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COMPARISON OF SURFACE ROUGHNESS OF COLD WORK AND HOT WORK TOOL STEELS IN HARD TURNING

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ABSTRACT: *The hard turning process has been attracting interest in different industrial sectors for finishing operations of hard materials at its hardened state. Surface roughness is investigated in hard turning of AISI D3 and AISI H13 steels of same hardness 62HRC. In this paper, an attempt has been made to model and predict the surface roughness in hard turning of AISI D3 and AISI H13 hardened steels using Response Surface Methodology (RSM). The combined effects of three machining parameters such as cutting speed, feed rate and depth of cut are investigated for main performance characteristic that is surface roughness. RSM based Central Composite Design (CCD) is applied as an experimental design. Al_2O_3/TiC mixed ceramic tool with corner radius 0.8 mm is employed to accomplish 20 tests with six center points. The acceptability of the developed models is checked using Analysis of Variance (ANOVA).The combined effects of cutting speed; feed rate and depth of cut are investigated using surface plots.*

KEYWORDS: Hard turning, Surface Roughness, AISI D3, AISI H13, RSM and ANOVA.

INTRODUCTION

Hard turning is the process of single point cutting of hardened ferrous material with a hardness value more than 45HRC in order to obtain finished workpieces directly from hardened parts [1-5]. Hardened steels are most widely used in multiple industrial applications like automotive, aeronautics, tool design and mold design. Many industrial steel components under influence of critical loads from automotive and aerospace parts to bearing and forming tool are made of hardened steel. These parts are normally finished by grinding, which is time consuming and costly. For this reason, hard turning has become the most important substitute to grinding for hardened steels [6, 7]. With advent of new kind of tools such as Cubic Boron Nitride (CBN), Polycrystalline Cubic Boron Nitride (PCBN), poly-crystalline diamond (PCD), coated, Chemical Vapor Deposition (CVD), Physical Vapor Deposition (PVD) and ceramic tools, better surface finish will be accessible without any finishing and complementary operation such as grinding. Reduction in machining costs, elimination of cutting fluids, increase in the flexibility and efficiency, reduction in part-handling costs and finally decrease in the set-up times when compared to grinding process are the advantages of hard turning [1,4]. Achieving better surface quality, tool life and dimensional accuracy are of crucial concerns in turning of hardened steels [4]. The major focus of present research is on surface roughness of the machined surfaces and it is one of the most important product quality characteristics. Achieving the suitable surface quality in hard turning especially in comparison with grinding is of great importance to the functional behavior of a machined part. Very few studies are reported on hard turning of AISI D3 with ceramic tool and also comparison of machining of both AISI D3 and AISI H13. The main scope of the present research is the experimental investigation of the

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effect of machining parameters (i.e., cutting speed, feed rate, depth of cut) on surface roughness in hard turning process of AISI D3 and AISI H13. In this experimental work, ANOVA is used to know the percentage of contribution of each parameter on performance. To analyze the effect of process parameters on surface roughness by plotting main effects graph and their individual interactions. Moreover, RSM and regression analysis are used to establish the correlation between factors and responses.

Al_2O_3/TiN-coated tungsten carbide tools for finish-turning of NiCr20TiAl nickel-based alloy under various cutting conditions, 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 and NiCr20TiAl nickel-based alloy are studied [8]. 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 coating layouts and cutting tool edge geometry can significantly affect heat distribution into the cutting tool [9]. 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 [10].

A method developed 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 [11]. 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 [12]. 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 [13]. In turning operations, for multi-response optimization Taguchi based grey relational approach is used to identify the optimum conditions to obtain better results [14, 15]. Prediction of flank wear and surface roughness during hard turning is performed using uncoated carbide inserts of various tool geometries [16].

EXPERIMENTATION

The materials used for experiments are AISI D3 and AISI H13. Bars of diameter 70 mm x 360 mm long are prepared. Test sample is trued, centred and cleaned by removing a 2 mm layer prior to actual machining tests. The chemical composition of the work piece materials are given in Table.1 and Table.2. The AISI D3 is oil-quenched from 980°C (1800°F) for hardening, followed by tempering at 200°C to attain 62HRC. The AISI H13 is hardened by oil quenching from 1050°C and tempered at 600°C to attain 62 HRC.

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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	84.8716

Table.2 Chemical composition of AISI H13 (wt%)

C	Si	Mn	P	S	Cr	Ni	Mo	V	Fe
0.4	1.05	0.35	0.03	0.003	5.03	0.3	1.4	1.0	90.437

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* having measuring range of 17.5mm 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 workpiece in order to reduce uncertainties.

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, the good level of toughness makes the grade suitable as first choice for machining hardened steels (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: $\chi = 75°$; $\alpha = 6°$; $\gamma = -6°$; $\lambda = -6°$. Three levels are defined for each cutting variable as given in Table.3. The variable levels are chosen within the intervals according to recommendations made by the cutting tool manufacturer. Three selected cutting variables at three levels led to a total of 20 tests.

Table.3. 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

ANALYSIS OF RESULTS

The analysis is made by considering experimental results of surface roughness (R_a) for various combinations of cutting conditions (cutting speed, feed rate and depth of cut) as per the design matrix. Data is analysed statistically using ANOVA, Contour plots and Surface plots are shown and discussed in the following sections.

Statistical Analysis

In RSM, the quantitative form of the relationship between the desired response and independent input process parameters can be represented by [17].

(1)

Where Y is the desired response and *f* is the response function. In the present investigation, the RSM-based mathematical model for surface roughness Ra, has been developed with cutting speed Vc, feed rate f and depth of cut a_p as the process parameters. The response surface equation for three factors is given by [17].

(2)

Where Y; desired response and a_1,..........., a_{33}; regression coefficients to be determined for each response.

The estimated Regression Coefficients for surface roughness of AISI D3 and AISI H13 for surface roughness Ra are shown in Table.4 and 5.

Table.4. Estimated Regression Coefficients for surface roughness of AISI D3 R_a (microns)

Term	Coef	SE Coef	T	P	Remarks
Constant	-16.55	29.814	-0.555	0.591	Insignificant
Speed(m/min)	0.27	0.39	0.69	0.506	Insignificant
Feed(mm/rev)	-121.55	54.994	-2.21	0.049	Significant
DoC(mm)	5.27	4.22	1.248	0.241	Insignificant
Speed(m/min) x Speed(m/min)	0	0.001	-0.548	0.595	Insignificant
Feed(mm/rev) x Feed(mm/rev)	1185.16	200.614	5.908	0.000	Significant
DoC(mm) x DoC(mm)	-0.35	1.393	-0.249	0.808	Insignificant
Speed(m/min) x Feed(mm/rev)	-0.48	0.294	-1.639	0.132	Insignificant
Speed(m/min) x DOC(mm)	-0.03	0.025	-1.102	0.296	Insignificant
Feed(mm/rev) x DOC(mm)	-5.62	9.802	-0.573	0.579	Insignificant
S = 0.207925 PRESS = 2.99659 R-Sq = 92.80% R-Sq(pred) = 50.11% R-Sq(adj) = 86.32%					

$$Ra = -16.55+0.27xX_1-121.55xX_2+5.27xX_3+1185.16xX_2^2 \quad (3)$$

Where X_1, X_2 and X_3 Speed, feed and Depth of cut.

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Table.5. Estimated Regression Coefficients for surface roughness of AISI H13 R_a(microns)

Term	Coef	SE Coef	T	P	Remarks
Constant	73.6655	29.541	2.494	0.032	Significant
Speed(m/min)	-0.9472	0.386	-2.453	0.034	Significant
Feed(mm/rev)	55.0202	54.49	1.01	0.336	Insignificant
DOC(mm)	-7.497	4.181	-1.793	0.103	Insignificant
Speed(m/min) x Speed(m/min)	0.003	0.001	2.446	0.034	Significant
Feed(mm/rev) x Feed(mm/rev)	37.0473	198.776	0.186	0.856	Insignificant
DOC(mm) x DOC(mm)	-0.2316	1.38	-0.168	0.87	Insignificant
Speed(m/min) x Feed(mm/rev)	-0.3428	0.291	-1.176	0.267	Insignificant
Speed(m/min) x DOC(mm)	0.0611	0.024	2.515	0.031	Significant
Feed(mm/rev) x DOC(mm)	-13.3917	9.712	-1.379	0.198	Insignificant
S = 0.206020 PRESS = 6.78960 R-Sq = 75.87% R-Sq(pred) = 0.00% R-Sq(adj) = 54.16%					

$$Ra = 73.66-0.94xX_1+55.02xX_2-7.49xX_3+0.003xX_1^2+0.061x(X_1 \text{ x } X_2) \qquad (4)$$

Where X_1 is Speed, X_2 is Feed and X_3 is Depth of cut.

Scatter plots identifies the relationship between two variables whether the relationship is positive, negative, or no relationship can be easily detected. It can be observed from figure.1 the residuals are located on straight line, which means that the errors are distributed normally. Hence the developed empirical models can represent the process significantly. Therefore these models can be further used for optimization of process parameters such as speed, feed and depth of cut.

Fig 1. Scatter plots for actual and predicted values of R_a of AISI D3 and AISI H13steels

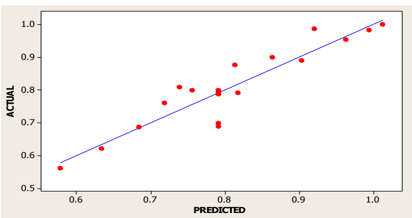

Fig.3a. Ra of AISI D3

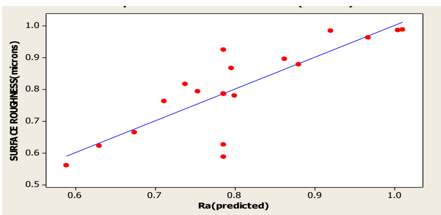

Fig.3b. Ra of AISI H13

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Analysis of Variance

It is clear from the results of ANOVA that the feed is the dominant factor affecting surface finish Ra. The second factor influencing Ra is cutting speed x feed for AISI D3 shown in table.6. Table.7.shown below is ANOVA for AISI H13.To understand the hard turning process in terms of surface roughness Ra, mathematical models are developed using multiple regression method. Ra models are given by equations (3&4). Its coefficient of correlation R^2 is 92.8 for AISI D3 and its value 75.87 for AISI H13.

The ANOVA has been applied to check the adequacy of the developed models. The ANOVA table consists of 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 (5):

(5)

The mean square is the ratio of sum of squares to degrees of freedom was calculated by the following equation (6):

(6)

F-value is the ratio of mean square of regression model to the mean square of the experimental error was calculated by the following equation (7):

(7)

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, then indicating the degree of influence on the result, was calculated by the following equation (8):

(8)

A low P-value indicates 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. To understand the hard turning process in terms of surface roughness Ra, mathematical model is developed using multiple regression method. Ra model is given by equations 1 and 2. Its coefficient of correlation R^2 is 92.80% for AISI D3 steel and 75.87% for AISI H13 steel.

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Table.6. Analysis of Variance for surface roughness AISI D3

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	9	5.5737	5.5737	0.6193	14.32	0
Speed(mm/min)	1	0.01166	0.0206	0.0206	0.48	0.506
Feed(mm/rev)	1	2.98608	0.21121	0.21121	4.89	0.049
DoC(mm)	1	0.05293	0.06731	0.06731	1.56	0.241
Speed(mm/min)*Speed(mm/min)	1	0.63689	0.01301	0.01301	0.3	0.595
Feed(mm/rev)*Feed(mm/rev)	1	1.70061	1.50886	1.50886	34.9	0.000
DoC(mm)*DoC(mm)	1	0.00269	0.00269	0.00269	0.06	0.808
Speed(mm/min)*Feed(mm/rev)	1	0.11616	0.11616	0.11616	2.69	0.132
Speed(mm/min)*DoC(mm)	1	0.05249	0.05249	0.05249	1.21	0.296
Feed(mm/rev)*DoC(mm)	1	0.0142	0.0142	0.0142	0.33	0.579
Residual Error	10	0.43233	0.43233	0.04323		
Total	19	6.00603				

Table.7. Analysis of Variance for surface roughness Ra of AISI H13

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	9	1.33475	1.33475	0.148306	3.49	0.032
Speed(mm/min)	1	0.03405	0.25548	0.255479	6.02	0.034
Feed(mm/rev)	1	0.00213	0.04327	0.043274	1.02	0.336
DoC(mm)	1	0.42271	0.13644	0.136442	3.21	0.103
Speed(mm/min)*Speed(mm/min)	1	0.46601	0.25398	0.253984	5.98	0.034
Feed(mm/rev)*Feed(mm/rev)	1	0.00075	0.00147	0.001474	0.03	0.856
DoC(mm)*DoC(mm)	1	0.00119	0.00119	0.001195	0.03	0.870
Speed(mm/min)*Feed(mm/rev)	1	0.05874	0.05874	0.058739	1.38	0.267
Speed(mm/min)*DoC(mm)	1	0.26846	0.26846	0.268461	6.33	0.031
Feed(mm/rev)*DoC(mm)	1	0.08070	0.08070	0.080702	1.90	0.198
Residual Error	10	0.42444	0.42444	0.042444		
Total	19	1.75919				

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 AISI D3 and AISI H13 responses are shown in figure.4. (a-f). The surface roughness is clearly shown that 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 also at low speed.

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Fig. 2. Contour plots for AISI D3 and AISI H13

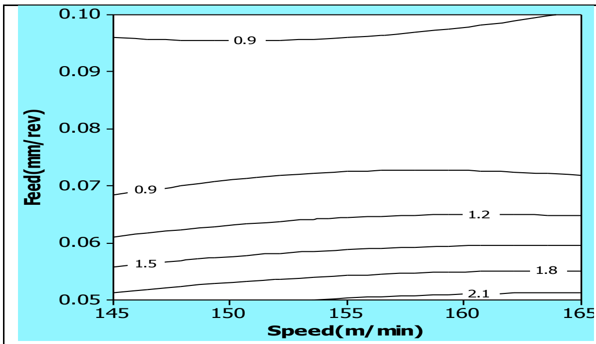

Fig.2a. R_a vs Speed and Feed(AISI D3)

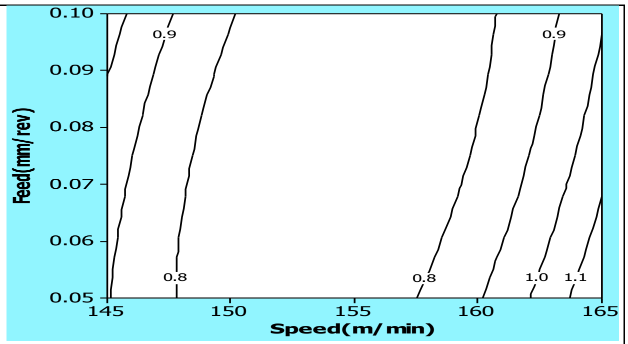

Fig.2b. R_a vs Feed and Speed(AISI H13)

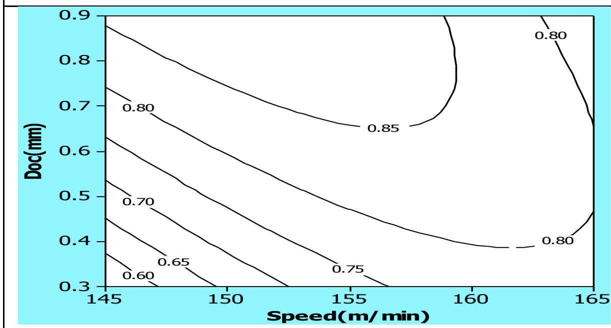

Fig.2c. R_a vs Speed and DOC (AISI D3)

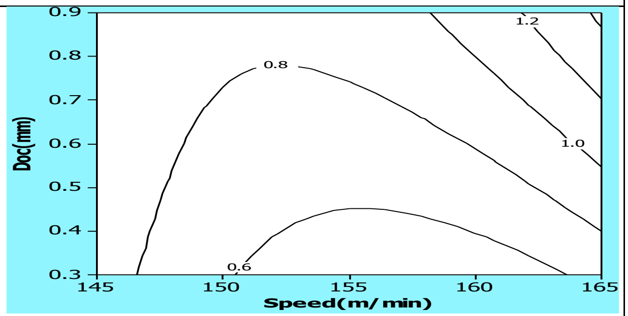

Fig.2d. R_a vs Speed and DOC (AISI H13)

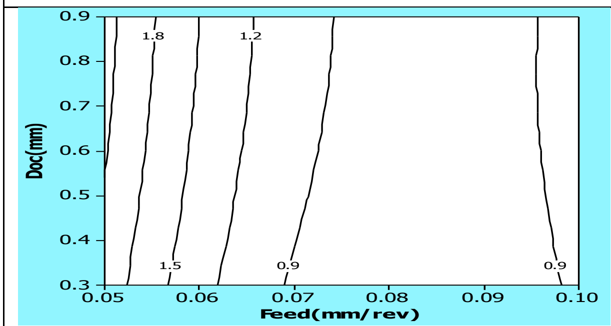

Fig.2e. R_a vs DOC and Feed (AISI D3)

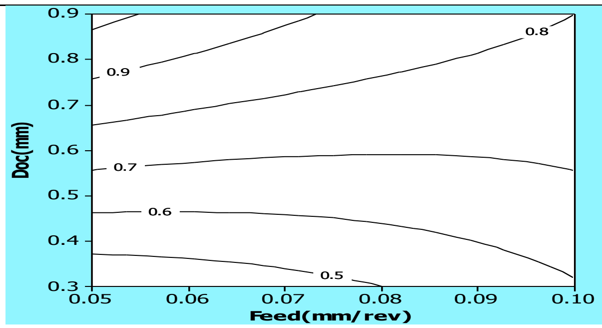

Fig.2f. R_a vs DOC and Feed (AISI H13)

3 D Surface plots

3D Surface plots of Ra vs. different combinations of cutting parameters are shown in figure 5a, 5c, 5e for AISI D3 and these figures obtained by RSM Fig. 5(a) presents the influences of cutting speed (Vc) and feed rate (f) on the surface roughness, while the depth of cut (a_p) is kept at the middle level. Fig.5(c) shows the estimated response surface in relation to the cutting speed (Vc) and depth of cut (a_p), while feed rate (f) is kept at the middle level. The effects of the feed rate (f) and depth of cut (a_p) on the surface roughness components are shown in Fig. 5(e), 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) for AISI D3. For AISI H13 figures shown in 5b, 5d and 5f.These 3D plots confirm the nodes observed during the principal effects plots analysis.

Fig. 3. Surface Plots for AISI D3 and AISI H13

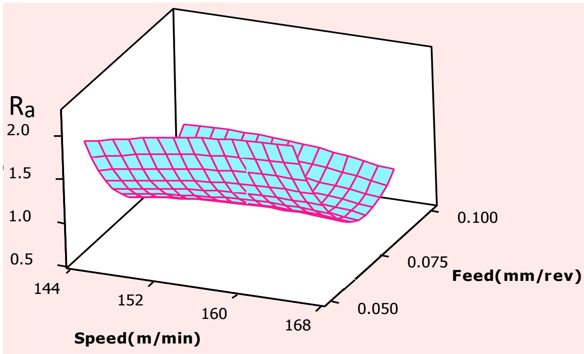

Fig.3a. Surface roughness vs Speed and Feed (AISI D3)

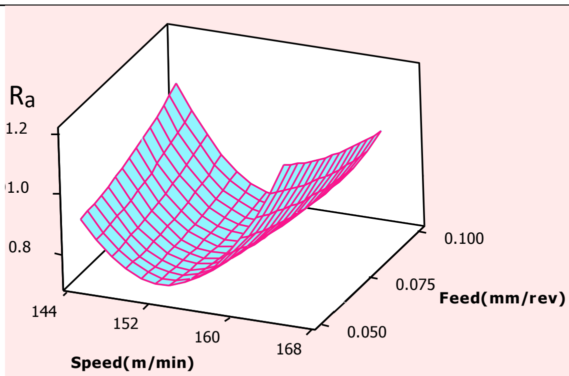

Fig. 3b. Surface roughness vs Speed and Feed (AISI H13)

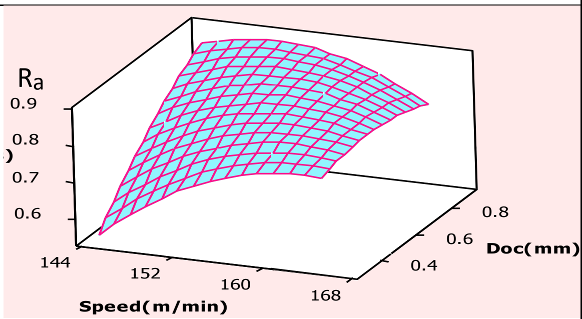

Fig.3c. Surface roughness vs Speed and DOC (AISI D3)

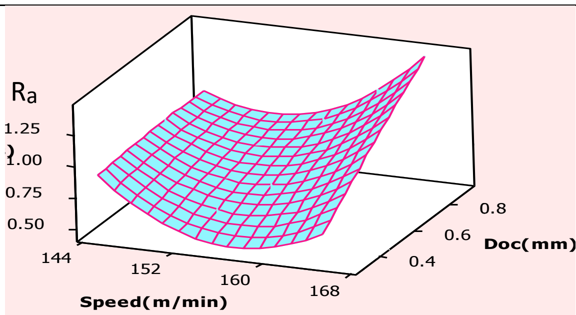

Fig. 3d.Surface roughness vs Depth of cut and Speed(AISI H13)

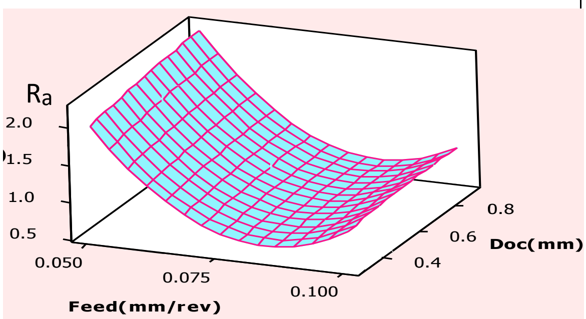

Fig.3e. Surface roughness Vs Feed and Depth of cut(AISI D3)

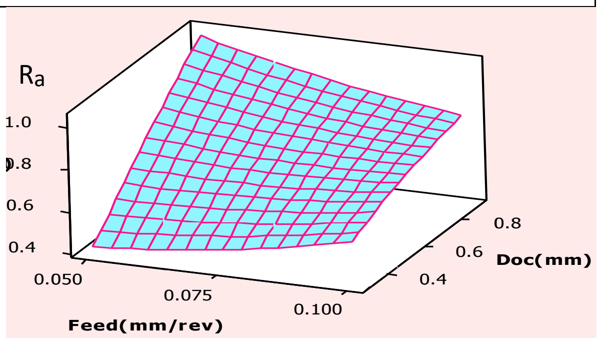

Fig. 3f.Surface roughness vs Feed and DOC(AISI H13)

CONCLUSIONS

The tests of straight turning carried out on AISI D3 and AISI H13 steels treated at 62 HRC, machined by a mixed ceramic tool enabled us to develop statistical models of surface roughness criteria.

- The results reveal that the feed rate is the most influencing parameter on surface roughness, than cutting speed and depth of cut for AISI D3.
- Surface roughness AISI H13 is influenced mostly by cutting speed than the other parameters such as feed rate and depth of cut.
- Statistical models deduced defined degree of influence of each machining condition on surface roughness criteria. These models can also be used for the optimization of hard turning process. This study confirms that in dry hard turning of AISI D3 and AISI H13 steels for all cutting conditions tested and found roughness criteria are close to those obtained in grinding.
- The surface roughness values of AISI D3 obtained higher when compared to AISI H13 for the same cutting conditions.

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