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Statistical Model for Surface Roughness in Hard Turning of AISI D3 Steel

Varaprasad Bhemuni[a] *, Srinivasa Rao Chalamalasetti[b]

[a]*GVP School of Engineering (Technical Campus), Rushikonda, Visakhapatnam, India.*

[b]*Mechanical Engineering Department, Andhra University, College of Engineering (A), Visakhapatnam, India.*

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Abstract

In the present experimental work, the effects of cutting speed, feed rate and depth of cut on surface roughness are investigated in hard turning of AISI D3 steel. AISI D3 steel is hardened to 62 HRC and is machined using a mixed ceramic tool. Mathematical models for surface roughness are developed using the Response Surface Methodology (RSM). Central Composite Design (CCD) is applied as an experimental design. Al_2O_3/TiC mixed ceramic tool with corner radius of 0.8 mm is employed to accomplish 20 tests with six centre points. The range of each parameter is set at three different levels, namely low, medium and high. The main effects of the factors and their interactions were considered in the present study using Analysis of variance (ANOVA). Various graphs and plots are drawn to evaluate the influence of the process parameters on surface roughness. Feed rate is the most influencing factor on surface roughness. Results revealed that the use of lower feed, lower depth of cut and higher cutting speed, while hard turning of AISI D3 hardened steel, ensures a better surface roughness.

Keywords: *Hard Turning, Surface Roughness, AISI D3, RSM, Main Effect Plots and ANOVA.*

1. Introduction

Hard turning is the process of single point cutting of hardened ferrous material with hardness more than 45HRC in order to obtain finished work pieces directly from hardened parts [1-5]. This process was developed as an alternative to grinding process in a bid to reduce the number of setup changes, process flexibility, compatible surface roughness, higher material removal rate, and less environment problems, which leads to a reduction in machining costs, an elimination of cutting fluids, an increase in the flexibility and efficiency, a reduction in part-handling costs and, finally, a decrease in the set-up times [1, 4]. Many industrial steel components, under the influence of critical loads from automotive and aerospace parts to bearing and forming tool, are made of hardened steel. These parts are produced by a series of sequential operations like turning, grinding and polishing, which are time consuming and costly. Therefore, hard turning is gaining importance to replace operations by single setup and single operation [6, 7]. The growth of hard turning process is indebted to the advent of new advanced cutting tools such as Cubic Boron Nitride (CBN), Poly Crystalline Boron Nitride (PCBN) and Ceramics since 1970 [4].

The surface quality is an index to evaluate the productivity of machine tools as well as the machined components. The surface roughness is used as a major quality indicator for the machined surfaces, which is the result of process parameters such as cutting conditions and tool geometry. In today's manufacturing industry, a special attention is being paid to the dimensional accuracy as well as surface finish and, hence, measuring and characterizing the surface finish can be considered as a machining performance index. Achieving a better surface quality, tool life and dimension accuracy are the crucial concerns in turning of hardened steels [4]. The cutting tool is one of the most critical elements in hard turning and the development of newer cutting tool materials has been characterized by an increase in wear resistance. Much work has been done on various hardened steels with CBN and PCBN cutting tools. According to the recent research, few studies have been reported on hard turning of AISI D3 with mixed ceramic (CC 6050).

Zou *et al.* [8] used Al_2O_3/TiN-coated tungsten carbide tools for finish turning of NiCr20TiAl nickel-based alloy under various cutting conditions and the cutting forces, surface integrity and tool wear are investigated and the inter diffusing and transferring of elements between Al_2O_3/TiN-coated tungsten carbide tool

* Corresponding author. e-mail: varaprasad.bhimuni11@gmail.com.

and $NiCr_20TiAl$ nickel-based alloy are studied. Fahad *et al.* [9] investigated the cutting performance of tungsten carbide tools with restricted contact length and multilayer chemical vapor deposition coatings, $TiCN/Al_2O_3/TiN$ and $TiCN/Al_2O_3$ TiN in dry turning of AISI 4140 and the results show that the coating layouts and cutting tool edge geometry can significantly affect heat distribution into the cutting tool. Hamdan *et al.* [10] presented an optimization method of the machining parameters in high-speed machining of stainless steel using coated carbide tool to achieve minimum cutting forces and better surface roughness using Taguchi's technique and pareto ANOVA and found that the feed rate is found to be more significant followed by the cutting speed and the depth of cut.

Suhail *et al.* [11] developed a method to identify surface roughness based on measurement of workpiece surface temperature and root mean square for feed vibration of the cutting tool during turning mild steel using grey relational analysis. Gopalsamy *et al.* [12] studied the machinability of hardened steel using grey relational approach and ANOVA to obtain optimum process parameters considering MRR, surface finish, tool wear and tool life for both rough and finish machining. Ahilan *et al.* [13] performed a multi-response optimization of turning parameters and nose radius over surface roughness and power consumed using Taguchi based grey relational approach and found that the main influencing parameter is cutting speed followed by feed rate and depth of cut. In turning operations, for a multi-response optimization Taguchi based grey relational approach is used [14, 15] to identify the optimum conditions that obtain better results. Prediction of flank wear and surface roughness during hard turning is performed using uncoated carbide inserts of various tool geometries [16].

Fnides *et al.* [17] investigated the productivity in terms of volume chip carved of six cutting tools for two different cutting conditions in straight hard turning of X38CrMoV5-1 (50 HRC). They found that, for the first set of cutting parameters (*Vc=120 m/min, Doc =0.15 mm*, and *f=0.08 mm/rev*), the productivity of the uncoated cermets CT5015, the coated cermets GC1525, the uncoated carbide H13A, the reinforced ceramic CC670, the coated car-bide GC3015, and the mixed ceramic CC650 are 2,160; 1,440; 6,480; 11,520; 23,040; and 70,560 mm^3, respectively. The productivity of these three selected tools, i.e., mixed ceramic CC650, reinforced ceramic CC670, and coated carbide GC3015, for the second set of cutting parameters (*f=0.08 mm/rev, Doc= 0.15 mm*, and *Vc = 90 m/min*) are 85,860; 12,960; and 30,780 mm^3, respectively. Their results prove that the mixed ceramic Al_2O_3+TiC (CC650) is more efficient than the other tools used in terms of productivity.

The main scope of the present work is the experimental investigation of the effect of machining parameters (i.e., cutting speed, feed rate, depth of cut) on surface roughness in hard turning process of AISI D3 which is widely used in manufacturing. ANOVA is used on the results obtained from experimentation to determine the main effect of parameters and their interactions. Moreover, RSM and regression analysis are used to establish the correlation between factors and responses.

2. Experimental Procedure

2.1. Material, Work piece and Tool

The work piece material used for experiments is AISI D3. The bar of diameter 68 mm x 360 mm long is prepared. Test sample is trued, centred and cleaned by removing a 2 mm depth of cut from the outside surface, prior to actual machining tests. A new insert was employed for each run of experiments in order to provide completely identical cutting edge conditions for each test. The chemical composition of the work piece material is given in Table.1. The workpiece is oil-quenched from 980^0C (1800^0F), hardened, followed by tempering at 200^0C to attain 62HRC. Figure 1 shows the image of cutting insert CC6050. Experimental set up is shown in Figure 2.

The lathe used for machining operations is Kirloskar; model Turn Master-35, spindle power 6.6KW. Surface roughness is measured using *Mitutoyo Surftest SJ 210* as shown in Figure 3 having measuring range of 17.5 mm and skid force less than 400 mN. Four readings with a sample length of 0.8 mm are recorded after each experiment and an average value is taken as the surface roughness. These values are obtained without disturbing the assembly of the work piece in order to reduce uncertainties.

Table 1 Chemical composition of AISI D3 (wt %)

C	Si	Mn	P	S	Cr	Ni	Mo	Al	Cu	Zn	Fe
2.06	0.55	0.449	0.036	0.056	11.09	0.277	0.207	0.0034	0.13	0.27	85

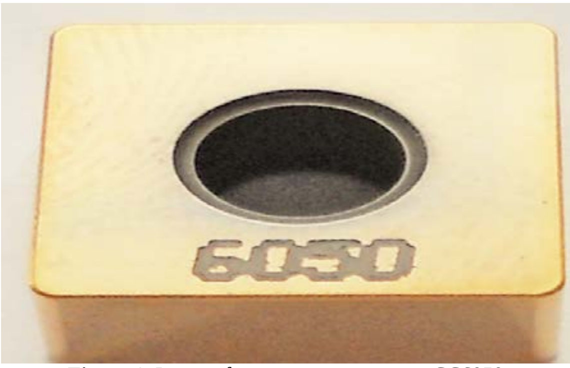

Figure 1. Image of ceramic cutting insert CC6050

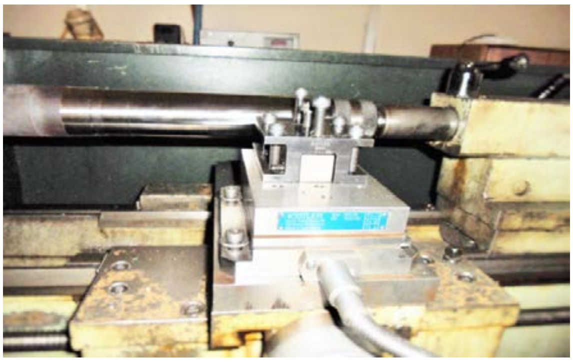

Figure 2. Experimental setup

Figure 3. Mitutoyo Surface Roughness tester SJ 210

The cutting insert used is a mixed ceramic removable, of square form with eight cutting edges and having designation SNGA 120408 T01020 *Sandvik* make CC6050 is a mixed ceramic grade based on alumina with an addition of titanium carbide. The high hot-hardness and the good level of toughness make the grade suitable as first choice for hardened steel (50 – 65HRC) in applications with good stability or with light interrupted cuts. The inserts are mounted on a commercial tool holder of designation PSBNR 2525 M 12 (ISO) with the geometry of active part characterized by the following angles: χ = 75°; α = 6°; γ = −6°; λ = −6°.

2.2. Experiments Design

RSM is a modelling approach for determining the relationship between the various factors and the responses with the desired criteria and searching the significance of these parameters on the responses. The RSM is useful for developing, improving and optimizing the processes, which provides an overall perspective of the system response within the design space [18]. In order to know surface quality values in advance, it is necessary to employ empirical models making it feasible to do predictions as a function of operational conditions. Using the design of experiments and applying the regression analysis, the modelling of the desired response to several independent process parameters can be obtained. The RSM is utilized to describe and identify the influence of the interactions of different process parameters on the performance characteristics when these are varied simultaneously. In the present investigation, the second-order RSM-based mathematical models for surface roughness (*Ra*) are developed with cutting speed (*Vc*), feed rate (*f*), and depth of cut (*Doc)* as the process parameters.

In the present study, the quantitative form of the relationship between the desired response and independent input process parameters can be represented by [18]:

$$Y = \phi(V_c, f, a_p) \quad (1)$$

Where *Y* is the desired response and ϕ is the response function. In the present investigation, the RSM-based mathematical models for surface roughness *Ra*, have been developed with cutting speed V_c, feed rate f and depth of cut (*Doc*) as the process parameters. The response surface equation for three factors is given by [18]:

$$Y = a_0 + a_1 V_c + a_2 f + a_3 a_p + a_{12} V_c f + a_{13} V_c a_p + a_{23} f a_p + a_{11} V_c^2 + a_{22} f^2 + a_{33} a_p^2 \quad (2)$$

Where *Y* is the desired response and a_0 is the free term of the regression equation, the coefficients a_1, a_2, a_3 and a_{11}, a_{22}, ...a_{33} are the linear and quadratic terms, respectively, while a_{12}, a_{13},..a_{23} are the interacting terms. The experimental plan is developed to assess the influence of cutting speed (V_c), feed rate (*f*), and depth of cut (*Doc*) on the surface roughness (*Ra*), regression coefficients to be determined for each response. The regression coefficients of linear, quadratic, and interaction terms of RSM-based mathematical models are determined by [18].

Three levels are defined for each cutting variable, as given in Table 2. The variable levels are chosen within the intervals recommended by the cutting tool manufacturer. Three cutting variables at three levels led to a total of 20 tests. The factors to be studied and the attribution of the respective levels are indicated in Table 3.

Table 2. Assignment of the levels to the variables

Parameters	**Range**		
	-1	0	+1
Speed (m/min)	145	155	165
Feed (mm/rev)	0.05	0.075	0.1
Depth of cut (mm)	0.3	0.6	0.9

3. Results and Discussion

Table 3 presents the experimental results of surface roughness (*Ra*) for various combinations of cutting conditions (cutting speed, feed rate and depth of cut) as per the design matrix.

The experimental data presented in Table 3, for which analysis has to be graphically done and represented. The following sections present the detailed discussion.

3.1. Statistical Analysis

The estimated regression coefficients for surface roughness *Ra* are shown in Table 4 and scatter plot is shown in Figure 4.

It can be observed from Figure 4 that, as the residuals are located on a straight line, the errors are distributed normally. Hence, the developed empirical models can represent the process significantly. Scatter plots identifies the relationship between two variables whether the relationship is positive, negative, or no relationship can be easily detected. Therefore, these models can be further used for the optimization of process parameters.

Table 3. Experimental results for surface roughness

S.No.	Coded Form			Un-Coded Form			Surface Roughness (Microns)	
	Speed	Feed	*Doc*	Speed (m/min)	Feed (mm/rev)	*Doc* (mm)	Actual	Predicted
1	-1	-1	-1	145	0.05	0.3	0.621	0.63319
2	1	-1	-1	165	0.05	0.3	0.561	0.57789
3	-1	1	-1	145	0.1	0.3	0.982	0.99469
4	1	1	-1	165	0.1	0.3	0.686	0.68439
5	-1	-1	1	145	0.05	0.9	0.79	0.81799
6	1	-1	1	165	0.05.	0.9	0.999	1.01269
7	-1	1	1	145	0.1	0.9	0.954	0.96349
8	1	1	1	165	0.1	0.9	0.889	0.90319
9	-1	0	0	145	0.075	0.6	0.876	0.81365
10	1	0	0	165	0.075	0.6	0.799	0.75585
11	0	-1	0	155	0.05	0.6	0.809	0.73825
12	0	1	0	155	0.1	0.6	0.899	0.86425
13	0	0	-1	155	0.075	0.3	0.759	0.71885
14	0	0	1	155	0.075	0.9	0.986	0.92065
15	0	0	0	155	0.075	0.6	0.787	0.79116
16	0	0	0	155	0.075	0.6	0.799	0.79116
17	0	0	0	155	0.075	0.6	0.786	0.79116
18	0	0	0	155	0.075	0.6	0.635	0.79116
19	0	0	0	155	0.075	0.6	0.931	0.79116
20	0	0	0	155	0.075	0.6	0.601	0.79116

Table 4. Estimated regression coefficients for surface roughness *Ra* (microns)

Term	**Coef**	**SE Coef**	**T**	**P**	**Remarks**
Constant	0.814091	0.02647	30.752	0.000	Significant
Speed(m/min)	-0.028900	0.02435	-1.187	0.263	Insignificant
Feed(mm/rev)	0.063000	0.02435	2.587	0.027	Significant
Doc (mm)	0.100900	0.02435	4.143	0.002	Significant
Speed(m/min)* Speed(m/min)	-0.015227	0.04644	-0.328	0.750	Insignificant
Feed(mm/rev)* Feed(mm/rev)	0.001273	0.04644	-0.027	0.979	Insignificant
Doc (mm)* *Doc* (mm)	0.019773	0.04644	0.426	0.679	Insignificant
Speed(m/min)*Feed(mm/rev)	-0.063750	0.02723	-2.342	0.041	Significant
Speed(m/min)* *Doc* (mm)	0.062500	0.02723	20296	0.045	Significant
Feed(mm/rev)* *Doc* (mm)	-0.054000	0.02723	-1.983	0.075	Insignificant
S = 0.0770070 R-Sq = 80.07% R-Sq(adj) = 62.14%					

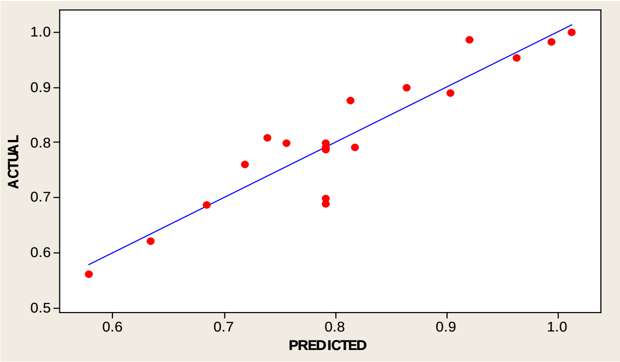

Figure 4. Scatter plot of Ra (actual Vs predicted)

3.2. Analysis of Variance

The ANOVA has been applied to check the adequacy of the developed models. The ANOVA table consists of a sum of squares and degrees of freedom. The sum of squares is performed into contributions from the polynomial model and the experimental value, and was calculated by the following equation:

$$ss_f = \frac{N}{N_{n_f}} \sum_{i=1}^{N_{n_f}} (\bar{y}_i - \bar{y})^2$$

The mean square is the ratio of the sum of squares to degrees of freedom; it was calculated by the following equation:

$$MS = \frac{MS_i}{DF_i}$$

F-value the ratio of mean square of regression model to the mean square of the experimental error, was calculated by the following equation:

$$F - value = \frac{MS_i}{MS_{error}}$$

This analysis was out for a 5% significance level, i.e., for a 95% confidence level. The percentage of each factor contribution (Cont. %) on the total variation, which indicates the degree of the influence on the result, was calculated by the following equation:

$$cont.\% = \frac{SS_i}{SS_{\text{mod}}} X100$$

A low P-value indicates a statistical significance for the source on the corresponding response. It is clear from the results of ANOVA that the depth of cut is the dominant factor affecting surface finish *Ra*. The second factor influencing *Ra* is cutting speed *feed rate. To understand the hard turning process in terms of surface roughness *Ra*, a mathematical model is developed using a multiple regression method. *Ra* model is given by equations 1 and 2. Its coefficient of correlation R^2 is 80.07%.

Table 5. Analysis of variance for surface roughness Ra (microns)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	9	0.238291	0.238291	0.026477	4.46	0.014
Speed (m/min)	1	0.008352	0.008352	0.008352	1.41	0.263
Feed (mm/rev)	1	0.03969	0.03969	0.03969	6.69	0.027
Doc (mm)	1	0.101808	0.101808	0.101808	17.17	0.002
Speed (m/min)*Speed (m/min)	1	0.000034	0.000638	0.000638	0.11	0.75
Feed (mm/rev)*Feed (mm/rev)	1	0.000242	0.000004	0.000004	0	0.979
Doc (mm)**Doc* (mm)	1	0.001075	0.001075	0.001075	0.18	0.679
Speed (m/min)*Feed (mm/rev)	1	0.032512	0.032512	0.032512	5.48	0.041
Speed (m/min)**Doc* (mm)	1	0.03125	0.03125	0.03125	5.27	0.045
Feed (mm/rev)**Doc* (mm)	1	0.023328	0.023328	0.023328	3.93	0.075
Residual Error	10	0.059301	0.059301	0.00593		
Total	19	0.297592				

3.3. Main Effect Plots and Interaction Plots for Surface Roughness

The effect of process parameters on performance characteristic is easy to explain with the help of the main effects plot. In Figure 5, the main effects for average surface roughness (*Ra*) is plotted.

It is clearly observed that the feed strongly changes the surface roughness. The feed rate has an increasing effect. It is known that the theoretical geometrical surface roughness is primarily a function of the feed for a given nose radius and changes with the square of the feed rate value. The cutting speed has an important and a decreasing effect. Surface roughness is improved by increasing cutting speed, though the improvement is very limited at higher cutting speed (155-165 m/min). Producing a better surface finish at higher cutting speed is well known in metal cutting.

During experimentation, where hardened steel is machined, the cutting speeds are higher than those favouring BUE formation. The higher the velocity is, the less significant the plastic behaviour becomes. The lateral plastic flow of the workpiece material along the cutting edge direction may increase the peak-to-valley height of the surface irregularity. If the material presents less plasticity by increasing cutting speed and, hence, deformation velocity, the surface finish can be improved as a result of less significant lateral plastic flow and, thus, less additional increase in the peak-to-valley height of the machined surface.

For the depth of cut (*Doc*), the influence value is the second statistical significance on surface roughness. However, low depth of cut should be used in order to reduce the tendency to chatter. The depth of cut (*Doc*) has a little direct influence on the surface roughness; however, with the increases in *Doc*, above nose radius of tool values (0.8 mm), a chatter may result causing degradation of the workpiece surface. Therefore, if the tool work system is not very rigid, such as in cutting slender parts, very fine depth of cut should be employed to avoid chatter. In this way, very good surface finish can be obtained. For all machining tests, the *Ra* values observed are in the range of 0.561-0.999 microns, indicating that Ceramic tool is able to produce parts with surfaces equivalent to those resulting from grinding and other finishing processes.

3.4. Contour Plots for Surface Roughness Vs Speed, Feed and Depth of cut.

Contour plots play a very important role in the study of the response surface. By creating contour plots using software for response surface analysis, the optimum is located by characterising the shape of the surface. Circular shaped contour represents the independence of factor effects and elliptical contours may indicate factor interaction. The contours of the responses are shown in Figures 6a, 6b & 6c. The surface roughness clearly showed that the minimum roughness is at low value of feed, because feed is the most influencing factor for surface roughness. *Ra* is minimum at low depth of cut and low speed.

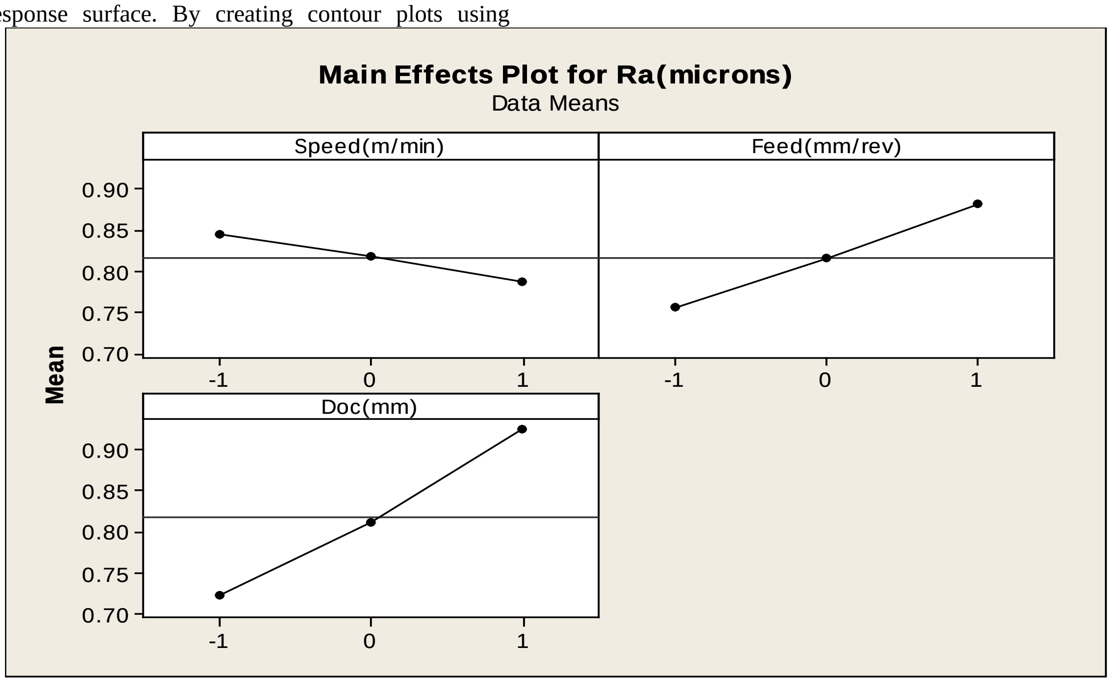

Figure 5. Main effect plots for mean Surface roughness against speed, feed and depth of cut.

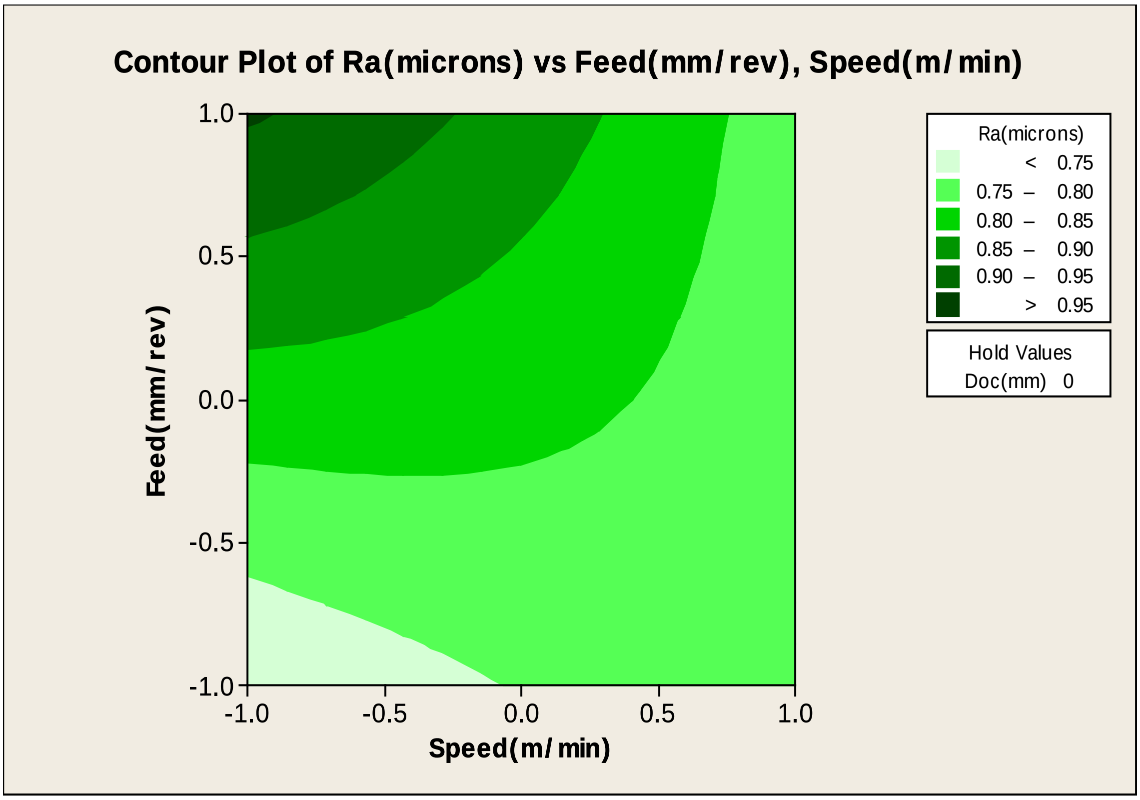

Figure 6a. contour plot of *Ra* vs Feed and Speed

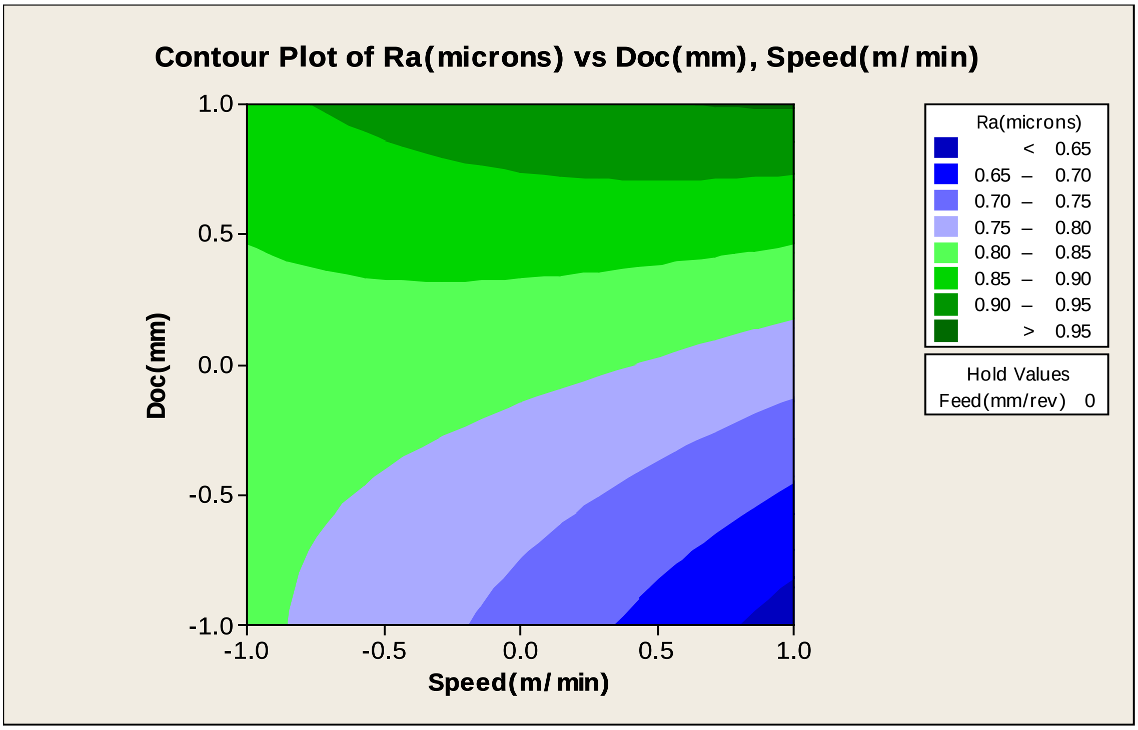

Figure 6b. contour plot of *Ra* vs a_p and Speed

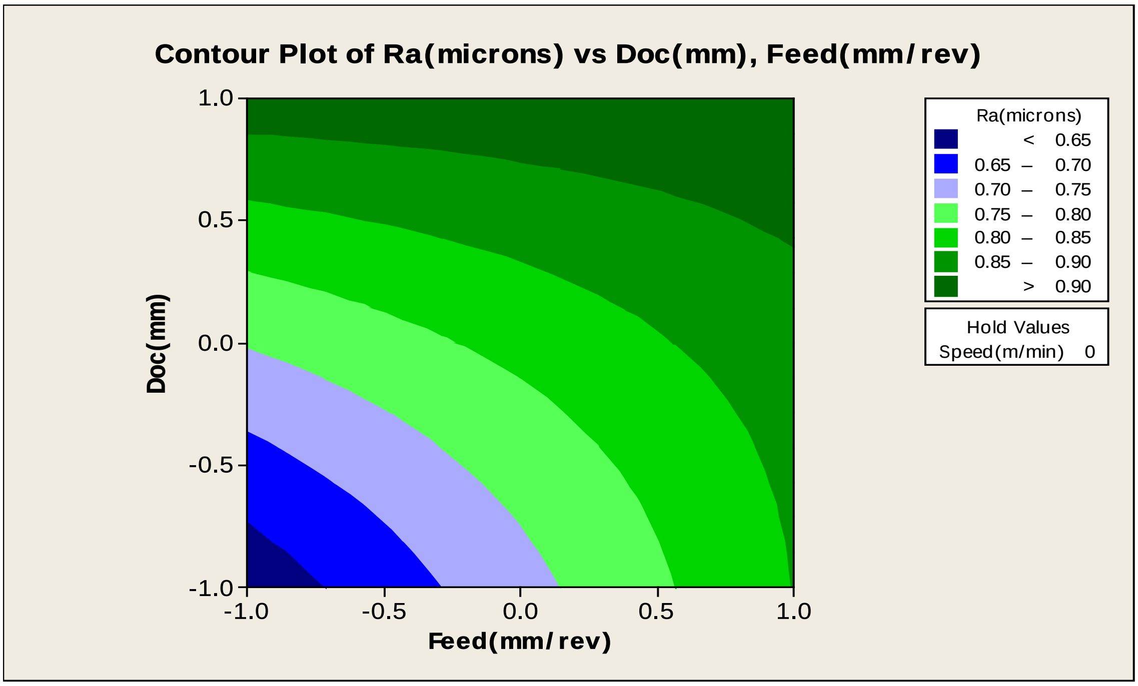

Figure 6c. contour plot of Surface roughness vs a_p and Feed

3.5. 3 D Surface Plots

3D Surface plots of *Ra* vs. different combinations of cutting parameters are shown in Figures 7a, 7b, 7c, and these figures obtained by RSM. Figure 7a presents the influences of cutting speed (*Vc*) and feed rate (*f*) on the surface roughness, while the depth of cut (*Doc*) is kept at the middle level. Figure 7b shows the estimated response surface in relation to the cutting speed (*Vc*) and depth of cut (*Doc*), while feed rate (*f*) is kept at the middle level. The effects of the feed rate (*f*) and depth of cut (*Doc*) on the cutting force components are shown in Figure 7c, while the cutting speed (*Vc*) is kept at the middle level. For each plot, the variables not represented are held at a constant value (the middle level). These 3D plots confirm the notes observed during the principal effects plots analysis.

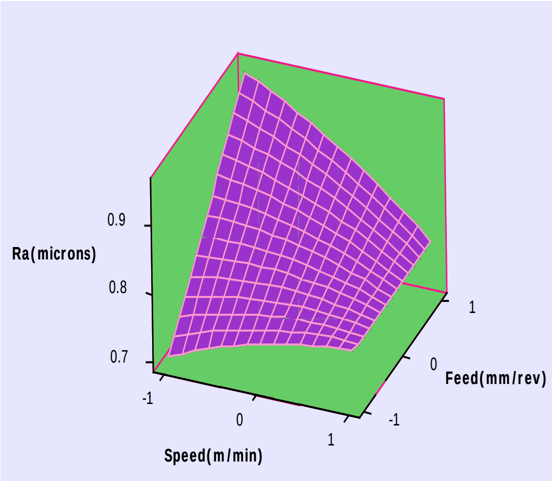

Figure 7a. Surface roughness vs Speed and Feed

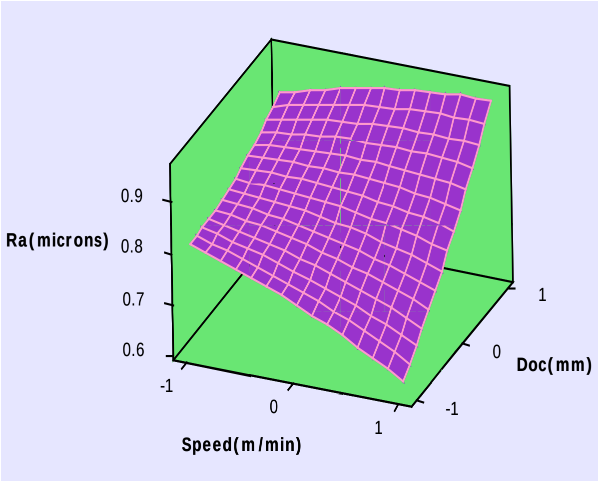

Figure 7b. Surface roughness vs Speed and *Depth of cut*

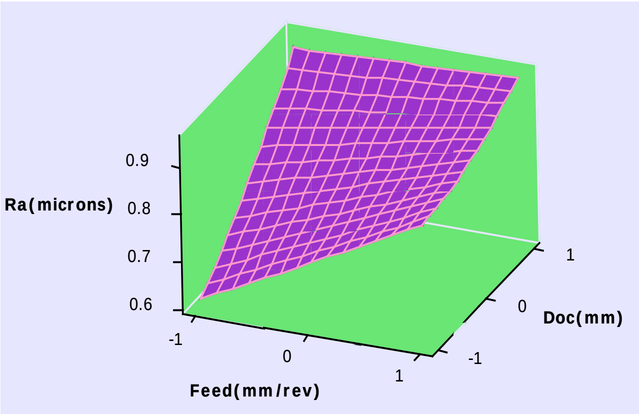

Figure 7c. Surface roughness vs Feed and Depth of cut

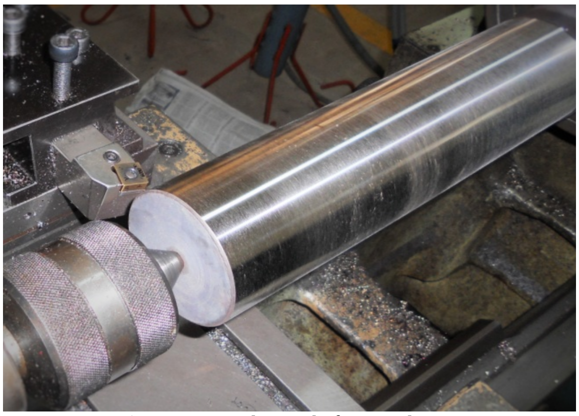

Figure 8a. Workpiece before machining

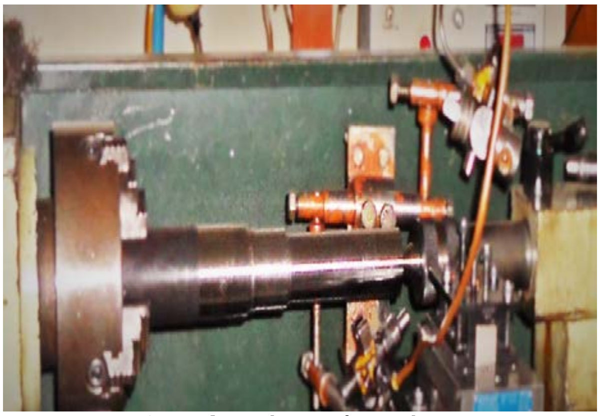

Figure 8b. Workpiece after machining

Figure 8. Workpiece before and after machining

4. Conclusions

The tests of hard turning, carried out on AISI D3 steel having 62 HRC which is machined with a mixed ceramic tool (insert CC6050), enabled us to develop statistical models of surface roughness criteria.

- These models are obtained using a multiple regression method in Minitab16 software. The results revealed that the feed rate seems to influence the surface roughness more significantly than the cutting speed.
- The depth of cut is found to be the second significant parameter after feed; thus, to get a good surface finish with a higher chip removal rate, the proposed process parameters are cutting speed at 165 m/min, feed rate at 0.05 mm/rev and depth of cut of 0.3 mm.
- The statistical models developed illustrate the degree of influence of each machining condition on surface roughness. These models can also be used for the optimization of hard cutting process.

This study confirms that dry hard turning of AISI D3 steel for the chosen cutting conditions shows the surface roughness to be close to that obtained in grinding.

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