The response surface analysis is then performed using the fitted surface. If the fitted surface is an adequate approximation of true response function, then analysis of the fitted surface will be approximately equivalent to analysis of the actual system. The model parameters can be expected most effectively if proper experimental designs are used to collect the data. Designs for fitting response surfaces are called response surface design.

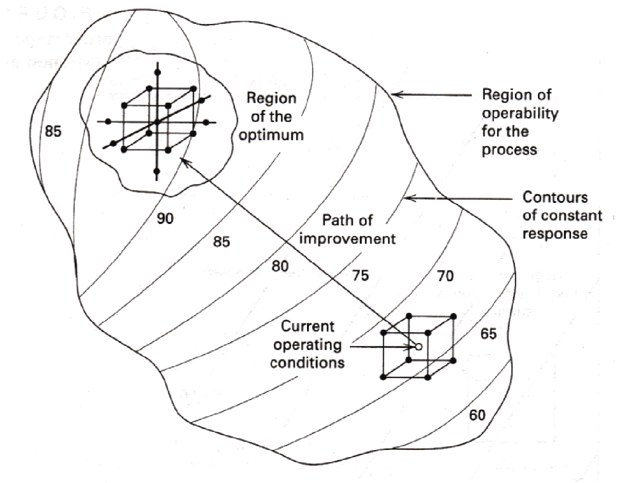

Fig. 6.5 The sequential nature of RSM

RSM is a sequential procedure. Often, when we are at a point on the response surface that is remote from the optimum, such as the current operating conditions in Figure 6.5, there is little curvature in the system and the first-order model will be appropriate. Our aim here is to lead the experimenter rapidly and efficiently along a path of improvement toward the general vicinity of the optimum. Once the region of the optimum has been found, a more elaborate model, such as the second-order model, may be employed, and an analysis may be performed to locate the optimum. From Figure 6.5, we see that the analysis of a response can be thought of as "climbing a hill," where top of the hill represents the point of highest response. If the true optimum is a point of least response, then we may think of "descending into a valley."

With the use of 3^4 full factorial design, below given experimental details for different materials with the use of Response surface methodology and optimization technique.

6.3 Experimental details for AISI 1040 Steel

In this study, the experiments were planned using 3^4 full factorial design with 81 numbers of experiments. The four cutting parameters are selected for the present investigation is cutting speed (v), feed (f), nose radius (r) and depth of cut (d). Since the considered factors are multi level variables and their outcome effects are not linearly related, it has been decided to use three level tests for each factor. The machining parameters used and their levels chosen are given in Table 6.1

Table 6.1 Parameters and their level (AISI 1040 Steel)

Parameters	Level -1	Level -2	Level -3
Cutting speed (v) (m/min)	220	250	280
Feed (f) (mm/rev)	0.1	0.15	0.2
Depth of cut (d) (mm)	0.3	0.6	0.9
Nose radius (r) (mm)	0.4	0.8	1.2

All the turning experiments were conducted on a Jobber XL model made by Ace designer CNC lathe machine (Fig.6.6) with specification given in Table 6.2. The machining tests were carried out in wet conditions using a water-soluble cutting fluid. In this study, ceramic inserts (supplied by Ceratizit) were used, ISO code TNMG160404 EN-TMF, TNMG 160408 EN-TM and TNMG 160412 EN-TM with different nose radius. (60^0 triangular shaped inserts). The inserts were mounted on a commercial tool.

Fig.6.6 Turning center Jobber X_L

Table 6.2 Specification of turning center

	Description	Measurement	Size
Control System	CNC System		Fanuc 0i- mate TD
	Maximum Turning Dia.	mm	270
	Maximum Turning Length	mm	400
Spindle	Spindle Nose		A2-5
	Maximum Bar Capacity	mm	25
	Max. Spindle Speed	RPM	4000
	Spindle Motor Power (15 min rating)	kW	7.5
	Continuous rating	RPM	1333-3000
Work holding	Standard Chuck Size	mm	165
Tooling	Maximum Number of Tools		8
	Maximum Boring Bar Dia.	mm	40
X-Axis	Type of Guide ways		Hardened & Ground
	X Axis Stroke	mm	150
	X Axis Rapid Rate	m/min	20
	X Ball Screw Dia. X Pitch	mm	32 X 10
	X Axis Motor		Fanuc; Beta 8i s/3000
	X Motor Torque	Nm	7
Z-Axis	Type of Guide way		Hardened & Ground
	Z Axis Stroke	mm	400
	Z Axis Rapid Rate	m/min	20
	Z Ball Screw Dia. X Pitch	mm	32 X 10
	Z Axis Motor		Fanuc; Beta 8i s/3000
	Z Motor Torque	Nm	7
Tailstock	Tailstock Base travel	mm	235
	Tailstock quill travel	mm	100
	Tailstock quill Dia.	mm	80
	Tailstock thrust	Kgf	500 @ 20 kg/cm^2
Coolant System	Coolant Pump		RV 100/200
	Coolant Tank Capacity	(liters)	110
Hydraulic System	Hydraulic Pump Capacity	lpm	14
	Hydraulic Power Pack Tank Capacity	(liters)	45
Overall machine Dimensions	L x W x H	mm	2200X1750X1750

In the present investigation, the bar of AISI 1040 steel with the following chemical composition were used as the work material: 0.470% C, 0.140 % Si, 0.781 % Mn, 0.019% P, 0.08 % Cr, 0.049 % Ni and 0.010 % Mo. A mechanical property of the material is given in Table 6.3. Microscopic analysis of the material is given in Fig.6.7. The average surface roughness (Ra) which is mostly used in industrial environments is taken up for the present study. Surface finish of the work piece material was measured by Surf test model No. SJ-400 (Mitutoyo make). The surface roughness was measured at three equally spaced locations around the circumference of the work pieces to obtain the statistically significant data for the test. A detail of the specification of SJ-400 is given in chapter 5.The result table from the machining test performed as per the 3^4 full factorial design is shown in Table 6.4. These results are fed into the Minitab-16 for analysis.

Table 6.3 Mechanical properties of AISI 1040 steel

Material properties	AISI 1040 steel
Physical density	7.85 g/cm^3
Mechanical hardness, Rockwell B	92
Tensile strength, ultimate	600 Mpa
Tensile strength, yield	350 Mpa
% of elongation	20

Fig.6.7 Material: AISI 1040 500X

Table 6.4 Result table (AISI 1040 Steel)

Run Order	Cutting speed (v) (m/min)	Feed (f) (mm/rev)	Depth of cut (d) (mm)	Nose radius (r) (mm)	Roughness (Ra) (µm)
1	220	0.1	0.3	0.8	1.13
2	220	0.15	0.6	0.4	2.25
3	220	0.1	0.3	1.2	0.80
4	250	0.1	0.3	1.2	0.64
5	280	0.1	0.6	1.2	0.63
6	280	0.2	0.3	0.4	2.51
7	280	0.15	0.3	0.8	0.93
8	220	0.15	0.9	1.2	1.15
9	220	0.15	0.9	0.4	2.35
10	220	0.2	0.3	0.8	1.75

11	280	0.1	0.9	0.8	0.71
12	220	0.1	0.6	0.4	1.35
13	220	0.2	0.3	1.2	1.35
14	280	0.1	0.6	0.8	0.68
15	280	0.1	0.9	0.4	1.03
16	280	0.15	0.6	0.8	0.87
17	280	0.15	0.9	1.2	0.80
18	280	0.2	0.9	0.8	1.42
19	220	0.1	0.3	0.4	1.42
20	220	0.2	0.6	0.8	1.74
21	220	0.15	0.9	0.8	1.40
22	250	0.1	0.9	1.2	0.73
23	280	0.15	0.3	1.2	0.69
24	220	0.1	0.6	1.2	0.85
25	250	0.15	0.3	0.8	0.96
26	220	0.2	0.6	1.2	1.40
27	250	0.1	0.9	0.8	0.89
28	250	0.15	0.6	0.4	1.79
29	250	0.15	0.3	1.2	0.72
30	220	0.15	0.6	1.2	1.08
31	250	0.2	0.9	1.2	1.28
32	220	0.15	0.3	0.4	2.21
33	280	0.2	0.6	0.4	2.62
34	250	0.1	0.6	0.4	1.02
35	250	0.15	0.3	0.4	1.81
36	280	0.1	0.3	0.8	0.67
37	220	0.2	0.9	1.2	1.46
38	250	0.2	0.6	0.4	2.73
39	280	0.1	0.3	0.4	0.97
40	250	0.15	0.9	0.8	1.02
41	280	0.2	0.9	1.2	1.14
42	220	0.2	0.3	0.4	3.30
43	250	0.2	0.3	0.8	1.35
44	280	0.2	0.6	0.8	1.28
45	250	0.1	0.3	0.4	0.98
46	220	0.2	0.9	0.4	3.39
47	220	0.1	0.9	1.2	0.89
48	250	0.1	0.9	0.4	1.05
49	250	0.2	0.3	1.2	1.23
50	250	0.1	0.6	0.8	0.85
51	220	0.15	0.3	0.8	1.39

52	250	0.15	0.6	1.2	0.77
53	280	0.1	0.3	1.2	0.58
54	280	0.15	0.6	0.4	1.62
55	250	0.2	0.6	0.8	1.38
56	280	0.2	0.9	0.4	2.65
57	280	0.15	0.3	0.4	1.62
58	250	0.1	0.6	1.2	0.69
59	280	0.2	0.3	0.8	1.33
60	280	0.1	0.9	1.2	0.69
61	250	0.15	0.9	1.2	0.79
62	220	0.1	0.9	0.4	1.45
63	220	0.1	0.6	0.8	1.14
64	280	0.15	0.9	0.4	1.72
65	280	0.2	0.3	1.2	1.03
66	220	0.15	0.6	0.8	1.42
67	250	0.2	0.9	0.4	2.79
68	280	0.2	0.6	1.2	1.08
69	220	0.15	0.3	1.2	0.99
70	280	0.1	0.6	0.4	1.01
71	280	0.15	0.6	1.2	0.72
72	250	0.2	0.9	0.8	1.48
73	250	0.1	0.3	0.8	0.86
74	250	0.2	0.6	1.2	1.25
75	250	0.15	0.6	0.8	0.99
76	250	0.15	0.9	0.4	1.84
77	220	0.2	0.6	0.4	3.33
78	220	0.1	0.9	0.8	1.18
79	220	0.2	0.9	0.8	1.80
80	250	0.2	0.3	0.4	2.73
81	280	0.15	0.9	0.8	0.93

6.3.1 Result and discussion

The analysis of variance (ANOVA) is used to check the adequacy of the proposed model. Table 6.5 shows estimated regression coefficient for roughness for linear model. The effectiveness of the model has been checked by using the R^2 value. In present work, R^2 value is 0.8154 and the Adj. R^2 is 0.8057 and predicted R^2 value is 0.7879. Table 6.6 shows ANOVA for linear model of surface roughness. Equation 6.5 gives surface roughness for linear model.

$$\mathrm{Ra} = 2.7471 - 0.007432 * \mathrm{v} + 9.5963 * \mathrm{f} - 1.3013 * \mathrm{r} + 0.1283 * \mathrm{d} \quad (6.5)$$

Table 6.5 Estimated Regression Coefficients for Roughness

Term	Coef	SE Coef	T	p
Constant	1.36444	0.03312	41.199	0.000
Cutting speed (v) (m/min)	-0.22296	0.04056	-5.497	0.000
Feed (f) (mm/rev)	0.47981	0.04056	11.829	0.000
Nose radius (r) (mm)	-0.52056	0.04056	-12.834	0.000
Depth of cut (d) (mm)	0.03852	0.04056	0.950	0.345

S = 0.298064 PRESS = 7.75726

R-Sq = 81.54% R-Sq (pred) = 78.79% R-Sq (adj) = 80.57%

Table 6.6 Analysis of Variance for Roughness (Linear) Ra

Source	DF	Seq SS	Adj SS	Adj MS	F value	p value
Regression	4	29.8294	29.8294	7.4574	83.94	0.000
Linear	4	29.8294	29.8294	7.4574	83.94	0.000
Cutting speed (v) (m/min)	1	2.6845	2.6845	2.6845	30.22	0.000
Feed (f) (mm/rev)	1	12.4320	12.4320	12.4320	139.93	0.000
Nose radius (r) (mm)	1	14.6328	14.6328	14.6328	164.71	0.000
Depth of cut (d) (mm)	1	0.0801	0.0801	0.0801	0.90	0.345
Residual Error	76	6.7520	6.7520	0.0888		
Total	80	36.5814				

Table 6.7 Estimated Regression Coefficients for Roughness (Quadratic) (Ra)

Term	Coef	SE Coef	T	p
Constant	1.00074	0.04219	23.721	0.000
Cutting speed (v) (m/min)	-0.22296	0.01722	-12.946	0.000
Feed (f) (mm/rev)	0.47981	0.01722	27.859	0.000
Nose radius (r) (mm)	-0.52056	0.01722	-30.225	0.000
Depth of cut (d) (mm)	0.03852	0.01722	2.236	0.029
v x v	0.12333	0.02983	4.134	0.000
f x f	0.11167	0.02983	3.743	0.000
r x r	0.29389	0.02983	9.852	0.000
d x d	0.01667	0.02983	0.559	0.578
v x f	-0.03389	0.02109	-1.607	0.113
v x r	0.07472	0.02109	3.542	0.001
v x d	0.00083	0.02109	0.040	0.969
f x r	-0.30694	0.02109	-14.552	0.000
f x d	0.00722	0.02109	0.342	0.733
r x d	0.00500	0.02109	0.237	0.813

S = 0.126562 PRESS = 1.58327

R-Sq = 97.11% R-Sq (pred) = 95.67% R-Sq (adj) = 96.50%

Table 6.7 shows estimated regression coefficient for roughness for quadratic model. In present work, R^2 value is 0.9711 and the Adj. R^2 is 0.9650. The predicted R^2 value is 0.9567. Table 6.8 shows ANOVA for quadratic model of surface roughness. The value of "p" in Table 6.8 for model is less than 0.05 which indicates that the model is adequately significant at 95% confidence level, which is desirable as it indicates that the term in the model, have a significant effect on the response. Similarly, the main effect of cutting speed (v), feed (f), nose radius(r) and depth of cut(d) and two level interaction of cutting speed and nose radius (v r), feed and nose radius (f r) and also square effect of v^2, f^2 and r^2 are significant model terms. Other model terms are not significant.

Table 6.8 Analysis of Variance for Roughness (Quadratic) (Ra)

Source	DF	Seq SS	Adj SS	Adj MS	F value	p value
Regression	14	35.5242	35.5242	2.5374	158.41	0.000
Linear	4	29.8294	29.8294	7.4574	465.56	0.000
Cutting speed (v) (m/min)	1	2.6845	2.6845	2.6845	167.59	0.000
Feed (f) (mm/rev)	1	12.4320	12.4320	12.4320	776.13	0.000
Nose radius (r) (mm)	1	14.6328	14.6328	14.6328	913.53	0.000
Depth of cut (d) (mm)	1	0.0801	0.0801	0.0801	5.00	0.029
Square	4	2.0579	2.0579	0.5145	32.12	0.000
Cutting speed (v)*Cutting speed (v)	1	0.2738	0.2738	0.2738	17.09	0.000
Feed (f)*Feed (f)	1	0.2244	0.2244	0.2244	14.01	0.000
Nose radius (r)*Nose radius(r)	1	1.5547	1.5547	1.5547	97.06	0.000
Depth of cut (d)*Depth of cut (d)	1	0.0050	0.0050	0.0050	0.31	0.578
Interaction	6	3.6369	3.6369	0.6061	37.84	0.000
Cutting speed (v)*Feed (f)	1	0.0413	0.0413	0.0413	2.58	0.113
Cutting speed (v)*Nose radius (r)	1	0.2010	0.2010	0.2010	12.55	0.001
Cutting speed (v)*Depth of cut (d)	1	0.0000	0.0000	0.0000	0.00	0.969
Feed (f)*Nose radius(r)	1	3.3917	3.3917	3.3917	211.75	0.000
Feed (f)*Depth of cut (d)	1	0.0019	0.0019	0.0019	0.12	0.733
Nose radius (r)*Depth of cut (d)	1	0.0009	0.0009	0.0009	0.06	0.813
Residual Error	66	1.0572	1.0572	0.0160		
Total	80	36.5814				

Since the difference between the first order and second order for multiple regression coefficient is 15.93 %. So it can be conclude that the second order model is required to represent the model for turning process. From response surface Eq .6.6 the most significant factor on the Surface roughness is feed rate. The next contribution on surface roughness is nose radius and cutting speed. Depths of cut have not significant effect on the surface roughness. Figs.6.8 and 6.9 shows main effect plot and interaction plots for surface roughness.

$$Ra = 11.8291 - 0.07759 * v + 13.8333 * f - 3.5199 * r - 0.22253 * d + 0.000137 * v^2 + 44.6667 * f^2 + 1.8368 * r^2 + 0.1851 * d^2 - 0.02259 * v * f + 0.006226 * v * r - 0.00009259 * v * d - 15.3472 * f * r + 0.481481 * f * d + 0.0416667 * r * d \quad (6.6)$$

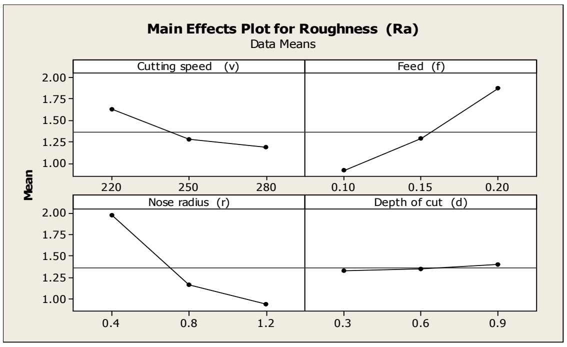

Fig. 6.8 Main effect plot for Roughness

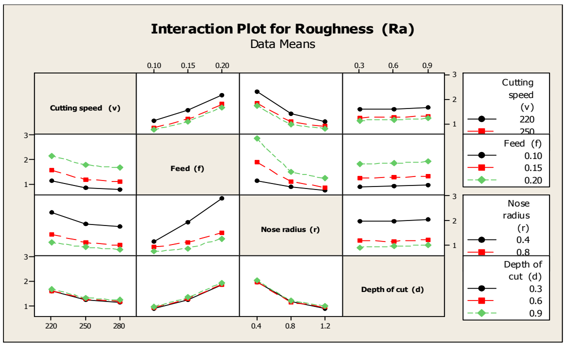

Fig. 6.9 Interaction plot for Roughness

The diagnostic checking of the model has been carried out using residual analysis and the results are presented in Figs. 6.10 and 6.11. The normal probability plot is presented in Fig. 6.10. The figure revealed that the residuals fall on a straight line implying that the errors are distributed normally. Figure 6.11 shows the standardized residuals with respect to the predicted values. The residuals do not show any obvious pattern and are distributed in both positive and negative direction. This implies that the model is adequate and there is no reason to suspect any violation of the independence or constant variance assumption. The relation between the experimental and the predicted values are shown in Fig. 6.12. The experimental values are very close to the predicted values hence this empirical model provides reliable prediction.

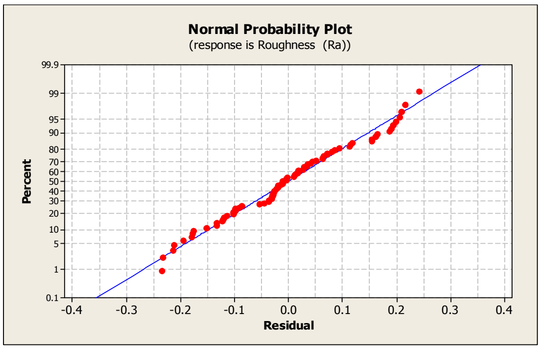

Fig. 6.10 Normal probability plot of Ra

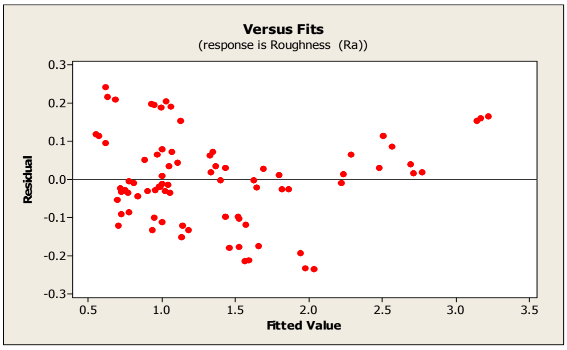

Fig. 6.11 Residual Vs. Fitted surface roughness

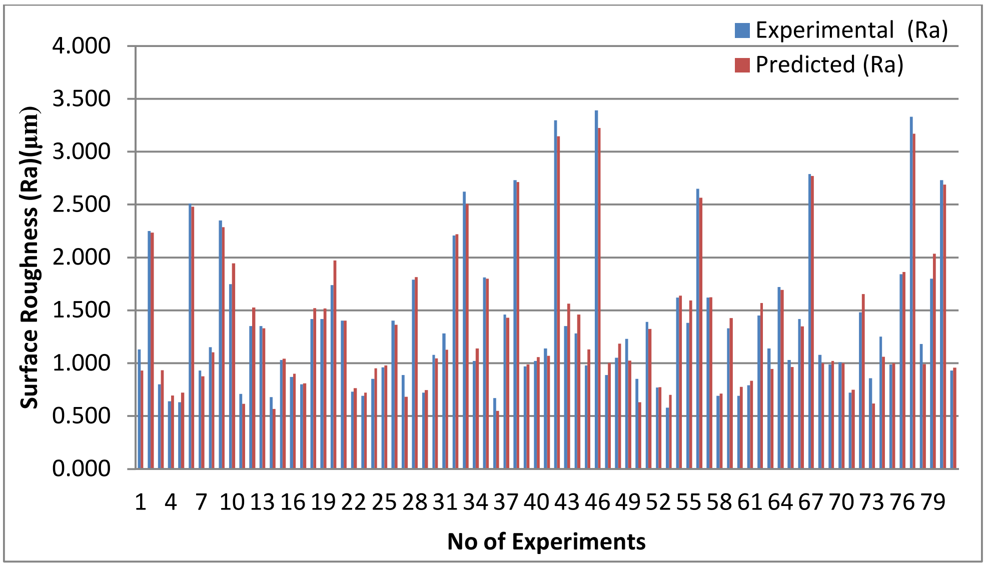

Fig. 6.12 Predicted and Experimental values for Surface Roughness

6.3.2 3 D and 2D Contour Plots

The analysis of response variable surface roughness can be explained through contour and surface plots. The typical two-dimensional (2D) contour plots for surface roughness in terms of the process variable are shown in Figs. 6.13 to 6.16. These response contours can help in the prediction of surface roughness at any zone of the experimental domain. It is clear from these figures that the surface roughness reduces with the increase of cutting speed. However, it increases with the increase of feed and decreases with increasing tool nose radius. By increasing the depth of cut it is not much affected by surface roughness.

The surface plot shows the influence of different machining variables, keeping the other variable at constant level. Figure 6.16 illustrates the surface model for surface roughness by varying the two variables nose radius and cutting speed and keeping the two parameters feed and depth of cut at constant level. The figure indicates that the surface roughness decreases with increase in nose radius and cutting speed. Figure 6.17 shows the effect of cutting speed with respect to feed on surface roughness. From the figure, it has been asserted that the increase of cutting speed reduces the surface roughness while increasing feed roughness also increases. Figure 6.18 shows the influence of cutting speed and depth of cut on surface roughness by keeping the nose radius and feed at constant level. From the figure, it can be asserted that the increase in cutting speed reduces the roughness while increases depth of cut not affected on Ra.

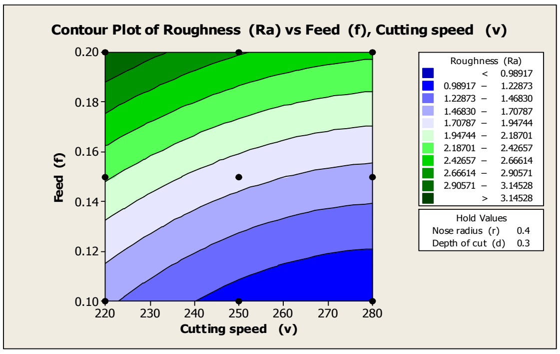

Fig. 6.13 Estimated contour plots for Ra (Const.: r and d)

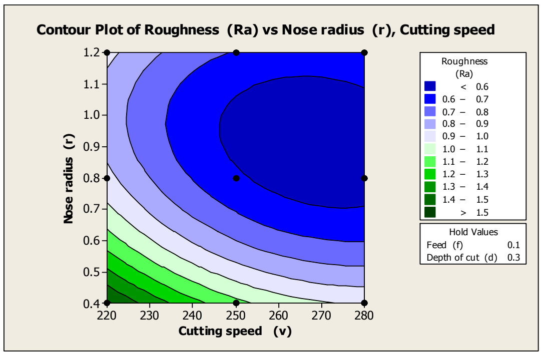

Fig.6.14 Estimated contour plots for Ra (Const.: f and d)

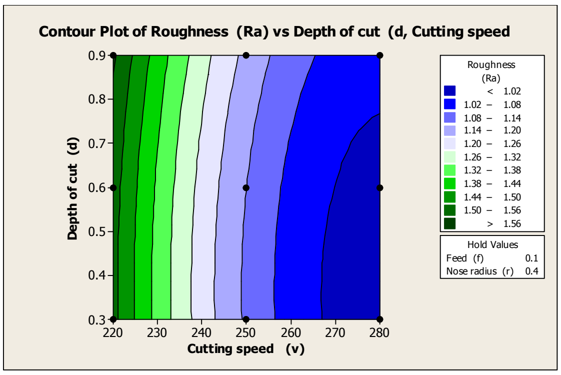

Fig. 6.15 Estimated contour plots for Ra (Const.: f and r)

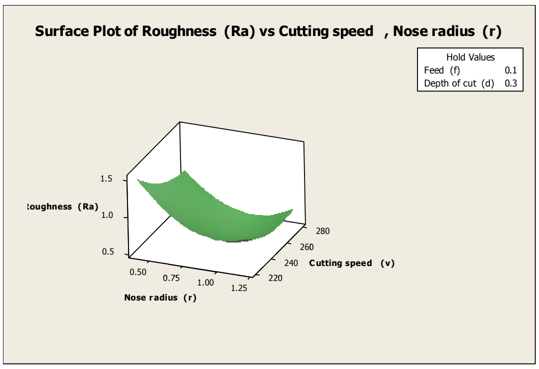

Fig. 6.16 3Dsurface plot for Ra Vs r & v

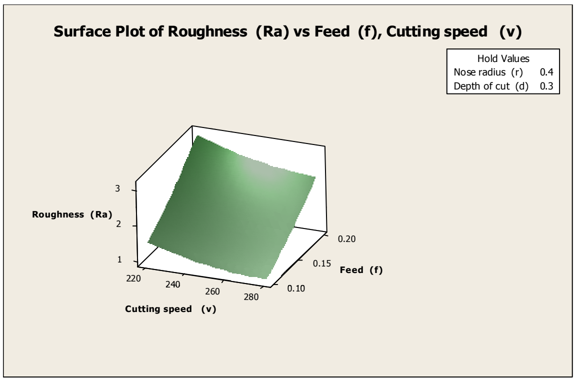

Fig. 6.17 3Dsurface plot for Ra Vs v & f

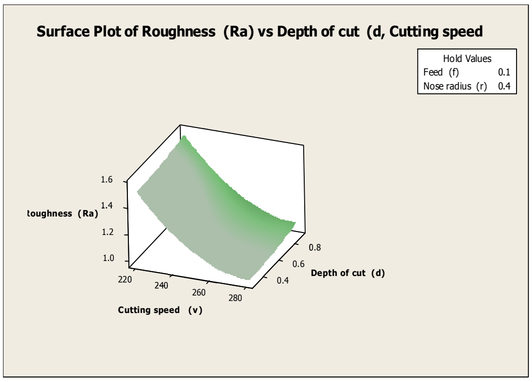

Fig. 6.18 3Dsurface plot for Ra Vs v & d

6.3.3 Confirmation test

The effectiveness of the model has been checked by validation with experimental results. In order to verify the adequacy of the model developed, five confirmation run experiments have been performed (Table 6.9 and Fig.6.19) at different cutting conditions. The test condition for the first three validation run experiments are among the cutting conditions that are performed previously while the remaining two validation run experiments are the conditions that have not been used previously. The experimental results have been validated by asserting that the predicted values are very close to each other and hence, the developed models are suitable for predicting the surface roughness in machining of AISI 1040 steel.

Table 6.9 Confirmation test (AISI 1040 steel)

Sr. no.	Speed(v) (m/min)	Feed (f) (mm/rev)	Nose radius (r) (mm)	Depth of cut (d) (mm)	Exp.(Ra) (µm)	Pred.(Ra) (µm)	Error (%)
1	280	0.1	0.8	0.9	0.65	0.615	5.3
2	250	0.15	0.4	0.6	1.79	1.815	1.3
3	250	0.2	1.2	0.6	1.10	1.058	3.8
4	220*	0.12	0.8	0.5	1.13	1.069	5.3
5	260*	0.18	0.4	0.7	2.33	2.249	3.4

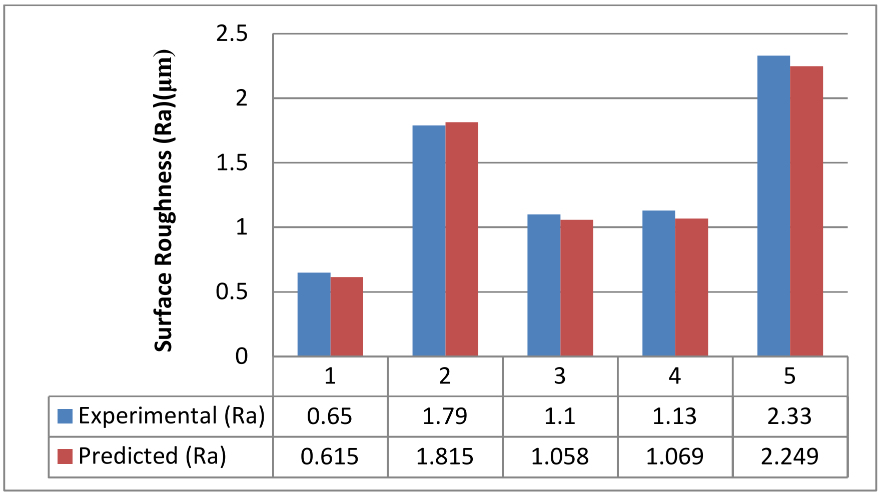

Fig. 6.19 Comparison of experimental and predicated values for Ra

6.3.4 Response surface optimization

One of the most important aims of experiments related to manufacturing is to achieve the desired surface roughness of the optimal cutting parameters. Response surface optimization is an ideal technique for determination of the best cutting parameters in turning operation. Here, the goal is to minimize surface roughness. RSM optimization results for surface parameters are shown in Fig 6.20 and Table 6.10. Optimum machining parameters are found to be cutting velocity of 270 m/min, feed of 0.1mm/rev, depth of cut of 0.3 mm and tool nose radius of 0.91mm. The optimized surface parameter is Ra = 0.5219 µm.

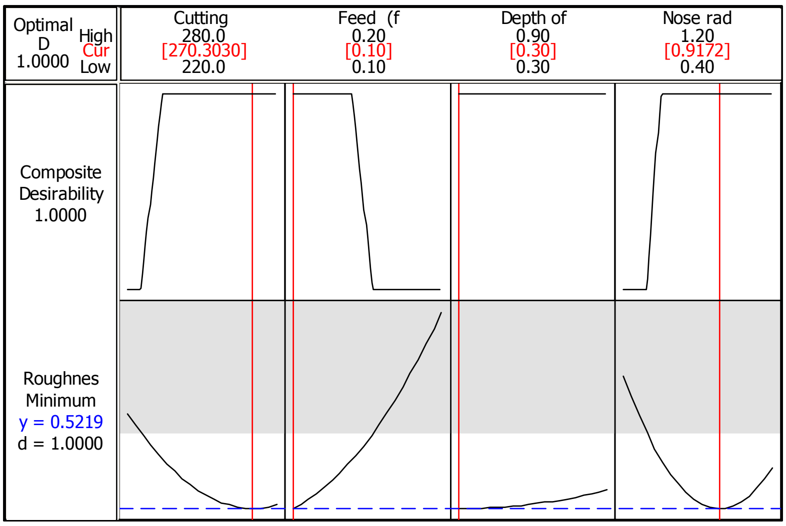

Fig. 6.20 Response optimization for surface roughness parameter

Table 6.10 Response optimization for surface roughness parameters (1040 steel)

Parameter	Goal	Optimum conditions				Lower	Target	Upper	Pre. resp.	Desi.
		v (m/min)	f(mm/rev)	d(mm)	r(mm)					
Ra (μm)	Min.	270.30	0.1	0.3	0.91	0.7	0.7	0.8	0.5219	1

6.4 Experimental details for AISI 410 Steel

In this study, the experiments were planned using 3^4 full factorial design with 81 numbers of experiments with AISI 410 steel. The four cutting parameters are selected for the present investigation is cutting speed (v), feed (f), nose radius (r) and depth of cut (d). Since the considered factors are multi level variables and their outcome effects are not linearly related, it has been decided to use three level tests for each factor. The machining parameters used and their levels chosen are given in Table 6.11.

Table 6.11 Parameters and their level (AISI 410 Steel)

Parameters	Level -1	Level -2	Level -3
Cutting speed (v) (m/min)	220	250	280
Feed (f) (mm/rev)	0.1	0.15	0.2
Depth of cut (d) (mm)	0.3	0.6	0.9
Nose radius (r) (mm)	0.4	0.8	1.2

All the turning experiments were conducted on a Jobber XL model made by Ace designer CNC lathe machine (Detailed is given in section 6.6). The machining tests were carried out in wet conditions using a water-soluble cutting fluid. In this study, ceramic inserts (supplied by Ceratizit) were used, ISO code TNMG160404 EN-TMF, TNMG 160408 EN-TM and TNMG 160412 EN-TM with different nose radius. (60^0 triangular shaped inserts). The inserts were mounted on a commercial tool. In the present investigation, the bar of AISI 410 steel with the following chemical composition were used as the work material: 0.149 % C, 0.506 % Si, 0.447 % Mn, 12.29 % Cr, 0.318 % Ni, and 0.039 % Mo. A mechanical property and microscopic analysis of the material is given in Table 6.12 and Fig.6.21. Surface finish of the work piece material was measured by Surf test model No. SJ-400 (Mitutoyo make). Detailed specification of the roughness tester is given in chapter 5. The result table from the machining test performed as per the 3^4 full factorial design are shown in Table 6.13. These results are fed into the Minitab-16 for further analysis.

Table 6.12 Mechanical properties of AISI 410 steel

Material properties	AISI 410 steel
Physical density	7.74 g/cm^3
Mechanical hardness, Rockwell B	99
Tensile strength, ultimate	510 Mpa
Tensile strength, yield	310 Mpa
% of elongation	25

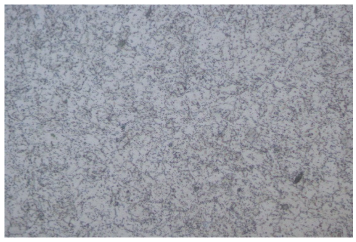

Fig. 6.21 Material: AISI 410 500X

Table 6.13 Result table (AISI410 steel)

Run Order	Cutting speed (v) (m/min)	Feed (f) (mm/rev)	Depth of cut (d) (mm)	Nose radius (r) (mm)	Roughness (Ra) (µm)
1	280	0.2	0.6	1.2	1.12
2	250	0.1	0.3	1.2	0.32
3	220	0.15	0.6	1.2	0.94
4	280	0.15	0.9	0.4	1.69
5	280	0.2	0.9	1.2	1.17
6	280	0.15	0.9	1.2	0.89
7	220	0.2	0.3	0.4	2.25
8	280	0.1	0.6	1.2	0.33
9	220	0.15	0.6	0.4	1.79
10	280	0.2	0.3	0.8	1.45
11	250	0.15	0.3	0.8	0.84
12	250	0.2	0.6	0.4	2.15
13	280	0.1	0.9	1.2	0.33
14	250	0.1	0.3	0.8	0.39
15	220	0.2	0.6	0.8	1.70
16	280	0.1	0.3	0.4	0.97
17	280	0.2	0.3	1.2	1.07
18	250	0.15	0.3	1.2	0.84
19	280	0.2	0.9	0.8	1.60
20	250	0.1	0.9	1.2	0.38
21	280	0.1	0.3	0.8	0.42
22	220	0.1	0.6	0.4	1.03
23	220	0.15	0.3	1.2	0.91
24	220	0.2	0.6	0.4	2.31

25	250	0.1	0.6	1.2	0.35
26	250	0.15	0.6	1.2	0.88
27	250	0.2	0.9	1.2	1.16
28	220	0.2	0.3	0.8	1.68
29	220	0.1	0.6	0.8	0.53
30	280	0.15	0.9	0.8	1.24
31	250	0.15	0.9	0.4	1.52
32	250	0.15	0.9	1.2	0.91
33	250	0.1	0.3	0.4	0.96
34	250	0.15	0.6	0.4	1.52
35	220	0.2	0.9	0.8	1.77
36	220	0.1	0.9	0.4	1.07
37	250	0.2	0.3	0.8	1.45
38	280	0.2	0.6	0.4	2.12
39	280	0.1	0.3	1.2	0.30
40	250	0.1	0.6	0.4	0.99
41	250	0.1	0.9	0.4	1.01
42	280	0.2	0.6	0.8	1.54
43	220	0.2	0.9	0.4	2.40
44	250	0.15	0.6	0.8	1.17
45	280	0.15	0.3	0.8	1.14
46	220	0.1	0.3	0.8	0.50
47	220	0.15	0.9	1.2	0.97
48	250	0.2	0.9	0.4	2.20
49	220	0.2	0.3	1.2	1.16
50	280	0.1	0.9	0.8	0.56
51	250	0.2	0.3	1.2	1.09
52	220	0.1	0.3	0.4	1.11
53	250	0.2	0.6	0.8	1.52
54	250	0.2	0.9	0.8	1.55
55	280	0.15	0.3	0.4	1.57
56	280	0.1	0.9	0.4	1.07
57	220	0.15	0.9	0.4	1.81
58	250	0.1	0.9	0.8	0.51
59	220	0.1	0.6	1.2	0.42
60	220	0.15	0.9	0.8	1.34
61	220	0.2	0.9	1.2	1.20
62	250	0.15	0.3	0.4	1.50
63	220	0.1	0.9	1.2	0.45
64	280	0.15	0.6	0.4	1.63
65	280	0.1	0.6	0.8	0.47
66	250	0.1	0.6	0.8	0.46
67	250	0.2	0.3	0.4	2.05
68	280	0.15	0.6	0.8	1.19
69	280	0.2	0.3	0.4	2.05

70	250	0.15	0.9	0.8	1.19
71	220	0.2	0.6	1.2	1.21
72	280	0.1	0.6	0.4	1.03
73	220	0.1	0.9	0.8	0.45
74	220	0.15	0.3	0.4	1.73
75	280	0.2	0.9	0.4	2.20
76	220	0.1	0.3	1.2	0.37
77	280	0.15	0.3	1.2	0.82
78	250	0.2	0.6	1.2	1.14
79	220	0.15	0.3	0.8	1.32
80	280	0.15	0.6	1.2	0.86
81	220	0.15	0.6	0.8	1.37

6.4.1 Result and discussion

Table 6.14 and Table 6.15 show estimated regression coefficient and ANOVA for linear model of surface roughness. Equation 6.7 gives linear model for surface roughness. The effectiveness of the model has been checked by using the R^2 value. In present work, R^2 value is 0.9476 and the Adj. R^2 is 0.9449 and predicted R^2 value 0.9407.

$$\mathrm{Ra} = 0.8279 - 0.001827 * \mathrm{v} + 10.1963 * \mathrm{f} - 1.0250 * \mathrm{r} + 0.1469 * \mathrm{d} \quad (6.7)$$

Table 6.14 Estimated Regression Coefficients for Roughness

Term	Coef	SE Coef	T	P
Constant	1.16877	0.01449	80.660	0.000
Cutting speed (v) (m/min)	-0.05481	0.01775	-3.089	0.003
Feed (f) (mm/rev)	0.50981	0.01775	28.727	0.000
Nose radius (r) (mm)	-0.41000	0.01775	-23.103	0.000
Depth of cut (d) (mm)	0.04407	0.01775	2.484	0.015

S = 0.130411 PRESS = 1.46332

R-Sq = 94.76% R-Sq (pred) = 94.07% R-Sq (adj) = 94.49%

Table 6.16 shows estimated regression coefficient for roughness for quadratic model. In present work, R^2 value is 0.9880 and the Adj. R^2 is 0.9854 and the predicted R^2 value 0.9825. Table 6.17 shows ANOVA for quadratic model of surface roughness. The value of "p" in Table 6.17 for model is less than 0.05 which indicates that the model is adequately significant at 95% confidence level, which is desirable as it indicates that the term in the model, have a significant effect on the response. Similarly, the main effect of cutting speed (v), feed (f) nose radius(r)and depth of cut(d) and two level interaction of cutting speed and feed (v f) and feed and nose radius (f r) and also square effect of v^2, f^2 and r^2 are significant model terms. Other model terms are not significant.

Table 6.15 Analysis of Variance for Roughness (Linear) (Ra)

Source	DF	Seq SS	Adj SS	Adj	F value	p
Regression	4	23.3798	23.3798	5.8449	343.68	0.000
Linear	4	23.3798	23.3798	5.8449	343.68	0.000
Cutting speed (v) (m/min)	1	0.1623	0.1623	0.1623	9.54	0.003
Feed (f) (mm/rev)	1	14.0352	14.0352	14.0352	825.26	0.000
Nose radius (r) (mm)	1	9.0774	9.0774	9.0774	533.75	0.000
Depth of cut (d) (mm)	1	0.1049	0.1049	0.1049	6.17	0.015
Residual Error	76	1.2925	1.2925	0.0170		
Total	80	24.6723				

Table 6.16 Estimated Regression Coefficients for Roughness (Quadratic) (Ra)

Term	Coef	SE Coef	T	p
Constant	1.11407	0.022351	49.844	0.000
Cutting speed (v) (m/min)	-0.05481	0.009125	-6.007	0.000
Feed (f) (mm/rev)	0.50981	0.009125	55.871	0.000
Nose radius (r) (mm)	-0.41000	0.009125	-44.932	0.000
Depth of cut (d) (mm)	0.04407	0.009125	4.830	0.000
v x v	0.08370	0.015805	5.296	0.000
f x f	-0.11241	0.015805	-7.112	0.000
r x r	0.12259	0.015805	7.757	0.000
d x d	-0.01185	0.015805	-0.750	0.456
v x f	-0.02528	0.011176	-2.262	0.027
v x r	0.01194	0.011176	1.069	0.289
v x d	0.01472	0.011176	1.317	0.192
f x r	-0.09500	0.011176	-8.501	0.000
f x d	0.01417	0.011176	1.268	0.209
r x d	-0.00556	0.011176	-0.497	0.621

S = 0.0670536 PRESS = 0.431365

R-Sq = 98.80% R-Sq (pred) = 98.25% R-Sq (adj) = 98.54%

Table 6.17 Analysis of Variance for Roughness (Quadratic) (Ra)

Source	DF	Seq SS	Adj SS	Adj MS	F value	p value
Regression	14	24.3755	24.3755	1.7411	387.24	0.000
Linear	4	23.3798	23.3798	5.8449	1299.98	0.000
Cutting speed (v) (m/min)	1	0.1623	0.1623	0.1623	36.09	0.000
Feed (f) (mm/rev)	1	14.0352	14.0352	14.0352	3121.58	0.000
Nose radius(r) (mm)	1	9.0774	9.0774	9.0774	2018.91	0.000
Depth of cut (d) (mm)	1	0.1049	0.1049	0.1049	23.33	0.000
Square	4	0.6266	0.6266	0.1567	34.84	0.000
Cutting speed (v)*Cutting speed	1	0.1261	0.1261	0.1261	28.05	0.000
Feed (f)*Feed (f)	1	0.2274	0.2274	0.2274	50.58	0.000
Nose radius(r)*Nose radius (r)	1	0.2705	0.2705	0.2705	60.17	0.000
Depth of cut (d)*Depth of cut (d)	1	0.0025	0.0025	0.0025	0.56	0.456
Interaction	6	0.3692	0.3692	0.0615	13.68	0.000
Cutting speed (v)*Feed (f)	1	0.0230	0.0230	0.0230	5.12	0.027
Cutting speed (v)*Nose radius(r)	1	0.0051	0.0051	0.0051	1.14	0.289
Cutting speed (v)*Depth of cut	1	0.0078	0.0078	0.0078	1.74	0.192
Feed (f)*Nose radius(r)	1	0.3249	0.3249	0.3249	72.26	0.000
Feed (f)*Depth of cut (d)	1	0.0072	0.0072	0.0072	1.61	0.209
Nose radius(r)*Depth of cut (d)	1	0.0011	0.0011	0.0011	0.25	0.621
Residual Error	66	0.2967	0.2967	0.0045		
Total	80	24.6723				

$$\begin{aligned} Ra &= 5.32260 - 0.0475792 * v + 31.1315 * f - 1.75949 * r - 0.208642 * d + 9.30041E-05 \\ &* v^2 - 44.9630 * f^2 + 0.766204 * r^2 - 0.1316870 * d^2 - 0.0168519 * v * f \\ &+ 0.000995370 * v * r + 0.00163580 * v * d - 4.75000 * f * r + 0.944444 * f * d \\ &- 0.0462963 * r * d \end{aligned} \tag{6.8}$$

Since the difference between the first order and second order for multiple regression coefficient is 4.05 %. So it can be conclude that the second order model is required to represent the model for turning process. From response surface Eq. 6.8, the most significant factor on the Surface roughness is feed rate. The next contribution on surface roughness is nose radius and cutting speed. Depths of cut have not much significant effect on the surface roughness. Figures 6.22 and 6.23 show main effect plot and interaction plot for surface roughness.

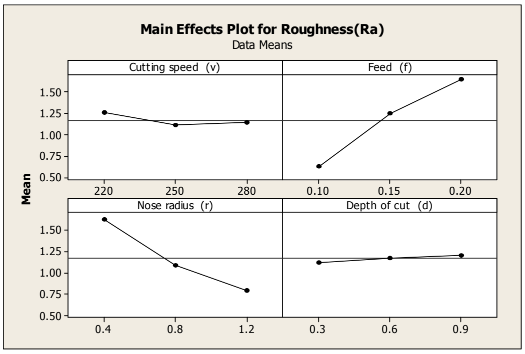

Fig. 6.22 Main effect plot for Roughness

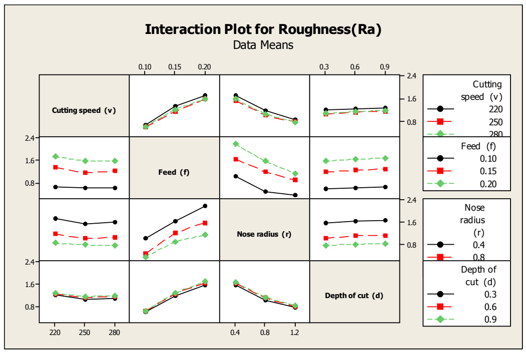

Fig. 6.23 Interaction plot for Roughness

The normal probability plot is presented in Fig. 6.34. The figure revealed that the residuals fall on a straight line implying that the errors are distributed normally. Figure 6.25 shows the standardized residuals with respect to the predicted values. The residuals do not show any obvious pattern and are distributed in both positive and negative direction. This implies that the model is adequate and there is no reason to suspect any violation of the independence or constant variance assumption. The relation between the experimental and the predicted values are shown in Fig. 6.26. The experimental values are very close to the predicted values hence this empirical model provides reliable prediction.

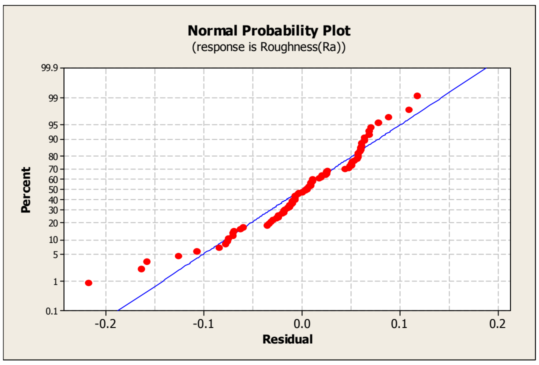

Fig. 6.24 Normal prob. plot of residual for Ra

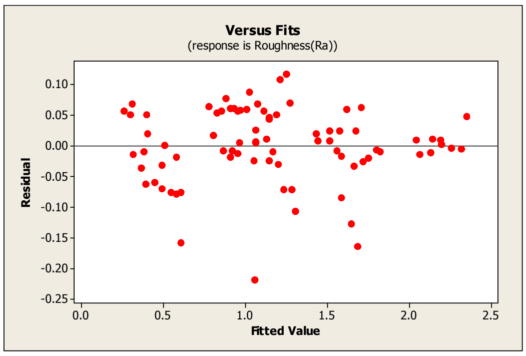

Fig. 6.25 Residual Vs. Fitted roughness values

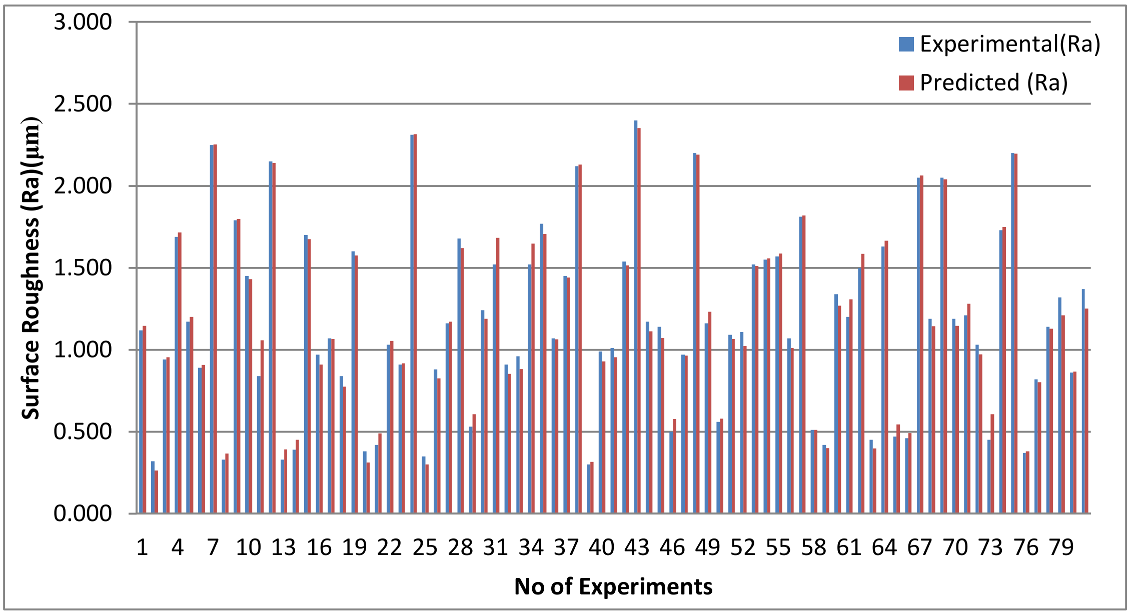

Fig. 6.26 Predicted and Experimental values for Surface Roughness

6.4.2 3D and 2D Contour Plots

The typical three-dimensional (3D) surface plots and two-dimensional (2D) contour plots for surface roughness in terms of the process variable are shown in Figs. 6.27 to 6.32. These response contours (2D) can help in the prediction of surface roughness at any zone of the experimental domain. It is clear from these figures that the surface roughness reduces with the increase of cutting speed. However, it increases with the increase of feed and decreases with increasing tool nose radius.

The surface plot shows the influence of different machining variables, keeping the other variable at constant level. Figure 6.30 illustrates the surface model for surface roughness by varying the two variables cutting speed and feed and keeping the two parameters nose radius and depth of cut at constant level. The figure indicates that the surface roughness decreases with increase in cutting speed and increases by increasing feed. Figure 6.31 shows the effect of nose radius with respect to cutting speed. From the figure, it has been asserted that the increase of cutting speed reduces the surface roughness while increasing nose radius reduces the surface roughness. Figure 6.32 shows the influence of nose radius and depth of cut on surface roughness by keeping the cutting speed and feed at constant level. From the figure, it can be asserted that the increases in nose radius reduces the surface roughness while increases in depth of cut not much affected Ra.

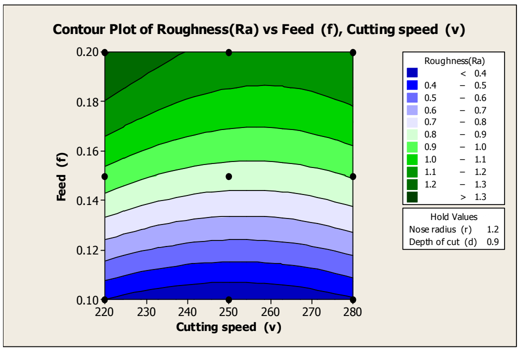

Fig. 6.27 Esti. Contour plots for Ra (Const.: r and d)

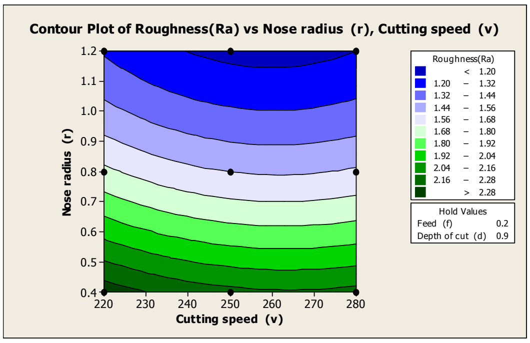

Fig. 6.28 Estimated contour plots for Ra (Const.: f and d)

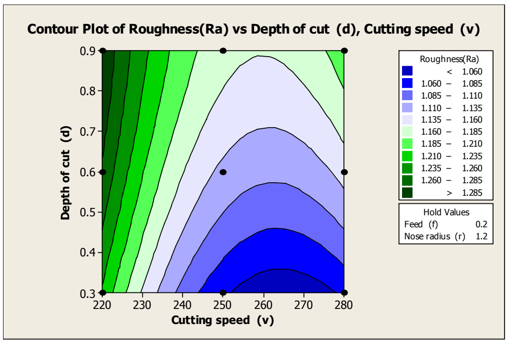

Fig. 6.29 Estimated contour plots for Ra (Const.: f and r)

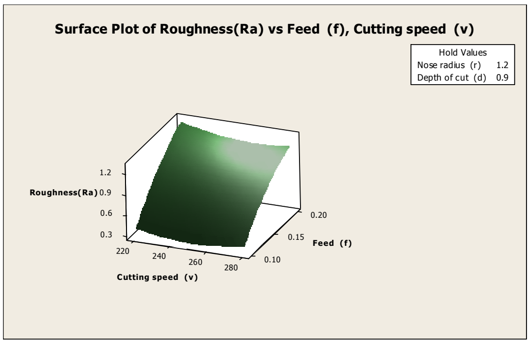

Fig. 6.30 3D surface plot for Ra Vs v and f

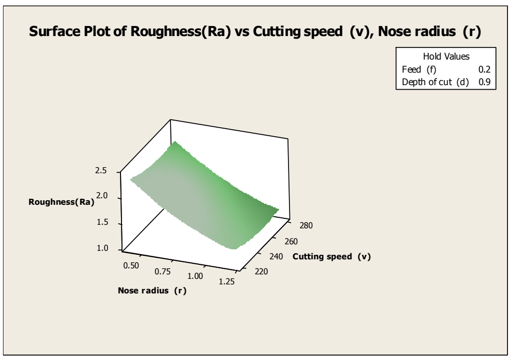

Fig. 6.31 3Dsurface plot for Ra Vs r and v

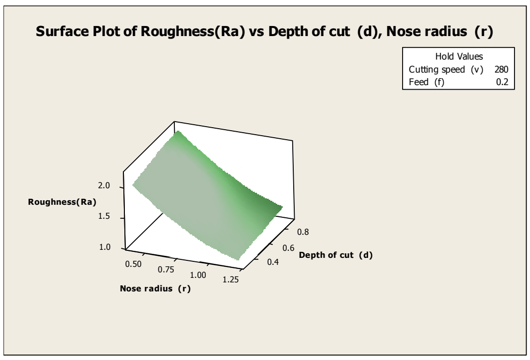

Fig. 6.32 3Dsurface plot for Ra Vs r and d

6.4.3 Confirmation test

In order to verify the adequacy of the model developed, five confirmation run experiments have been performed (Table 6.18 and Fig. 6.33) at different cutting conditions. The test condition for the first three validation run experiments are among the cutting conditions that are performed previously while the remaining two validation run experiments are the conditions that have not been used previously. The experimental results have been validated by asserting that the predicted values are very close to each other and hence, the developed models are suitable for predicting the surface roughness in machining AISI 410 steel.

Table 6.18 Confirmation test (AISI 410 steel)

Sr. no.	Speed (v) (m/min)	Feed (f) (mm/rev)	Nose radius (r) (mm)	Depth of cut(d) (mm)	Exp. (Ra) (µm)	Pred. (Ra) (µm)	Error (%)
1	280	0.1	1.2	0.6	0.37	0.366	1.08
2	250	0.1	0.8	0.3	0.44	0.450	2.22
3	220	0.1	0.4	0.6	1.03	1.055	2.36
4	260*	0.1	0.8	0.9	0.52	0.514	1.15
5	240*	0.14	0.4	0.3	1.52	1.497	1.51

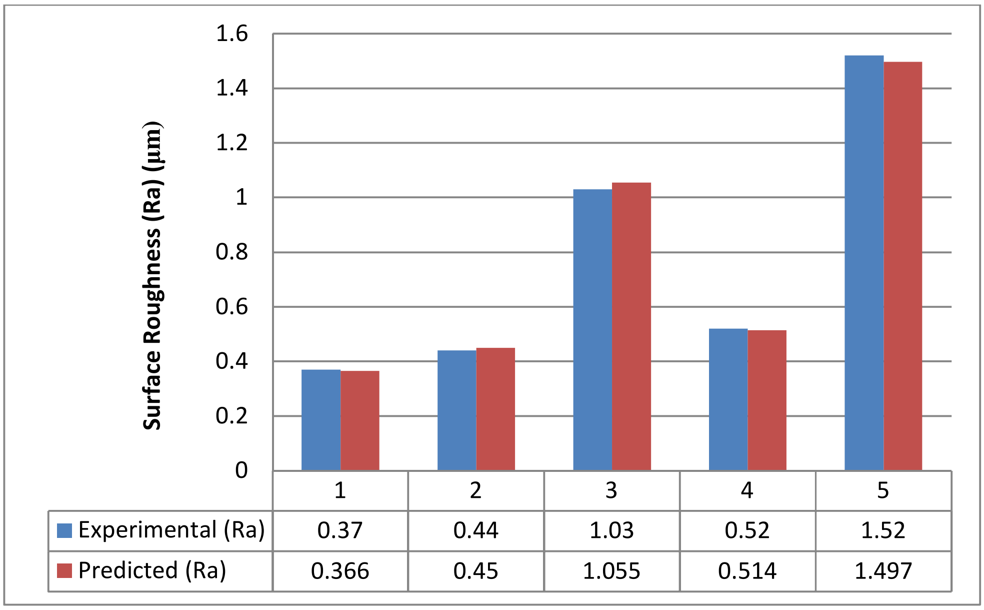

Fig. 6.33 Comparison of experimental and predicated values for Ra

6.4.4 Response surface optimization

Response surface optimization is an ideal technique for determination of the best cutting parameters in turning operation. Here, the goal is to minimize surface roughness.RSM optimization results for surface parameters are shown in Table 6.19 and Fig. 6.34. Optimum machining parameters are found to be cutting velocity of 255.7 m/min, feed of 0.1mm/rev, depth of cut of 0.3 mm and tool nose radius of 1.2 mm. The optimized surface roughness parameter is Ra = 0.2601 µm.

Table 6.19 Response optimization for surface roughness parameters

Parameter	Goal	Optimum conditions				Lower	Target	Upper	Pre. resp.	Desi.
		v(m/min)	f(mm/rev)	d(mm)	r(mm)					
Ra (µm)	Min.	255.7	0.1	0.3	1.2	0.7	0.7	0.8	0.2601	1

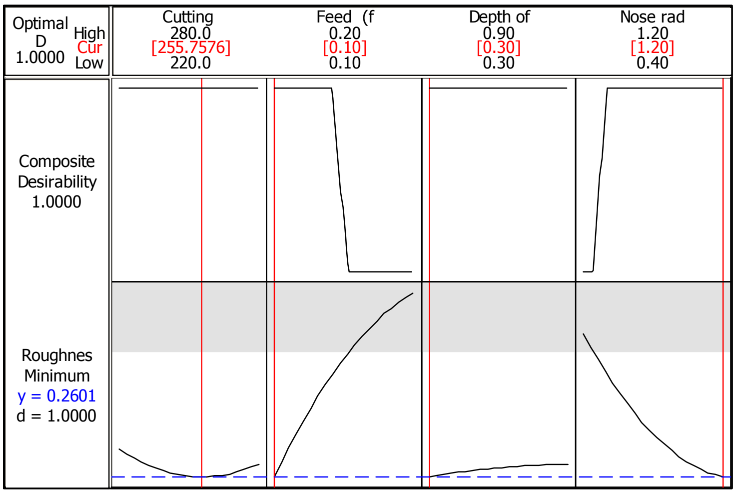

Fig. 6.34 Response optimization for surface roughness parameter

6.5 Experimental details for Mild steel

In this study, the experiments were planned using 3^4 full factorial design with 81 numbers of experiments with Mild steel. The four cutting parameters are selected for the present investigation is cutting speed (v), feed (f), nose radius (r) and depth of cut (d). Since the considered factors are multi level variables and their outcome effects are not linearly related, it has been decided to use three level tests for each factor. The machining parameters used and their levels chosen are given in Table 6.20.

Table 6.20 Parameters and their levels (Mild steel)

Parameters	Level -1	Level -2	Level -3
Cutting speed (v) (m/min)	220	250	280
Feed (f) (mm/rev)	0.1	0.15	0.2
Depth of cut (d) (mm)	0.3	0.6	0.9
Nose radius (r) (mm)	0.4	0.8	1.2

All the turning experiments were conducted on a Jobber X_L model made by Ace designer CNC lathe machine (Detailed is given in previous session). The machining tests were carried out in wet conditions using a water-soluble cutting fluid. In this study, ceramic inserts (supplied by Ceratizit) were used, ISO code TNMG160404 EN-TMF, TNMG 160408 EN-TM and TNMG 160412 EN-TM with different nose radius. (60^0 triangular shaped inserts). The inserts were mounted on a commercial tool.

In the present investigation, the bar of Mild steel with the following chemical composition was used as the work material: 0.353 % C, 0.181 % Si, 0.560 %Mn, 0.03% P and 0.171 % Cr. A mechanical property and microscopic analysis of the material is given in Table 6.21 and Fig.6.35. Surface finish of the work piece material was measured by Surf test model No. SJ-400 (Mitutoyo make). Detailed specification of the roughness tester is given in chapter 5.The result table from the machining test performed as per the 3^4 full factorial design are shown in Table 6.22. These results are fed into the Minitab-16 for further analysis. The procedure of experimental scheme is shown in Fig.6.48.

Table 6.21 Mechanical properties of Mild Steel

Material properties	Mild Steel
Physical density	7.85 g/cm^3
Mechanical hardness, Rockwell B	98
Tensile strength, ultimate	500 Mpa
Tensile strength, yield	300 Mpa
% of elongation	15

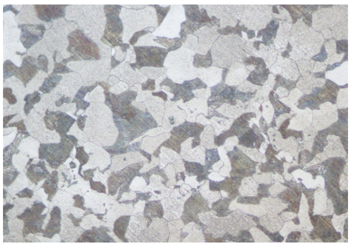

Fig.6.35 Material: M.S 500X

Table 6.22 Result table (Mild Steel)

Run Order	Cutting speed (v) (m/min)	Feed (f) (mm/rev)	Depth of cut (d) (mm)	Nose radius (r) (mm)	Roughness (Ra) (μm)
1	250	0.2	0.9	1.2	1.29
2	280	0.1	0.6	1.2	0.7
3	250	0.2	0.6	1.2	1.23
4	220	0.1	0.6	0.8	1.39
5	220	0.1	0.9	1.2	1.06
6	280	0.2	0.6	1.2	1.2
7	280	0.15	0.9	0.8	1.26
8	220	0.2	0.3	0.4	4.25
9	280	0.2	0.9	0.4	2.85
10	250	0.2	0.6	0.4	4.14
11	250	0.15	0.6	0.4	2.12
12	250	0.2	0.9	0.4	4.31
13	220	0.2	0.9	0.4	4.38
14	250	0.15	0.3	0.4	1.96
15	220	0.2	0.9	0.8	2.2
16	280	0.1	0.3	1.2	0.69
17	250	0.15	0.3	0.8	1.23
18	280	0.1	0.3	0.8	0.83
19	250	0.1	0.3	0.4	1.12
20	280	0.2	0.6	0.4	2.85
21	220	0.1	0.6	0.4	1.48
22	220	0.1	0.3	0.8	1.35
23	220	0.15	0.3	0.8	1.65
24	220	0.15	0.6	0.4	2.14
25	220	0.1	0.9	0.4	1.5
26	220	0.1	0.3	0.4	1.45

27	250	0.15	0.3	1.2	1.08
28	220	0.1	0.9	0.8	1.44
29	250	0.2	0.3	0.8	1.53
30	250	0.2	0.3	0.4	3.92
31	250	0.15	0.6	1.2	0.99
32	280	0.15	0.6	0.8	1.15
33	250	0.2	0.9	0.8	1.58
34	250	0.1	0.3	0.8	0.93
35	250	0.1	0.6	1.2	0.76
36	250	0.2	0.3	1.2	1.2
37	280	0.15	0.6	1.2	0.91
38	280	0.2	0.9	0.8	1.45
39	280	0.15	0.3	1.2	0.88
40	280	0.15	0.6	0.4	1.7
41	250	0.1	0.6	0.8	0.94
42	280	0.2	0.6	0.8	1.56
43	280	0.2	0.3	1.2	1.15
44	280	0.1	0.3	0.4	1.07
45	220	0.2	0.6	1.2	1.55
46	250	0.2	0.6	0.8	1.56
47	250	0.15	0.6	0.8	1.23
48	280	0.15	0.3	0.4	1.67
49	250	0.1	0.3	1.2	0.75
50	280	0.1	0.6	0.8	0.86
51	220	0.15	0.9	0.4	2.2
52	250	0.1	0.9	0.8	0.95
53	220	0.15	0.9	1.2	1.26
54	250	0.1	0.9	0.4	1.17
55	220	0.2	0.6	0.4	4.35
56	220	0.2	0.3	1.2	1.51
57	280	0.15	0.9	1.2	1.01
58	280	0.1	0.6	0.4	1.19
59	220	0.15	0.3	0.4	2.14
60	250	0.1	0.6	0.4	1.15
61	220	0.2	0.9	1.2	1.62
62	220	0.1	0.6	1.2	1.01
63	280	0.15	0.3	0.8	1.17
64	250	0.15	0.9	0.8	1.26
65	280	0.1	0.9	0.8	0.82

66	280	0.1	0.9	1.2	0.77
67	220	0.2	0.6	0.8	2.15
68	220	0.1	0.3	1.2	0.95
69	280	0.2	0.3	0.8	1.45
70	250	0.15	0.9	1.2	1.01
71	280	0.1	0.9	0.4	1.2
72	280	0.2	0.9	1.2	1.21
73	220	0.15	0.9	0.8	1.74
74	250	0.1	0.9	1.2	0.82
75	220	0.15	0.6	0.8	1.7
76	250	0.15	0.9	0.4	2.12
77	280	0.15	0.9	0.4	1.71
78	220	0.15	0.6	1.2	1.23
79	280	0.2	0.3	0.4	2.75
80	220	0.15	0.3	1.2	1.17
81	220	0.2	0.3	0.8	2.1

6.5.1 Result and discussion

Table 6.23 and Table 6.24 show estimated regression coefficient and ANOVA for linear model of surface roughness. Equation 6.9 gives linear model for surface roughness. The effectiveness of the model has been checked by using the R^2 value. In present work, R^2 value is 0.7236 and the Adj. R^2 is 0.7091 and predicted R^2 value 0.6823.

Table 6.23 Estimated Regression Coefficients for Roughness

Term	Coef	SE Coef	T	p
Constant	1.597	0.0532	30.022	0.000
Cutting speed (v) (m/min)	-0.276	0.06516	-4.237	0.000
Feed (f) (mm/rev)	0.611	0.06516	9.376	0.000
Nose radius (r) (mm)	-0.627	0.06516	-9.62	0.000
Depth of cut (d) (mm)	0.041	0.06516	0.637	0.526

S = 0.478834 PRESS = 20.0324
R-Sq = 72.36% R-Sq (pred) = 68.23% R-Sq (adj) = 70.91%

$$\mathrm{Ra} = 3.2371 - 0.00920 * \mathrm{v} + 12.2185 * \mathrm{f} + 0.138272 * \mathrm{d} - 1.5685 * \mathrm{r} \tag{6.9}$$

Table 6.24 Analysis of Variance for Roughness (Linear) (Ra)

Source	DF	Seq SS	Adj SS	Adj	F	p value
Regression	4	45.6207	45.6207	11.4052	49.74	0.000
Linear	4	45.6207	45.6207	11.4052	49.74	0.000
Cutting speed (v) (m/min)	1	4.1168	4.1168	4.1168	17.96	0.000
Feed (f) (mm/rev)	1	20.1544	20.1544	20.1544	87.90	0.000
Nose radius(r) (mm)	1	21.2566	21.2566	21.2566	92.71	0.000
Depth of cut (d) (mm)	1	0.0929	0.0929	0.0929	0.41	0.526
Residual Error	76	17.4255	17.4255	0.2293		
Total	80	63.0462				

Table 6.25 Estimated Regression Coefficients for Roughness (Quadratic)

Term	Coef	SE Coef	T	P
Constant	1.23630	0.09173	13.478	0.000
Cutting speed (v) (m/min)	-0.27611	0.03745	-7.373	0.000
Feed (f) (mm/rev)	0.61093	0.03745	16.314	0.000
Nose radius (r) (mm)	-0.62741	0.03745	1.108	0.000
Depth of cut (d) (mm)	0.04148	0.03745	0.665	0.272
v x v	0.04315	0.06486	0.665	0.508
f x f	0.19093	0.06486	2.944	0.004
r x r	0.0043	0.06486	4.837	0.000
d x d	-0.00630	0.06486	-0.097	0.923
v x f	-0.11500	0.04586	-2.507	0.015
v x r	0.11278	0.04586	2.459	0.017
v x d	-0.00583	0.04586	-0.127	0.899
f x r	-0.50056	0.04586	-10.914	0.000
f x d	0.01222	0.04586	0.266	0.791
r x d	-0.01222	0.04586	-0.266	0.791

S = 0.275179 PRESS = 7.48726

R-Sq = 92.07% R-Sq(pred) = 88.12% R-Sq(adj) = 90.39%

Table 6.25 shows estimated regression coefficient for roughness for quadratic model. In present work, R^2 value is 0.9207 and the Adj. R^2 is 0.9039 and the predicted R^2 value 0.8812. Table 6.26 shows ANOVA for quadratic model of surface roughness. The value of “p” in Table 6.26 for model is less than 0.05 which indicates that the model is adequately significant at 95% confidence level, which is desirable as it indicates that the term in the model, have a significant effect on the response. Similarly, the main effect of cutting speed (v), feed (f) nose radius (r) and two level interaction of cutting speed and feed (v f), cutting velocity and nose radius (v r) and feed and nose radius (f r) and also square effect of f^2 and r^2 are significant model terms. Other model terms are not significant.

Table 6.26Analysis of Variance for Roughness (Quadratic) (Ra)

Source	DF	Seq SS	Adj SS	Adj MS	F value	p value
Regression	14	58.0485	58.0485	4.1463	54.76	0.000
Linear	4	45.6207	45.6207	11.4052	150.62	0.000
Cutting speed (v) (m/min)	1	4.1168	4.1168	4.1168	54.37	0.000
Feed (f) (mm/rev)	1	20.1544	20.1544	20.1544	266.16	0.000
Nose radius (r) (mm)	1	21.2566	21.2566	21.2566	280.71	0.000
Depth of cut (d) (mm)	1	0.0929	0.0929	0.0929	1.23	0.272
Square	4	2.4618	2.4618	0.6154	8.13	0.000
Cutting speed (v)*Cutting speed (v)	1	0.0335	0.0335	0.0335	0.44	0.508
Feed (f)*Feed (f)	1	0.6561	0.6561	0.6561	8.67	0.004
Nose radius (r)*Nose radius (r)	1	1.7714	1.7714	1.7714	23.39	0.000
Depth of cut (d)*Depth of cut (d)	1	0.0007	0.0007	0.0007	0.01	0.923
Interaction	6	9.9660	9.9660	1.6610	21.94	0.000
Cutting speed (v)*Feed (f)	1	0.4761	0.4761	0.4761	6.29	0.015
Cutting speed (v)*Nose radius (r)	1	0.4579	0.4579	0.4579	6.05	0.017
Cutting speed (v)*Depth of cut (d)	1	0.0012	0.0012	0.0012	0.02	0.899
Feed (f)*Nose radius (r)	1	9.0200	9.0200	9.0200	119.12	0.000
Feed (f)*Depth of cut (d)	1	0.0054	0.0054	0.0054	0.07	0.791
Nose radius(r)*Depth of cut (d)	1	0.0054	0.0054	0.0054	0.07	0.791
Residual Error	66	4.9977	4.9977	0.0757		
Total	80	63.0462				

$$\begin{aligned} Ra &= 4.7491 - 0.02880 * v + 28.0074 * f - 3.23981 * r + 0.34351 * d + 0.00004794 * v^2 \\ &+ 76.3704 * f^2 + 1.9606 * r^2 - 0.069958 * d^2 - 0.0766 * v * f + 0.009398 * v * r \\ &- 0.0006881 * v * d - 25.0278 * f * r + 0.81481 * f * d - 0.10185 * r \\ &* d \end{aligned} \quad (6.10)$$

Since the difference between the first order and second order for multiple regression coefficient is 19.48 %. So it can be conclude that the second order model is required to represent the model for turning process. From response surface Eq. 6.10 the most significant factor on the Surface roughness is feed rate. The next contribution on surface roughness is nose radius and cutting speed. Depth of cut has not significant effect on the surface roughness. Figures 6.36 and 6.37 shows main effect plot and interaction plot for roughness.

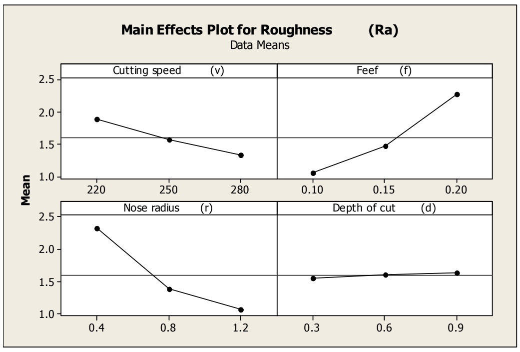

Fig. 6.36 Main effect plot for Roughness

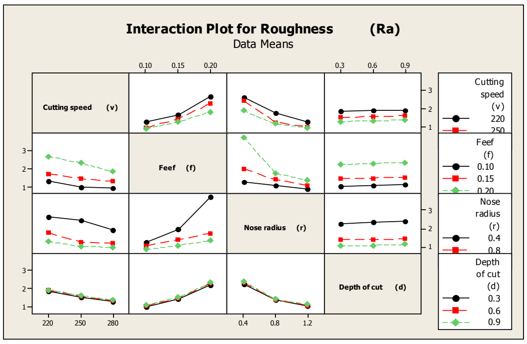

Fig. 6.37 Interaction plot for Roughness

The normal probability plot is presented in Fig.6.38. The figure revealed that the residuals fall on a straight line implying that the errors are distributed normally. Figure 6.39 shows the standardized residuals with respect to the predicted values. The residuals do not show any obvious pattern and are distributed in both positive and negative direction. This implies that the model is adequate and there is no reason to suspect any violation of the independence or constant variance assumption. The relation between the experimental and the predicted values are shown in Fig.6.40. The experimental values are very close to the predicted values hence this empirical model provides reliable prediction.

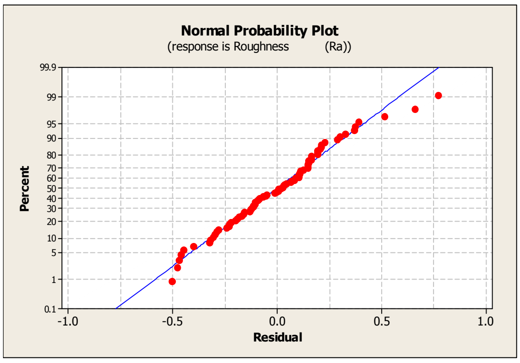

Fig. 6.38 Normal prob. plot of residual for Ra

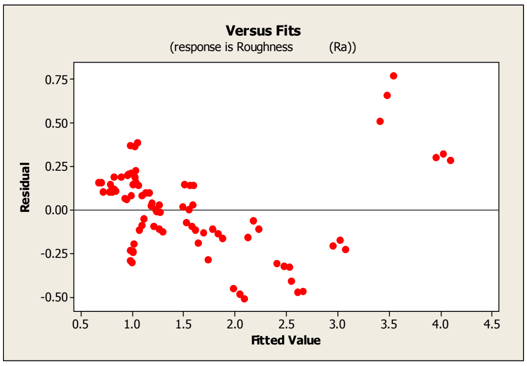

Fig. 6.39 Residual Vs. Fitted roughness values

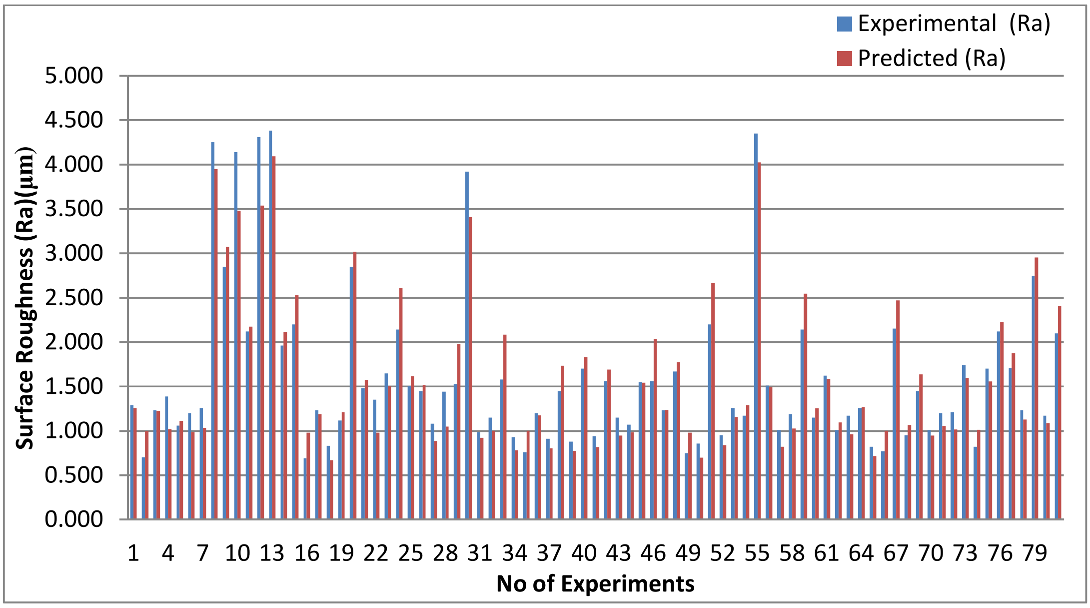

Fig.6.40 Predicted and Experimental values for Surface Roughness

6.5.2 3 D and 2D Contour Plots

The typical three-dimensional (3D) surface plots and two-dimensional (2D) contour plots for surface roughness in terms of the process variable are shown in Figs.6.41 to 6.46. These response contours (Figs. 6.41-6.43) can help in the prediction of surface roughness at any zone of the experimental domain. It is clear from these figures that the surface roughness reduces with the increase of cutting speed. However, it increases with the increase of feed and decreases with increasing tool nose radius. By increasing the depth of cut it is not much affected by surface roughness.

The surface plot shows the influence of different machining variables, keeping the other variable at constant level. Figure 6.44 illustrates the surface model for surface roughness by varying the two variables cutting speed and feed and keeping the two parameters nose radius and depth of cut at constant level. The figure indicates that the surface roughness decreases with increase in cutting speed and increases by increasing feed. Figure 6.45 shows the effect of nose radius with respect to depth of cut. From the figure, it has been asserted that the increase of nose radius reduces the surface roughness. Figure 6.46 shows the influence of nose radius and cutting velocity on surface roughness by keeping the depth of cut and feed at constant level. From the figure, it can be asserted that the increases in nose radius reduce the surface roughness while an increase in cutting velocity reduces the surface roughness. Finally depth of cut has not significant effect on the surface roughness.

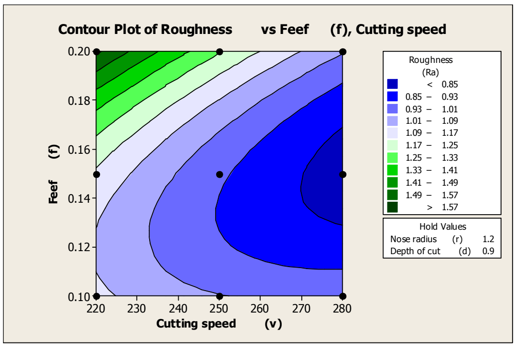

Fig. 6.41 Esti. Contour plots for Ra (Const. r and d)

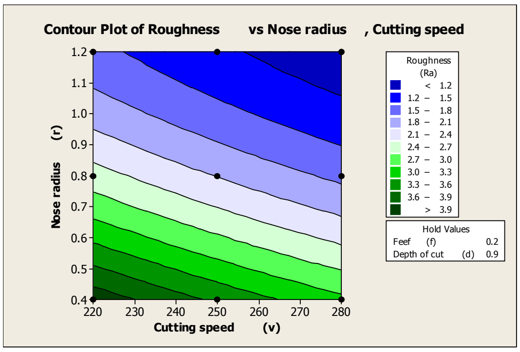

Fig. 6.42 Estimated contour plots for Ra (Const. f and d)

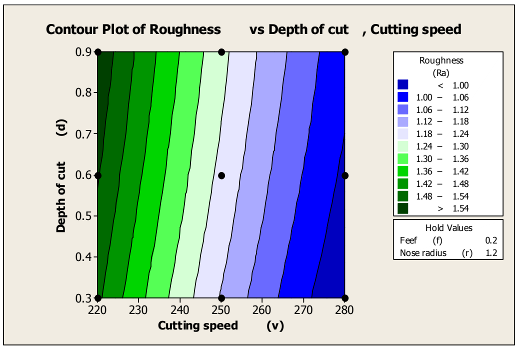

Fig. 6.43 Estimated contour plots for Ra (Const.: f and r)

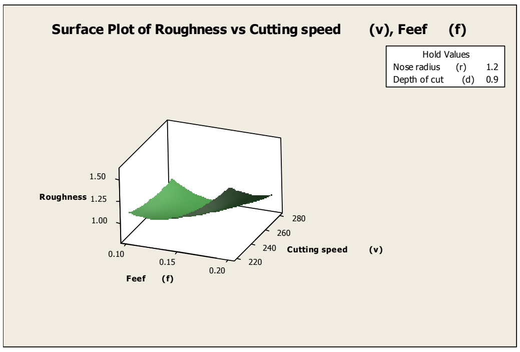

Fig. 6.44 3Dsurface plot for Ra Vs f and v

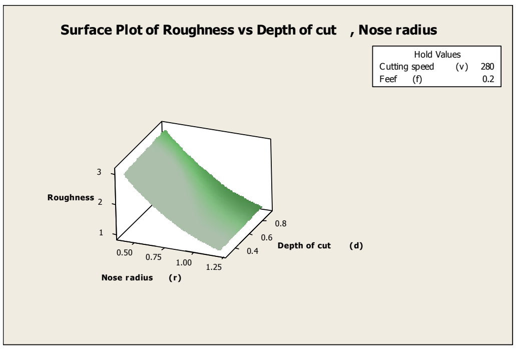

Fig. 6.45 3Dsurface plot for Ra Vs r & d

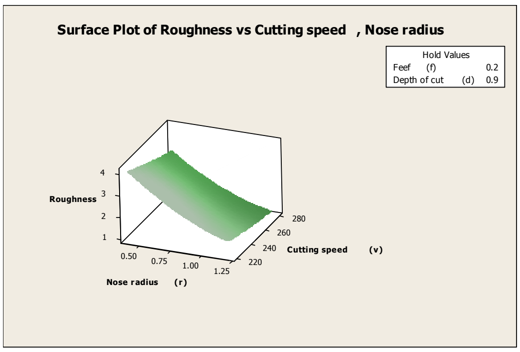

Fig. 6.46 3Dsurface plot for Ra Vs r & v

6.5.3 Confirmation test

In order to verify the adequacy of the model developed, five confirmation run experiments have been performed (Table 6.27 and Fig. 6.47) at different cutting conditions. The test condition for the first three validation run experiments are among the cutting conditions that are performed previously while the remaining two validation run experiments are the conditions that have not been used previously. The experimental results have been validated by asserting that the predicted values are very close to each other and hence, the developed models are suitable for predicting the surface roughness in machining Mild Steel.

Table 6.27 Confirmation test (Mild steel)

Sr. no.	Speed (v) (m/min)	Feed (f) (mm/rev)	Nose radius (r) (mm)	Depth of cut (d) (mm)	Experimental (Ra) (µm)	Predicted (Ra) (µm)	Error (%)
1	250	0.15	0.4	0.6	2.12	2.177	2.61
2	220	0.15	0.8	0.3	1.54	1.502	2.46
3	250	0.15	1.2	0.6	0.96	0.923	3.85
4	220*	0.12	0.8	0.5	1.21	1.172	3.14
5	240*	0.14	0.4	0.8	2.19	2.117	3.33

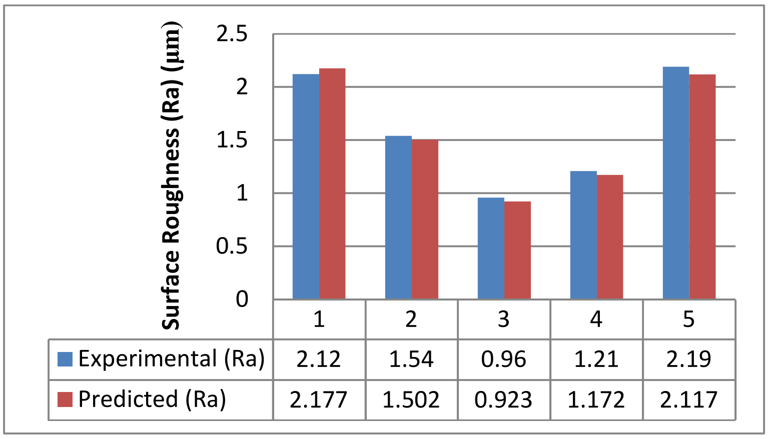

Fig. 6.47 Comparison of experimental and predicated values for Ra

6.5.4 Response surface optimization

Response surface optimization is an ideal technique for determination of the best cutting parameters in turning operation. Here, the goal is to minimize surface roughness.RSM optimization results for surface parameters are shown in Table 6.28 and Fig. 6.49. Optimum machining parameters are found to be cutting velocity of 280 m/min, feed of 0.1 mm/rev, depth of cut of 0.3 mm and tool nose radius of 0.8 mm. The optimized surface roughness parameter is Ra = 0.6686 µm.

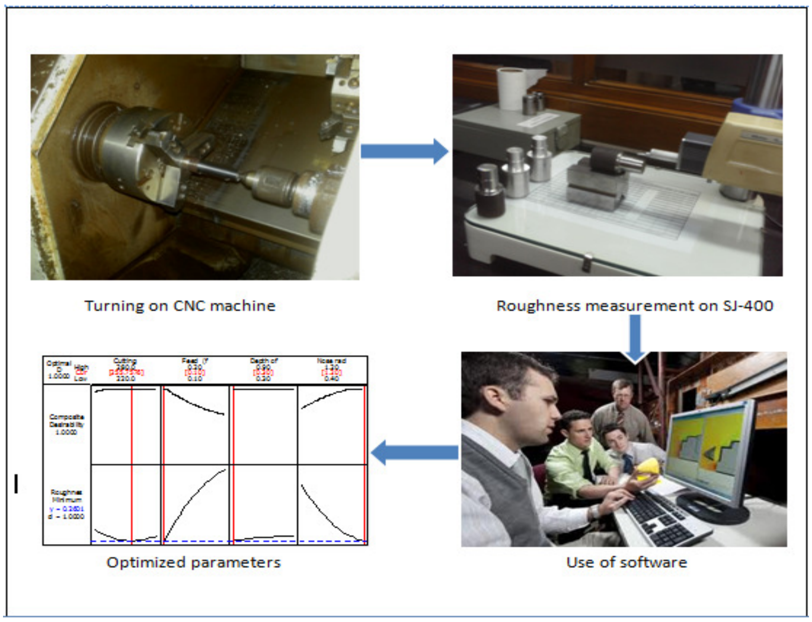

Fig.6.48 Experimental scheme.

Table 6.28 Response optimization for surface roughness parameters

Parameter	Goal	Optimum conditions				Lower	Target	Upper	Pre. resp.	Desi.
		v(m/min)	f(mm/rev)	d(mm)	r(mm)					
Ra (µm)	Min.	280	0.1	0.3	0.804	0.8	0.8	0.9	0.668	1

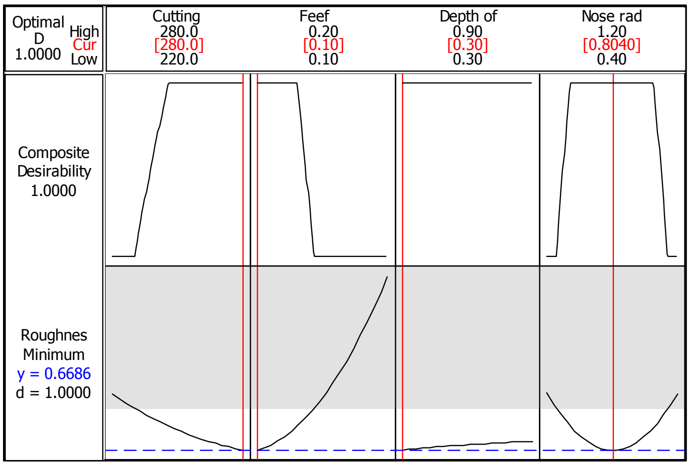

Fig. 6.49 Response optimization for surface roughness parameter

6.6 Experimental details for Aluminium

In this study, the experiments were planned using 3^4 full factorial design with 81 numbers of experiments. The four cutting parameters are selected for the present investigation is cutting speed (v), feed (f), nose radius (r) and depth of cut (d). Since the considered factors are multi level variables and their outcome effects are not linearly related, it has been decided to use three level tests for each factor. The machining parameters used and their levels chosen are given in Table 6.29.

Table 6.29 Parameters and their levels (Aluminium)

Parameters	Level -1	Level -2	Level -3
Cutting speed (v) (m/min)	220	250	280
Feed (f) (mm/rev)	0.1	0.15	0.2
Depth of cut (d) (mm)	0.3	0.6	0.9
Nose radius (r) (mm)	0.4	0.8	1.2

All the turning experiments were conducted on a Jobber XL model made by Ace designer CNC lathe machine with detailed specification given in previous session. The machining tests were carried out in wet conditions using a water-soluble cutting fluid. In this study, ceramic inserts (supplied by Ceratizit) were used, ISO code TNMG160404 EN-TMF, TNMG 160408 EN-TM and TNMG 160412 EN-TM with different nose radius. (60^0 triangular shaped inserts). The inserts were mounted on a commercial tool. In the present investigation, the bar of Aluminium with the following chemical composition was used as the work material: 0.897 % Si, 0.595 % Mn, 0.812 Mg, 0.260 % Fe and 97.3% Al. A mechanical property and microscopic analysis of the material is given in Table 6.30 and Fig. 6.50. Surface finish of the work piece material was measured by Surf test model No. SJ-400 (Mitutoyo make). Detailed specification of the roughness tester is given in chapter 5. The result table from the machining test performed as per the 3^4 full factorial design are shown in Table 6.31. These results are fed into the Minitab-16 for further analysis.

Table 6.30 Mechanical properties of Aluminium

Material properties	Aluminium
Physical density	2.65 g/cm^3
Mechanical hardness, Rockwell B	60
Tensile strength, ultimate	140-170 Mpa
Tensile strength, yield	90-110 Mpa
% of elongation	3

Fig. 6.50 Material: Al. 100 x

Table 6.31 Experimental result (Aluminium)

Run order	Cutting speed (v) (m/min)	Feed (f) (mm/rev)	Depth of cut (d) (mm)	Nose radius (r) (mm)	Roughness (Ra) (µm)
1	250	0.15	0.6	1.2	0.56
2	280	0.20	0.3	0.8	1.09
3	250	0.15	0.3	0.4	2.05
4	280	0.20	0.6	1.2	0.83
5	220	0.20	0.3	0.4	2.67
6	280	0.100	0.6	0.4	0.68
7	250	0.15	0.6	0.8	0.76
8	280	0.15	0.6	0.4	1.88
9	280	0.15	0.3	1.2	0.52
10	250	0.20	0.6	0.4	2.34
11	220	0.15	0.6	1.2	0.64
12	220	0.15	0.3	0.8	0.78
13	250	0.10	0.6	0.4	0.83
14	220	0.10	0.6	0.4	0.93
15	250	0.20	0.6	1.2	0.93
16	250	0.20	0.9	1.2	0.93
17	250	0.10	0.9	1.2	0.34
18	250	0.10	0.9	0.4	0.82
19	250	0.15	0.3	0.8	0.72
20	250	0.10	0.3	1.2	0.30
21	280	0.15	0.9	0.4	1.9
22	220	0.10	0.6	1.2	0.33
23	250	0.20	0.9	0.8	1.23
24	220	0.10	0.9	1.2	0.34
25	220	0.20	0.3	0.8	1.33
26	250	0.20	0.3	0.4	2.36
27	220	0.15	0.3	1.2	0.62
28	280	0.10	0.9	0.8	0.30
29	280	0.20	0.6	0.4	2.20

30	280	0.15	0.9	0.8	0.66
31	220	0.15	0.9	0.8	0.79
32	220	0.20	0.6	0.8	1.37
33	280	0.10	0.9	1.2	0.29
34	250	0.10	0.3	0.4	0.79
35	220	0.15	0.6	0.8	0.79
36	280	0.20	0.9	0.4	2.22
37	280	0.10	0.3	1.2	0.27
38	220	0.10	0.9	0.4	0.94
39	220	0.20	0.6	0.4	2.66
40	250	0.20	0.3	1.2	0.92
41	220	0.15	0.3	0.4	2.14
42	220	0.10	0.3	1.2	0.27
43	280	0.20	0.9	0.8	1.08
44	220	0.10	0.3	0.8	0.39
45	280	0.20	0.6	0.8	1.08
46	280	0.15	0.3	0.8	0.66
47	250	0.20	0.9	0.4	2.33
48	250	0.10	0.6	0.8	0.38
49	250	0.20	0.6	0.8	1.24
50	250	0.15	0.3	1.2	0.53
51	250	0.10	0.3	0.8	0.39
52	250	0.10	0.6	1.2	0.30
53	220	0.10	0.6	0.8	0.39
54	250	0.15	0.9	0.8	0.75
55	280	0.15	0.3	0.4	1.87
56	280	0.15	0.6	0.8	0.64
57	250	0.15	0.6	0.4	1.99
58	220	0.15	0.9	1.2	0.67
59	280	0.20	0.3	0.4	2.22
60	220	0.20	0.9	0.8	1.35
61	220	0.15	0.9	0.4	2.12
62	280	0.10	0.6	1.2	0.28
63	280	0.20	0.9	1.2	0.85
64	280	0.15	0.6	1.2	0.52
65	280	0.10	0.9	0.4	0.66
66	220	0.20	0.9	1.2	1.05
67	220	0.20	0.3	1.2	0.99
68	280	0.10	0.6	0.8	0.33
69	280	0.10	0.3	0.8	0.34
70	220	0.20	0.9	0.4	2.66
71	250	0.15	0.9	1.2	0.58
72	280	0.15	0.9	1.2	0.55
73	220	0.15	0.6	0.4	2.11
74	250	0.10	0.9	0.8	0.38

75	280	0.10	0.3	0.4	0.67
76	220	0.10	0.3	0.4	0.92
77	250	0.15	0.9	0.4	1.98
78	220	0.10	0.9	0.8	0.41
79	280	0.20	0.3	1.2	0.82
80	220	0.20	0.6	1.2	1.02
81	250	0.20	0.3	0.8	1.24

6.6.1 Result and discussion

The analysis of variance (ANOVA) is used to check the adequacy of the proposed model. Table 6.32 and Table 6.33 show estimated regression coefficient for roughness and ANOVA for linear model. The effectiveness of the model has been checked by using the R^2 value. In present work, R^2 value is 0.8339 and the Adj. R^2 is 0.8252. The predicted R^2 value 0.8111. Equation 6.11 gives surface roughness for linear model.

Table 6.32 Estimated Regression Coefficients for (Ra)

Term	Coef	SE Coef	T	P
Constant	1.03778	0.03228	32.151	0.000
Cutting speed (v) (m/min)	-0.09759	0.03953	-2.469	0.016
Feed (f) (mm/rev)	0.51370	0.03953	12.994	0.000
Nose radius (r) (mm)	-0.56833	0.03953	-14.376	0.000
Depth of cut (d) (mm)	0.00574	0.03953	0.145	0.885

S = 0.290508 PRESS = 7.29613
R-Sq = 83.39% R-Sq (pred) = 81.11% R-Sq(adj) = 82.52%

Table 6.33 Analysis of Variance for Roughness (Linear) (Ra)

Source	DF	Seq SS	Adj SS	Adj MS	F value	p
Regression	4	32.2084	32.2084	8.0521	95.41	0.000
Linear	4	32.2084	32.2084	8.0521	95.41	0.000
Cutting speed (v) (m/min)	1	0.5143	0.5143	0.5143	6.09	0.016
Feed (f) (mm/rev)	1	14.2501	14.2501	14.2501	168.85	0.000
Nose radius (r) (mm)	1	17.4421	17.4421	17.4421	206.67	0.000
Depth of cut (d) (mm)	1	0.0018	0.0018	0.0018	0.02	0.885
Residual Error	76	6.4140	6.4140	0.0844		
Total	80	38.6224				

$$\mathrm{Ra} = 1.43512 - 0.00325 * \mathrm{v} + 10.274 * \mathrm{f} + 0.01913 * \mathrm{d} - 1.4208 * \mathrm{r} \quad (6.11)$$

Table 6.34 Estimated Regression Coefficients for Roughness (Quadratic)

Term	Coef	SE	T	p
Constant	0.835926	0.04259	19.626	0.000
Cutting speed (v) (m/min)	-0.097593	0.01739	-5.613	0.000
Feed (f) (mm/rev)	0.513704	0.01739	29.543	0.000
Nose radius (r) (mm)	-0.568333	0.01739	-32.685	0.000
Depth of cut (d) (mm)	0.005741	0.01739	0.330	0.742
v x v	0.005741	0.03012	0.092	0.927
f x f	-0.097778	0.03012	-3.247	0.002
r x r	0.397222	0.03012	13.189	0.000
d x d	0.000556	0.03012	0.018	0.985
v x f	-0.044722	0.02130	-2.100	0.040
v x r	0.051389	0.02130	2.413	0.019
v x d	-0.004722	0.02130	-0.222	0.825
f x r	-0.244444	0.02130	-11.478	0.000

S = 0.127777 PRESS = 1.59913
R-Sq = 97.21% R-Sq (pred) = 95.86% R-Sq(adj) = 96.62%

Table 6.35 Analysis of Variance for Roughness (Quadratic) (Ra)

Source	DF	Seq SS	Adj SS	Adj	F	p
Regression	14	37.5448	37.5448	2.6818	164.25	0.000
Linear	4	32.2084	32.2084	2084	493.18	0.000
Cutting speed (v) (m/min)	1	0.5143	0.5143	0.5143	31.50	0.000
Feed (f) (mm/rev)	1	14.2501	14.2501	14.2501	872.80	0.000
Nose radius(r) (mm)	1	17.4421	17.4421	17.4421	1068.30	0.000
Depth of cut (d) (mm)	1	0.0018	0.0018	0.0018	0.11	0.742
Square	4	3.0124	3.0124	0.7531	46.13	0.000
Cutting speed (v)*Cutting speed(v)	1	0.0001	0.0001	0.0001	0.01	0.927
Feed (f)*Feed (f)	1	0.1721	0.1721	0.1721	10.54	0.002
Nose radius(r)*Nose radius(r)	1	2.8401	2.8401	2.8401	173.95	0.000
Depth of cut (d)*Depth of cut (d)	1	0.0000	0.0000	0.0000	0.00	0.985
Interaction	6	2.3241	2.3241	0.3873	23.72	0.000
Cutting speed (v)*Feed (f)	1	0.0720	0.0720	0.0720	4.41	0.040
Cutting speed (v)*Nose radius(r)	1	0.0951	0.0951	0.0951	5.82	0.019
Cutting speed (v)*Depth of cut (d)	1	0.0008	0.0008	0.0008	0.05	0.825
Feed (f)*Nose radius(r)	1	2.1511	2.1511	2.1511	131.75	0.000
Feed (f)*Depth of cut (d)	1	0.0002	0.0002	0.0002	0.01	0.917
Nose radius(r)*Depth of cut (d)	1	0.0049	0.0049	0.0049	0.30	0.586
Residual Error	66	1.0776	1.0776	0.0163		

Table 6.34 shows estimated regression coefficient for roughness for quadratic model. In present work, R^2 value is 0.9721 and the Adj. R^2 is 0.9662 The predicted R^2

value 09586. Table 6.35 shows ANOVA for quadratic model of surface roughness. The value of "p" in Table 6.38 for model is less than 0.05 which indicates that the model is adequately significant at 95% confidence level, which is desirable as it indicates that the term in the model, have a significant effect on the response. Similarly, the main effect of cutting speed (v), feed (f) nose radius(r) and two level interaction of cutting speed and nose radius (v r), feed and nose radius (f r) and vf also square effect of f^2 and r^2 are significant model terms. Other model terms are not significant.

Since the difference between the first order and second order for multiple regression coefficient is 14.1%. So it can be conclude that the second order model is required to represent the model for turning process. From response surface Eq. 6.12 the most significant factor on the Surface roughness is feed rate. The next contribution on surface roughness is nose radius and cutting speed. Depths of cut have not significant effect on the surface roughness. Fig. 6.51 and 6.52 shows main effect plot and interaction plots for surface roughness.

$$Ra = 0.3636 - 0.003435 * v + 39.3278 * f - 4.68866 * r + 0.08734 * d + 0.000003086 * v^2 - 39.111 * f^2 + 2.48264 * r^2 + 0.006172 * d^2 - 0.02981 * v * f + 0.004282 * v * r - 0.005246 * v * d - 12.222 * f * r - 0.1481 * f * d + 0.09722 * r * d \quad (6.12)$$

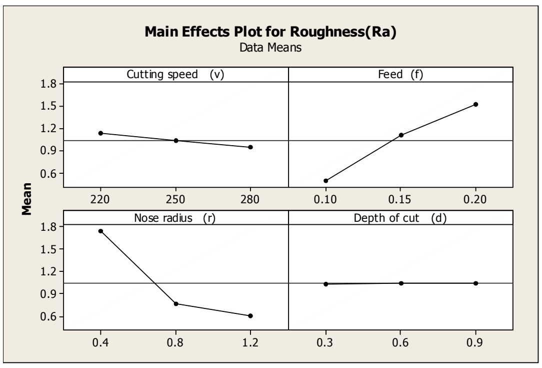

Fig. 6.51 Main effect plot for Roughness

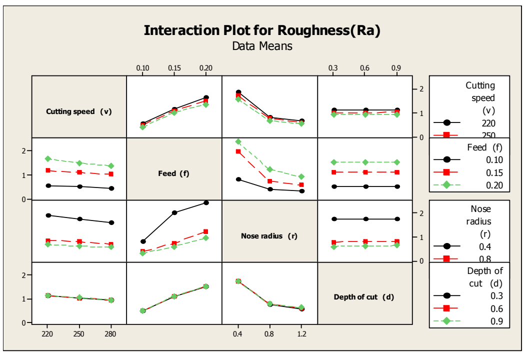

Fig. 6.52 Interaction plot for Roughness

The diagnostic checking of the model has been carried out using residual analysis and the results are presented in Figs.6.53 and 6.54. The normal probability plot is presented in Fig. 6.53. The figure revealed that the residuals fall on a straight line implying that the errors are distributed normally. Figure 6.54 shows the standardized residuals with respect to the predicted values. The residuals do not show any obvious pattern and are distributed in both positive and negative direction. This implies that the model is adequate and there is no reason to suspect any violation of the independence or constant variance assumption. The relation between the experimental and the predicted values are shown in Fig.6.55. The experimental values are very close to the predicted values hence this empirical model provides reliable prediction.

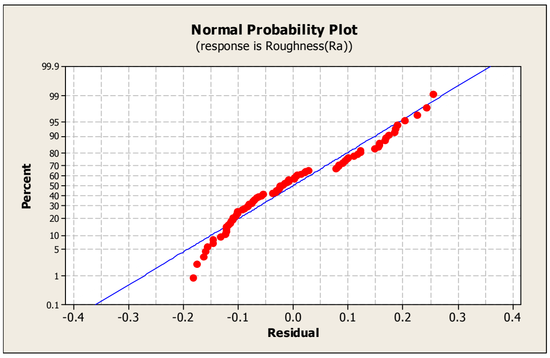

Fig. 6.53 Normal prob. plot of residual for Ra

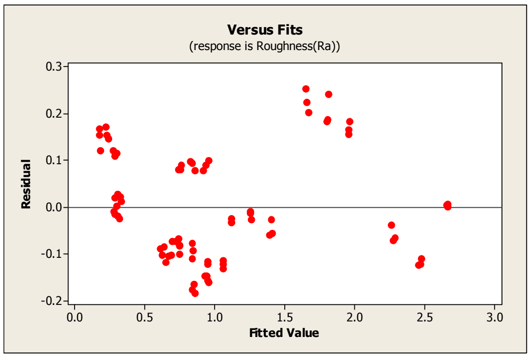

Fig. 6.54 Residual vs. Fitted surface roughness values

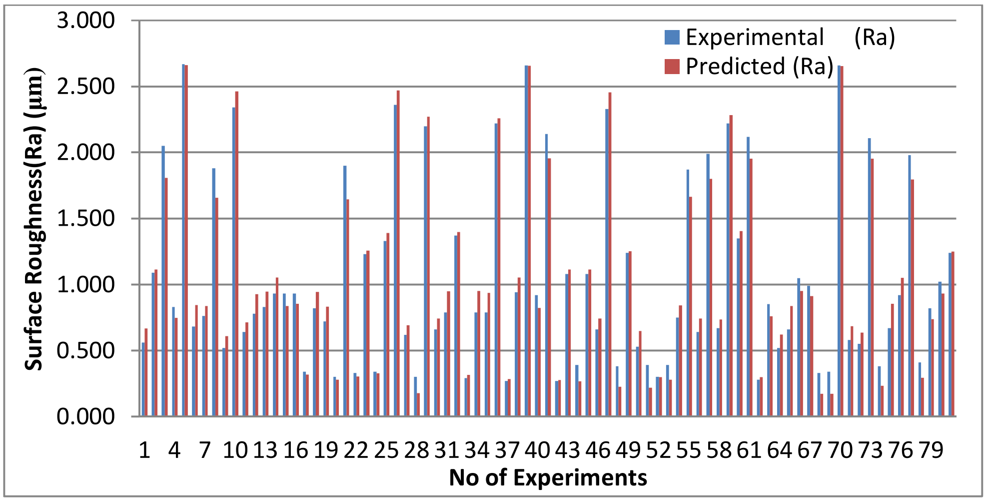

Fig. 6.55 Predicted and Experimental values for Surface Roughness

6.6.2 3 D and 2D Contour Plots

The analysis of response variable surface roughness can be explained through contour and surface plots. The typical three-dimensional (3D) surface plots and two-dimensional (2D) contour plots for surface roughness in terms of the process variable are shown in Figs. 6.56 to 6.61. These response contours (Figs. 6.56 to 6.58) can help in the prediction of surface roughness at any zone of the experimental domain. It is clear from these figures that the surface roughness reduces with the increase of cutting speed. However, it increases with the increase of feed and decreases with increasing tool nose radius. By increasing the depth of cut it is not much affected by surface roughness.

The surface plot shows the influence of different machining variables, keeping the other variable at constant level. Figure 6.59 illustrates the surface model for surface roughness by varying the two variables nose radius and cutting speed and keeping the two parameters feed and depth of cut at constant level. The figure indicates that the surface roughness decreases with increase in nose radius and cutting speed. Figure 6.60 shows the effect of feed with respect to depth of cut on surface roughness. From the figure, it has been asserted that the increase of feed increases the surface roughness while depth of cut has no significant effect on the surface roughness. Figure 6.61 shows the influence of nose radius and depth of cut on surface roughness by keeping the cutting speed and feed at constant level. From the figure, it can be asserted that the increases nose radius reduces the surface roughness while increasing depth of cut, not much affected of the surface roughness.

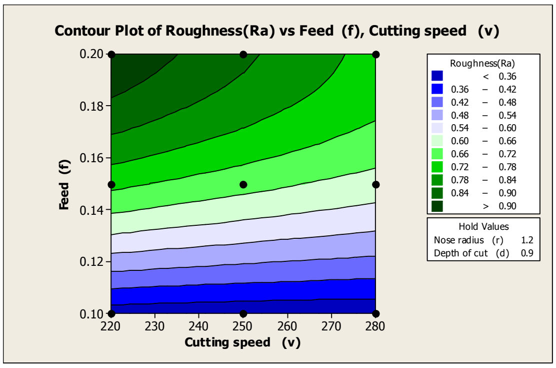

Fig. 6.56 Estimated contour plots for Ra (Const.: r and d)

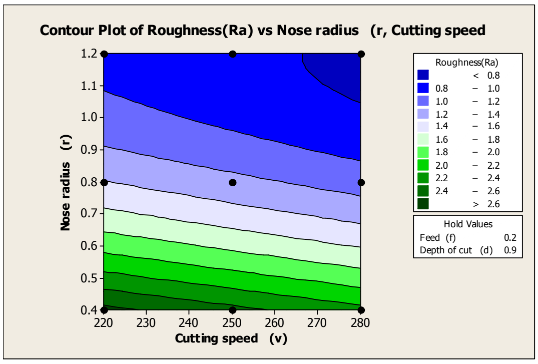

Fig. 6.57 Estimated contour plots for Ra (Const.: f and d)

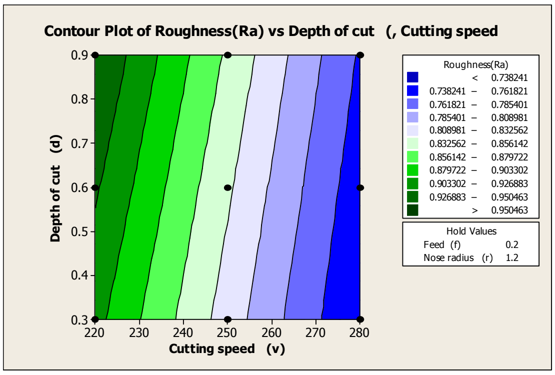

Fig.6.58 Estimated contour plots for Ra (Const.: f and r)

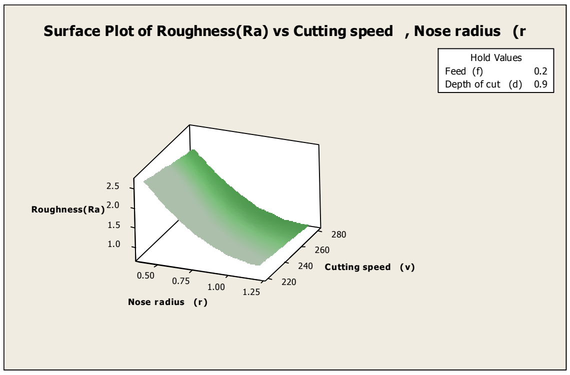

Fig.6.59 3D surface plots for Ra Vs r & v

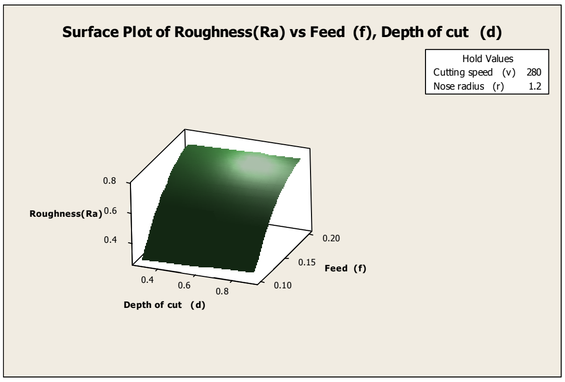

Fig 6.60 3D surface plots for Ra Vs d & f

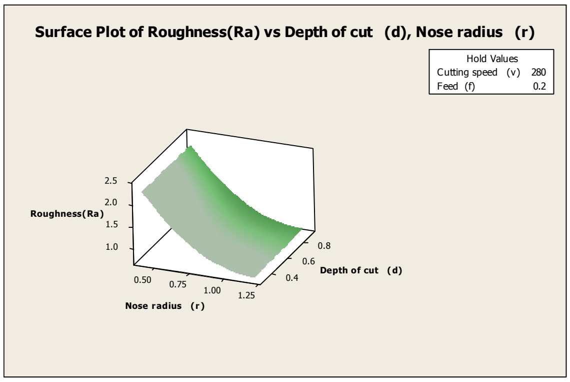

Fig.6.61 3Dsurface plots for Ra Vs r & d

6.6.3 Confirmation test

The effectiveness of the model has been checked by validation with experimental results. In order to verify the adequacy of the model developed, five confirmation run experiments have been performed (Table 6.36 and Fig.6.62) at different cutting conditions. The test condition for the first three validation run experiments are among the cutting conditions that are performed previously while the remaining two validation run experiments are the conditions that have not been used previously. The experimental results have been validated by asserting that the predicted values are very close to each other and hence, the developed models are suitable for predicting the surface roughness in machining Aluminium.

Table 6.36 Confirmation test (Aluminium)

Sr. no.	Speed (v) (m/min)	Feed (f) (mm/rev)	Nose radius (r) (mm)	Depth of cut(d) (mm)	Exp. (Ra) (µm)	Pred. (Ra) (µm)	Error (%)
1	220	0.1	0.8	0.3	0.28	0.268	4.28
2	250	0.15	0.4	0.6	1.86	1.801	3.17
3	280	0.1	0.8	0.3	0.18	0.172	4.44
4	260*	0.12	0.4	0.5	1.32	1.273	3.56
5	240*	0.18	0.8	0.5	1.19	1.148	3.52

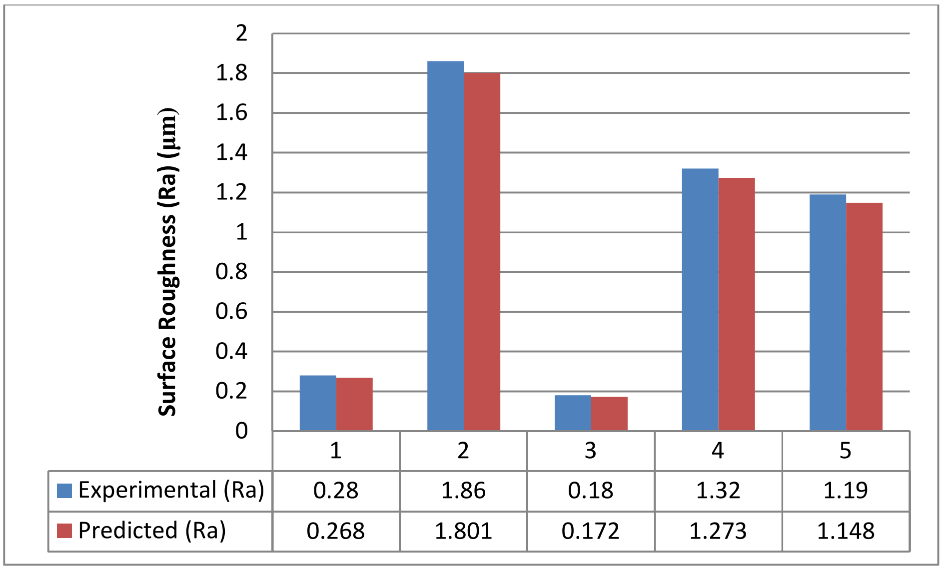

Fig. 6.62 Comparison of experimental and predicated values for Ra

6.6.4 Response surface optimization

One of the most important aims of experiments related to manufacturing is to achieve the desired surface roughness of the optimal cutting parameters. Response surface optimization is an ideal technique for determination of the best cutting parameters in turning operation. Here, the goal is to minimize surface roughness (Ra). RSM optimization results for surface parameters are shown in Table 6.37 and Fig.6.63. Optimum machining parameters are found to be cutting velocity of 280 m/min, feed of

0.1 mm/rev, depth of cut of 0.3 mm and tool nose radius of 0.94 mm. The optimized surface roughness parameter is Ra = 0.1209 µm.

Table 6.37 Response optimization for surface roughness parameters

Parameters	Goal	Optimum conditions				Lower	Target	Upper	Pre. resp.	Desi.
		v(m/min)	f(mm/rev)	d(mm)	r(mm)					
Ra (µm)	Min.	280	0.1	0.3	0.94	0.45	0.45	0.5	0.1209	1

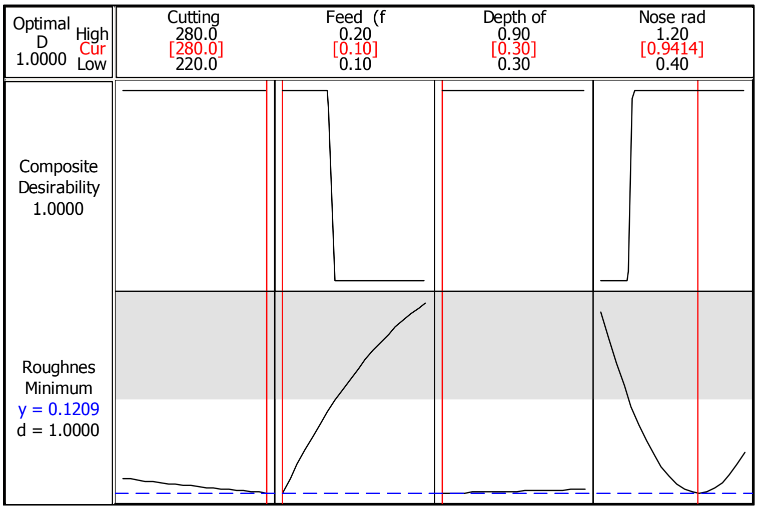

Fig. 6.63 Response optimization for surface roughness parameter

From the experiments on the different materials in Chapter 6, it concludes that Feed rate is dominant factor for surface roughness followed by nose radius and cutting speed. The surface roughness was found to increase with the increase in the feed rate and it decreased with increase in the tool nose radius and cutting speed. Depths of cut have no significant effect on the surface roughness. 3D surface counter plots are useful in determining the optimum condition to obtain particular values of surface roughness. By using response surface methodology and (3^4) full factorial design of experiment, quadratic model has been developed with 95% confidence level.

In last chapter concluding remarks for turning centre components is done by using FEA software and optimization of cutting parameters for different materials is done by using Response surface methodology.