An Investigation on Cutting Forces and Surface Roughness during Hard Turning of AISI H13 Die Tool Steel with CBN Inserts using RSM

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Abstract: This experimental study focus on the assessment of machinability study of AISI H13 die tool steel with CBN inserts. The study explore the influence of machining parameters, tool nose radius and workpiece hardness (45HRC, 50 HRC & 55 HRC) on cutting forces and surface roughness during hard turning. To assess the effects of five-factors (cutting speed, feed rate, depth of cut, workpiece hardness and nose radius), a central composite design has been used for design of experimentation. For statistical analysis, analysis of variance has been performed and mathematical model have been developed for surface roughness and cutting forces. The study showed that higher workpiece hardness generates better surface roughness, as well produced higher forces. Further feed rate, depth of cut and workpiece hardness found to be statistically significant on cutting forces. In addition desirability approach has been used to obtain the optimum results for surface roughness and cutting forces.

Keywords: Hard turning, Cutting Force, Workpiece Hardness, CBN, Surface Roughness, AISI H13 die tool steel

I. INTRODUCTION

Hardened steel possess a wide range of applications in industrial field like, cutting tools, bearing, thread rolls, burnishing rolls and dies manufacturing etc. [1]. Die making industry widely make use of AISI H13 hot working steel for manufacturing of various types of hot working dies. This material possesses a blend of various properties like, good hardness, toughness and ability to retain hardness at elevated temperature [2]. Generally the material used for die making has the hardness range in between 45-60 HRC. Conventional methods of machining for hard material includes various steps, such as rough turning in annealed condition, heat treatment and then finishing process with the grinding. The conventional method of finishing was a time consuming and very costly [3]. Hard turning is a process which facilitates the manufacturers to machine hardened material of hardness more than 45 HRC in a single setup. Even hard turning can achieve a surface finishing less than 0.3 micron and maintain up to +/- 0.010mm size tolerance. As hard turning deals with the machining of hardened material, therefore the cutting forces are more than the conventional turning operation.

Various efforts have been reported and analyzed by the researchers for the understanding the cutting force profile in hard turning. It has been reported that during the turning of a material at 55 HRC, the forces are 30% more than the turning of the similar material at its annealed conditions [4].

Cicek A. et al. [5] analyzed the machinability of conventional heat treated (CHT), cryo-treated (CT) and cryo-treated and tempered (CTT) treated AISI H13 die tool steel by using ceramic tool in different environment conditions. The results reported that the CTT sample has the lowest ranges of cutting forces and surface roughness. They also found the coolant to be ineffective on the cutting forces and surface roughness. Fnides et al. [6] investigated the cutting forces during the finish turning of AISI H11 material at 50 HRC by using the ceramic inserts. This study found the depth of cut a dominant parameter affecting the cutting forces. Ding. T. et al. [7] carried out a study on H13 work material and evaluated the machining parameters for cutting forces and surface roughness. Ozel et al. [8] studied the effects of workpiece hardness and cutting tool geometry for AISI H13 tool steel. Study reported that the combination of hone edge geometry with low workpiece hardness show the better surface roughness, in fact they noticed the low tangential and radial forces exhibit at lower workpiece hardness and at low edge radius. Nakayama, K. [9] stated that material properties such as microstructures also play an important role during machining. He found that in some cases; during machining hardened material require lesser cutting force as compare to annealed material. Therefore the aim of the present study is to find out the optimal cutting condition for machinability study (surface roughness and cutting forces) during hard turning of AISI H13 die tool steel by using the CBN tool.

II. MATERIAL AND METHODS

The present study evaluates the machinability conditions during turning of hardened ASIS H13 die tool steel with CBN inserts. Hard turning experiments have been performed under dry machining condition at a temperature of 26° and humidity of 34% according to reference standards. The experiments were performed on a SPRINT 16 TC CNC (BATLIBOI, make) machine.

A. Workpiece Material and cutting tool

AISI H13 widely used to make forging extrusion dies, hot forming dies and mandrels etc in a range of hardness 45HRC to 60 HRC. Workpiece have been used in three different hardness of 45HRC, 50HRC and 55HRC. The workpiece material is in the form of round bars having 50mm diameter and 150 mm length. The cutting tool inserts used for the experiments were Cubic Boron Nitride (CBN) of SUMITOMO make.

B. Design of Experiments

The objective of this study to model and to establish the optimum formulation for surface roughness and cutting forces for AISI H13 steel with CBN tool. Five parameters were selected for the machinability study such as cutting speed (A), Feed rate (B), Depth of Cut (C), workpiece hardness (D) and Nose radius (E). Various parameters and their corresponding levels are depicts in the table 1.

Response Surface Methodology (RSM) technique has been used to optimize surface roughness and cutting forces. Response Surface Methodology is an interaction of mathematical and statistical technique that are useful for modeling and analyzing the response variables which is influenced by several variable [10]. Central composite design (CCD) is the most commonly used design methods in RSM to finding the functional relationship between response and the input variables. This is the most widely used experimental design for experimentation of second order response surface modeling. In the rotatable design, all the points are at same radial distance from the centre points and have the same magnitude and infirmity prediction error. On the basis of central composite design (CCD), total 120 run has been designed and performed during experimentations.

Table 1. Cutting Parameters and Their Levels

S.No.	Parameters (Unit)	Level 1	Level 2	Level 3	Level 4	Level 5
1	Cutting Speed (m/min)	75	100	125	150	175
2	Feed Rate (mm/rev)	0.05	0.075	0.10	0.125	0.15
3	Depth of cut (mm)	0.05	0.07	0.09	0.11	0.13
4	Nose radius (mm)	0.4	0.8			
5	Workpiece Hardness (HRC)	45	50	55		

III. RESULTS AND DISCUSSION

The experimental results were analyzed and optimize by using Response Surface Methodology (RSM). The selection of appropriate model and the development of response surface models have been carried out by using statistical software, Design Expert (DX-7). To check the adequacy and significance of the model various test used to be performed, as test for significance of regression model, the test for significance on individual model coefficient and lack of fit test.

ANOVA shows the significant model term for all the value whose “Prob. > F” is less than 0.05. “Coefficient of correlation” (R^2) evaluates the goodness of fit of the model and explains the variability of the result, while the “coefficient of variance” (CV) predicts the precision and reliability of the model. “Adjusted R^2” value compares the models with the number of terms. “Adequate precision” compare the predicted value at design point to the average prediction error and also measure the signal to noise ratio. This ratio should be greater than 4, to model to be desirable. “Prediction error sum of square” (PRESS) measure how well the model predicts the response in new experiments, a small value of PRESS is desirable. The adequacies of the developed models were tested for 5% significance level that is for a 95 % confidence level.

A. Responses Surface Model for Surface Roughness (R_a)

A reduced quadratic model was suggested for surface roughness. ANOVA results found the “Model F-value” 21.09 which depicts the model to be significant. During ANOVA of surface roughness various model terms A, B, C, D, E, BE, DE are found to be significant and "Lack of Fit F-value" 0.99 implies the Lack of Fit is not significant. Table 2 shows the ANOVA results for surface roughness.

Normal probability plot of the residual, residuals analysis has been carried out to check the adequacy of the model. Residual plot illustrated the difference between the observed response and respective predicted response. As the residuals on the plots falls on a straight line, indicating the model to be adequate as shown in fig. 1. A perturbation plots has been shown in fig. 2. in which various line representing the individuals behavior of the factors A (Cutting Speed), B (Feed), C (Depth of Cut), D (Workpiece Hardness) and E (Nose Radius). The plot shows the effect of each parameter with respect to a centre point by keeping the other parameters constant. Fig. 2 shows that there is decreasing trends of surface roughness with increase in cutting speed, workpiece hardness and nose radius. This graph indicated the increases trend of surface roughness with the increase in Feed.

Table 2. ANOVA for Surface Roughness

Source	**Sum of squares**	**df**	**Mean Square**	**F Value**	**P Value Prob>F**	
Model	4.44	18	0.25	21.09	< 0.0001	*significant*
A-Cutting Speed	*0.14*	*1*	*0.14*	*11.67*	*0.0009*	
B-Feed	*0.76*	*1*	*0.76*	*64.67*	*< 0.0001*	
C-Depth of Cut	*0.22*	*1*	*0.22*	*19.23*	*< 0.0001*	
D-Work Piece Hardness	*0.92*	*1*	*0.92*	*78.83*	*< 0.0001*	
E-Nose Radius	*1.75*	*1*	*1.75*	*150.07*	*< 0.0001*	
BE	*0.048*	*1*	*0.048*	*4.11*	*0.0454*	
DE	*0.44*	*1*	*0.44*	*37.79*	*< 0.0001*	
Residual	1.18	101	0.012			
Lack of Fit	*0.83*	*71*	*0.012*	*0.99*	*0.5345*	*not significant*
Pure Error	*0.35*	*30*	*0.012*			
Cor Total	5.62	119				

Std. Dev.	0.11	R-Squared	0.7898
Mean	0.77	Adj R-Squared	0.7524
C.V. %	14.05	Pred R-Squared	0.7136
PRESS	1.61	Adeq Precision	20

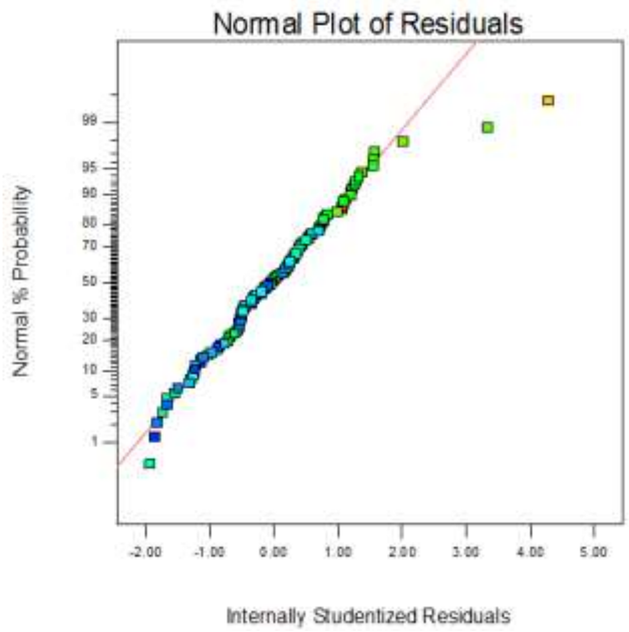

Fig. 1. Normal residual plot for Surface roughness

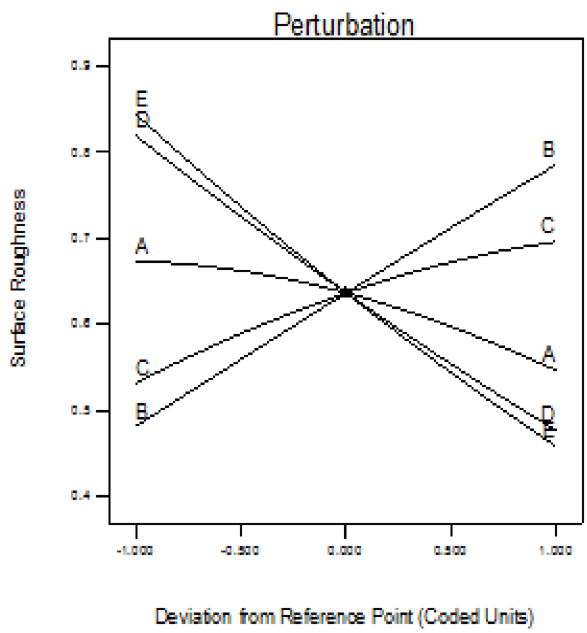

Fig. 2. Effects of cutting parameters on surface roughness

B. Effects of machining parameters on surface roughness (R_a)

In order to investigate the parametric influences on surface roughness (R_a), response surfaces has been drawn. Fig. 3(a), (b) and (c) illustrating the effects of various parameters on surface roughness.

Fig. 3(a) shows that there is a increasing trends of surface roughness with increase in feed rate, while cutting speed has negatively affected the surface roughness. Best results of surface roughness found at lower feed rate at higher cutting speed. Results indicating the best surface roughness at low feed rate and higher cutting speed. This showing the agreement with the experimental observation reported in literature that surface roughness decreases with the increases in cutting speed, [11][12]. Fig. 3(b) and (c) shows that decreases in surface roughness with increase in workpiece hardness and nose radius.

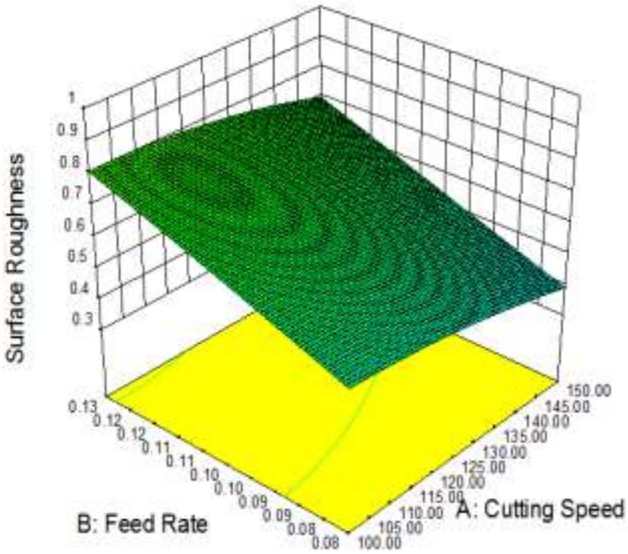

Fig.3(a) Effects of feed rate and cutting speed on surface roughness

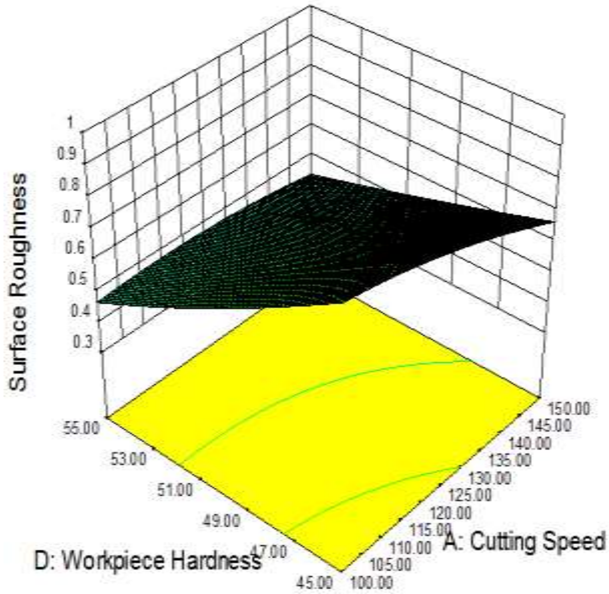

Fig.3(b) Effects of workpiece hardness and cutting speed on surface roughness

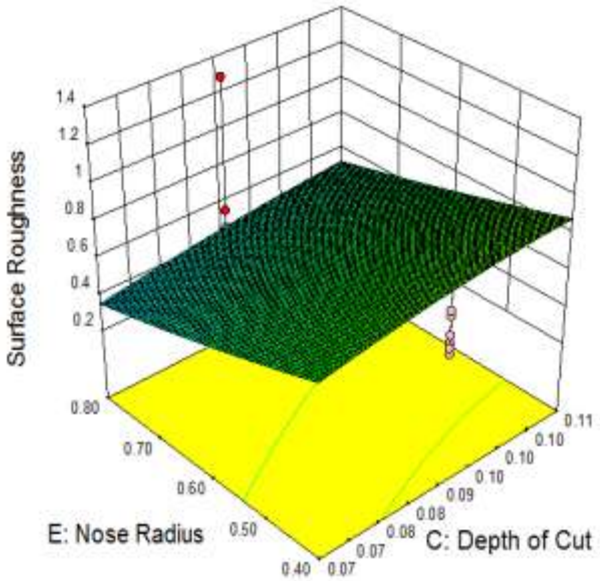

Fig.3(c) Effects of nose radius and depth of cut on surface roughness

C. Responses Surface Model for Tangential force (F_c) and Thrust forces (F_t)

A reduced quadratic model was suggested for tangential force (F_c) and thrust forces (F_t). ANOVA results found that for tangential force (F_c) "Model F-value" was 12.79 which confirm that model to be significant and model terms B, C, D, E, BD, DE are found to be significant and "Lack of Fit F-value" 1.51 implies the Lack of Fit is not significant. Similarly ANOVA result for thrust force (F_t) in which "Model F-value" 113.11 shows the model to be significant and model terms B, C, D, E, DE, A^2, B^2, C^2 are significant and "Lack of Fit F-value" 1.44 implies the Lack of Fit is not significant. ANOVA results for tangential force and thrust force are shown in table 3 and table 4 respectively.

Table 3. ANOVA for Tangential Force

Source	***Sum of square***	***df***	***Mean Square***	***F value***	***p-value Prob > F***	
Model	22906.25	18	1272.57	12.79	< 0.0001	*significant*
B-Feed Rate	*4286.83*	*1*	*4286.83*	*43.07*	*< 0.0001*	
C-Depth of Cut	*6096.87*	*1*	*6096.87*	*61.26*	*< 0.0001*	
D-Worpiece Hardness	*7469.11*	*1*	*7469.11*	*75.04*	*< 0.0001*	
E-Nose Radius	*2960.13*	*1*	*2960.13*	*29.74*	*< 0.0001*	
BD	*573.5*	*1*	*573.5*	*5.76*	*0.0182*	
DE	*621.61*	*1*	*621.61*	*6.25*	*0.0141*	
Residual	10052.55	101	99.53			
Lack of Fit	*7851.38*	*71*	*110.58*	*1.51*	*0.1068*	*not significant*
Pure Error	*2201.17*	*30*	*73.37*			
Core Total	32958.8	119				
Std. Dev.	9.98			R-Squared		0.695
Mean	53.4			Adj R-Squared		0.6406
C.V. %	18.68			Pred R-Squared		0.5915
PRESS	13462.89			Adeq Precision		17.385

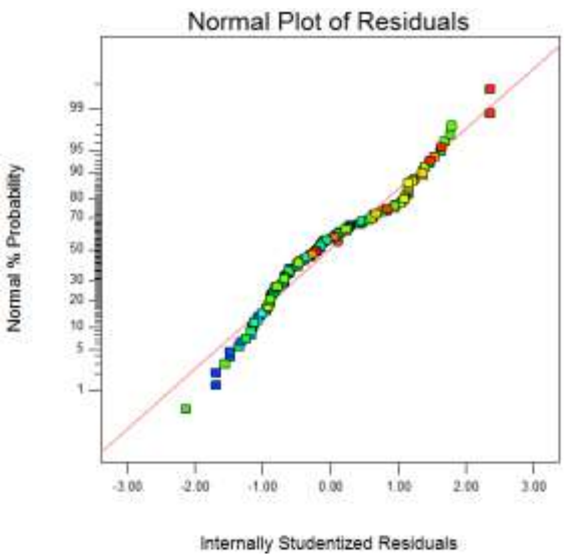

Fig. 4 Normal residual plot for tangential force

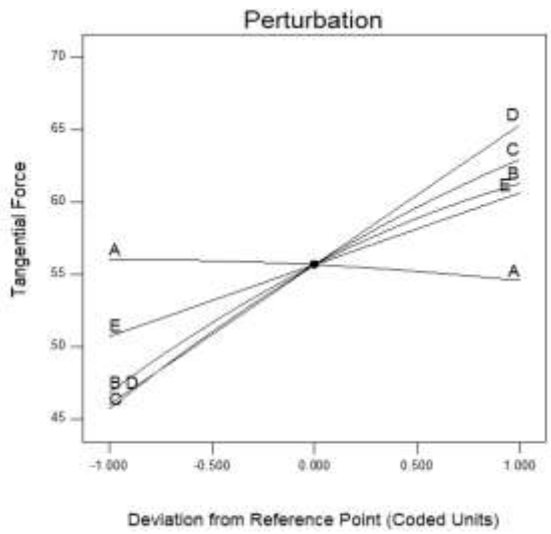

Fig. 5 Effects of cutting parameters on tangential force

Table 4. ANOVA for Thrust Force

Source	***Sum of***	***df***	***Mean***	***F value***	***p-value***

	square		Square		Prob > F	
Model	191.94	18	10.66	113.11	< 0.0001	*significant*
B-Feed Rate	*3.21*	*1*	*3.21*	*34.1*	*< 0.0001*	
C-Depth of Cut	*14.62*	*1*	*14.62*	*155.09*	*< 0.0001*	
D-W/p Hardness	*133.51*	*1*	*133.51*	*1416.1*	*< 0.0001*	
E-Nose Radius	*32.01*	*1*	*32.01*	*339.55*	*< 0.0001*	
DE	*3.12*	*1*	*3.12*	*33.15*	*< 0.0001*	
A2	*0.64*	*1*	*0.64*	*6.75*	*0.0108*	
B2	*4.46*	*1*	*4.46*	*47.29*	*< 0.0001*	
C2	*0.47*	*1*	*0.47*	*4.95*	*0.0283*	
Residual	9.52	101	0.094			
Lack of Fit	*7.36*	*71*	*0.1*	*1.44*	*0.1356*	*not significant*
Pure Error	*2.16*	*30*	*0.072*			
Cor Total	201.47	119				
Std. Dev.	0.31				R-Squared	0.9527
Mean	9.68				Adj R-Squared	0.9443
C.V. %	3.17				Pred R-Squared	0.936
PRESS	12.89				Adeq Precision	42.482

Fig. 4 and fig.5 shows the normal probability plot and perturbation plot for tangential force (F_c). Fig. 5 depicts that cutting speed has least impact on tangential force. Similarly fig. 6 and fig. 7 representing the normal probability plot and perturbation plot for thrust force (F_t). Fig. 7 illustrating that thrust force increasing with increase in workpiece hardness (D), feed rate (B) , depth of cut (C) and nose radius(E).

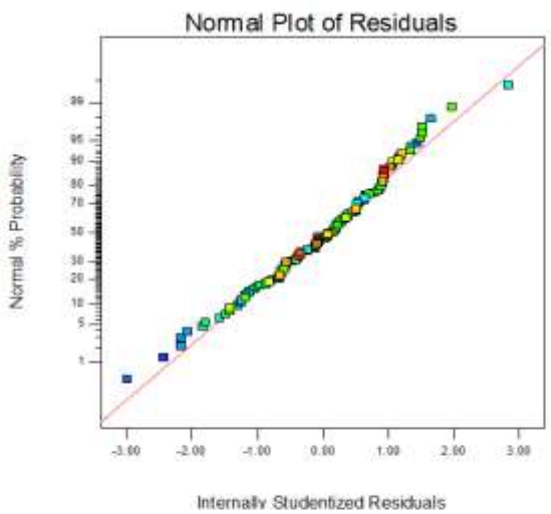

Fig. 6 Normal residual plot for thrust force

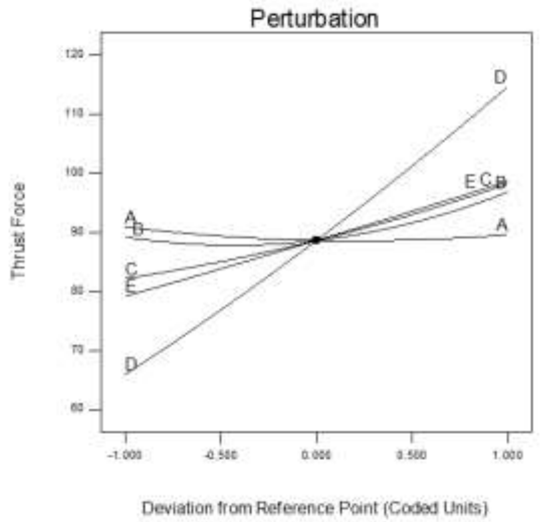

Fig. 7 Effects of cutting parameters on thrust force

D. Effects of machining parameters on tangential force (F_c)

Fig. 8(a) revealed that tangential force increasing rapidly with increase in work material hardness. Because at higher hardness a fine grains strucher as compared to lower hardness work material, as a result as a result more energy is required to deform the material at higher hardness [13][14]. Fig. 8 (b) and (c) also represents the increasing trends of tangential force with increase in depth of cut and nose radius repectively[15]. This is because of increase in tool chip interface area with increase in depth of cut and nose radius.

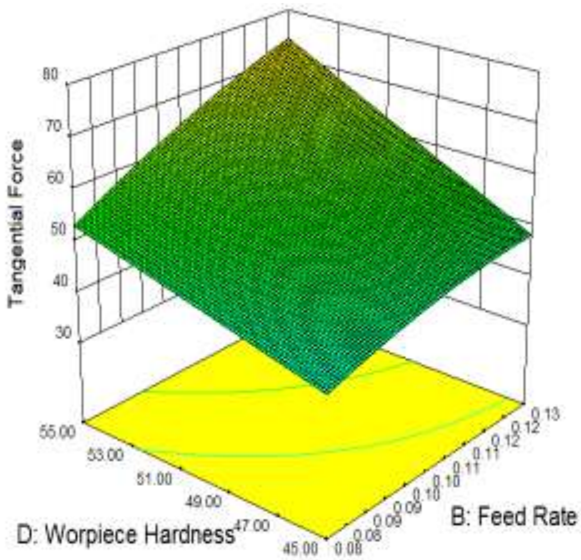

Fig.8(a) Effects of workpiece hardness and feed rate on tangential force

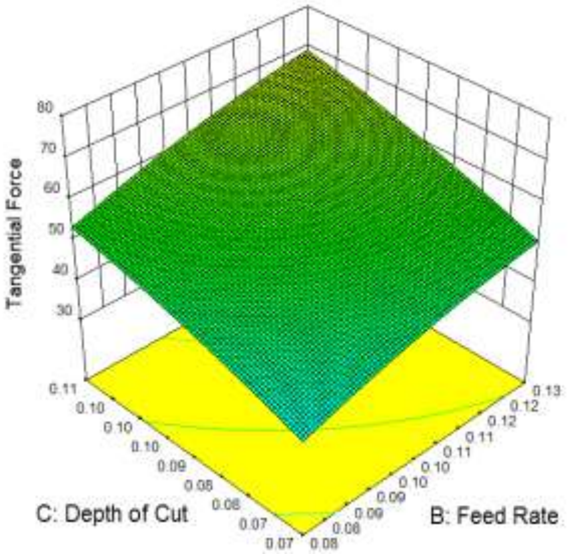

Fig.8(b) Effects of depth of cut and feed rate on tangential force

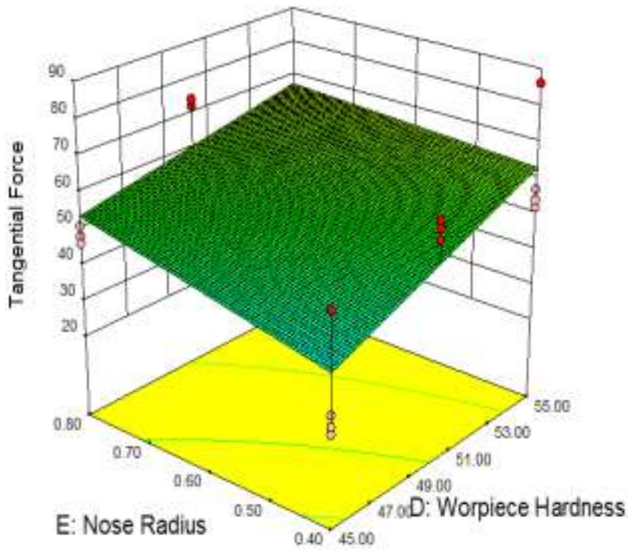

Fig.8(c) Effects of workpiece hardness and nose radius on tangential force

E. Effects of machining parameters on thrust force(F_t)

During hard turning of AISI H13 die tool steel thrust forces have been noticed 45% to 100% higher than the tangential forces. Fig. 9(a) revealed the increasing trends of thrust force with depth of cut and workpiece hardness respectively [16, 17]. While cutting speed has the neglegible effects on thrust force. Fig. 9 (b) and (c) shows that thrust force increases with increase in nose radius and feed rate.

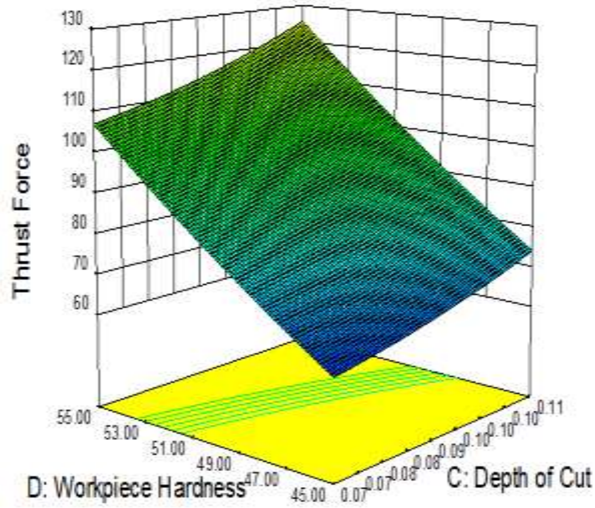

Fig. 9(a) Effects of workpiece hardness and depth of cut on thrust force

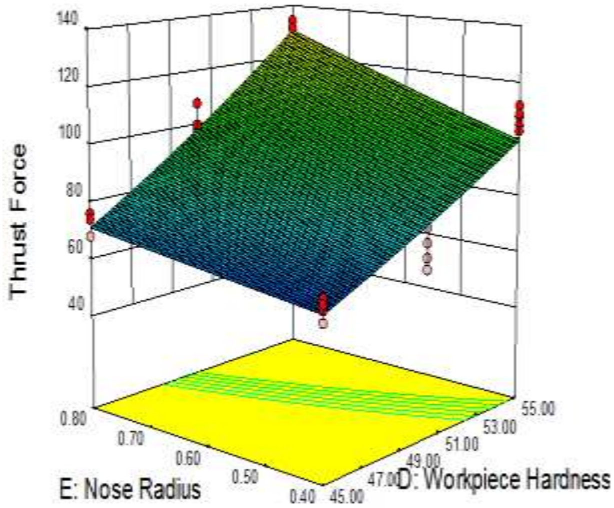

Fig. 9(b) Effects of workpiece hardness and nose radius on thrust force

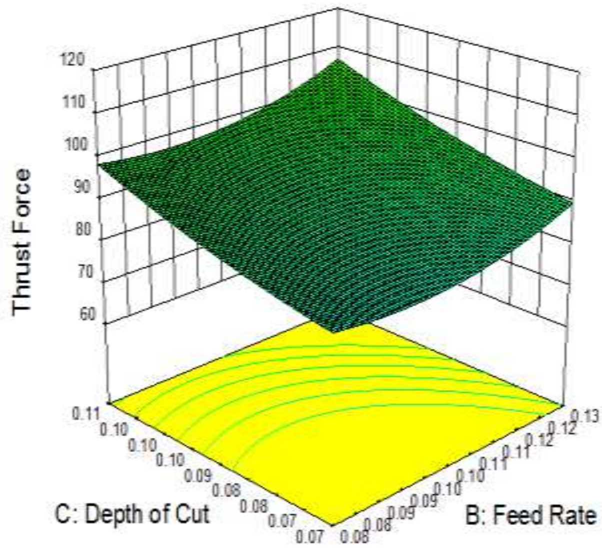

Fig. 9(c) Effects of depth of cut and feed rate on thrust force

IV. Optimization of Cutting Conditions Using Desirability Approach

For multi-response optimization of various parameters, desirability approach have been used.. Fig.10-12 represents the contour plots of desirability for surface roughness (R_a), tangential force (F_c) and thrust force (F_t) respectively, which predict the desirability at different zone of the experimental domain. Optimal region was located nearer to the bottom region of plots.

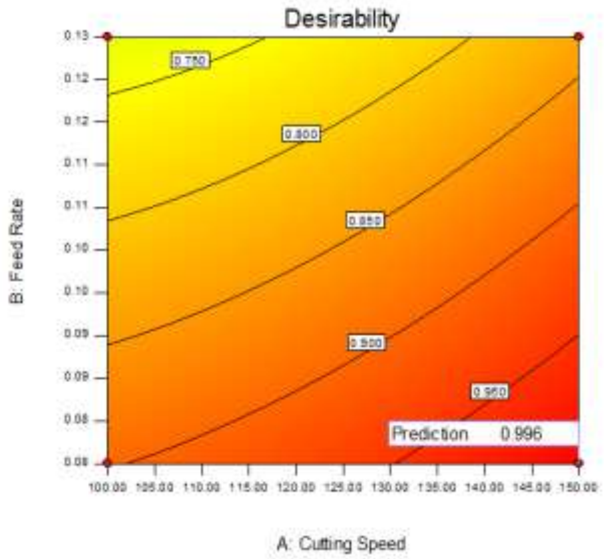

Fig. 10 Result for desirability function for surface roughness

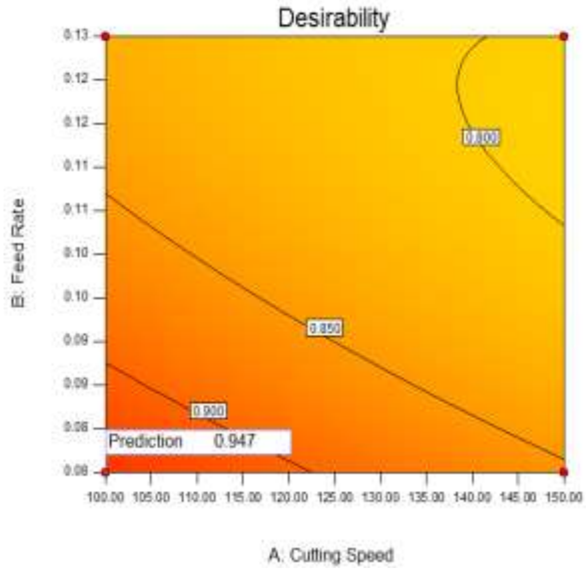

Fig. 11 Result for desirability function for tangential force

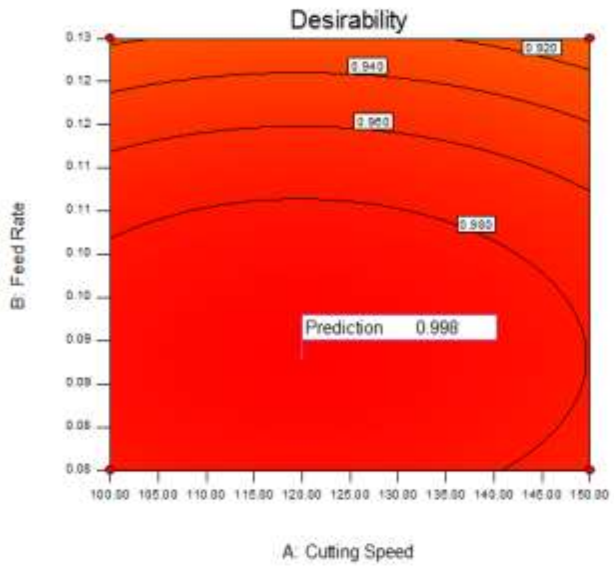

Fig. 12 Result for desirability function for thrust force

Table 5 shows the optimum values which were obtained during turning of hardened AISI H13 die tool steel by using desirability approach.

Table 5. Optimal Solution

Surface Roughness(Ra)

Solution Number	Cutting Speed	Feed Rate	Depth of Cut	Workpiece Hardness	Nose Radius	Surface Roughness	Desirability
1	150	0.08	0.07	45	0.8	0.176392	0.996 Selected

Cutting Force (Fc)

Solution Number	Cutting Speed	Feed Rate	Depth of Cut	Workpiece Hardness	Nose Radius	Cutting Force (N)	Desirability
1	100	0.08	0.07	45	0.4	21.756	0.947 Selected

Thrust Force (Ft)

Solution Number	Cutting Speed	Feed Rate	Depth of Cut	Workpiece Hardness	Nose Radius	Thrust Force (N)	Desirability
1	119.96	0.09	0.07	45	0.4	55.26	0.998 elected

V. CONCLUSIONS

The present study evaluate the optimum machining parameters during the hard turning of AISI H13 die tool steel with CBN inserts.

Results show that hard turning can produce tight tolerances and can generate the up to 0.17 µm surface roughness. Which shows that hard turning can be a good alternate to the grinding process. Study found that workpiece hardness to be most significant parameters for response characteristics. The major conclusions from the study are as follows:

- Surface roughness decreases with the increases in nose radius, workpiece hardness and cutting speed. Higher hardness (55HRC) shows the better surface roughness as compare to lower hardness.
- Surface roughness increases with the increase in feed rate and depth of cut.
- Thrust forces are 1.2 to 1.8 times higher than the tangential force.
- Tangential and thrust forces increase with increase in nose radius, workpiece hardness and feed rate, nose radius.
- Cutting forces shows the decreases trends with the increments in cutting speed.
- The optimal solution obtained for hard turning of AISI H13 die tool steel for surface roughness (Ra), cutting force (Fc) and thrust force (Ft) are 0.176392µm, 21.756 N and 55.26 N with 0.996, 0.947 and 0.998 desirability respectively.

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