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MACHINING PERFORMANCE ASSESSMENT OF HARDENED AISI 52100 STEEL USING MULTILAYER COATED CARBIDE INSERT

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Abstract

The present work investigated some machinability study, regression modeling and optimization aspects during dry hard turning of AISI 52100 bearing steel (55 ± 1 HRC) using economical coated carbide insert which is little being investigated as per literature study. The multilayer coated carbide insert present itself an alternative avenue to costly cBN and ceramic insert in machining of difficult-to-cut bearing steel at hardened state. The steady progression of flank wear with no chipping and fracturing is observed during studied range. Abrasion is predominant wear failure seen in the experiment. Quadratic regression model shows the accurate of results and may be implemented in dry hard turning environment. The optimum results are recommended as: cutting speed (110 m/min)-feed (0.04 mm/rev)-depth of cut (0.2 mm) while turning hardened AISI 52100 steel through coated carbide insert. At this optimized parametric conditions, the flank wear and surface roughness values are obtained to be 0.06 mm and 0.81 microns which is well within the criteria limit. The potential benefits of low cost coated carbide insert under dry finish turning of hardened bearing steel has been noticed at moderate cutting speed.

Keywords: Hard turning, Machinability, Multilayer coated carbide, Flank wear, Surface roughness, Chip morphology, Regression.

1.Introduction

Hard turning is adopted now-a-days in production industries for finishing of hardened components thus successively replacing traditional grinding operations. Basically machining of more than 45 HRC hardened work material is termed as hard turning. Turning of hardened material is usually done by super-hard tool materials like cubic boron nitride (cBN) and ceramic. It has several benefits such

Nomenclatures

d	Depth of cut, mm
F	Fisher's ratio
f	Feed, mm/rev
P	Probability of significance
Ra	Arithmetic surface roughness average, µm
R^2	Determination coefficient
Tc	Machining time, minute
VBc	Flank wear at nose radius corner, mm
v	Cutting speed, m/min

Abbreviations

AISI	American Iron and Steel Institute
ANN	Artificial Neural Network
ANOVA	Analysis of Variance
Al_2O_3	Aluminium Oxide
cBN	Cubic Boron Nitride
CNC	Computerised Numerical Control
DOE	Design of Experiment
HRC	Rockwell hardness in C Scale
TiCN	Titanium Carbo nitride
TiN	Titanium Nitride

as reduction of manufacturing cycle, process flexibility, reduction of cycle time thus reducing cost, higher material removal rate and ecological advantages due to operation under without cooling media. Besides it produces various contour geometry and producing complex forms as reported by Bouacha et al. [1]. Various researchers have investigated some machinability aspects during hard turning using cBN and ceramic inserts. But, the machinability study using economical coated carbide insert is rarely investigated so as to be suitable in hard turning. The acceleration of flank wear severely influences the product quality of the machined surface and tool life and thus represents a burning issues and challenges in machining industries. 'Therefore' research is continued to enhance the life of cutting inserts in aggressive machining environments like hard turning for producing finishing components for aerospace, automobile, die and mould manufacturing industries. Sahoo and Sahoo [2] studied some machinability analysis through response surface methodology, grey relational analysis and studied the economical aspects during hard turning of AISI 4340 steel using coated carbide insert. Sahu et al. [3] compared the machining performance of hardened steel to 43 HRC under different cutting environments such as dry and spray. Spray environment performed well in comparison to dry cutting operation during hard turning. Singh and Rao [4] investigated hard turning of AISI 52100 steel using mixed ceramic insert. Feed was dominant parameter for surface roughness next to nose radius and cutting speed.

Paiva et al. [5] used TiN coated mixed ceramic tool for experimental investigation on hardened bearing steel on material removal rate and surface quality. Recommended cutting speed of 238 m/min, feed of 0.08 mm/rev and 0.32 mm depth of cut has been obtained. Singh and Rao [6] experimentally investigated on hard turning of AISI 52100 steel using solid lubricants (molybdenum disulphide and graphite). Improvement of surface quality was noticed in comparison to dry cutting. Molybdenum disulphide as solid lubricant was found to be effective to minimize the surface roughness due to strong adhesion. Zhang et al. [7] studied the surface integrity aspects in hard turning of bearing steel with the help of cBN insert. In the experiment, feed was dominant parameter for surface finish. Sahin [8] observed that cBN insert performed better compared to ceramic insert in machining hardened AISI 52100 steel. Cutting speed was significant factor for tool wear next to hardness and feed rate.

Huang et al. [9] observed abrasion, adhesion and diffusion predominant wear mechanisms during hard turning using cBN tool. Yallese et al. [10] investigated machining of 100Cr6 steel using cBN tool and suggested the cutting speed range of 90-220 m/min where better results were obtained in context to tool wear, surface roughness and cutting temperature. Ozel et al. [11] studied turning of hardened AISI H13 tool steel through cBN cutting tool on surface roughness. Workpiece hardness, cutting edge geometry, feed and cutting speed were significant parameter for surface roughness. Honed edge geometry and lower workpiece surface hardness played a significant role for lowering surface roughness and tangential and radial component of cutting force. Horng et al. [12] observed in machinability study that cutting speed and interaction effect of feed with nose radius affects more on flank wear during machining austenitic Hadfield steel using Al_2O_3/TiC mixed ceramics insert. Cutting speed and nose radius was significant parameter for surface roughness.

Grzesik and Zalisz [13] observed different wear mechanisms during machining hardened AISI 5140 steel (60 HRC) using mixed ceramic insert. Yusof et al. [14] investigated the machining performance of conventional and wiper coated ceramic insert using hardened D2 steel. The wiper tool observed slightly shorter tool life but surface finish was better compared to conventional ceramic insert. Gaitonde et al. [15] obtained better machining performance using TiN coated wiper ceramic insert for hardened D2 steel. Conventional ceramic insert performed better for reduction of cutting force, power and specific cutting force. Davim and Figueira [16] observed that using wiper ceramic insert, good surface quality of less than 0.8 μm surface roughness was achieved during turning of hardened D2 steel. The dominant parameters for flank wear were observed to be cutting time and cutting speed. Feed dominated more on specific cutting pressures. Sahoo and Pradhan [17] observed abrasion and adhesion as the dominant wear mechanisms during turning Al/SiCp metal matrix composites.

Sahoo et al. [18] applied Taguchi's DOE methodology and regression analysis for optimization and modeling in turning AISI 1040 steel. For simultaneous optimization of responses, Grey based Taguchi technique has been proposed. Guddat et al. [19] studied on surface integrity aspects using PCBN wiper inserts and observed to be improvement in surface finish and higher compressive residual stresses compared to conventional insert. Gaitonde et al. [20] investigated the effects of cutting parameters on machinability aspects in hard turning with conventional and wiper ceramic inserts on cutting force, surface roughness and tool wear. Developed ANN model predicted well on machinability. Gaitonde et al. [21] studied the machinability aspects of hardened AISI D2 steel and analyzed the effects of cutting parameters and machining time on machining force, surface roughness and tool wear using wiper ceramic insert through response surface methodology based mathematical models.

Gaitonde et al. [22] observed the better performance of CC650WG wiper ceramic insert on surface roughness and tool wear during hard machining of AISI D2 steel whereas CC650 conventional insert reduces machining force, power and specific cutting force during machining. Quiza et al. [23] investigated hard machining of AISI D2 steel using ceramic insert on tool wear and developed regression and ANN model. ANN model was obtained to be accurate and predicted well compared to regression model for tool wear. Sahoo and Sahoo [24] experimentally investigated machinability aspects on flank wear, surface roughness, cutting force and chip morphology in hard machining of AISI 4340 steel (47±1 HRC) using coated carbide insert. Surface roughness of less than 1.6 microns was produced and comparable with cylindrical grinding. Cutting speed and feed were dominant parameters on tool wear and surface roughness and thrust force was observed to be the largest component in finish hard turning.

Thus, hard machining is a recent emerging technology and can be performed using tools with geometrically defined cutting edges and hardness of work material varies from 45-70HRc range [25]. Based on the review, it is revealed that the machining of hardened bearing steel (AISI 52100) is usually performed by cBN and ceramic inserts and found to be acceptable. ‘Therefore’, use of low cost multilayer coated carbide insert in turning of bearing steel at hardness range of 55 HRC is limited and almost empty. This brings a motivation to conduct some machinability investigation so as to judge its applicability in actual machining industries under dry environment. Therefore, the present study deals with

a) Machinability investigation of hardened AISI 52100 steel (55 ± 1 HRC) using multilayer coated carbide insert under dry environment with respect to flank wear, surface roughness and chip morphology.
b) Development of mathematical model using quadratic regression analysis and optimization of the cutting parameters for its useful utilization.

2. Experimental Procedure

Round bar of bearing steel AISI 52100 was used as the workpiece material of 40 mm diameter and 120 mm long respectively. The workpiece is heat treated through quenching and tempering followed by air cooling to obtain hardness of 55±1 HRC. The commercially available cutting inserts are coated carbide with different coating layers such as TiN/TiCN/Al_2O_3/TiN(TN7105, WIDIA) and mounted on the tool holder coded PCLNR2525M12 and inserts are of CNMG120408 type. The machining experiment was carried out on CNC Lathe (Jobber XL, ACE Designers, India, 16 kW, 3500 rpm maximum rotational speed) without cutting fluid (Fig. 1). The selected cutting parameters were chosen as: cutting speed (v), feed (f) and depth of cut (d) with four levels such as v = 70, 110, 150 and 190 m/min, f = 0.04, 0.08, 0.12 and 0.16 mm/rev and d = 0.1, 0.2, 0.3 and 0.4 mm respectively. Based on Taguchi L_{16} orthogonal array, experiments are conducted which constitutes 16 experimental runs. The arithmetic surface roughness average (*Ra*) was measured by Taylor Hobson, Surtronic 25 surface roughness tester three times at different locations of workpiece.

The cutoff length is taken as 0.8 mm and assessment length of 4 mm and average values are reported. The wear of inserts was monitored by Nikon profile projector and images are taken by Stereo zoom microscope. The shape, colour and images are captured by digital camera. The turning length was taken as 100 mm for individual experimental run and before experiment, rust skin layers was removed by conducting some preliminary cut. At each experimental run, new cutting edge was used. The experimental results and images of flank wear and chips are presented in Table 1, Figs. 2 and 3 respectively.

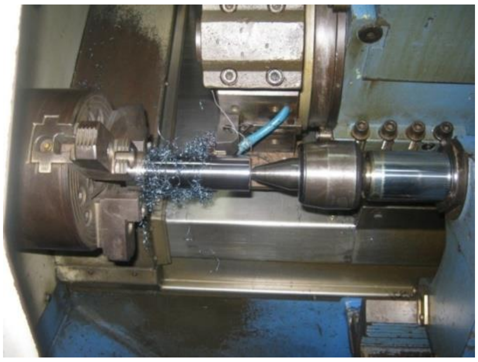
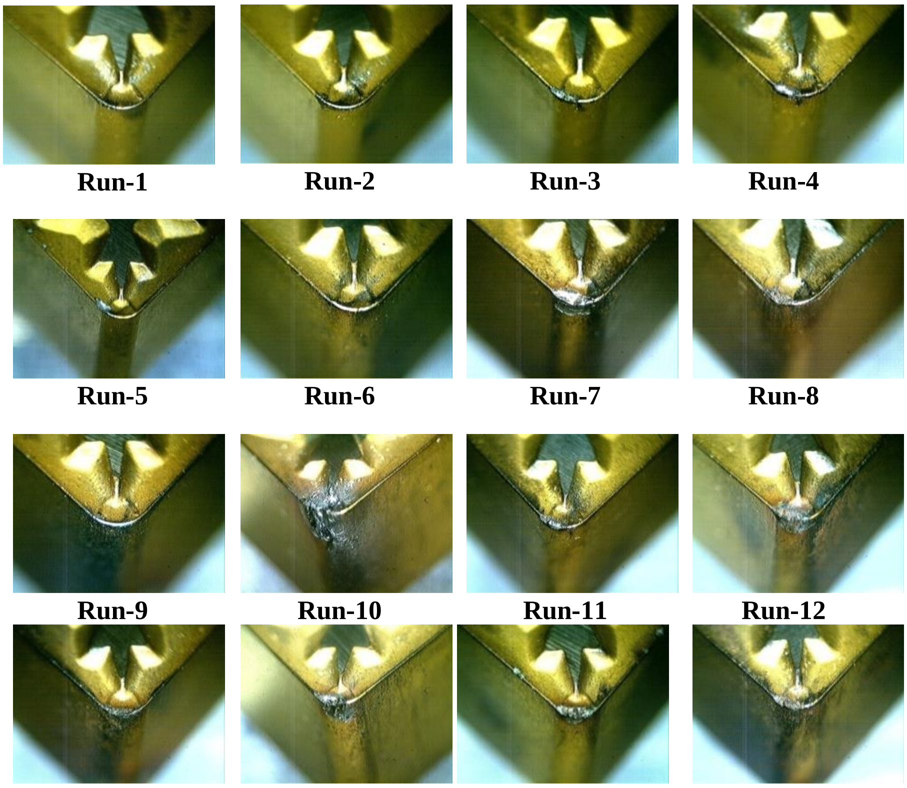


Fig. 1. Experimental setup.



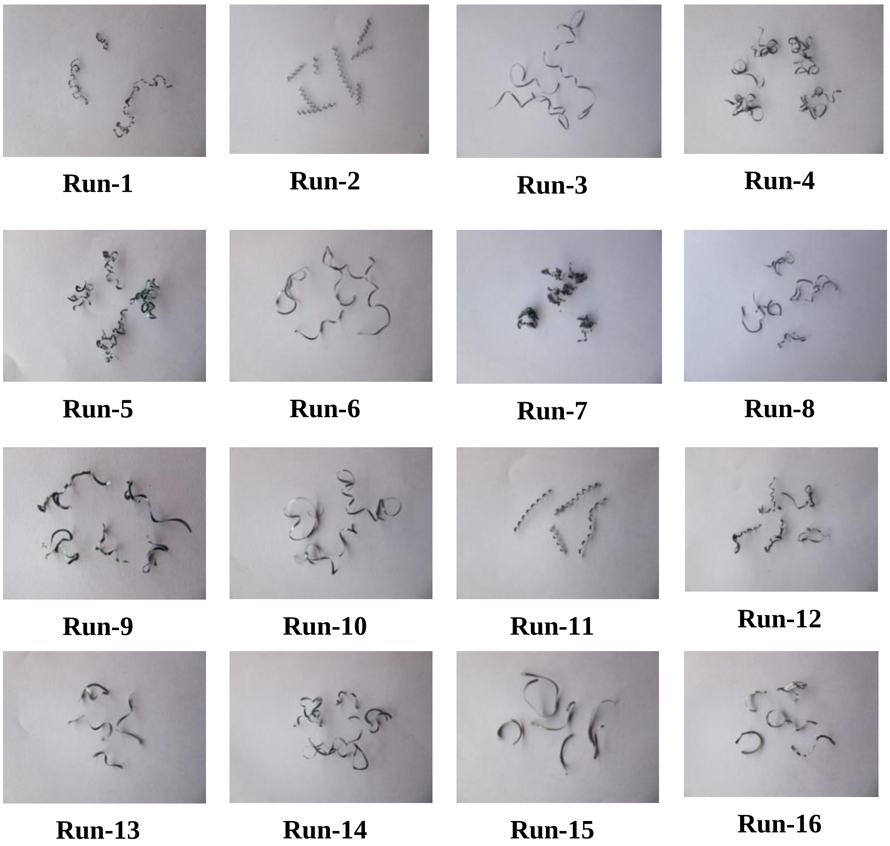
Run-1 **Run-2** **Run-3** **Run-4**

Run-5 **Run-6** **Run-7** **Run-8**

Run-9 **Run-10** **Run-11** **Run-12**

Run-13 **Run-14** **Run-15** **Run-16**

Fig. 2. Images of flank wear at different runs.



Run-1 **Run-2** **Run-3** **Run-4**

Run-5 **Run-6** **Run-7** **Run-8**

Run-9 **Run-10** **Run-11** **Run-12**

Run-13 **Run-14** **Run-15** **Run-16**

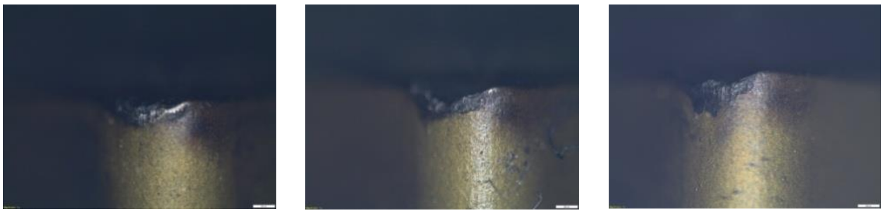
Fig. 3. Images of chips at different runs.

Table 1. Experimental result of *VBc* and *Ra* and chip morphology.

Run No.	Cutting parameters			Experimental results		Chip morphology	
	d	*f*	*v*	*VBc*	*Ra*	Shape	colour
1	0.1	0.04	70	0.056	1.15	Helical	Blue
2	0.1	0.08	110	0.102	1.03	Helical	Blue
3	0.1	0.12	150	0.151	1.42	Ribbon	Blue
4	0.1	0.16	190	0.264	1.31	Ribbon	Burnt blue
5	0.2	0.04	110	0.063	0.81	Ribbon	Blue
6	0.2	0.08	70	0.061	1.17	Ribbon	Blue
7	0.2	0.12	190	0.765	1.86	Ribbon	Burnt blue
8	0.2	0.16	150	0.498	1.91	Ribbon	Burnt blue
9	0.3	0.04	150	0.241	0.76	Ribbon(saw)	Burnt blue
10	0.3	0.08	190	0.898	1.65	Ribbon(saw)	Blue
11	0.3	0.12	70	0.153	1.82	Helical	Blue
12	0.3	0.16	110	0.541	2.44	Ribbon	Grey
13	0.4	0.04	190	0.594	0.91	Ribbon(saw)	Burnt blue
14	0.4	0.08	150	0.525	1.20	Ribbon (saw)	Burnt blue
15	0.4	0.12	110	0.429	1.78	Ribbon	Grey
16	0.4	0.16	70	0.338	2.85	Ribbon (saw)	Grey

3. Analysis of Experimental Results

At depth of cut of 0.1 mm (Run 1, 2, 3 and 4), the evolution of flank wear was observed to be steady and good stability. No premature failure like chipping is observed at the cutting zone. The principal mechanism of tool wear is observed to be abrasion in the studied experiments. The ranges of flank wear are of 0.056 mm and 0.264 mm for TiN coated tools. The measured surface roughness readings are within 1.03 to 1.42 microns respectively which is well within the 1.6 microns referred as acceptable to grinding operations. The chips are of helical and ribbon type with blue colour. 'Therefore', at higher cutting speed (190 m/min) at Run-4, burnt blue colour chips are obtained showing the rise of cutting temperature at the tool tip. In continuation to further research, flank wear of cutting insert has been analyzed at run1 and tool life is assessed considering 0.3 mm flank wear criterion. This has been performed through experimentation with successive machining time (*Tc*)to assess the evolution of flank wear under dry environment and shown in Fig. 4. The machining operation was stopped up when flank wear reaches 0.3 mm and tool life is estimated. The progression of flank wear is steady with successive runs and there is no premature tool failure by fracturing and chipping observed up to 8 minute (Fig. 4). Abrasive marks are obtained due to rubbing action between chip and flank surface of tool. It has been traced that the width of wear gradually improved with machining time and exceeds the value of 0.3 mm and reaches 0.302 mm after 15 minutes of machining. So, the tool life of cutting insert at run-1 is observed to be 15 minute.



(a) *Tc* = 8 min, *VBc* = 0.255 mm **(b) *Tc* = 11.5 min, *VBc* = 0.263 mm** **(c) *Tc* = 15 min, *VBc* = 0.302mm**

Fig. 4. Images of flank wear with successive machining time at run 1 (*d* = 0.1mm, *f* = 0.04 mm/rev and *v* = 70 m/min).

At of 0.2 mm depth of cut (Run 4, 5, 6 and 7), with rise of feed and cutting speed up to 0.08 mm/rev and 110 m/min, flank wear and surface roughness are below the criteria limit of 0.3 mm and 1.6 microns respectively. No catastrophic failure of cutting tool or chipping and fracturing was observed at the cutting edge and machining was steady. 'Therefore', at higher feed (0.12 and 0.16 mm/rev) and cutting speed range (150 and 190 m/min), flank wear exceeds 0.3 mm (0.765 and 0.498 mm at run 7 and 8) and roughness values are above 1.6 microns (1.86 and 1.91 microns at run 7 and 8) respectively. It is quite depicted from the images of flank wear at run 7 and 8 respectively (Fig. 2) and chips are ribbon type with burnt blue colour (Fig. 3).

At of 0.3 mm depth of cut (Run 9, 10, 11 and 12), particularly at Run 10 and Run 12 which is at higher cutting speed and feed range, flank wear and surface roughness values exceeds 0.3 mm and 1.6 microns respectively. The saw tooth ribbons like chips are obtained with blue colour at this runs. The chips are undergone severe plastic deformation and most of the heat is transferred into the chips. This heat concentrates on the local shear band of the chip and hence saw tooth chips are formed as reported by Thamizhmanii and Hasan [26]. For Run 9 and 11, the evolution of flank wear was steady without any fracturing with acceptable limit of surface roughness values.

At depth of cut of 0.4 mm (Run 13, 14, 15 and 16), the flank wear completely overcomes 0.3 mm and chipping is clearly observed from the images of runs. ‘Therefore’, surface roughness exceeds the value of 1.6 microns at higher feed range such as 0.12 and 0.16 mm/rev only. The burnt blue color ribbon like saw tooth chips are obtained in Run 13, 14, 15 and 16 thus reveals the generation of higher cutting temperature in hard machining. It leads to softening of cutting inserts and consequently diffusion process occurs. Thus brings to the quick dulling of cutting insert edge and chipping prevails causing cutting edge degradation and adversely affects surface quality and part dimensions. These observations clearly depicts that at any range of cutting speed and feed range but at a depth of cut of 0.4 mm, machining does not perform well because of rapid wear of tools, thus not recommended for industrial applications.

From above analysis, it clearly shows that at Run 1, 2, 3, 4, 5, 6, 9 and 11, the flank wear progresses steadily as it is well within the criteria of 0.3 mm. Also, surface roughness values are well within the criteria of 1.6 microns in many runs except Run 7, 8, 10, 11, 12, 15 and 16. The outperformed performance of multilayer coated carbide insert may be attributed due to coating material on carbide substrate as top TiN coating layer called lubricious layer that reduces friction and heat generation. Also subsequent Al_2O_3 coating layer which have oxidation resistance and thermal barrier property and next TiCN coating layer offers wear resistance property that delays the evolution of flank wear and wear progression was steady. Abrasion was seen as the principal wear mechanism in machining hardened steel and chipping is observed at the higher cutting speed range.

Next, main effect plot was drawn to evaluate the effects of parameters on responses. Analysis of variance (ANOVA) is studied to identify the significance of parameters on responses at 95% confidence level. If probability of significance (P-value) for a process parameter is less than 0.05, then the corresponding parameter is said to be significant on the selected response. It is evident that with increase of all machining parameters, flank wear increases. ‘Therefore’, growth of flank wear with respect to feed is minimal (Fig. 5). The rubbing action at the junction of flank and machined contact surface area occurs very rapidly with rise of cutting speed and depth of cut that subsequently brings thermal softening of tool tip and deteriorates the cutting edge of the tool. Similarly, surface roughness rises with rise of depth of cut and feed (Fig. 6). ‘Therefore’, a decrease of surface roughness is noticed with rise of cutting speed up to 150 m/min and then rises at higher cutting speed (190 m/min). This may be due to the reason of increase of tool wear thus deteriorates the surface quality of the workpiece at increased cutting speed. Cutting speed is dominant for flank wear and feed drastically influences the surface roughness from ANOVA study as p-value exceeds 0.05 at 95% confidence level (Tables 2 and 3). Feed-depth of cut does not have influenceon flank wear. Also, cutting speed and depth of cut do not affect so much on response like surface roughness.

Table 2. ANOVA for *VBc* (TiN coated carbide).

Source	DF	SS	MS	*F*	*P*	Remarks
d	3	0.2765	0.0921	2.78	0.132	Insignificant
f	3	0.0749	0.0249	0.75	0.559	Insignificant
v	3	0.4882	0.1627	4.91	0.047	Significant
Error	6	0.1989	0.0331			
Total	15	1.0385				
S = 0.182		R^2= 80.85 %				

Table 3. ANOVA for *Ra* (TiN coated carbide).

Source	DF	SS	MS	*F*	*P*	Remarks
d	3	0.5615	0.1872	1.38	0.336	Insignificant
f	3	3.3982	1.1327	8.35	0.015	Significant
v	3	0.3899	0.13	0.96	0.471	Insignificant
Error	6	0.8139	0.1356			
Total	15	5.1634				
S =0.3683	R^2 = 84.24 %					

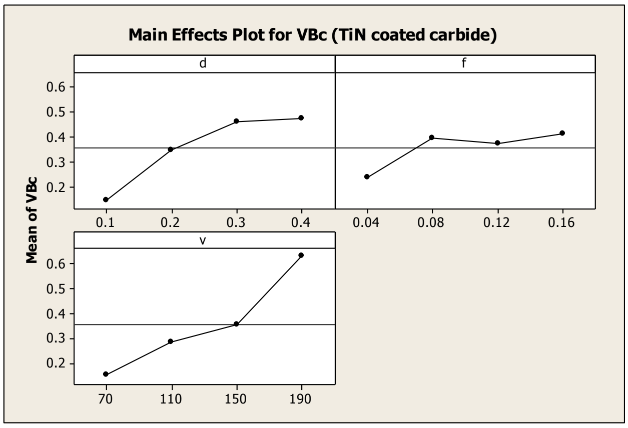


Fig. 5. Main effects plot for *VBc*.

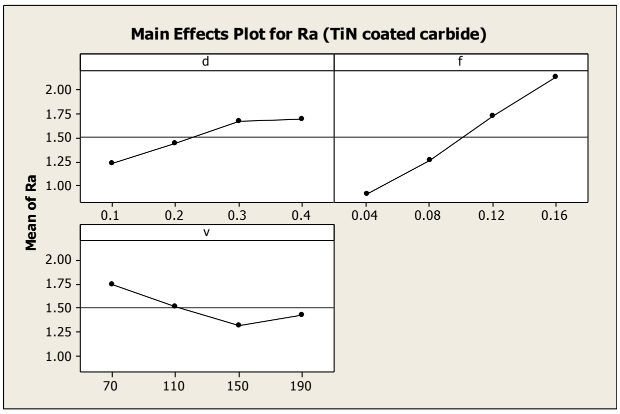


Fig. 6. Main effect plot for *Ra*.

From above discussions, it clearly shows the benefit of utilizing coated carbide insert under dry finish turning of hardened AISI 52100 steel (55±1 HRC) at moderate cutting speed. 'Therefore', there is a need to develop prediction model and optimization of process parameter for its better outcomes in hard turning utility.

4. Regression Based Modeling

In hard turning, cutting parameters influences more on responses like flank wear and surface roughness where both responses are dependent on each other because excessive tool wear affects adversely surface quality. Quadratic regression methodology for development of mathematical model is an efficient approach to address this relationship. In the present model, a second order equation is developed through multiple regression technique which can predict the responses at different levels of parameter settings. The adequacy of model is checked through its *p*-value which should be less than 0.05, determination coefficients (R^2), normal probability plot and Anderson-darling test where *p*-value should be more than 0.05). The more is the R^2 value, i.e., when an approach to one, the greater is the significance of model.

Developed mathematical models are presented in equation 1 and 2 with corresponding R^2 value.

Flank wear (R^2 = 99%)

$$VBc = 0.4716 - 2.7833d - 1.2579f - 0.0062v - 4.7563d^2 - 19.1016f^2 + 0.00v^2 + 31.0313df + 0.0249dv + 0.0061fv \tag{1}$$

Surface roughness (R^2 = 89.9%)

$$Ra = 1.8123 - 5.9923d + 1.1229f - 0.0089v - 4.8125d^2 + 8.2031f^2 + 0.0001v^2 + 68.3239df + 0.0176dv - 0.0613fv \tag{2}$$

From the above equation, it is revealed that the R^2 value approaches to 1 which indicates best fit of the model and presents good correlation between experimental and predicted data which can be seen from Figs 7 and 8 respectively. A close relationship between experimental and predicted values is observed. Also ANOVA analysis of model for flank wear and surface roughness shows the statistically significance because of its *p*-value (0.000) is less than 0.05 (Tables 4 and 5). Also the residuals are falling on a line signifying the significance of model (Figs. 9 and 10) depicted from normal probability plots. From Anderson-Darling test of probability, the *p*-value is found to be more than 0.05 at 95 % confidence level which is obviously observed from Figs. 11 and 12 that determines the significance of model developed. Plot of residuals versus fitted value shows the structure less distribution of residuals that are independently distributed and models are adequate and significant (Figs. 13 and 14). Thus, the models sufficiently predict accurate results and may be implemented in machining environment. The contour plots (Figs. 15 and 16) shows the curvilinear profile as per the quadratic regression model obtained.

From the contour plots, a range of cutting parameters, i.e., cutting speed from 0-110 m/min for *VBc* and 0-150 m/min for *Ra*, feed of 0-075 m/min for *VBc* and *Ra* and depth of cut from 0.1-0.4 mm for *VBc* and *Ra* may be selected for minimization of both responses in hard turning. Thus, low level of cutting speed (70 m/min)-feed (0.04 mm/rev)-depth of cut (0.1 mm) is recommended as far as both responses are concerned. At these parametric conditions, *VBc* and *Ra* values are experimentally obtainedas0.056 mm and 1.15 microns that is quite under the criterion limit of 0.3 mm and 1.6 microns respectively. It is interesting to note that, experimental trial No. 5 possess actually better machining performance than the one determined as the best (trial No. 1). Namely, under these conditions one obtains *Ra* of 0.81 microns in comparison with *Ra* of 1.15 which is considerably better and *VBc* of 0.063 mm which is comparable to *VBc* of 0.056 mm. ‘Therefore’, under these conditions, material removal rate is much better, considering that depth of cut and cutting speed are higher and well within the domain of parameters obtained from contour plots for both responses. Hence, cutting speed of 110 m/min, feed of 0.04 mm/rev and depth of cut of 0.2 mm (Run 5) may be considered as optimized cutting parameters for flank wear and surface roughness in hard turning of AISI 52100 bearing steel using multilayer coated carbide insert under dry environment.

Table 4. ANOVA for *VBc* model.

Source	DF	Seq SS	Adj SS	Adj MS	*F*	*P*	Remarks
Regression	9	1.038	1.038	0.1153	1202.64	0.000	Significant
Linear	3	0.7418	0.0327	0.0109	113.91	0.000	
Square	3	0.072	0.072	0.024	250.58	0.000	
Interaction	3	0.224	0.224	0.0746	778.76	0.000	
Residual Error	6	0.0005	0.0005	0.0000			
Total	15	1.0385					

Table 5. ANOVA for *Ra* model.

Source	DF	Seq SS	Adj SS	Adj MS	*F*	*P*	Remarks
Regression	9	5.1057	5.1057	0.5673	59.01	0.000	Significant
Linear	3	4.1631	0.1209	0.0403	4.19	0.064	
Square	3	0.1571	0.1571	0.0523	5.45	0.038	
Interaction	3	0.7854	0.7854	0.2618	27.23	0.001	
Residual Error	6	0.0576	0.0576	0.0096			
Total	15	5.1633					

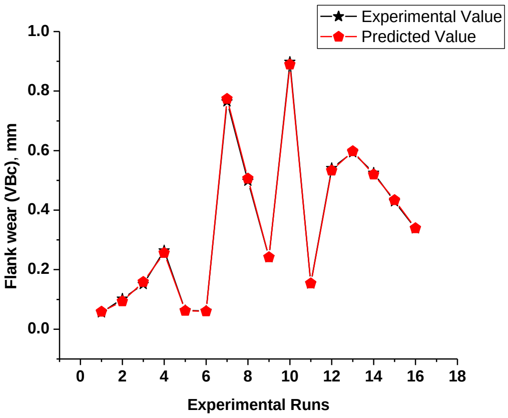


Fig. 7. Experimental vs. predicted values of *VBc*.

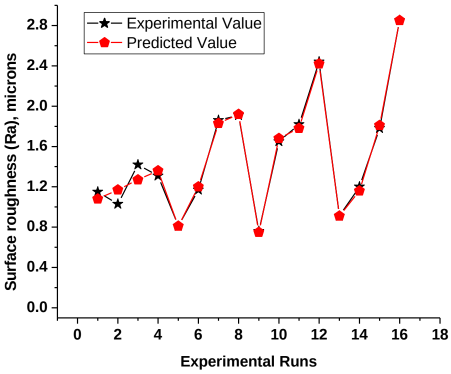


Fig. 8. Experimental vs. predicted values of *Ra*.

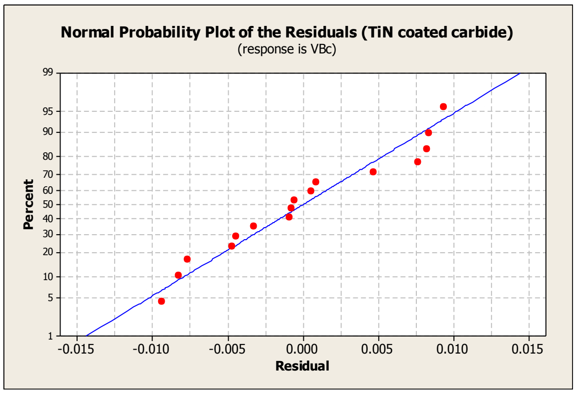


Fig. 9. Normal probability plot for *VBc*.

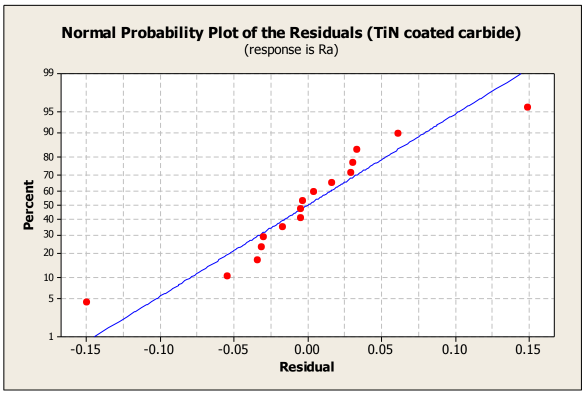


Fig. 10. Normal probability plot for *Ra*.

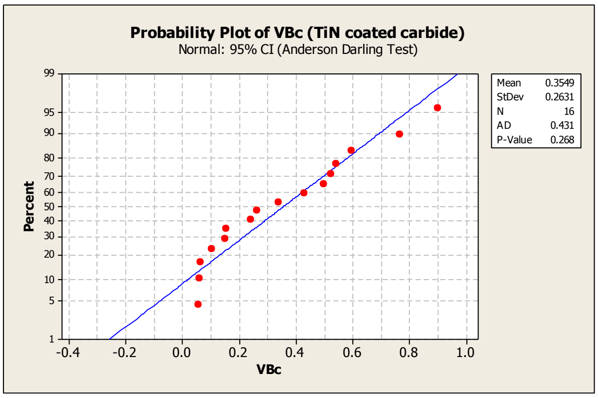


Fig. 11. Anderson-Darling test for *VBc*.

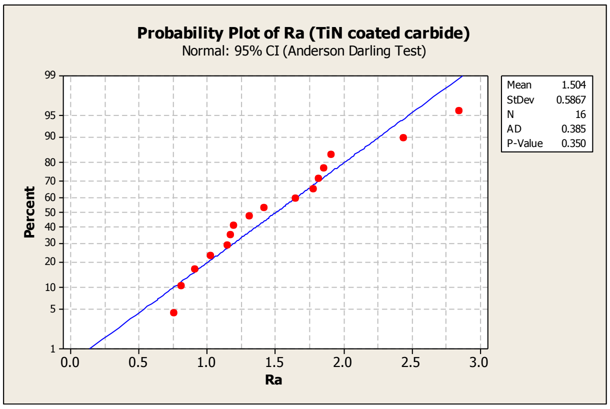


Fig. 12. Anderson-Darling test for *Ra*.

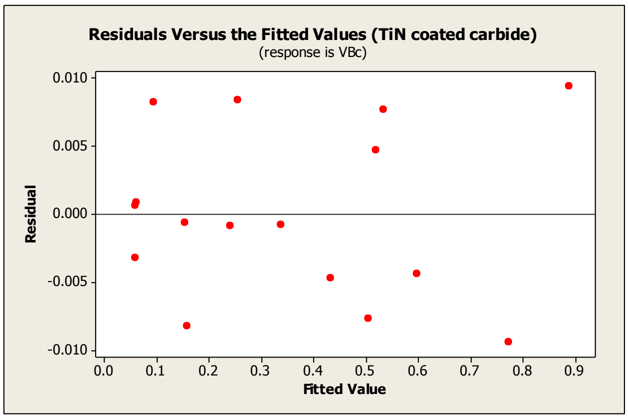


Fig. 13. Residuals vs. fitted values for *VBc*.

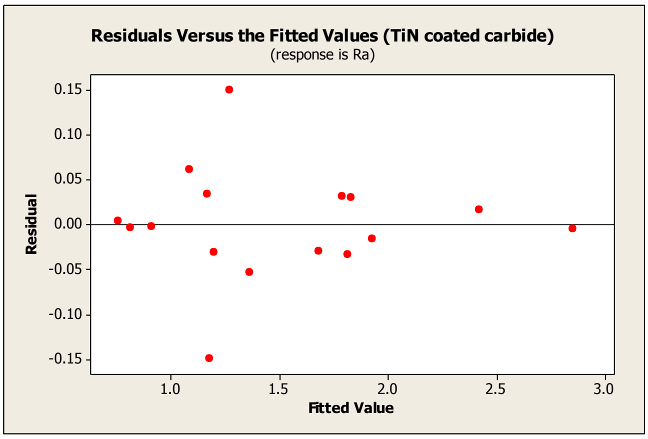


Fig. 14. Residuals vs. fitted values for *Ra*.

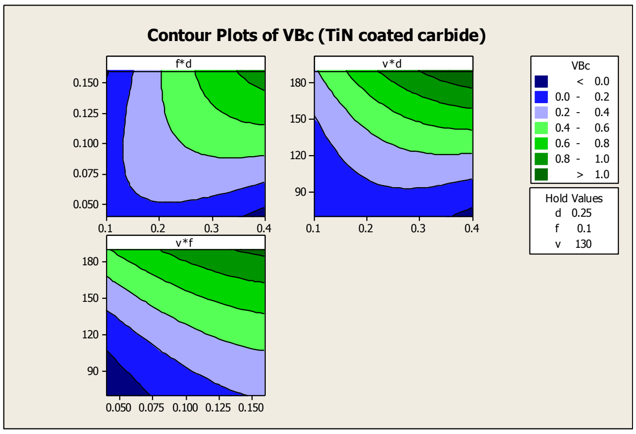


Fig. 15. Contour plots for *VBc*.

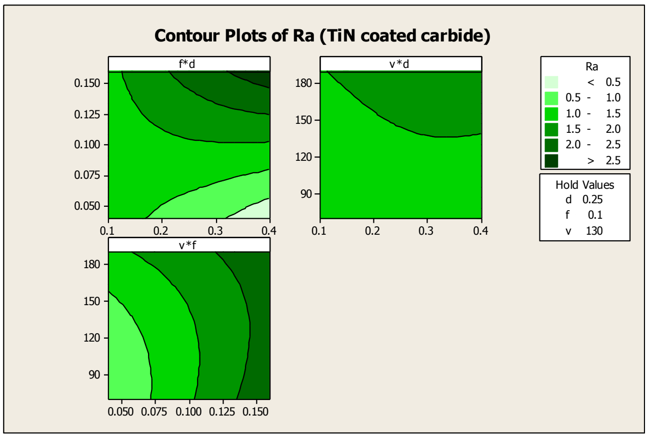


Fig. 16. Contour plots for *Ra*.

5. Conclusions

In the machinability study, thorough investigation and analyses have been assessed in order to find out the extent of utilization of multilayer coated carbide insert in machining hardened AISI 52100 bearing steel. Based on investigations, following findings are summarized as follows:

- No evidence of chipping and fracturing was observed during machining of hardened AISI 52100 bearing steel and the growth of flank wear was steady and gradual. The surface roughness values are well within 1.6 microns in most of the runs. The principal mechanism of wear is observed to be abrasion. 'Therefore', chipping is observed at elevated cutting speed range which brings to the quick dulling of cutting edge and adversely affects the surface finish.
- It has been observed that the width of wear gradually improved with machining time and exceeds the value of 0.3 mm after 15 minutes of machining. Abrasive marks are obtained due to rubbing action between chip and flank surface of tool. Tool life of cutting insert at run-1 is observed to be 15 minute.
- The chips are in the form of helical and ribbon type saw tooth appearance with blue colour obtained during hard turning. Hard turning yields better surface finish with minimal flank wear at some runs for AISI 52100 selected steel.
- Cutting speed is dominant parameter for flank wear and for surface roughness; feed affects more from ANOVA study as *p*-value exceeds 0.05 at 95% confidence level. Quadratic regression model presents good correlation between experimental and predicted data and found to be statistical significant.
- Experimental trial No. 5 possesses actually better machining performance than the one determined as the best (trial No. 1). Under these conditions one obtains *Ra* of 0.81 microns in comparison with *Ra* of 1.15 which is considerably better and *VBc* of 0.063 mm which is comparable to *VBc* of 0.056 mm. Material removal rate is much better, considering that depth of cut and cutting speed are higher and well within the domain of parameters obtained from contour plots for both responses. Hence, cutting speed of 110 m/min, feed of 0.04 mm/rev

and depth of cut of 0.2 mm (Run 5) may be considered as optimized cutting parameters for flank wear and surface roughness.

- The outperformed performance of multilayer coated carbide insert may be attributed due to the presence of TiN, Al_2O_3 and TiCN hard thin coating layer above carbide substrates enables delay of the growth of flank wear.
- From above discussions, it clearly shows the benefits of utilizing low cost coated carbide insert under dry finish turning of hardened AISI 52100 steel (55±1 HRC) at moderate cutting speed.

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