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Analysis and Optimization of Ceramic Cutting Tool In Hard Turning of EN-31 Using Factorial Design

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Abstract - Manufacturers around the globe persistently looking for the cheapest and quality manufactured machined components to compete in the market. Good surface quality is desired for the proper functioning of the produced parts. The surface quality is influenced by cutting speed, feed rate and depth of cut and many other parameters. In the present study attempt has been made to evaluate the performance of ceramic inserts during hard turning of EN-31 steel. The analysis of variance is applied to study the effect of cutting speed, feed rate and depth of cut on Flank wear and surface roughness. Model is found to be statically significant using regression model, while feed and depth of cut are the factor affecting Flank wear and feed is dominating factors for surface roughness. The analysis of variance was used to analyze the input parameters and there interactions during machining. The developed model predicted response factor at 95% confidence level.

Keywords - *Hard turning, ANOVA, Surface roughness, Flank wear*

I. INTRODUCTION

Hard turning is defined as the turning of materials having hardness higher than 45 HRC. In the modern machining processes hard turning is the most emerging process for manufacturers to machine tool steel, alloy steel and other steel parts in the condition of high hardness with single point cutting tool in dry cutting conditions. Finishing of hard steel is a time consuming process through grinding because the shape of grinding wheel limits the ability to finish the complex geometry parts. High material removal rate and reduction of process time is possible by finishing complex geometry parts through turning process. Surface quality is the important criteria for the machined parts for manufacturers to achieve their parts to function according to geometric, dimensional and surface requirements. The demand of quality products is increasing so it is difficult for manufacturers to increase productivity without compromising quality. Tool wear is the main criteria to evaluate the performance of tool used for hard turning. The mechanism involved in wear of cutting tools during hard turning is complicated and may include different interacting effects linked together in a complex manner.

The feed rate has the most dominant effect on surface roughness value produced by tungsten carbide tools. The major effect on the surface roughness is due to the feed rate. Hence smaller values of feed rate and depth of cut must be selected in order to achieve better surface finish during steel turning operation. . It can be seen that the cutting speed, feed rate and depth of cut has the most influential effect on the surface roughness [1]. Increasing the feed rate will increase the surface roughness significantly and also the depth of cut using Taguchi method [2].]. Akkuş et al. found that the feed rate is the significant factor which contributes to the surface roughness using ANOVA and regression [3]. Chowdhury et al. noticed that the rate of growth of flank wear increases irrespective of feed with the increase of speed under minimum quality lubrication and dry condition respectively [4]. According to Grzesik and Wanat the results show that keeping equivalent feed rates, 0.1 mm/rev for conventional and 0.2 mm/rev for wiper inserts, the obtained surfaces have similar roughness parameters and comparable values of Skew and Kurtosis [5]. With wiper inserts and high feed rate is possible to obtain machined surfaces with <0.8µm of R_a compared to conventional insets which present high values of surface roughness [6]. Kushnaw et.al observed that the main factor affecting the inclination angle is the diameter of periphery and machined diameters which are depend upon change of depth of cut, the cutting condition [10].

Flank wear, nose wear, crater wear, notch wear, edge chippings or combination of these is the performance measure of tool but out of these flank wear has significant effect on tool wear. The required response is minimum flank wear selected for better tool performance. It is very necessary to predict tool wear during hard turning to determine the optimum cutting conditions [7]. Godoy observed that, for cutting speed of 150m/min in continuous cutting, the mixed ceramic wear rate was almost 3 times bigger than the CBN-L wear rate. In continuous cutting, the main wear mechanism of the ceramic tool was abrasion, while that of the CBN tool was abrasion for the lowest cutting speed and diffusion for the highest cutting speed [8]. Hakim et al. concluded Mixed alumina ceramic and coated carbide tool materials can see longer tool life than c-BN tools when machining the selected work piece material. Both CBN tools showed poor behavior with this HSS at higher cutting speeds [9]. Wear mechanisms in $Al_2 O_3$- TiC ceramics sliding against the hardened low alloyed steel involve abrasion, fracture, plastic flow, adhesive tacking and material transfer and also tribochemical effects depending on the mechanical and thermal conditions generated in the machining tests [11].

II. EXPERIMENTAL DETAILS

A. *Work Piece Material*

The work piece material was EN-31 steel in the form of round bars of 40 mm diameter and length of 100 mm axial cutting length. The composition of material is 0.9-1.2% C, 0.10-0.35% Si, o.3-0.75% Mn, 1-1.6% Cr, 0.025% Co, 0.05% S and 0.05% P. Components with this material properties are used to make axels, gears, camshafts, driving pinion and link components for transportation and energy products as well as many applications in general mechanical engineering. The work piece of EN-31 was firstly hardened followed by oil quenching at a temperature of 850°C to achieve a hardness of 60 HRC throughout. A rough turning pass was conducted initially to eliminate the run out of the work piece, after that diameter obtained for experimentation is approximately 39 mm.

B. Cutting Inserts

The cutting inserts used are mixed ceramic with PVD coated ceramic according to ISO designation of TNGA 160408(332) AB2010. The edge preparation provided on the inserts was 20°×0.2mm chamfer with honing. The nose radius is constant 0.8 mm supplied by manufacturer. The cutting inserts were clamped on the tool holder (make: Sandvik coromat, model: DCLNL 25×25 mm)

C. *Experimental Apparatus*

The hard turning of work piece in dry turning conditions were conducted on CNC lathe (Make: BATLIBOI; Model: SPRINT 16TC) having following specifications: Maximum Power: 5.5/7 KW, Spindle speed: 50-5000 rpm, Maximum turning diameter: 225 mm, Maximum turning length: 300 mm.

D. *Measurement Of Flank Wear And Surface Roughness*

- During experimentation the tool wear carried on inserts is measured with the help of Tool maker's microscope.
- The surface roughness of the turned samples was measured with Mitutoyo make Surface roughness tester (SJ-301) with a cut-off length of 0.8 mm over three sampling lengths. The average value of surface roughness (R_a) was used to quantify the roughness achieved on machined surfaces.

E. *Design Of Experiment*

In this investigation three factors were studied and their low level and high level are given in Table 1. The levels are selected according to the recommendation of manufacturer. Two-level full Factorial design was used for the planning of experiments because it was widely used for involving several factors for a response.

Table 1: Factors and Levels of Process Parameters

Factors	Low level (-1)	High level (+1)
Speed, m/min	50	250
Feed, mm/rev	0.05	0.2
Depth of cut, mm	0.2	0.5

The design layout is produced by the software Design Expert Version 7.1.6 (Stat-Ease Inc., Minneapolis, and 185 MN USA) is given in Table 2.

Table 2: Experimental layout and desired Response

Std	Run	A:Speed (m/min)	B:Feed (mm/rev)	C:DOC (mm)	Flank Wear Vb (mm)	Surface Roughness Ra (μm)
5	1	50	0.05	0.5	0.21	0.19
6	2	250	0.05	0.5	0.137	0.35
8	3	250	0.2	0.5	0.35	2.27
7	4	50	0.2	0.5	0.493	1.89
2	5	250	0.05	0.2	0.23	0.26
3	6	50	0.2	0.2	0.178	1.67
1	7	50	0.05	0.2	0.139	0.17
4	8	250	0.2	0.2	0.185	1.8

III. RESULT AND DISCUSSION

The analysis of the responses flank wear (Vb) and Surface roughness (Ra) using ANOVA is described in Table 3-4. The analysis of results was done using the software.

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Table 3 : ANOVA results for Flank Wear (Vb)

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	
Model	0.1	6	0.017	712.67	0.0287	significant
A-Speed	1.74E-03	1	1.74E-03	71.04	0.0752	Not significant
B-Feed	0.03	1	0.03	1225	0.0182	significant
C-DOC	0.026	1	0.026	1070.22	0.0195	significant
AB	2.97E-03	1	2.97E-03	121	0.0577	Not significant
AC	0.012	1	0.012	503.04	0.0284	significant
BC	0.032	1	0.032	1285.73	0.0177	significant
Residual	2.45E-05	1	2.45E-05			
Cor Total	0.1	7				

Std.Dev. 4.950E-003, R-squared 0.9998, Mean 024, Adj R-squared 0.9984, C.V % 12.06, Pred R-squared 0.9850, PRESS 1.568E-003, Adeq Precesion 76.889.

Table 4 : ANOVA results for Surface roughness (Ra)

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	
Model	5.62	6	0.94	2999.35	0.0140	significant
A-Speed	0.099	1	0.099	316.84	0.0357	significant
B-Feed	5.33	1	5.33	17056.36	0.0049	significant
C-DOC	0.11	1	0.11	345.96	0.0342	significant
AB	0.019	1	0.019	60.84	0.0812	Not significant
AC	4.513E-003	1	4.513E-003	14.44	0.1638	Not significant
BC	0.063	1	0.063	201.64	0.0448	significant
Residual	3.125E-004	1	3.125E-004			
Cor Total	5.62	7				

Std.Dev. 0.018, R-squared 0.9999, Mean 1.06, Adj R-squared 0.9996, C.V % 1.67, Pred R-squared 0.9964, PRESS 0.020, Adeq Precesion 126.240

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A. *ANALYSIS OF VARIANCE (ANOVA)*

The ANOVA test was performed to evaluate the statistical significances of the fitted regression model and factors involved therein for the response factors viz Vb and R_a. ANOVA table is used to summarize the test for significance of regression model, test for significance for individual model coefficient. Summary output reveals that quadratic model is statistically significant for the selected response. Significant model terms were identified at 95% significance level. Goodness of fit was evaluated from R^2 and CV in order to check the reliability and precision of the model. The probability > F for the model in Table 3 is less than 0.05 which indicates that the model is significant, which is desirable as it indicates that the terms in the model have a significant effect on the response. In case of flank wear the Model F-value of 712.67 implies the model is significant. There is only a 2.87% chance that a "Model F-Value" this large could occur due to noise. In this case B, C, AC, BC are significant model terms. The ANOVA table for regression model indicated that the model is significant at $p < 0.0001$. The desirable value of R^2 is close to one, which is R^2= 99.98% shows that this much percentage of the variability of result is explained by the model. The predicted R^2 value of 0.9850 is in reasonable agreement with the adjusted R^2 of 0.9984. "Adeq Precision" measures the signal to noise ratio. A ratio greater than 4 is desirable. In this case ratio of 76.889 indicates an adequate signal. This model can be used to navigate the design space. PRESS stands for "Predicted residual error sum of squares "and it is a measure of how well the model for the experiment is likely to predict the responses in new experiments. Small values of PRESS are desirable. In this case the value is 0.001567. The equation (1) and (2) are the final empirical models in terms of coded (standardized) and actual factors (un-standardized) for the response Vb.

Final equation interms of coded factors:

Vb = +0.24 -0.015×A +0.061×B +0.057×C-0.019×A×B -0.039×A×C +0.063×B × C ……. (1)

Final Equation in Terms of Actual Factors: Vb = +0.085236 +1.08917E-003×Speed -0.75056×Feed +0.076944×DOC -2.56667E-003×Speed×Feed -2.61667E-003×Speed×DOC +5.57778× Feed× DOC …..(2)

In case of surface roughness the Model F-value of 2999.35 implies the model is significant. There is only a 1.40% chance that a "Model F-Value" this large could occur due to noise. Values of "Prob > F" less than 0.0500 indicate model terms are significant. In this case A, B, C, BC are significant model terms. R^2 =99.9% which is close to one and desirable, which shows that this much percentage of the variability of result is explained by the model. The predicted R^2 value of 0.9964 is in reasonable agreement with the adjusted R^2 of 0.9996. "Adeq Precision" measures the signal to noise ratio. A ratio greater than 4 is desirable. In this case ratio of 126.240 indicates an adequate signal. This model can be used to navigate the design space. The value of PRESS in this is 0.020 which is small and desirable. The equation (3) and (4) are the final empirical models in terms of coded (standardized) and actual factors (un-standardized) for the response Ra.

Final equation interms of coded factors:

Ra = +1.06 +0.11×A +0.82×B +0.12×C +0.049×A×B +0.024×A×C +0.089×B×C …. (3)

Final Equation in Terms of Actual Factors :

Ra = -0.18965 -2.54167E-004×Speed +7.14722×Feed 0.44861×DOC +6.50000E-003×Speed×Feed +1.58333E-003×Speed×DOC +7.88889×Feed×DOC (4)

B. EFFECT OF MACHINING PARAMETERS ON RESPONSE FACTORS

A (a) FLANK WEAR(Vb)

Figure 1-3 shows the influence of machining parameters on the Flank wear, the interaction graph have been plotted. It have been observed that flank wear (Vb) increases as the feed increases, as a result of that abrasive wear of tool dominates, Whereas the depth of cut and feed are dominating factors on tool flank wear, it is increasing rapidly with increase of depth of cut and feed rate. The minimum value of flank wear is achieved at high speed rate. The 3D surface plot has been shown for flank wear.

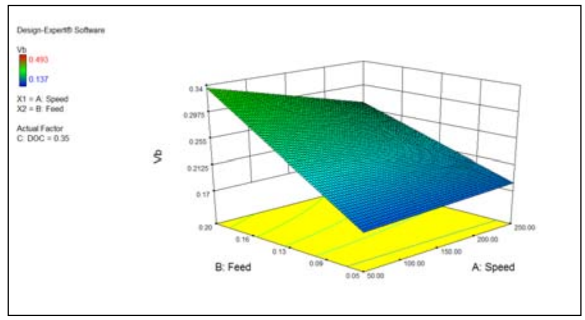

Fig 1 : Effect of Speed and Feed on Flank wear

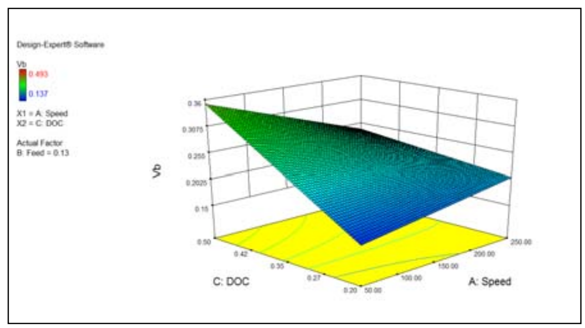

Fig 2 : Effect of Speed and Depth of cut on Flank wear

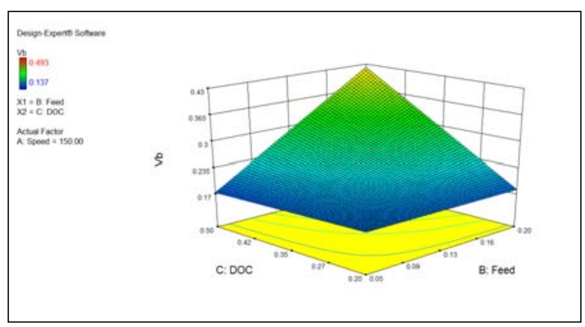

Fig 3 : Effect of Feed and Depth of cut on Flank wear

B (b) SURFACE ROUGHNESS *(Ra)*

Figure 4-6 shows the influence of machining parameters on the surface roughness, the interaction graph have been plotted. The feed is the most dominating factor on the surface roughness, Ra increases with increase of feed. The effect of depth of cut has not much influence on surface roughness. The minimum value of surface roughness is achieved at low feed. The 3D surface plot has been shown for surface roughness.

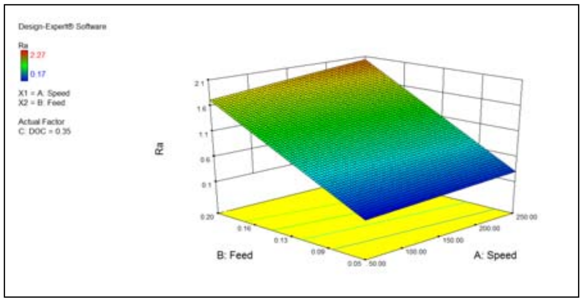

Fig 4 : Effect of feed and speed on surface roughness

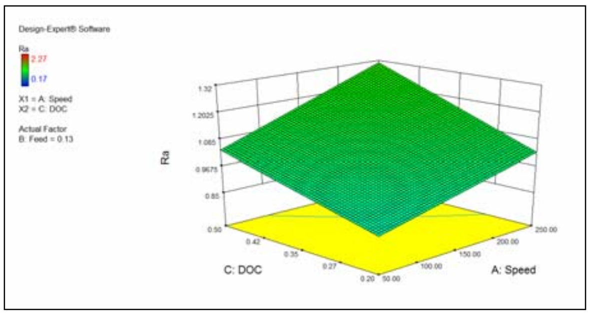

Fig 5 : Effect of Depth of cut and speed on surface roughness

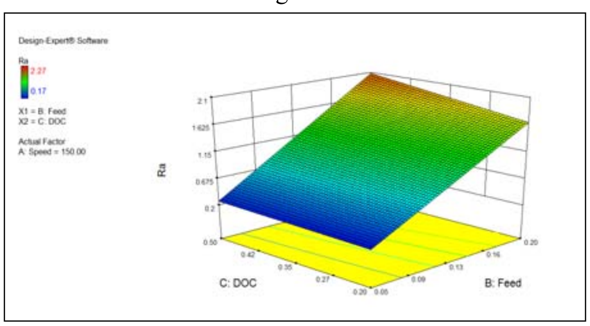

Fig 6 : Effect of Depth of cut and Feed on surface roughness

D. OPTIMIZATION OF RESPONSE

The essential goals of experiments related to hard turning is to achieve the desired surface roughness and flank wear of the optimal cutting parameters. For this multiple response optimization is the ideal technique for determination of the best machining parameters combination in turning. The goal is to minimize surface roughness and flank wear by taking machining parameters in range as a constraint. The optimal value of flank wear is 0.14075 and surface roughness is 0.17625 corresponds to speed = 50 m/min, feed = 0.05 mm/rev and depth of cut = 0.2 mm. The desirability value of 0.993 corresponds to minimum value of Vb and Ra in the given range of parameters during hard turning of the material. The contours of the responses are shown in Figure 7-8. It is clear from the figure that the minimum flank wear is low at minimum feed and speed, it is increasing either with the increase of feed or speed. In case of surface roughness it is clearly shown that minimum roughness is at low value of feed, because feed is the most dominating factor for surface roughness.

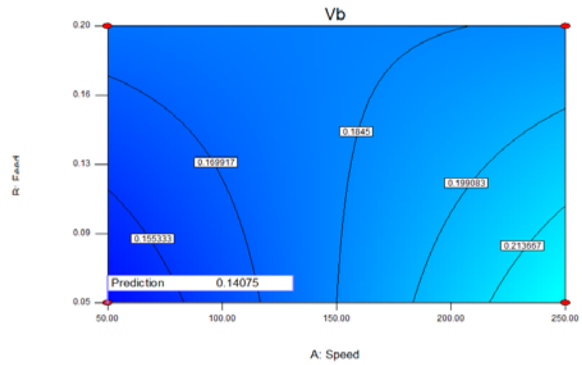

Fig 7: Contour Plot for optimum flank wear

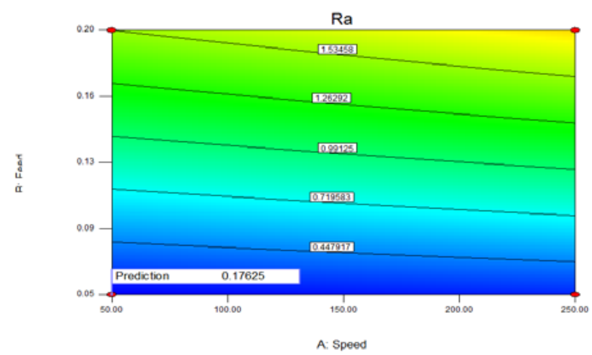

Fig 8: Contour Plot for optimum Surface roughness

E. CONCLUSION

This investigation shows the effect of machining parameters such as speed, feed and depth of cut on hard turning of EN-31 hardened to 58 HRC using mixed ceramic PVD-coated inserts. The conclusion of the present research are as follows:

1. The result of ANOVA proved that the mathematical models allow prediction of flank wear and surface roughness with 95% of confident interval.
2. The optimum value of flank wear is 0.14075 mm and surface roughness is 0.17625 µm is obtained at speed = 50 m/min, feed = 0.05 mm/rev and depth of

cut = 0.2 mm as the optimal value of process parameters.

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