Optimization of Surface Roughness, Cutting Tool Flank Wear in Turning on D3 Steel by Coated Carbide Tool using Extended RSM Approach

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Abstract- ***In the current study, efforts are made to explore the use of economical coated carbide cutting tools for hard machining applications, which otherwise is dominated by costlier CBN and ceramic cutting tools. This paper attempts to model the flank wear and surface roughness during finish machining of AISI H13 steel with coated carbide (PVD) cutting tool by Multiple Linear Regression and Response Surface Methodology (RSM). An Attempt has also been made to optimize the cutting conditions speed, feed, and depth of cut to minimize the response parameters. ANOVA analysis and 3D factor interaction graphs have been plotted to evaluate the statistically significant parameters influencing the response parameters. In addition to validating the developed models statistically, the confirmation experiments conducted predicted the responses with less than 5% error.***

Keywords: Surface Roughness, Tool wear, PVD, RSM.

I. INTRODUCTION

Hardened steel has been increasingly used in industrial and automotive applications such as gear, bearing, tool, and die. Requirements on surface finish and dimensional accuracy of hardened steel can be achieved by finishing operation and finishing hardened steel are usually made by traditional machining such as grinding. However, grinding operations are not economical because they are time consuming, limited to the range of geometry, and require coolant.

As such, continual improvements in the technological performance of machining operations have been sought through research and development including new and more wear resistant tool materials as well as new geometrical tool designs **(**Kalpakjian and Schmid, 2003, Wang.j, 2000**)**. Finish hard turning is a process by which hardened steels with hardness Rockwell C (HRC) 45 and above are finish turned.

Coated tools are developed for use at high cutting speeds so that time required for machining can be reduced and subsequently the cost of machining could be minimized. Common coating material used are Titanium carbide (TiC), titanium nitride (TiN) and titanium carbonitride (TiCN). It is generally 2-10 μm in thickness and these coatings are applied on the cutting tools and inserts by chemical vapour deposition (CVD) and physical vapour deposition (PVD) techniques. In physical vapour deposition process, the surface of the tool that needs to be coated will be cleaned by inert gas ion at low pressure (Ghosh 1986 and Jehming 2001). The type of wear takes place on the flank and results in a flank land. Wear land formation is not always uniform along the flank land. Flank wear affects the dimensional tolerance of machined parts over a period of time. Wear on the flank (relief) face is called Flank wear and results in the formation of a wear land. Surface roughness is an important parameter in manufacturing engineering with significant influence on the performance of mechanical parts. Failures, sometimes catastrophic failures, leading to high costs, have been imputed to a component's surface roughness. The Taguchi design of experiments was used to optimize the cutting parameters.

II. LITERATURE SURVEY

A. Hard turning

Hard turning refers to turning of workpiece with hardness value above 45 HRC. Typical workpiece materials suitable for hard turning operations include heat treated materials e.g, quenched and tempered case hardened materials (Gallopi et al., 2006). Hard turning mostly need high hardness tools with negative rake angle, lower feed rate and depth of cut in order to produce better performance. However, large nose radius (generally 0.8 mm) is selected to achieve better surface finish (Kumar et al., 2003). The selection of cutting tools for hard turning applications generally involve the use ceramic and CBN tools since these tools typical have high hardness, toughness, and wear resistance. Hard turning has the potential for replacing grinding operation and hard turning significant is attained growth due to increased productivity and low production cost compared to grinding. Generally, the grinding process involves low materials removal rate, and requires large quantities of coolants that impact both the operator health and may cause environmental pollution. However, hard turning offers several advantages over grinding such as reduce machining time, high geometry flexibility, less energy required, environmental friendly, and able to obtain better surface finish quality.

Due to increasing demand on hard turning the finished components should satisfy high quality requirements such as dimensional accuracy and quality surface finish and dry hard turning can achieve these requirements. Jiang et al. (2006) found that hard turning using a tool with nose radius of 0.8 mm is able to produce parts with surface finish quality equivalent to mechanical grinding process. The surface roughness in hard turning is comparable to the result obtained by grinding process (Remadna et al., 2006).

B.Cutting temperature and heat generated

Luo et al. (1999) carried out the experiment on the hard turning of steel AISI 4340 with hardness value above 50 HRC. It shows that increased in the cutting speed will increase the temperature. However, the cutting temperature is also increased with the increase of work material hardness. Additionally, increase in the hardness value at high feed rate significantly increases the cutting temperature (Hua et al., 1995)

C. Chip formation during hard turning

One of the common chips formed during hard turning is the serrated chip or saw tooth. (Poulachon et al., 2001) reported that when turning 100Cr (AISI 52100) with hardness 38-60 HRC using PCBN tool, the chip formed is saw tooth. They concluded that, when turning steel with hardness range of 10-50 HRC continuous chips was produced. However, when the hardness is in excess of 50 HRC, saw tooth chips appears.

D. Tool life criteria

Tool life is defined as the cutting time required to reach a tool life criterion (Boothroyd, 1975). The factors affecting the tool life criteria are workpiece material tool material, and cutting

E. Surface integrity and surface roughness

Surface integrity is term which involves: surface finish and freedom from cracks, chemical change, thermal damage (burn, transformation, and over tempering), and residual stress (Shaw, 2005).

F. Response Surface Methodology

The RSM is important in designing, formulating, developing, and analyzing new scientific studying and products. It is also efficient in the improvement of existing studies and products. The most common applications of RSM are in Industrial, Biological and Clinical Science, Social Science, Food Science, and Physical and Engineering Sciences. Since RSM has an extensive application in the real-world, it is also important to know how and where Response Surface Methodology started in the history. According to Hill and Hunter, RSM method was introduced by G.E.P. Box and K.B. Wilson in 1951 (Wikipedia 2006). Box and Wilson suggested to use a first-degree polynomial model to approximate the response variable. They acknowledged that this model is only an approximation, not accurate, but such a model is easy to estimate and apply, even when little is known about the process (Wikipedia 2006). Moreover, Mead and Pike stated origin of RSM starts 1930s with use of Response Curves (Myers, Khuri, and Carter 1989). One of the important facts is whether the system contains a maximum or a minimum or a saddle point, which has a wide interest in industry. Therefore, RSM is being increasingly used in the industry. Also, in recent years more emphasis has beenplaced by the chemical and processing field for finding regions where there is an improvement in response instead of finding the optimum response (Myers, Khuri, and Carter 1989). In result, application and development of RSM will continue to be used in many areas in the future.

III. EXPERIMENTAL DETAILS

The work piece material was AISI H13 steel. It was hardened to 52 HRC. H13 steel, resistant and good thermal conductivity used for very high requirements available as mould plates inserts for injection for plastics and die moulds to a high load.

Table 1

C	Si	Mn	Cr	Mo	V
0.36	1	0.43	4.9	1.25	0.36

Coated carbide cutting tool been chosen to hard turn the workpiece.TH1000 inserts coated with PVD super fine grained grade intended for machining of steel components with both hardened and soft areas was used in the study. The superior edge toughness provides excellent performance in continuous and interrupted cuts in hardened steels as well as in hard surface removal. The combination of properties in TH1000 makes this grade ideal for hard turning steels having hardness in the range of 40 and 65 HRC. And, because of the coating, this grade can also handle light interruptions.

A. Machine tool and Equipments:

Rough turning of the specimens was carried out on an engine lathe prior to heat treatment as shown in Fig. 3.3. The outermost 2 mm layer present on all the specimens was turned off to avoid machining of oxidized layer during the subsequent hard turning tests. The prepared specimens after heat treatments were hard turned on CNC centre Lathe. A Mitutoyo Surftest SJ-301 Portable Surface Roughness Tester was used to measure the roughness profile data after each cut. Tool wear measured with tool maker's microscope of Mitutoyo having least count of 0.01µm.

B. Experimental Plan

In this experiment, Response Surface Methodology was used to design the experimental plan. Cutting speed, feed rate and depth of cut were varied in this experiment. The limiting value of average flank wear (i.e. 200µm) was selected as tool life criterion. In this process, the recording of wear was recorded after two passes, and when the value of tool wear reaches 200 µm then experiment has to be turned off. The surface roughness is measured using portable stylus type surface analyzer. The value of surface roughness was taken at three different locations on the work piece circumference. The value of surface roughness was obtained by averaging the surface roughness values. The measurement was taken without removing the work piece. The purpose was to prevent any deviation of the cutting position during the experiments; the surface roughness (Ra value) should be less than 1.6 µm.

Table 2 Cutting condition for the experiment

Cutting parameter	**Unit**	**Variable**		
		Level 1	**Level 2**	**Level 3**
Cutting speed	m/min	130	155	180
Feed rate	mm/rev	0.05	0.10	0.15
Depth of cut	mm	0.10	0.25	0.40

Table 3 Levels of Machining Parameters Selected

Level	Cutting Speed (A) m/min.	Feed rate (B) mm/rev.	Depth of Cut (C) mm
-1	130	0.05	0.1
0	155	0.1	0.25
1	180	0.15	0.4

IV. EXPERIMENTAL RESULT ANALYSIS

A. Experimental Design

Table 3 Experiment design

Run No.	Input parameters			Response factors	
	Speed m/min	Feed mm/rev.	Depth of cut mm	Flank wear-VB µm	Surface roughness-Ra µm
1	180	0.05	0.1	120	0.91
2	180	0.1	0.25	100	0.47
3	180	0.05	0.4	90	0.72
4	180	0.15	0.1	75	0.8
5	130	0.15	0.4	110	1.44
6	130	0.05	0.1	107	0.7
7	130	0.1	0.4	130	0.79
8	130	0.05	0.4	90	0.66
9	180	0.05	0.1	100	1.1
10	155	0.05	0.25	25	0.5
11	130	0.15	0.25	80	1.04
12	180	0.15	0.4	80	1.3
13	155	0.1	0.1	95	0.54
14	130	0.15	0.1	90	0.93
15	180	0.05	0.4	100	0.48
16	130	0.05	0.1	90	1.03
17	180	0.15	0.1	70	0.99
18	155	0.15	0.4	60	1.2

Both the fitted models were found to be significant. Since for all the responses, the probability of F (Prob. > F) are observed to be less than 0.0001. In other words, there is only a 0.01% chance that "Model F-Value" larger than those reported in Tables 4 and 6 could occur due to noise.

Table 4 ANOVA Results for Flank Wear (VB)

Source	**Sum of Squares**	**DF**	**Mean Square**	**F-Value**	**Prob> F**	**Remarks**
Model	8906.53	9	989.61	14.29	0.0005	significant

A	200.97	1	200.97	2.9	0.1268	
B	189.51	1	189.51	2.74	0.1366	
C	0.47	1	0.47	6.73E-03	0.9367	
A2	3391.86	1	3391.86	48.99	0.0001	
B2	2968.17	1	2968.17	42.87	0.0002	
C2	1680.2	1	1680.2	24.27	0.001	
AB	904.26	1	904.26	13.06	0.0068	
AC	25.9	1	25.9	0.37	0.5578	
BC	529.8	1	529.8	7.65	0.0244	
Residual	553.92	8	69.24			
Lack of Fit	146.92	4	36.73	0.36	0.8263	not significant
Pure Error	407	4	101.75			
Cor Total	9460.44	17				

Table 5 Model Summary Statistics for Flank Wear (VB)

Std. Dev.	8.32	(R^2)	0.9414
Mean	89.56	Adjusted (R^2)	0.8756
C.V.(%)	9.29	Predicted (R^2)	0.7233
Press	2617.85	Adequate Precision (AP)	16.73

The values of "Prob> F" less than 0.050 observed for some factors involved in model equations, indicate that the contribution of these terms to the model is significant. On the other hand, the value of "Prob> F" greater than 0.10 indicates that the impact of model terms are not significant. The ANOVA results for flank wear show that A2, B2, C2, AB, BC are the significant model terms (Table 4). Whereas, the ANOVA results for surface roughness (Ra) reveal that B, B2, BC, are the significant model terms (Table 6).

In addition to this, the F-value corresponding to “Lack of Fit” test for different response factors were also evaluated. The "Prob> F" for all these tests was found in excess of 0.05, implying that the lack of fit is insignificant as revealed from Tables 5.2 and 5.4

The coefficients of correlation (R2) for both the models was observed to be greater than 0.90 (Table 4 and 6), which inspire confidence in the developed models. The predicted and adjusted R2 values for VB were in excellent agreement whereas, for Ra these were observed to be in reasonable agreement, which again validates the fitness of developed models. The coefficient of variation (C.V.) defined as {(S.D./Mean) x 100} of model is measurement of error. The Low value of C.V. obtained for both the models indicates improved precision and reliability of experiments performed. The press value, defined as signal to noise ratio for the fitted value, was significantly higher than 4 (Table 5 and 7), indicating the suitability of models for future prediction.

The regression equations were obtained for both response factors by using multiple regressions. The developed model equation is given below:

$$\begin{aligned} VB(avg.) = &+1416.27045 - 18.60119 * A + 3679.71019 * B - 635.57020 * C + 0.062061 * A^2 \\ &- 14513.78944 * B^2 + 1213.32728 * C^2 - 6.90329 * A * B - 0.38945 * A * C \\ &+ 880.66889 * B * C \end{aligned}$$

$$\begin{aligned} Ra(avg.) = &+6.32435 - 0.058577 * A - 20.22201 * B - 4.26714 * C + 2.05043E-004 * A^2 \\ &+ 110.05601 * B^2 + 7.44130 * C^2 - 0.029176 * A * B - 0.011171 * A * C + 25.05545 * B * C \end{aligned}$$

Table 6 ANOVA Results for Surface Roughness (Ra)

Source	Sum of Squares	DF	Mean Square	F-Value	Prob> F	Remarks

Model	1.29	9	0.14	9.20	0.0023	significant
A	4.677E-003	1	4.677E-003	0.30	0.5982	
B	0.44	1	0.44	28.63	0.0007	
C	0.017	1	0.017	1.07	0.3312	
A2	0.037	1	0.037	2.38	0.1612	
B2	0.17	1	0.17	10.99	0.0106	
C2	0.063	1	0.063	4.07	0.0784	
AB	0.016	1	0.016	1.04	0.3377	
AC	0.021	1	0.021	1.37	0.2752	
BC	0.43	1	0.43	27.61	0.0008	
Residual	0.12	8	0.016			
Lack of Fit	4.907E-003	4	1.227E-003	0.041	0.9954	not significant
Pure Error	0.12	4	0.030			
Cor Total	1.41	17				

Table 7 Model Summary Statistics for Surface Roughness (Ra)

Std. Dev.	0.12	(R^2)	0.9119
Mean	0.87	Adjusted (R^2)	0.8128
C.V.(%)	14.38	Predicted (R^2)	0.6908
PRESS	0.44	Adequate Precision (AP)	10.412

The predicted values of the response factors VB, and Ra corresponding to different combination of machining parameters reported in Table 5 & 7 are compared with the corresponding experimental values and a nice agreement is observed between these values as evident from Figs. 1 and 2

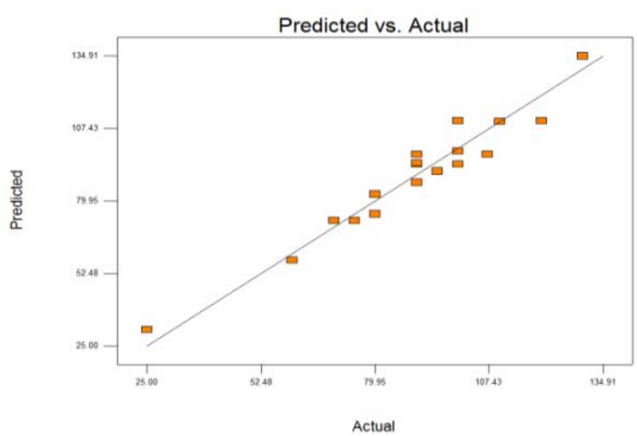

Figure. 1 Comparison between measured and predicted values of VB

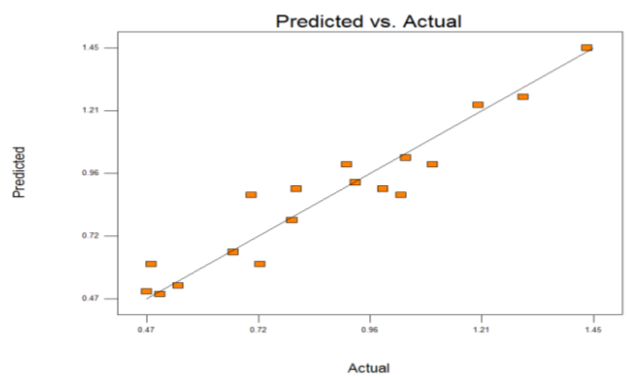

Figure. 2 Comparison between measured and predicted values of Ra

V. EFFECT OF MACHINING PARAMETERS ON RESPONSE FACTORS

A. Flank wear

In order to investigate the influence of machining parameters on the flank wear (VB), the factor interaction graphs are plotted. Fig. 3 depicts the influence of cutting speed and feed on the flank wear VB.

The VB appears to be decreasing with the increase in cutting speed up to 155m/min., Fig. 3. It appears that at low cutting speed the binder of the hard particles present in cutting tool is easily removed from the substrate due to high cutting force arising from less softening of work material as a result of low cutting temperature, and therefore abrasion dominates tool wear. However, when the cutting speed is further increased, cutting temperature becomes the dominant factor instead of the cutting force, leading to removal of protective coating on tool surface thereby accelerating the tool wear. With increase in cutting speed beyond 155m/min., the flank wear although exhibits an increasing trend, but it still remains lower than the limiting value of 200μm clearly demonstrating the suitability of coated carbide tools within the range of parameters selected.

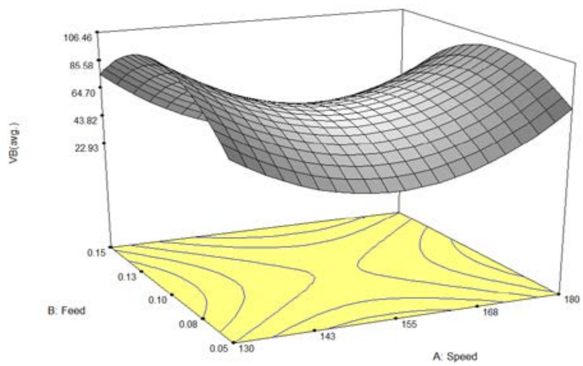

Figure 3 Effect of cutting speed and feed rate on flank wear (depth of cut 0.25mm.)

The flank wear (VB) initially increases with increasing feed rate up to feed up to 0.10 mm/rev as expected, beyond this value the VB decreases with increase in feed, Fig. 3.

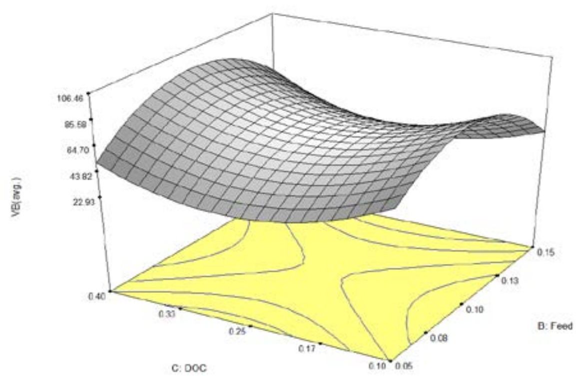

Figure 4 Effect of depth of cut and speed on flank wear

Fig. 4 shows the variation of Flank wear (VB) with depth of cut (C) and cutting speed (A). At low DOC, the flank wear initially decreases with increasing depth of cut but beyond DOC = 0.25mm it exhibits an increasing trend with increase in depth of cut. When the work depth of cut the tool is low, the tool has to work against relatively much harder material. However, when the depth of cut is increased, the tool is to work against relatively softer material, as the hardness of cylindrical work piece decreases radially inward due difference in quenching rate from outer surface towards core during hardening process. As a consequence the flank wear is reduced at larger depth of cut, i.e up to 0.25mm. When DOC is increased further, great effort (cutting force) is required to plough the material, thereby increasing the tool wear.

B. Surface Roughness

Fig. 5 shows the effect of speed and feed on surface roughness (Ra). The surface roughness does not vary much with cutting speed at low feed rate, however it decreases marginally at higher speed feed combination. The best surface roughness has been achieved corresponding to the combination of lowest feed rate and lowest cutting speed. The surface roughness increases sharply with increase in feed rate as expected.

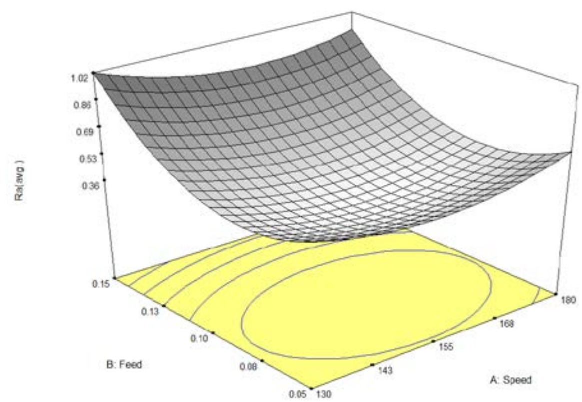

Figure 5 Effect of cutting speed and feed rate on surface roughness

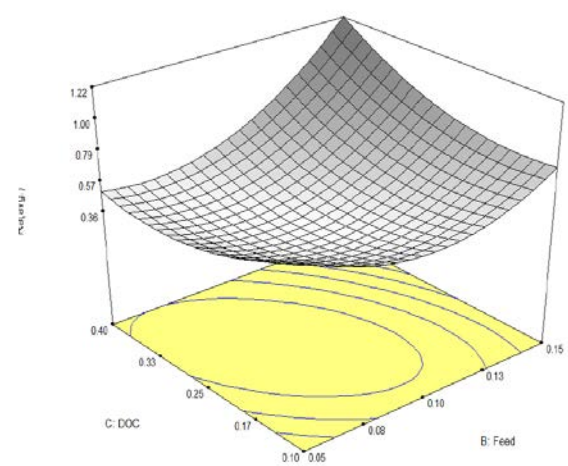

Figure 6 Effect of depth of cut and feed on surface roughness

Fig. 6 depicts the influence of DOC and feed rate on surface roughness. The surface roughness increases with increase in feed rate. However corresponding to high feed high Doc it exhibits an abrupt rise in surface roughness, thereby depicting the limitation of carbide tool at such higher DOC.

C. Optimization of Cutting Conditions

In the present study desirability function optimization of RSM has been employed for multi response (VB and Ra) optimization. The optimization module searches for a combination of factor levels that simultaneously satisfy the requirements placed on each of the responses and factors in an attempt to establish the appropriate model. During the optimization process the aim was to find the optimal values of cutting parameters in order to minimize the value of the flank wear (VB) and surface roughness (Ra) the constraints used during the process are summarized in Table 9. The optimized solutions are reported in Table 10 in the order of decreasing desirability level.

Table 8 Optimization of Cutting Conditions

Name	Goal	Lower Limit	Upper Limit
Speed	is in range	130	180
Feed	is in range	0.05	0.15
D.O.C	is in range	0.1	0.4
VB	minimize	25	130
Ra	minimize	0.47	1.44

Table 9 Constraints for optimization of Cutting conditions

Speed m/min	Feed mm/rev	D.O.C mm	Flank Wear (VB) µm			Surface roughness (Ra) µm		
			Model	Exp.	% Error	Model	Exp.	% Error
153.5	0.05	0.27	30.5	98.5	1.7	0.47	6956	0.12
130	0.1	0.25	105.8	110	3.8	0.61	0.64	4.68
180	0.15	0.4	81.54	84	2.92	1.38	1.42	2.81

Table 10 Optimization results

No.	Speed	Feed	D.O.C	VB	Surface roughness	Desirability
1	153.50	0.05	0.27	30.58	0.4699	0.973024
2	153.18	0.05	0.27	30.59	0.4699	0.973004
3	153.09	0.05	0.28	30.66	0.4660	0.972673
4	153.99	0.05	0.26	30.66	0.4766	0.969291
5	158.29	0.14	0.21	39.64	0.6482	0.8381

C. Confirmation Experiments

A set of 3 confirmation experiments, including the best optimal solution were performed to verify the adequacy of developed mathematical models given in eqn. (4), and (5). The plan of confirmation experiments is given in Table 10. The percentage error between the experimental and the predicted value of VB and Ra were observed to be less than 5%. Therefore, all the experimental values for confirmation runs are within the 95% prediction interval which clearly demonstrates the accuracy of models developed in this study.

Table 5.8 Plan of Confirmation experiments and results

Speed m/min	Feed mm/rev	D.O.C mm	Flank Wear (VB) µm			Surface roughness (Ra) µm		
			Model	Exp.	% Error	Model	Exp.	% Error
153.5	0.05	0.27	30.5	98.5	1.70	0.47	6956	0.12
130	0.1	0.25	105.80	110	3.8	0.61	0.64	4.68
180	0.15	0.40	81.54	84	2.92	1.38	1.42	2.81

VI. CONCLUSION

In this study RSM was applied to develop mathematical models of the flank wear and surface roughness so as to investigate the influences of machining parameters during finish turning of AISI H13 hardened steel with coated carbide cutting tool. For finding optimum value of machining parameters, the quadratic model of RSM associated with desirability function numerical optimization was utilized.

The following conclusions of experimental investigation are drawn:

a) Both the developed models were found to be statistically significant in determining flank wear and surface roughness.
b) The results of ANOVA and the validation experiments confirm that the developed mathematical models for flank wear, surface roughness excellently fit and predict the values of these response factors close to the experimental values with 95% confident interval.
c) The ANOVA results for flank wear show that A^2, B^2, C^2, AB, BC are the significant model terms. whereas, the ANOVA results for surface roughness (Ra) reveal that B, B^2, BC, are the significant model terms
d) The VB appears to be decreasing with the increase in cutting speed up to 155m/min. With increase in cutting speed beyond 155m/min., the flank wear although exhibits an increasing trend, but it still remains lower than the limiting value of 200µm clearly demonstrating the suitability of coated carbide tools within the range of parameters selected.
e) The flank wear (VB) initially increases with increasing feed rate up to feed up to 0.10 mm/rev as expected, beyond this value the VB decreases with increase in feed rate.
f) At low DOC, the flank wear initially decreases with increasing depth of cut but beyond DOC = 0.25mm it exhibits an increasing trend with increase in depth of cut.
g) The surface roughness does not vary much with cutting speed at low feed rate, however it decreases marginally at higher speed feed combination.
h) The surface roughness increases sharply with increase in feed rate.
i) The surface roughness increases with increase in feed rate. However corresponding to high feed high Doc it exhibits an abrupt rise in surface roughness, thereby depicting the limitation of carbide tool at such higher DOC.
j) The optimized machining conditions for minimizing tool wear and surface roughness are approaching: cutting speed = 153.50 m/min , feed rate = 0.05mm/rev, depth of cut = 0.27 mm, with flank wear 30.58 µm and surface roughness 0.47 µm.
k) The percentage error between the predicted values of response factors and the values of response factors obtained during the confirmation experiments are within 5%.

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