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Effect of Process Parameters on Tool Wear and Surface Roughness during Turning of Hardened Steel with Coated Ceramic Tool

R. Suresh[a]*, S. Basavarajappa[b]

[a]*Alliance College of Engineering and Design, Alliance University, Bangalore-562106, India*
[b] *UBDT College of Engineering, Davangere-577004,Karnataka, India*

Abstract

Tool wear and surface roughness prediction plays a significant role in machining industry for proper planning and control of machining parameters and optimization of cutting conditions. This paper deals with developing a response surface method as a function of cutting parameters in turning of hardened AISI H13 steel (55 HRc) with PVD coated (Ti CN) ceramic tool under dry cutting condition. The mathematical models correlating the machining parameters with tool wear and surface roughness has been established. Plan of experiments was employed based on the central composite design (CCD) concept of response surface methodology (RSM) in order to data in controlled way. The obtained results reveal that cutting speed possesses the most dominating effect over tool wear followed by feed rate and depth of cut. Abrasion was the principal wear mechanism observed at higher cutting conditions. The feed rate is most significant parameter influences on surface roughness followed by depth of cut and cutting speed. The developed RSM models exhibited better proximity between predicted values and experimental values with 95% confidence intervals. The results imply that the model can be used easily to forecast tool wear and surface roughness in response to cutting parameters.

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Keywords: Hard turning; coated ceramic tool; tool wear; surface roughness; response surface methodology

1. Introduction

Hard turning has been used increasingly in industry. Numerous studies have been reported on the successful

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* Corresponding author. Tel.: +91 80 3069923; fax: +91 80 27841600.
E-mail address: sureshchiru09@gmail.com

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implementation of hard turning. Most of these studies involve work materials with hardness values in the range of 45–65HRc and also they involve the use of ceramic and CBN cutting tools. The hard turning can offer a reasonably high accuracy for the hardened components, but the major problems occur with tool wear and surface quality (Abrao et al. (2011), Yallase et al. (2009), Fnides et al. (2009) and Bouacha et al. (2010)). Several mathematical models have been proposed by different researchers to analyze the influence of cutting conditions on tool performance, surface finish and to optimize machining parameters for turning of hardened steel (Bouacha et al. (2010), Horng et al. (2008), Yang and Tarng, (1998) and Chou et al. (2002)).

Yong and Tarng (1998) used Taguchi method for optimizing the cutting parameters on tool wear in turning of hardened steel with carbide inserts. They observed that abrasion is the dominant wear mechanism under the consistent cutting conditions and diffusion wear under higher cutting conditions. Horng et al. (2008) applied the response surface methodology (RSM) to investigate the influence of cuting conditions on surface roughness and tool wear in turning of hardened steel with ceramic inserts. The results indicated that the flank wear is influenced by the cutting speed, and the interaction effect of cutting speed and feed rate with tool nose radius have significant effect on the surface roughness. Chou et al. (2002) observed a better surface finish in turning of hardened steel with low-CBN content tools. Similarly, Benga and Abrao (2003) and Kumar et al. (2003) achieved high surface quality with ceramic tools during hard turing.

Grzesik (2008) investigated the effect of tool wear on surface roughness in turning of hardened steel. The results shows that there is a good replication of the cutting tool on the surface roughness profile. the tool wear and feed rate affects the surface quality. Davim and Figueira (2007) carried out the optimization of process parameters for the machining of hardened AISI D2 tool steel with ceramic tools using statistical techniques. They observed that the better surface finish can be attaind by selecting suitable cutting parameters. Lima et al. (2005) investigated the machinability characteristics of hardened steels using ceramic tool. They found that the surface roughness of the machined parts was improved with increase in cutting speed and deteriorates with increase in feed rate.

Aslan et al.(2007) studied the effect of cutting parameters on surface roughness and tool flank wear during turning of hardened AISI 4140 steel with ceramic tools by using Taguchi techniques. They achived optimum cutting conditions as results of their investigations. They identified that ceramic tools are most suitable cuting tool for hard machining process. Ozel and Karpat (2005) developed the multiple regression models and artificial neural network (ANN) for predicting the tool wear and surface roughness in turning of hardened steel with CBN tools. Quiza et al. (2008) also established a tool wear prediction models for turning of hardened D2 steel with ceramic tool using statistical and ANN techniques.

From the literature review, it reveals that the CBN tools are excellent performance during turning of hardened steels; however, their costs are reasonably higher as compared to ceramics (Ezugwu et al.(2005)). The main objective of this study is to optimize the cutting parameters for attaining minimum surface roughness and longer tool life, while machining of hardened AISI H13 steel with coated ceramic tool. And also it is important to understanding of the relationship between cutting process, workpiece properties and cutting performance. Response surface methodology (RSM) has been used to accomplish this objective. Additionally, a statistical analysis (ANOVA) is performed to see which cutting parameters are statisticaly significant and also multiple linear regressions were exploited.

2. Experimental Detail

2.1 Workpiece material and cutting tool

The machining tests were performed on the work material selected for this investigation is an AISI H13 hot work die steel in the form of round bars of 100mm diameter and 400mm length. The work piece was through hardened followed by tempering process to attain hardness level of 55HRc. The chemical composition of the work piece material is given in Table 1. The PVD (TiN) coated ceramic insert grade *KY4400* with *ISO* geometry *CNMG 120408* was used to turning of hardened AISI H13 steel. The inserts were mounted on a *PCLNL 2525M12 (ISO)* tool holder, which resulted in the following geometry; nose radius=0.8mm, rake angle=-6°; clearance angle=-6°; including angles=80º and approach angle=95°.

Table 1. The chemical composition of AISI H13 steel workpiece in percentage by weight

C	Si	Mn	P	S	Cr	Ni	Mo	V
0.4	1.04	0.35	0.03	0.003	5.3	0.3	1.4	1

2.2 Experimental Procedure

The dry turning of hardened AISI H13 steel was performed using CNC lathe having maximum spindle speed of 5000rpm and spindle power of 22*kW.* The photograph of the experimental setup is shown in Fig.1. The cutting parameters and their levels were selected based under preliminary tests. The workpiece materials were cleaned by removing outer layer and centered, prior to actual turning tests. In each cutting condition, fresh cutting tool was used at a fixed cutting time of 4.0min. The experiments were repeated twice at each cutting condition in order to minimize the experimental errors. The average surface roughness (*Ra*) on machined surface was measured by surface roughness tester. The average width of flank wear was measured using an optical measuring microscope connected to a digital camera and computer.

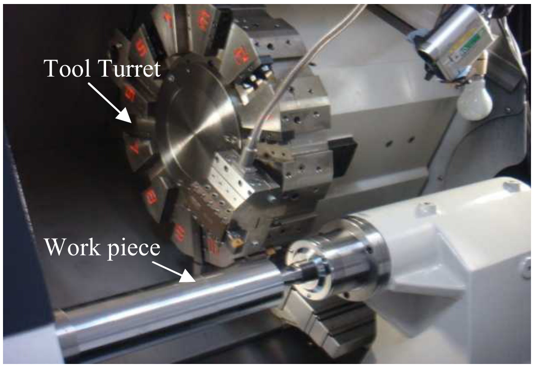


Fig.1. Experimental setup

2.3 Response Surface Methodology (RSM)

The RSM is useful for developing, analyzing, improving and optimizing the product/process that provides an overall perspective of the system response within the design space. In the present study, cutting parameters such as cutting speed (V_c), feed rate (*f*) and depth of cut (*d*) are identified as process parameters. The tool wear and surface roughness are the output responses. The influence of the cutting parameters on surface roughness and tool wear were tested through a set of experiments based on standard RSM design called central composite design (CCD). The factorial portion of CCD is full factorial design with all combination of the factors (-1.6817; +1; 0; -1 and +1.6817) and composed of eight star points and six central point (level-0) which is the midpoint between the highest and lowest levels. The star points are at the face of the cubic portion on the design which corresponds to α-*value* of 1and this type of design is commonly called the face centered design (Horng et al. (2008)). According to CCD design, factors and their levels were reported in Table 2. The number of performance tests involved 16 trials. The result of the trials was reported in the design layout Table 3.

Table 2. Machining parameters and their levels

Cutting parameters/ levels	**Lowest**	**Low**	**Centre**	**high**	**Highest**
	-1.6817	-1	0	+1	+1.6817
Vc (m/min)	42	80	140	200	238
f (mm/rev)	0.04	0.08	0.014	0.20	0.24
d (mm)	0.05	0.15	0.30	0.45	0.55

3. Analysis of Results

The experimental results are analyzed with the help of statistical analysis software *(Minitab-R16*), which is widely used in many fields of engineering research. The Analysis of variance (ANOVA) has been applied to check the adequacy of the developed models. The ANOVA table consists of sum squares, mean squares, degrees of freedom and percentage of contributions. The sum of square is the ratio sum squares to degree of freedom and *F*-ratio is the ratio of mean square to the mean square error. As for the ANOVA, the calculated value of *F*-ratio of developed model should be more than *F*-performed into contributions. The mean square is the ratio of table for the model to be adequate for a specified confidence interval. The results of ANOVA for tool wear ($VB_{\max}$) and surface roughness (R_a) are summarized in Table 4.

Mathematical models to predict tool wear and surface roughness are formulated by response surface regression analysis. The adequacy and significance of the developed regression model was tested using estimated regression coefficients method. In ANOVA, factors with 95% or *p-value* of 0.05 are considered as significant. The significance of a factor can be confirmed by main effect plot and normal probability plot. The quadratic terms of the factors are included in the analysis in order to incorporate the results of the composite part of CCD which may have curvilinear effect on the response. Second and higher orders to interactions are also considered for ANOVA. The influence of cutting parameters on tool flank wear (VB_{max}) and surface roughness (R_a) are discussed with the help of estimated regression coefficients and respective main effect plots.

Table 3. Experimental results for tool wear and surface roughness

Sl. No.	Machining Parameters			Response factors	
	V_c (m/min)	*f* (mm/rev)	*d* (mm)	VB_{max} (mm)	R_a (µm)
1	140	0.14	0.30	0.065	0.74
2	80	0.08	0.15	0.050	0.65
3	200	0.08	0.45	0.069	0.42
4	80	0.08	0.45	0.055	0.82
5	80	0.20	0.45	0.065	1.14
6	140	0.14	0.30	0.065	0.74
7	200	0.20	0.15	0.096	0.76
8	80	0.20	0.15	0.058	0.86
9	200	0.08	0.15	0.072	0.36
10	200	0.20	0.45	0.092	0.80
11	140	0.24	0.30	0.075	0.98
12	140	0.14	0.55	0.086	0.82
13	140	0.14	0.05	0.060	0.54
14	238	0.14	0.30	0.105	0.55
15	140	0.04	0.30	0.065	0.44
16	42	0.14	0.30	0.048	1.30

3.1 Analysis of Tool Wear

Table 4 shows the results of ANOVA for response surface quadratic model for tool wear ($VB_{\max}$). Factors cutting speed (V_c), feed rate (*f*) and depth of cut (*d)* are significant as their *P-value* is less than 0.05. It is observed from the ANOVA table, the cutting speed (47.407%) is the most significant cutting parameter followed by feed rate (28.148%). However, depth of cut has list effect (15.814%) in controlling the tool wear which is less statistically significant. The interactions terms of V_c*f, *Vc*d* and *f*d* are less significant. Quadratic term of V_c*V_c is less significant and *d*d and f*f* terms are insignificant. It indicates that the model adequate at 95% confidence level to represents the relationship between machining response and machining parameters of the hard turning process.

Table 4. ANOVA for response surface reduces quadratic model of tool wear (VB_{max})

Source	DF	Seq SS	Adj SS	Adj MS	F-value	P	Cont. (%)	Remarks
Vc (m/min)	1	0.002756	0.002756	0.002756	711.21	0.000	47.407	Significant
f(mm/rev)	1	0.001638	0.001638	0.001638	422.86	0.000	28.148	Significant
d (mm)	1	0.000922	0.000922	0.000922	237.86	0.000	15.814	Significant
*Vc*f*	1	0.000025	0.000025	0.000025	6.32	0.031	0.3617	Significant
*Vc*d*	1	0.000113	0.000113	0.000113	29.04	0.000	1.8777	Significant
*f*d*	1	0.000072	0.000072	0.000072	18.58	0.002	1.1714	Significant
*Vc*Vc*	1	0.000224	0.000075	0.000075	19.39	0.001	1.2223	Significant
*f*f*	1	0.000017	0.000014	0.000014	3.52	0.090	0.1722	Insignificant
*d*d*	1	0.000000	0.000000	0.000000	0.04	0.852	-0.0690	Insignificant
Error	6	0.000039	0.000039	0.000004			3.8960	
Total	15	0.005805					100.00	

Similarly, regression model give extensive insight to understand any problem in general, and optimize the factors influencing the response in particular. Table 5 shows the response surface regression analysis for tool wear ($VB_{\max}$). The regression model in the terms of coded values is represented by *Eqn.* (1) and its coefficients of correlation *R-sq* is 99.14%. The desirable value is close to one, which is *R-sq*= 99.14% shows that this much percentage of the variability of result is explained by the model. The *Enq*. (1) illustrate that the cutting parameters and interaction term cutting speed and feed rate has a vital role for determination of tool wear at the time of turning.

Table 5. Estimated regression coefficients for tool wear ($VB_{\max}$)

Term	Coef	SE Coef	T	P
Constant	0.06593	0.002384	27.66	0.000
Vc(m/min)	0.01306	0.001595	8.185	0.000
f(mm/rev)	0.00928	0.001595	5.813	0.000
d (mm)	0.00506	0.001595	3.172	0.011
*Vc*Vc*	0.00264	0.001603	1.647	0.130
*f*f*	0.00039	0.001603	0.243	0.813
*d*d*	0.00133	0.001603	0.828	0.429
*Vc*f*	0.00463	0.002059	2.246	0.050
*Vc*d*	0.00013	0.002059	0.061	0.953
*f*d*	-0.00088	0.002059	-0.425	0.681

The regression equation for tool wear ($VB_{\max}$) is,

$$\mathbf{VB_{max}(mm)} = 0.06593+0.01306V_c +0.00928f +0.00506d +0.00264\ V_c*V_c +0.00039f*f +0.00133\ d*d +0.00463\ V_c*f+0.00013V_c*d -0.0009*f*d, \qquad \mathbf{(1)}$$

$R\text{-}sq = 99.14\%$, $R\text{-}sq\ (adj) = 97.62\%$

Fig. 2 shows the main effect plot for tool wear ($VB_{\max}$), which is the graphical representation of the main factors affecting the tool wear in turning of hardened AISI H13steel. The results show that with the increase in cutting speed there is a continuous increase in tool wear. Similar effect can be noticed for feed rate and depth of cut. The result reveals the characteristic of tool wear is caused by the fact that, the speed is no longer the influential factor on wear. However, it is more likely that tool wear is the consequence of the feed rate and depth of cut. It could be seen in Fig. 2 that the optimum testing conditions for the tested samples became lower cutting parameters for main control factors in this study.

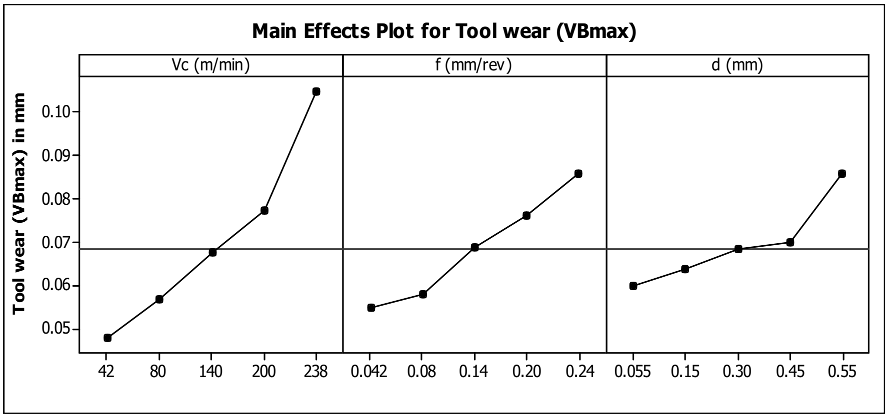


Fig. 2. Main effect plot for tool wear (VB_{max})

3.2 Analysis of Surface Roughness

Table 6 shows the ANOVA table for response surface quadratic model for surface roughness (R_a). The surface roughness is highly sensitive to variation of cutting parameters. From the ANOVA table, it is observed that the feed rate (49.551%) has highest statistical significant followed by depth of cut (40.307%), whereas cutting speed (8.832%) was found to be less significant on the surface roughness. The interaction term of V_c*f *is* less significant and $f*d$ and V_c*d are insignificant. Quadratic terms V_c*V_c, $d*d$ *and* $f*f$ are insignificant. The feed rate has the most dominant effect on machining the hard materials, followed by the depth of cut. However, less significant effect was observed for cutting speed. This model can also enable an insight the interaction effects on the surface roughness. This equation shows that the surface roughness increased with the increase of feed rate and depth of cut, but decreased with increasing the cutting speed.

Table 5: ANOVA for response surface reduces quadratic model of surface roughness (*R*a)

Source	DF	Seq SS	Adj SS	Adj MS	F-value	P	Cont. (%)	Remarks
V_c (m/min)	1	0.037577	0.037577	0.037577	203.36	0.000	8.832	Significant
f (mm/rev)	1	0.209960	0.209960	0.209960	1136.29	0.000	49.551	Significant
d (mm)	1	0.170825	0.170825	0.170825	924.49	0.000	40.307	Significant
V_c*f	1	0.001176	0.001176	0.001176	6.37	0.030	0.234	Significant
V_c*d	1	0.000210	0.000210	0.000210	1.14	0.311	0.006	Insignificant
$f*d$	1	0.000276	0.000276	0.000276	1.49	0.250	0.022	Insignificant
V_c*V_c	1	0.001361	0.000481	0.000481	2.60	0.138	0.278	Insignificant
$f*f$	1	0.000008	0.000002	0.000002	0.01	0.927	-0.049	Insignificant
$d*d$	1	0.000107	0.000107	0.000107	0.58	0.465	-0.018	Insignificant
Error	6	0.001848	0.001848	0.000185			0.837	
Total	15	0.423348					100.00	

The correlations between the main factors in machining the hardened H13 steel with coated ceramic tool were obtained by multiple regressions. Table 7 shows the response surface regression analysis for surface roughness (*R*a). The estimated regression coefficients for surface roughness (R_a) are given in *Eqn. (2)* and its coefficients of correlation *R-sq* is 98.67%.

Table 6: Estimated Regression Coefficients for surface roughness (R_a)

Term	Coef	SE Coef	T	P
Constant	0.74665	0.02466	30.282	0.000
V_c(m/min)	-0.17511	0.01650	-10.612	0.000
f (mm/rev)	0.16589	0.01650	10.053	0.000
d (mm)	0.07404	0.01650	4.487	0.002
V_c*V_c	0.05740	0.01658	3.462	0.007
$f*f$	-0.02322	0.01658	-1.401	0.195
$d*d$	-0.03447	0.01658	-2.079	0.067
V_c*f	0.02875	0.02130	1.350	0.210
V_c*d	-0.04125	0.02130	-1.936	0.085
$f*d$	0.01375	0.0213	0.645	0.535

The regression equation for surface roughness (R_a) is;

$$\boldsymbol{R_a}(\mathbf{\mu m})=0.74665-0.17511V_c+0.16589f+0.07404d+0.0574V_c*V_c-0.02322f*f-0.03447d*d+0.02875V_c*f-0.04125V_c*d+0.01375f*d, \tag{2}$$

$R\text{-}sq = 98.67\%$, $R\text{-}sq(adj) = 96.96\%$

The main effects plot for the surface roughness (R_a) of the H13 steel machining is shown in Fig. 3. It indicates that the feed rate has the dominant effect on surface roughness(R_a) followed depth of cut but least effect was showed by cutting speed. It can be concluded that the higher cutting speed and lower feed and depth of cut is best for machining for hardened H13 steel with coated ceramic tool.

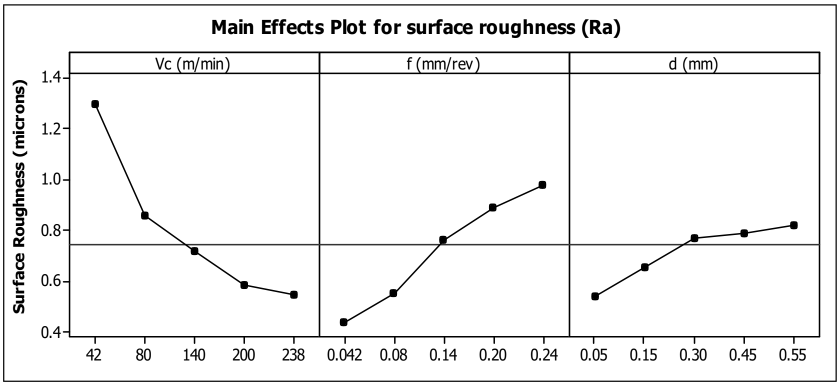
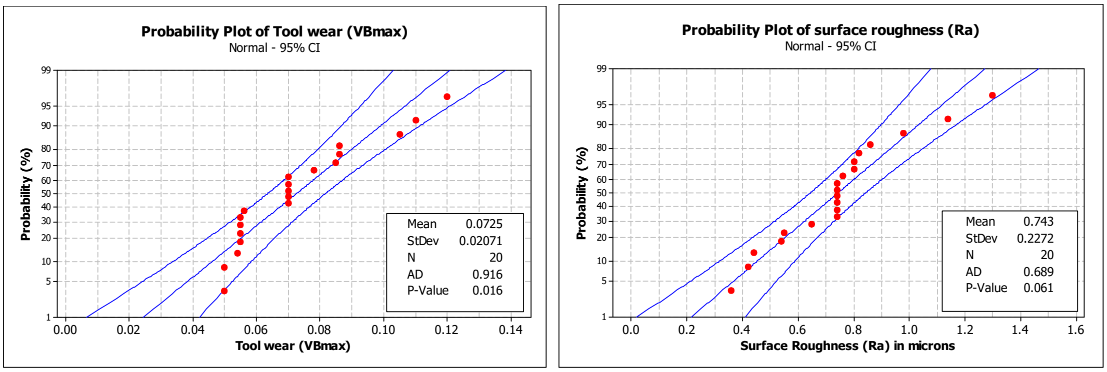


Fig. 3. Main effect plot for Surface roughness (*Ra*)

Inspection of some diagnostic plots of the model was done to test the statistical validity of the models. The Anderson–Darling test and normal probability plots of the residuals versus the predicted response for the tool wear (VB_{max}) and surface roughness (R_a) are plotted in Fig. 4(a) and 4(b). The test data very closely follows the straight line. The null hypothesis is that the data distribution law is normal and the alternative hypothesis is that it is non-normal. Using the *P- value* which is greater than alpha of 0.05 (level of significance), the null hypothesis cannot be rejected. It indicates that the proposed models were adequate with test results.

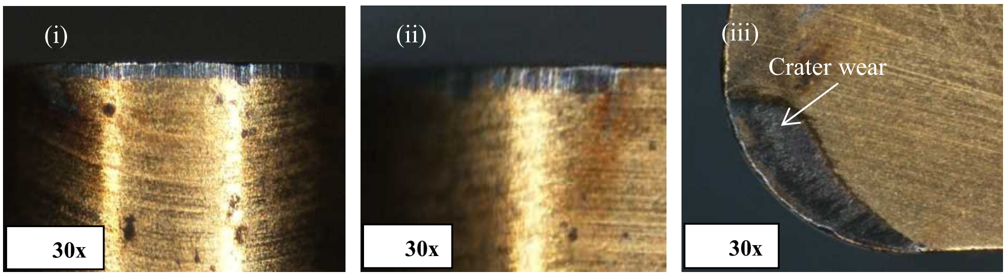


(a) (b)

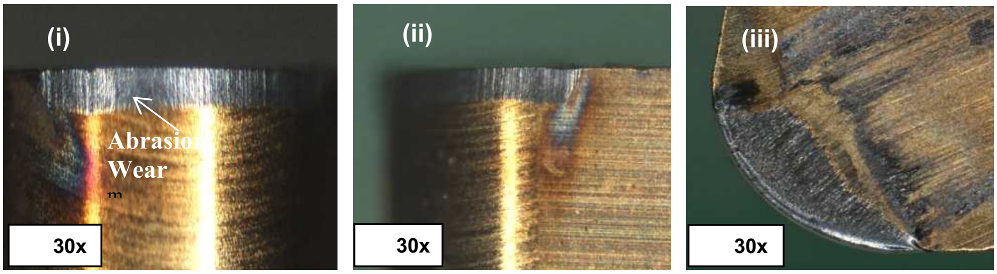
Fig. 4. Normal Probability for (a) tool wear ($VB_{\max}$) and (b) surface roughness (R_a)

4. Discussion

The tool wear is one of the important aspects in hard turning. Usually, abrasion, adhesion and diffusion are considered to be the main tool wear mechanisms in hard machining; however, the individual effect of each mechanism depends on the tool geometry, tool grade, cutting parameters and work piece hardness (Kopac (2006)). In Fig. 2, the behavior of tool wear ($VB_{\max}$) with different cutting parameters is shown. The tool wear linearly increases with increase in cutting parameters. It indicates that the increase in tool wear at higher cutting conditions is probably due to the abrasion at the rake and flank faces as the machining time progresses. Abrasion was the principal wear mechanisms observed at higher cutting conditions and adhesion at lower cutting conditions during turning of hardened H13 steel using coated ceramic tool.



(a) Vc= 140 m/min, f= 0.14mm/rev and d =0.3mm



(b) Vc=200m/min, f=0.20mm/rev and d=0.45mm

Fig. 6. Micrographic images of worn cutting edge of coated ceramic tool at different cutting conditions

Fig. 6 shows the optical micrographic of the tool wear profile of ceramic tool at different cutting conditions. It appears that both the rake face and flank face were severely worn under test conditions. Ridges and mechanical plowing grooves are clearly evident on the flank wear surfaces, and it is indicative of typical abrasive wear. And also serrated chips abrade the tool rake face and create scars in the rake wear surface. Fig. 7 shows the evidence for the short saw toothed loose arc types chips obtained during turning of hardened H13 steel. However, when the cutting temperature is very high due to the increase of cutting speed and feed rate, the coated layer on the tool face becomes soft. Under such conditions, it can be easily abraded by the hard particles of the work material, and tool wear is accelerated. Therefore, the life of coated ceramic tools would gradually be reduced. It is also revealed from the investigation that the tool wear is concentrated typically on the nose region because of higher stresses and thermal softening of tool material due to higher temperature at this region (Horng et al. (2008)).

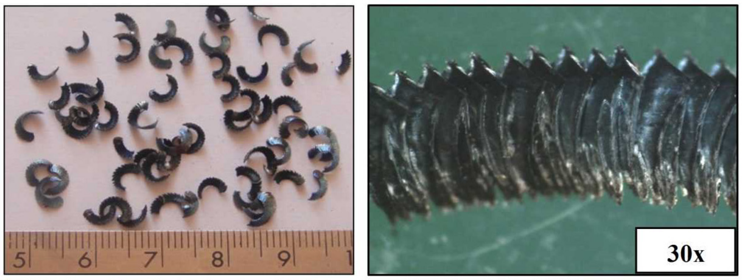


Fig.7. Chip formation during hardened H13 turning at V_c=200m/min, f=0.2 mm/rev and d=0.45mm

Surface roughness influences not only dimensional accuracy of machined components but also their mechanical and chemical properties. Surface roughness is a significant parameter to evaluate the performance of the cutting tools during hard machining. The irregularity of a machined surface is the result of the machining process. It is including selection of cutting conditions, environmental conditions. In hard turning process, the surface roughness is prominently affected by a number of factors such as tool geometry, tool nose radius, work hardness and cutting conditions. Fig. 3 shows the Influence of cutting parameters on surface roughness (R_a) during machining of hardened AISI H13 steel with coated ceramic tool. The surface quality of the machined part increases with increase in cutting speed. It can be concluded that the lower surface roughness values are obtained at higher cutting speeds due to less vibration and lower forces (cutting force and thrust force) generated (Lima et al. (2005)). And the second point is that, at high cutting speed, better surface finish was obtained since less heat was dissipated to the work material as it was swept away in the flowing chips. The minimal surface roughness results with the combination of low feed rate and depth of cut with high cutting speed. The surface roughness increases with increasing feed rates, however it remains almost unaffected at lower feed rate. It indicates that the amount of heat generation increases with increase in feed rate, because the cutting tool has to remove more volume of material from the work piece. The plastic deformation of the work piece is proportional to the amount of heat generation in the work piece and promotes roughness on the work piece surface (Grezisk, (2008), Ozel and Karpat (2008)). And the second point is that cutting with coated ceramic tool having a certain wear generates surface roughness than a fresh tool, because the tool wear is proportional to the cutting feed rate and roughness is a reproduction of the tool nose profile on the work piece surface.

5. Conclusions

Based on the experimental results, the following conclusions can be drawn.

- The central composite design (CCD) employed in this study proved to be an effective tool for modeling the tool wear and surface roughness. The reduced quadratic model developed using RSM is reasonably accurate and can be used for prediction within the limits of the factors investigated.
- The cutting speed (47.4%) has most significant effect on the tool wear and feed rate (28.15%) and then depth of cut (15.8%). In hard turning, increased cutting speed significantly increases the temperature at the contact zone, subsequently resulting in drastic increase of the tool wear.
- Abrasion was the principal wear mechanisms observed at higher cutting conditions and adhesion at lower cutting conditions.
- The feed rate was the highest influencing factor on surface finish (49.55%), cutting speed (40.3%), and followed by depth of cut (8.8%). The surface finish was improved as cutting speed was increased and deteriorated with feed rate.

- The relationship between cutting parameters and the performance measures (tool wear and surface roughness) are expressed by multiple regression equation which can be used to estimate the expressed values of the performance level for any parameter levels.
- The use of coated ceramic tools (PVD TiN) with suitable cutting parameters on hard turning of AISI H13 steel permit a surface roughness (R_a <0.8μm) corresponding a great dimensional accuracy without necessity of grinding process.

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