Optimization of Surface Roughness Using RSM Techniques in Dry Turning of Hardened Steel

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Abstract— With the advent of coating material on cutting tools, machining of hardened steel using multilayer coated carbide tools provides lot of opportunities in saving machining time as compared to traditional grinding processes. In this paper, optimization of cutting parameters in hard turning of AISI D3 steel using multilayer coated carbide inserts under dry turning operations were done. Several experiments were conducted using Response Surface Methodology with face centered design. Analysis of Variance (ANOVA) was performed to find out the effect of machining parameters on surface roughness in hard turning. Cutting speed, feed and depth of cut were selected as parameters to optimize surface roughness. Effect of individual independent variables and their interaction plots were drawn to study the effect of input parameters on output parameter. It was found that feed rate was most significant factor influencing the surface roughness in hard turning. Quadratic model was proposed to predict surface roughness value.

Keywords—Hard turning, Coated carbide tools, Response surface methodology, Surface Roughness

I. INTRODUCTION

Traditionally, the machining of hardened steel is done with advanced tool materials like CBN, PCBN, etc. [1]. With the advent of coating materials, it now feasible to carryout machining using coated carbide tools. Many authors [2] [3] [4] have used tools like ceramic, CBN or diamond tools to machine hardened steel. Using these advanced tool materials will help in decreasing machining time as compared to traditional grinding processes. But these tools are costly. Recent development of carbide tools and coating material have made possible to carry out the machining operations using coated carbide tools [5]. To achieve desired surface finish, generally grinding processes are used [5]. Many authors have suggested the adjusting of various processes parameters, a good surface finish can be achieved which is comparable to grinding process [3] [6] [7].

Aslan et al. [8] suggested that machining of hardened steel, AISI 4140 having 63 HRC hardness, can be effectively carried out using ceramic tools. Taguchi method was used to optimize flank wear and surface finish by varying speed, feed and depth of cut. It was observed that speed and feed were most influential on flank wear and feed was most important parameter for achieving good surface finish. Ozel et al. [9] investigated effects of cutting tool parameters like tool edge geometry, speed and feed on surface roughness using cubic boron nitrite.

It was observed that effect of cutting edge geometry was major contributor on surface roughness. Gaitonde et al. [10] studied the effect of machining parameters on hard turning of AISI D2 steel. This study was carried out to develop an alternative to grindings process which is time consuming and costly. It was concluded that higher feed rate will reduce cutting force. Higher cutting speed and low feed rate will reduce the surface roughness. Sankar and Rao [11] studied the effect of speed, depth of cut, nose radius and feed rate on forces produced using PCBN. Taguchi orthogonal array was used to develop the model. Nouioua et al. [12] developed the model of predicting tangential force and surface roughness using Surface Response Methodology (RSM)) and artificial neural network. Mean and root mean square errors match with values obtained by RSM design. Johanssona et al. [13] studied Taylor tool life model and coding models to compare the capability of prediction of various models. Different types of tool materials and work materials were used during experimentation.

By carrying out the literature review, it is found that the machining of hard steel is generally carried out using advanced tool materials like diamond tools, ceramic tools or PCBN tools. With the advancement in coating material, it has made it possible to carry out machining of hardened steel using coated carbide tools. This makes machining cost cheaper and saves time as compared to grinding operations. This paper presents an investigation carried out in optimizing the cutting parameters in hard turning using coated tungsten carbide tools.

II. EXPERIMENTAL INVESTIGATION

The experimental procedure was done using coated tungsten carbide tool and cutting parameters selected were feed, speed and depth of cut. Response surface method with Central Composite Design (CCD) [14] was implemented to minimize the surface roughness.

A. *Workpiece and Tool Material*

Work piece material used was AISI D3 steel. It has high compressive strength. Various applications where this steel is used are in making rolls in rolling mills, punches and dies, etc. The chemical composition of AISI D3 is given in *TABLE 1*. The workpiece selected was of 70 mm in diameter. Initial cut and through run was carried out before conducting experiments. The workpiece material was hardened to 61 HRC (±1 HRC).

The experiments were performed using multi-layer coated tungsten carbide inserts (TiCN-AL2O3-TiN). The geometry of

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tool was CNMG 120408 (0.8 mm nose radius). Tool holder, ISO Code PCLNR1616H12 I7D, was used.

TABLE 1
PERCENTAGE COMPOSITION OF AISI D3 STEEL

C	Cr	Si	S	P	Mg	Ni	Mo	Va
2.25	11.70	0.27	0.04	0.02	0.34	0.16	0.01	0.02

B. *Experiments Design*

Three independent variables; viz; speed, feed and depth of cut (DOC) were selected to optimize surface roughness. From literature survey [15] [16], it was observed that input and output relationships were not linear but had curvature. Hence, Response Surface Methodology (RSM) with Central Composite Design (CCD) [14] was selected with relationship as shown in equation 1:

$$Y = \beta_0 + \sum_{i=1}^{k}\beta_i x_i + \sum_{i=1}^{k}\beta_{ii} x_i^{2} + \sum_{i<j=2}^{2}\beta_{ij} x_i x_j + \varepsilon_r \qquad 1$$

Where y – Response
x_i – Input variables
x_i^2 – Squared terms
$x_i x_j$ – Interaction terms
ϵ_r – Error term
β_0 β_i β_{ii} *and* β_{ij} – Regression coefficient (unknown)

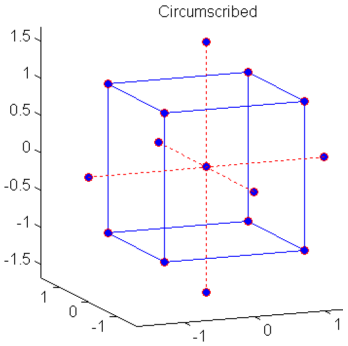


Fig. 1. Central Composite design for three variables [17]

Full factorial design with all the possible combination of factors (-1.68, -1, 0 +1, +1.68) were selected. So, experimental design consists of six star points, eight points on vertices of cube and two central points as shown in Figure 1. Central Composite Design for three variables [17], which amounts to total sixteen experiments is used. This methodology is called faced centered design [18]. The values of independent variables selected are shown in TABLE 2.

TABLE 2
VALUES OF INDEPENDENT VARIABLES

Parameter	Unit	Coded values		
		-1	0	+1
Speed	mts/min	80	120	160
Feed	mm	0.1	0.2	0.3
Depth of Cut	mm	0.1	0.3	0.5

The cutting experiments were carried out on CNC lathe machine with Hinumerik controller under dry cutting conditions. The outer surface of workpiece, which was rough, removed. The following *TABLE 3* shows experimental data:

TABLE 3
DESIGN MATRIX – RSM

		Factor 1	Factor 2	Factor 3	Response
Std	Run	A:Speed	B:Feed	C:Depth of Cut	Surface Roughness
		m/min	mm/rev	mm	µm
3	1	80	0.3	0.1	1.98
8	2	160	0.3	0.5	3.03
10	3	187.27	0.2	0.3	1.65
13	4	120	0.2	-0.036	1.62
9	5	52.72	0.2	0.3	3.12
1	6	80	0.1	0.1	1.95
11	7	120	0.031	0.3	1.32
15	8	120	0.2	0.3	2.22
5	9	80	0.1	0.5	2.46
6	10	160	0.1	0.5	0.9
4	11	160	0.3	0.1	2.88
2	12	160	0.1	0.1	1.08
7	13	80	0.3	0.5	3.42
14	14	120	0.2	0.63	2.46
16	15	120	0.2	0.3	2.22
12	16	120	0.36	0.3	2.94

The experiments were performed as per experimental design shown in above TABLE 3. The surface roughness was measured using Mitutoyo surface roughness tester.

III. RESULTS AND DISCUSSION

TABLE 4 summarizes the responses in terms of surface roughness that varies from 3.013 to 5.895 µm with mean of 4.17 µm.

TABLE 4
SUMMARY OF RESPONSES

Source	**Sum of Squares**	**df**	**Mean Square**	**F-value**	**p-value**
Model	8.4	9	0.9336	23.77	0.0005
A-Speed	1.41	1	1.41	35.96	0.001
B-Feed	4.28	1	4.28	108.93	< 0.0001
C-Depth of Cut	0.8133	1	0.8133	20.7	0.0039
AB	1.08	1	1.08	27.5	0.0019
AC	0.49	1	0.49	12.48	0.0123
BC	0.1984	1	0.1984	5.05	0.0657
A^2	0.0394	1	0.0394	1	0.3551
B^2	0.0058	1	0.0058	0.1464	0.7151
C^2	0.0298	1	0.0298	0.7592	0.4171

Residual	0.2357	6	0.0393		
Lack of Fit	0.2357	5	0.0471		
Pure Error	0	1	0		
Cor Total	8.64	15			

The F-value of model of 23.77 implies the model is significant. Significant terms have p-values less than 0.05. In this case A, B, C, AB, AC are significant terms. Modified ANOVA model with significant terms are as shown in TABLE 5. The Predicted R-Squared of 0.7842 is in reasonable agreement with the Adjusted R-Squared of 0.9644; i.e. the difference is less than 0.2. The significant terms were selected and modified ANNOVA model is shown in TABLE 5.

TABLE 5
MODIFIED ANALYSIS OF VARIANCE

Source	**Sum of Squares**	**df**	**Mean Square**	**F-value**	**p-value**	**% Contribution**
Model	8.27	6	1.38	34.07	< 0.0001	
A-Speed	1.41	1	1.41	34.9	0.0002	17.5
B-Feed	4.28	1	4.28	105.73	< 0.0001	53.0
C-Depth of Cut	0.8133	1	0.8133	20.1	0.0015	10.0
AB	1.08	1	1.08	26.7	0.0006	13.4
AC	0.4901	1	0.4901	12.11	0.0069	6.1
Residual	0.3642	9	0.0405			
Lack of Fit	0.3642	8	0.0455			
Pure Error	0	1	0			
Cor Total	8.64	15				

The graphs of effect of each factor on surface roughness are shown in **Error! Reference source not found.**. These graphs are helpful to find effect of parameter on surface roughness. Percentage contribution of each parameter on surface roughness is shown in TABLE 5. According to TABLE 5, the percentage contributions of feed is 53% whereas speed and depth of cut are 17% and 10%. Hence the most dominating factor influencing the surface roughness was feed rate.

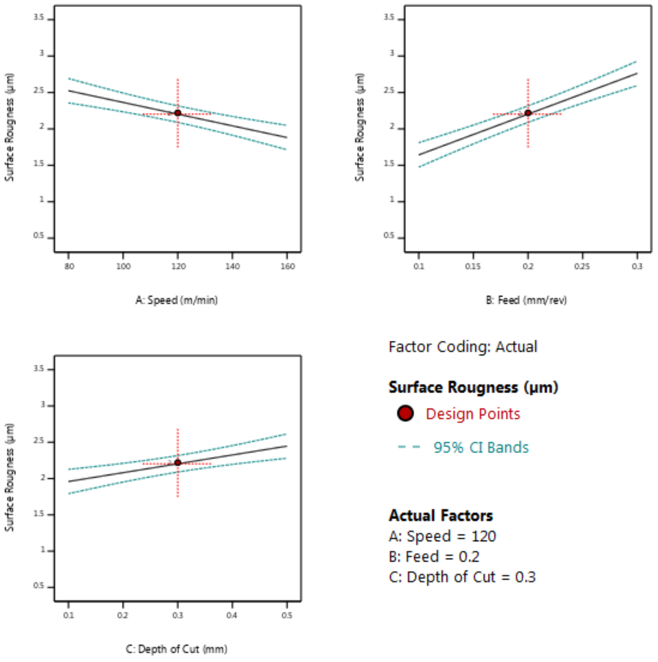


Fig. 2. Effect of each factor on surface roughness (Ra)

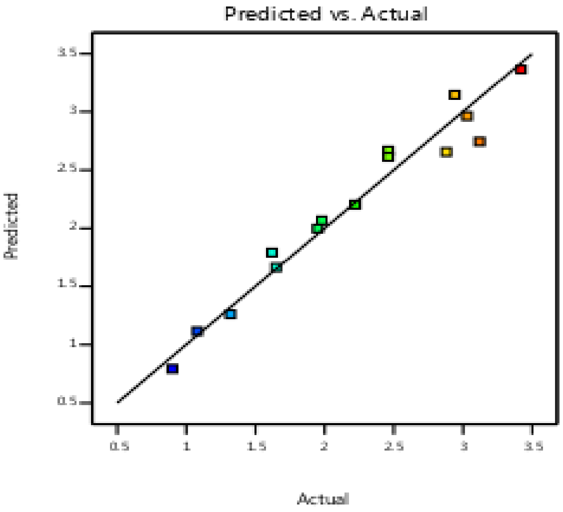


Fig. 3. Actual versus predicted values for surface roughness

Fig. *3* shows the graph of actual values versus predicted values. These values are very close to each other and hence the model can predict the value of surface roughness to a reasonable accuracy.

Fig. *4* shows the graph to ascertain constant variance. It is found to be linear and constant. All residuals follow straight line path, except very few points scattered which is acceptable.

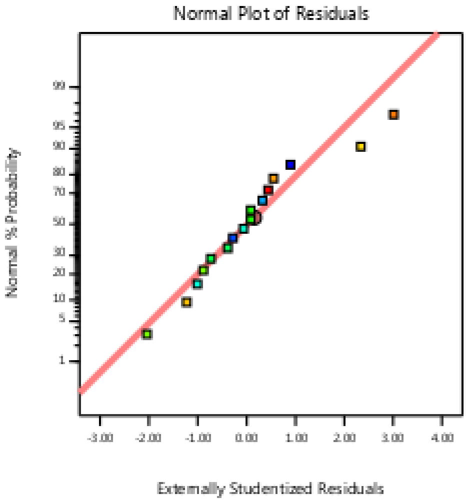


Fig. 4. Normal plot of residual

Fig. 5 shows the graph of residual versus run plot. The responses are within the lines. There is no trend component and hence graph varies due to common-cause variations only.

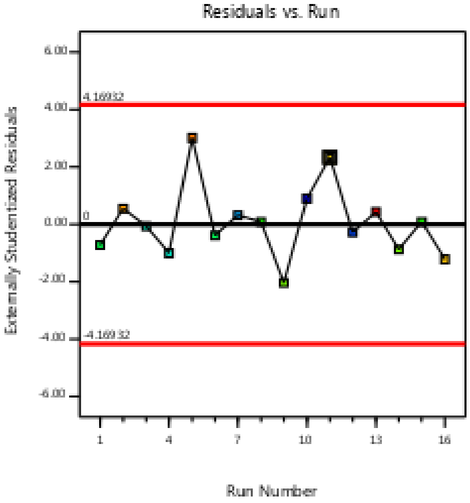
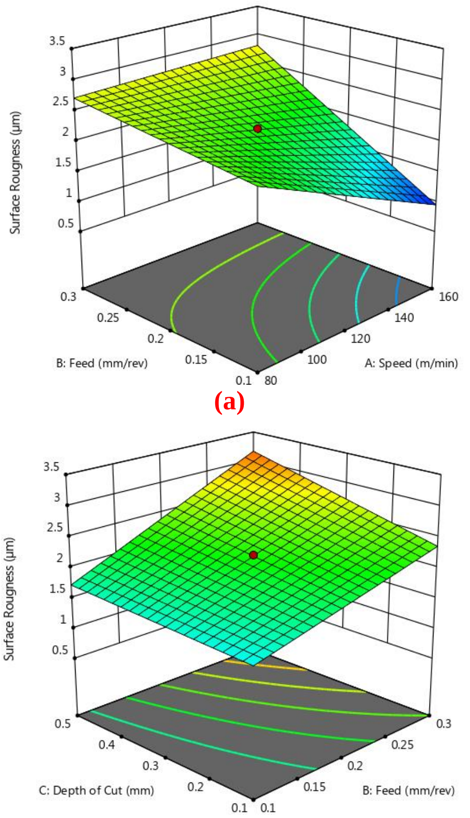


Fig. 5. Residual versus Run

Fig. *6* shows 3D surface graphs for the interaction effects of cutting speed and feed rate on surface roughness. Fig. *6* (a) shows that selecting highest speed and lowest feed will give the minimum value of surface roughness. By increasing the feed and decreasing the speed will increase the value of surface roughness significantly. Fig. *6* (b) shows that we can decrease surface roughness by decreasing feed and depth of cut.



(a)

(b)

Fig. 6. (a) 3 Dimensional surface plot of Interaction effects of speed and feed on surface roughness (b) 3 Dimensional surface plot of Interaction effects of speed and DOC on surface roughness

The model for predicting surface roughness is given below and TABLE 6:

$$Ra = 3.24616 - 0.017134*A - 7.78994*B + 3.35766*C + 0.091875*A*B - 0.030937*A*C \quad (2)$$

TABLE 6
ESTIMATED VALUES OF COEFFICIENT OF MODEL FOR SURFACE ROUGHNESS

Factor	Coefficient Estimate
Intercept	3.24616
A-Speed	-0.017134
B-Feed	-7.78994
C-Depth of Cut	3.35766
AB	0.091875
AC	-0.030937
BC	7.875

IV. CONCLUSION

This paper discussed the optimization of surface roughness in machining of hard steel, AISI D3, using the coated carbide inserts. After investigating the effects of cutting parameters; i.e.; speed, feed and depth of cut, it was observed that response surface methodology with face centered design was effective strategy to determine the optimal cutting parameters to minimize value of surface roughness. The minimum value of surface roughness of 0.9 µm was obtained at cutting speed of 160 m/min, feed rate of 0.1mm/rev and depth of cut of 0.5 mm. It was observed that by increasing cutting speed and decreasing feed reduces the surface roughness in machining. The reduced feed rate and depth of cut decreases the surface roughness in machining. The results shows that the feed rate is most influential parameter, which effects surface roughness.

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