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Statistical regression modeling and machinability study of hardened AISI 52100 steel using cemented carbide insert

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The present study investigates performance and feasibility of application of low cost cemented carbide insert in dry machining of AISI 52100 steel hardened to (55 ± 1 HRC) which is rarely researched as far as machining of bearing steel is concerned. Machinability studies i.e. flank wear, surface roughness and morphology analysis of chip has been investigated and statistical regression modeling has been developed. The test has been conducted based on Taguchi L_{16} OA taking machining parameters like cutting speed, feed and depth of cut. It is observed that uncoated cemented carbide insert performs well at some selected runs (Run 1, 5 and 9) which show its feasibility for hard turning applications. The developed serrated saw tooth chip of burnt blue colour adversely affects the surface quality. Adequacy of the developed statistical regression model has been checked using ANOVA analysis (depending on F value, P value and R^2 value) and normal probability plot at 95% confidence level. The results of optimal parametric combinations may be adopted while turning hardened AISI 52100 steel under dry environment with uncoated cemented carbide insert.

1. Introduction

Machining of hardened steel is becoming now an emerging technology due to high flexibility, high productivity, and reduction of cycle time, higher productivity and being utilized under dry cutting conditions. It is widely now-a-days applied in manufacturing industry and concerned about the finishing of hardened materials above 45 HRC. For successful implementation of hard turning, tool materials like cubic boron nitride (CBN) and ceramics are used in operation. However with the advent of advanced cutting inserts and rigid machining systems, turning of workpiece below 45 HRC is treated now-a-days as soft turning and in between 45-65 HRC, it is referred as hard turning. As different variables like cutting speed, feed and depth of cut, geometrical parameters (nose radius, rake angle, edge geometry), hardness, cutting tool vibrations and environmental parameters like cutting fluids affects the machinability performance in hard turning, the research in this field is continuing for its successful implementation in the industry. Aerospace and automobile industries produces components and machining plays key role of it for fine surface finish which obviously deteriorates with the evolution of tool wear. Therefore the

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study of machinability is essentially needed and a brief literature review is presented with the various works performed by the researchers.

2. Literature review

Chen (2000) investigated the machining of hardened steel (45-55 HRC) using CBN insert. It is observed that the thrust force is higher compared to cutting force component. The surface finish is found to be close to the grinding process. The surface finish is influenced by variables like cutting speed, tool wear and plastic behaviour of the work material using CBN insert in operation. Davim and Figueira (2007) studied the machinability of D2 (60 HRC) steel. The surface roughness less than 0.8 microns can be obtained with the suitable selection of parameters. This concludes that the hard turning can successively replace the traditional grinding operations. Sahin and Motorcu (2008) utilized the response surface methodology for hard turning of AISI 1050 steel using cubic boron nitride (CBN) cutting inserts under different conditions and developed model for surface roughness. Feed rate is found to be most influencing parameters for surface roughness. Singh and Rao (2007) studied turning of hardened AISI 52100 steel using mixed ceramic insert. The influence of cutting conditions and tool geometry has been investigated on surface roughness. Feed rate is found to be the most affecting parameter for surface finish and next parameter is nose radius and lastly cutting speed. Bouacha et al. (2010) studied tool wear and force behavior on machining hardened AISI 52100 steel (64 HRC) with CBN insert and developed model through response surface methodology. Thrust force components is found to be largest and parameters like depth of cut influences more on it compared to cutting speed and feed rate.

Guddat et al. (2011) investigated on hard turning of AISI 52100 (100Cr6) (58-62 HRC) steel using wiper PCBN inserts. The influence on surface integrity and cutting forces has been studied and developed a statistical model for cutting forces and surface roughness. Azizi et al. (2012) studied the influence of cutting parameters and workpiece hardness on surface roughness and cutting force during turning hardened AISI 52100 steel with coated Al_2O_3 + TiC mixed ceramic cutting tools. The contributing effect of surface roughness is found to be feed rate, workpiece hardness and cutting speed. Similarly, the significant effect on cutting force components are obtained to be depth of cut; workpiece hardness and feed rate respectively. Zahia et al. (2015) studied on hard turning of AISI 4140 (56 HRC) steel using PVD coated ceramic insert. Feed rate and depth of cut are found to be the most significant parameters affecting surface roughness and cutting forces from analysis of variance (ANOVA) study. Chinchanikar et al. (2014) investigated during turning hardened AISI52100 steel (60-62HRC) using PVD-coated nano laminated TiSiN-TiAlN carbide tool taking various cooling medium and parameters on surface roughness. It is observed that under dry condition, lower surface roughness is obtained. At higher cutting speed, application of coconut oil lowers surface roughness values. It is more effective at higher feed and depth of cut also. Singh and Rao (2010) studied hard turning using ceramic insert and developed model for flank wear. It is observed that during progression of flank wear, normal load/force occurred at the flank face of the tool is found to be constant. Huang and Dawson (2005) studied and developed the model for crater wear depth in hard turning of AISI 52100 steel incorporating abrasion, adhesion and diffusion wear mechanisms and experimentally validated. Dureja (2012) presented a response surface model for flank and crater wear during hard turning of AISI-H11 steel with TiN coated CBN tool. It is evident that the cutting speed and feed have the significant effect on flank wear. Mandal et al. (2011) studied some aspects of machinability of AISI4340 steel using Zirconia Toughened Alumina (ZTA) ceramic inserts with respect to flank wear. The investigation revealed that depth of cut dominated flank wear to a greater extent followed by cutting speed. Sahoo and Sahoo (2012) experimentally investigated machining performance of hardened AISI 4340 steel (47HRC) applying uncoated and multilayer coated carbide inserts. Multilayer TiN outer layer coated carbide inserts performs well in comparison to uncoated and outer ZrCN coated carbide inserts. Sahu et al. (2015) experimentally investigated dry machining performance of hardened AISI 1015 (43 HRC) steel using carbide insert and compared under environment of spray cooling. It is better to adopt spray cooling environment than dry cutting conditions as machining performance improves significantly. Sahoo et al. (2013) developed prediction model for flank wear during dry hard turning of EN 24 steel with PVD TiN coated mixed ceramic insert. The principal wear mechanism during hard turning is obtained to be abrasion and diffusion. Most influencing factor for flank wear is observed to be machining time from ANOVA study. Das et al. (2015) experimentally investigated during dry hard turning operation in context to surface roughness, flank wear and chip morphology with coated carbide and ceramic insert and developed the predicted model. For surface roughness, feed is obtained as the influencing parameter and dominant wear mechanism is shown as abrasion. Saw tooth chip at higher feed degrades the surface finish. Models are found to be significant and adequate. Sahoo and Sahoo (2013) investigated multi-response parametric optimization and modeling aspects through RSM and grey relational analysis along with economical feasibility in turning hardened steel using multilayer coated carbide insert. Sahoo and Mishra (2014) performed optimization and modeling studies in turning hardened steel through RSM and desirability analysis. RSM model has been found to be good degree of accuracy.

Mhamdi et al. (2013) conducted hard turning tests for D2 steel (62 HRC) with various cutting conditions and obtained chip formation mechanisms and optimal parametric results. Sahoo and Sahoo (2013) assessed progression of flank wear and tool life in dry turning of hardened AISI 4340 steel (47 ± 1 HRC) with ZrCN outer multilayer coated carbide inserts. The principal wear mechanism is obtained to be abrasion. Zhang et al. (2006) studied the surface integrity aspects during turning hardened bearing steel (62-63 HRC) using CBN insert. The process generates appropriate cutting parameters for surface integrity. Feed rate has been found to be the dominant impact on the surface finish during study. Paiva et al. (2007) utilized TiN coated mixed ceramic tool during hard turning of AISI 52100 steel and studied the effect of cutting parameters. Cutting speed of 238 m/min, feed rate of 0.08 mm/rev and depth of cut of 0.32 mm yields maximum material removal rate (MRR) with good surface quality. Davim and Figueira (2007) compared the performance of utilizing wiper and conventional ceramic inserts in turning hardened D2 steel (60 HRC). For flank wear, factors such as cutting time and cutting velocity affects more. Feed rate affects more on specific cutting pressures of inserts. Wiper ceramic insert produced less than 0.8 microns of surface roughness during machining. It is revealed from literature review that tool wear affects more on quality of workpiece and also accuracy of dimensions of product. Most of study of hard turning is based on using CBN and ceramic inserts and subsequently models have been developed. Some studies have undertaken for medium hardened steel using coated carbide insert. Hard turning of AISI 52100 steel of hardness range of 55 HRC or more has been investigated using costly CBN and ceramic insert which has found itself wide application in the bearing industry and can successfully replace the traditional grinding process. However the study on some machinability aspects during machining hardened AISI 52100 steel at higher hardness level around 55-60 HRC using cemented carbide insert is lacking from the review of literature and research is essentially needed for the wide application of carbide inserts in hard machining. This also may lead to an economic alternative to the tool already adopted during hard machining. Therefore, some machinability study and modeling and optimization study for the tool wear and surface roughness in machining hardened AISI 52100 steel using cemented carbide insert is extremely valuable.

In this framework, the present study is focused on some machinability study of AISI 52100 steel (55±1 HRC) using uncoated cemented carbide insert under dry conditions using Taguchi L_{16} orthogonal array in context to responses such as flank wear, surface roughness and analyzing chip samples. Also, the parametric influences on responses are analyzed through ANOVA study and prediction models have also been presented through quadratic regression analysis. The optimized cutting parameters have also been suggested.

3. Experimental procedure

The selected material for test specimen are hardened AISI 52100 steel (55±1 HRC) popularly used as bearing steel. This has taken in the shape of cylindrical rods of 40 mm diameter and length of 120 mm. The hard turning experiments are conducted on a CNC lathe of 3500 rpm spindle speed (maximum) and

16 KW power with controller of sinumeric under dry environment (Fig. 1). The material for the cutting tool insert is commercially available uncoated cemented carbide diamond shape of CNMG 120408 type. The insert is mounted on a PCLNR2525 M12 type right hand tool holder. The levels of three cutting parameters (depth of cut, feed and cutting speed) are shown in Table 1. As per Taguchi L_{16} orthogonal array design, sixteen experiments are performed which is shown in Table 2 (Roy, 2001). For each experimental run, fresh cutting edge was used. With the help of surface roughness tester (Taylor Hobson, Surtronic 25) of cutoff length and assessment length of 0.8mm and 4mm and Nikon profile projector, responses i.e. arithmetic average surface roughness (Ra) and flank wear (VBc) for every run are measured and captured the images by Stereo zoom microscope. As the depth of cut chosen (0.1 - 0.4 mm) is smaller than nose radius (0.8 mm), flank wear occurred at the corner of nose radius (VBc) and measured. The calibration of surface roughness tester was done before start of the measurements. The readings were obtained at four different surfaces of work surfaces and repeated two times at each location and average values are taken. Chips are collected at every runs. Control limit for surface roughness (Ra) and maximum flank wear land has been set as 1.6 microns and 0.6 mm respectively for machining with uncoated cemented carbide insert.

Table 1
Machining parameters and levels.

Parameters	Notation	Unit	Levels of factors			
			Level 1	Level 2	Level 3	Level 4
Depth of cut	d	mm	0.1	0.2	0.3	0.4
feed	f	mm/rev	0.04	0.08	0.12	0.16
Cutting speed	v	m/min	70	110	150	190

Table 2
Taguchi L_{16} orthogonal array design

Run	d	f	v	Run	d	f	v
1	1	1	1	9	3	1	3
2	1	2	2	10	3	2	4
3	1	3	3	11	3	3	1
4	1	4	4	12	3	4	2
5	2	1	2	13	4	1	4
6	2	2	1	14	4	2	3
7	2	3	4	15	4	3	2
8	2	4	3	16	4	4	1

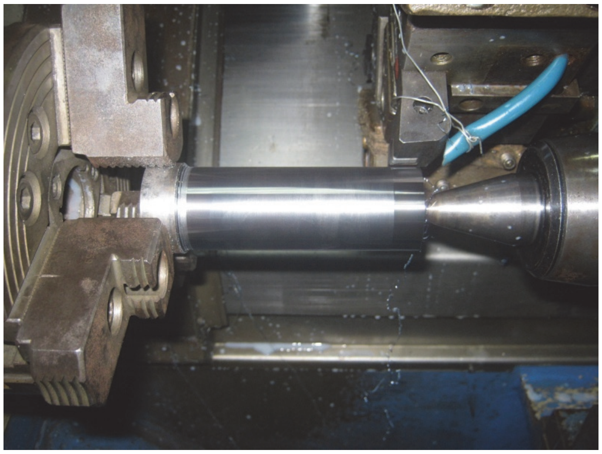


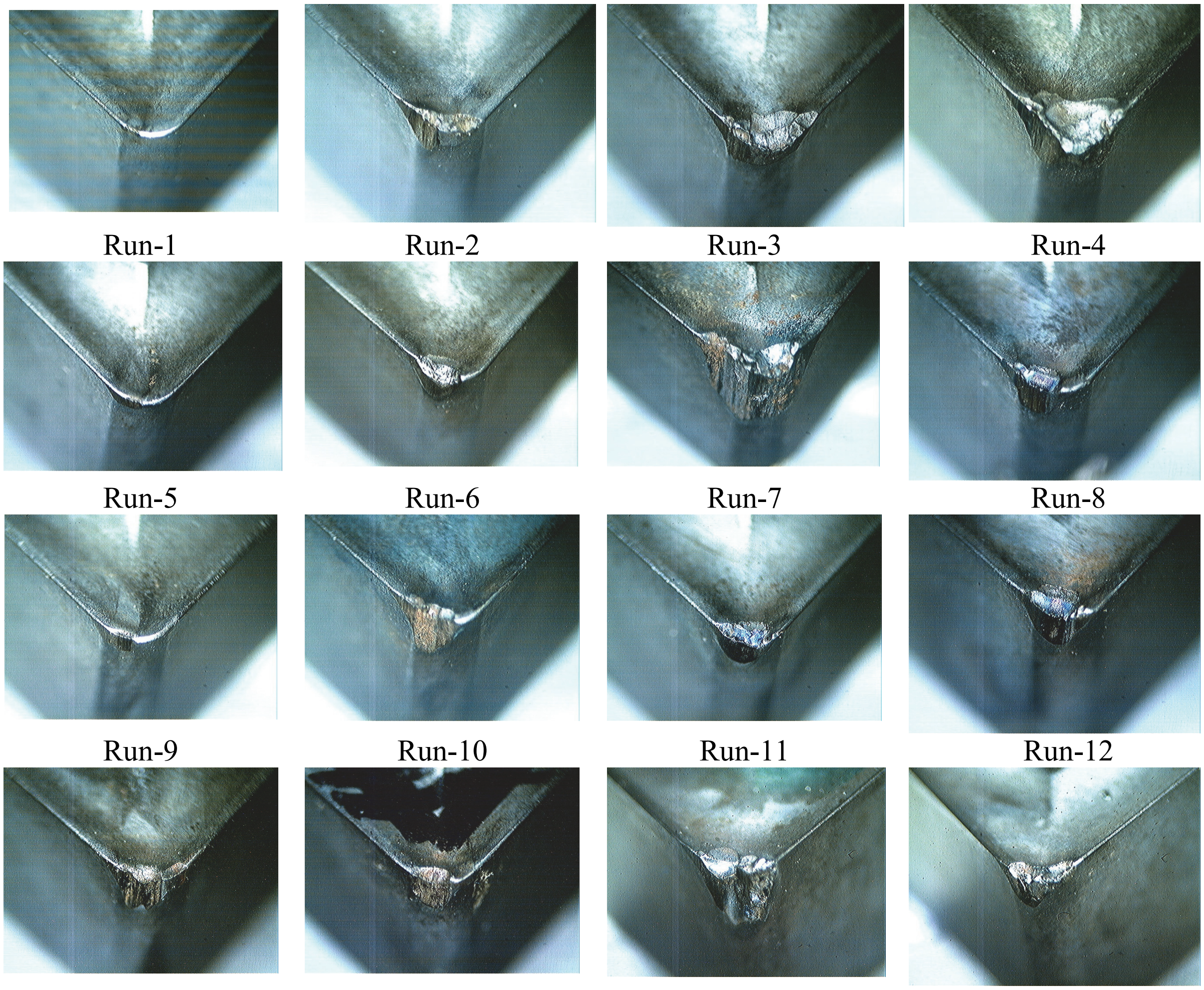
Fig. 1. Experimental setup

4. Results & discussion

The experimental results and images of inserts at each run are shown in Table 3 and Fig. 2, respectively.

Table 3
Test results of VBc and Ra

Run No	Cutting parameters			Experimental results	
	d	f	v	VBc	Ra
1	0.1	0.04	70	0.218	1.28
2	0.1	0.08	110	0.706	2.23
3	0.1	0.12	150	0.717	2.28
4	0.1	0.16	190	1.178	2.98
5	0.2	0.04	110	0.220	1.17
6	0.2	0.08	70	0.745	2.15
7	0.2	0.12	190	1.810	2.82
8	0.2	0.16	150	1.117	2.92
9	0.3	0.04	150	0.434	1.61
10	0.3	0.08	190	1.488	2.74
11	0.3	0.12	70	0.702	2.44
12	0.3	0.16	110	1.318	2.55
13	0.4	0.04	190	1.027	2.79
14	0.4	0.08	150	1.581	2.81
15	0.4	0.12	110	1.552	2.87
16	0.4	0.16	70	0.993	2.92



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. Flank wear images at different runs

Fig. 3. Image of chips at Run 7 (v = 190 m/min, f = 0.12 mm/rev and d = 0.2 mm)

4.1 Analysis of experimental results

From the chosen cutting parametric ranges, various wear mechanisms and modes of cutting tool failure were found and seen during experimentation. With continuous rubbing, some elements of cutting tools are removed away and attrition mechanisms are observed. It is observed that uncoated carbide inserts suffered from excessive flank wear at lower cutting speeds, higher feed-depth of cut cutting conditions (Run 6, 11 and 16). Failure of tool tip, abrasive scars at flank surface, adhesion of metal and deformation of cutting edge and chipping is clearly observed from the captured figures of worn out inserts (Fig. 2). Catastrophic failure of the cutting edge was seen and probably owing to mechanical fatigue (Run 7 and 10)**.** Accelerated wear at flank face is observed for uncoated carbide insert which is due to lack of hot hardness property**.** Thus, the uncoated carbide insert failed to perform due to accelerated tool wear by abrasion, cutting edge dulling due to plastic deformation under stress and cutting temperature in most of the runs except Run 1, 5 and 9. Severe chipping at the cutting edge was seen particularly in run 7, 10, 13, 14 and 15 respectively.

The tool tip fracture is clearly noticed and this may be because of high shear stresses generated by the sudden rise of temperature gradient for uncoated carbide insert during machining hardened AISI 52100 steel. At higher cutting speed and feed rate, cutting edges undergo plastic deformation as hardness of cutting insert reduces with rise in cutting speed. Thus chipping is the primary source of cutting tool failure noticed in the studied range and probably because of inadequate strength to sustain high stress at elevated parametric conditions. From the experiment, it is observed that for a flank wear (VBc) upto 0.6 mm, the corresponding arithmetic surface roughness averages (Ra) are within 1.6 microns. When flank wear exceeds 0.6 mm, surface roughness increases. The analysis reveals that surface roughness is dependent on the flank wear closely. That means evolution of flank wear degrades the surface quality. Serrated saw tooth chips with burnt blue colour are obtained in majority of runs when machining with uncoated carbide insert (Fig. 3). This reveals the higher cutting temperature induced during machining that leads to failure of sharp edge of cutting tool and consequently degrades the surface quality. It is evident from experimental results that the uncoated carbide did not perform well for machining operation as it crosses criteria wear limit of 0.6 mm except Run-1, 5 and 9 only. Chipping or fracturing of cutting edges are not observed in Run-1, 5 and 9 respectively and machining was steady. It is clear from the experimental findings that the arithmetic surface roughness average obtained by uncoated carbide insert has lower value i.e. less than or approaches to 1.6 microns for Run 1, 5 and 9 respectively. For all other runs, it exceeds the surface roughness of 1.6 microns. The main effect plot is constructed to reveal the influence of cutting parameters on responses. From the figure of main effect plot (Fig. 4 and Fig. 5), flank wear and surface roughness increases as the cutting parameters increases. With the rise of cutting speed, cutting temperature at the contact zone increases. This may cross the limit of thermal stability of the uncoated carbide insert used in the machining by virtue of which flank wear increases drastically. Also at higher cutting speed, the rubbing between the flank and workpiece occurs vary faster rate and significant increase of temperature evolved at minimum contact time. Thus cutting edge softens to a larger extent due to rise of cutting temperature and accelerates the flank wear (Suresh et al., 2012). Again from interaction plot (Fig. 6 and Fig. 7), feed-cutting speed has significance on flank wear and Interaction effect of feed-depth of cut; feed-cutting speed and cutting speed-depth of cut have been found to be very significant on surface roughness. The surface roughness sharply increases with the feed. As the thrust force increases due to rise of feed in hard machining which is observed by Gaitonde et al. (2009) and Suresh et al. (2012) in his experimentation, vibration of machine tool becomes more predominant that leads to failure of cutting edge and responsible for degradation of surface quality.

From analysis of variance (ANOVA), feed is found to be the most significant factor for flank wear followed by cutting speed as its P-value is less than 0.05 at 95% confidence level (Montgomery, 2000) which is shown in Table 4 and 5 respectively. Similarly, feed plays a major role for surface roughness followed by cutting speed and depth of cut. From the above findings, it is evident that the uncoated carbide insert performs well at run 1, 5 and 9 respectively which indicates its potential at higher cutting speed range from 70 m/min to 150 m/min but at lower feed range only (0.04 mm/rev). At Run 1, 5 and 9, the flank wear and surface roughness values are well within the recommended range of VBc = 0.6 mm and Ra = 1.6 microns which shows its feasibility for hard turning applications. Therefore there is need to improve the performance of uncoated carbide insert so as to be suitable for hard turning applications. Thus, the optimized process parameters and prediction model for responses are essentially required for its effective application which has been described in subsequent sections.

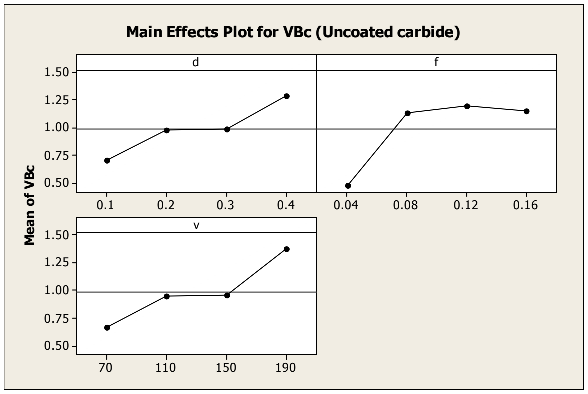


Fig. 4. Main effects plot for VBc

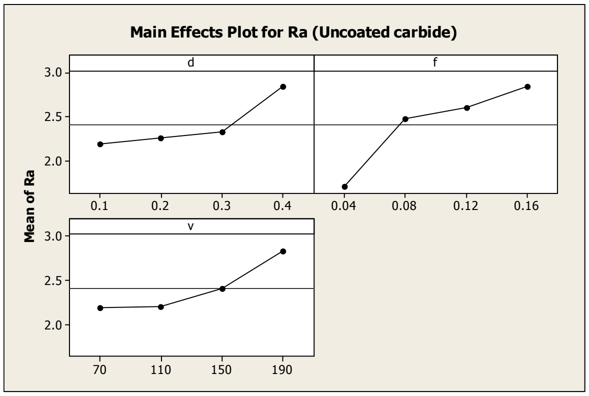


Fig. 5. Main effects plot for Ra

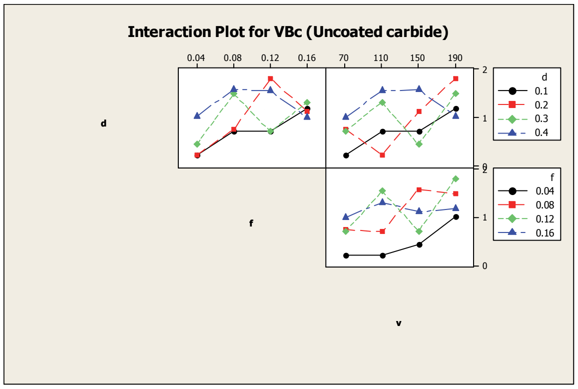


Fig. 6. Interaction plot for VBc

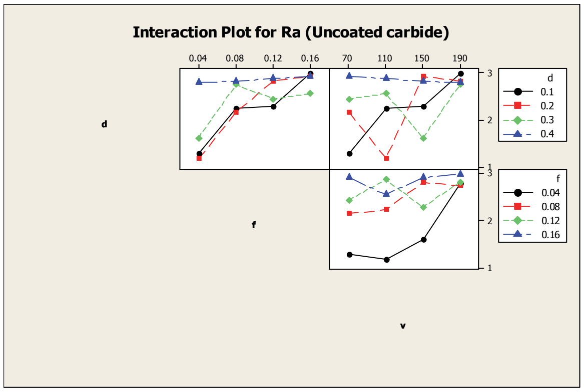


Fig. 7. Interaction plot for Ra

Table 4

ANOVA for VBc

Source	DF	SS	MS	F	P	Remarks
d	3	0.6824	0.2274	3.27	0.101	Insignificant
f	3	1.4131	0.471	6.76	0.024	Significant
v	3	1.0287	0.3429	4.92	0.047	Significant
Error	6	0.4177	0.0696			
Total	15	3.542				

Table 5

ANOVA for Ra

Source	DF	SS	MS	F	P	Remarks
d	3	1.0614	0.3538	8.77	0.013	Significant
f	3	2.8635	0.9545	23.65	0.001	Significant
v	3	1.0628	0.3542	8.78	0.013	Significant
Error	6	0.2422	0.0403			
Total	15	5.23				

4.2 Development of mathematical model and optimization of cutting parameters

The quadratic regression models for responses such as flank wear and surface roughness have been developed at a 95% confidence level taking the results of data obtained from experiment. The input variables or the predictors are responses i.e. depth of cut (d), feed (f) and cutting speed (v) respectively. The model is said to be statistically significance when the P-value (probability of significance) of its input parameters is found to be less than 0.05. Determination coefficients (R^2) were evaluated for best fitting of prediction models and model is adequate and significant if higher R^2 value is obtained. Similarly, the significance of models have been tested if P-value is less than 0.05 (95% confidence level).

The models are presented in Eqs. (1-2) as follows:

$$VBc = 0.791 – 4.4\,d + 9.723\,f - 0.014\,v + 0.862\,d^2 – 109.219\,f^2 + 0.00\,v^2 + 31.977\,df + 0.03\,dv + 0.093\,fv$$

$$R^2 = 95.7\ \%,\ R^2\ (adj) = 89.3\ \% \qquad (1)$$

$$Ra = 1.6952 – 6.2182\,d + 33.4276\,f - 0.0209\,v + 11\,d^2 – 82.8125\,f^2 + 0.0001\,v^2 – 16.6477\,df + 0.0332\,dv - 0.0072\,fv$$

$$R^2 = 96.1\ \%,\ R^2\ (adj) = 90.2\ \% \qquad (2)$$

The determination coefficient (R^2) values for both models of VBc and Ra are observed to be higher i.e. 0.957 and 0.961 (close to 1) explaining 95.7 % and 96.1 % of the variability in the responses. This shows high significance of the model statistically. It indicates good agreement and correlation between experimental values and predicted values and model is significant. Also, the adjusted R^2 (89.3% and 90.2%) value is approximately near to the predicted R^2 that shows also the significance of the model. From the result of ANOVA model for flank wear and surface roughness **(**Table 6 and Table 7**),** it implies that the quadratic regression models are significant as the P-value is less than 0.05. Normal probability plot of the residuals for the flank wear and surface roughness are plotted to test also the statistical validity. It shows that the residuals closely follow a straight line implying that the models are significant (Fig. 8 and Fig. 9). The structure less distributions of plot of residuals versus fitted values (Fig. 10 and Fig. 11**)** indicates models are adequate and significant. Thus, the developed quadratic regression models are sufficient enough to assess accurate prediction of responses in turning hardened AISI 52100 steel (55 ± 1 HRC) using cemented carbide inserts. Furthermore, contour plots are plotted for prediction of responses at desired domain of experimentation. The contour plot of flank wear and surface roughness in different planes are shown in Fig. 12 and Fig. 13, respectively. Contour plots resembles with the curvilinear profile shape as per quadratic regression models. From the contour plots, optimal parametric combinations such as for low level of cutting speed (70 m/min)-feed (0.04 mm/rev)-depth of cut (0.1 mm) is obtained for lowering flank wear and surface roughness respectively. Thus this optimized parametric combination is suggested in reducing tool wear and surface roughness in hard turning of AISI 52100 steel (55 ± 1 HRC) under dry environment using cemented carbide insert. At optimized cutting conditions, the flank wear (VBc) and surface roughness (Ra) values are observed to be 0.218 mm and 1.28 microns respectively which is well within the recommended range and shows its feasibility in machining hardened steel.

Table 6
ANOVA for VBc model.

Source	DF	Seq SS	Adj SS	Adj MS	F	P	Remarks
Regression	9	3.3902	3.3901	0.3766	14.88	0.002	Significant
Linear	3	2.4217	0.1681	0.056	2.21	0.187	
Square	3	0.5064	0.5064	0.1688	6.67	0.024	
Interaction	3	0.4619	0.4619	0.1539	6.08	0.03	
Residual Error	6	0.1518	0.1518	0.0253			
Total	15	3.542					

Table 7
ANOVA for Ra model.

Source	DF	Seq SS	Adj SS	Adj MS	F	P	Remarks
Regression	9	5.0246	5.0246	0.5582	16.31	0.001	Significant
Linear	3	4.1784	0.8111	0.2703	7.9	0.017	
Square	3	0.6509	0.6509	0.2169	6.34	0.027	
Interaction	3	0.1952	0.1952	0.065	1.9	0.231	
Residual Error	6	0.2054	0.2054	0.0342			
Total	15	5.23					

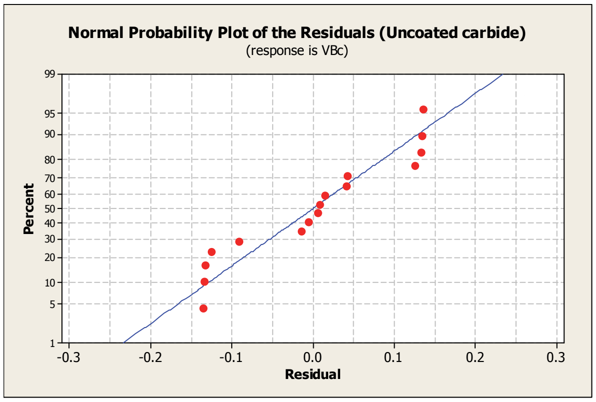


Fig. 8. Normal probability plot for flank wear

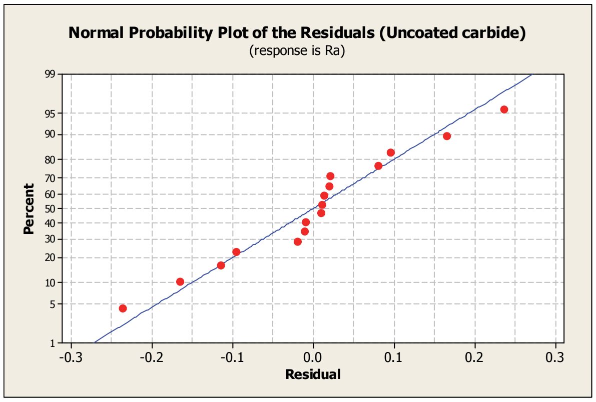


Fig. 9. Normal probability plot for surface roughness

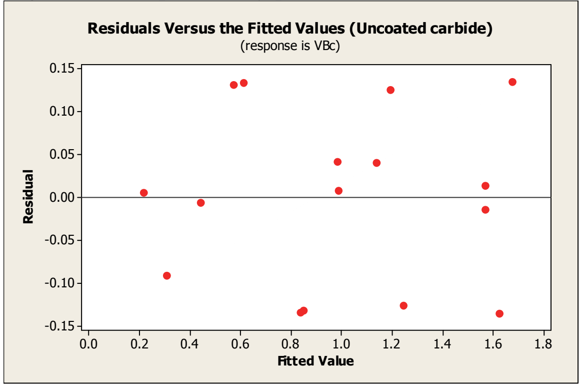


Fig. 10. Residuals vs. fitted values for flank wear

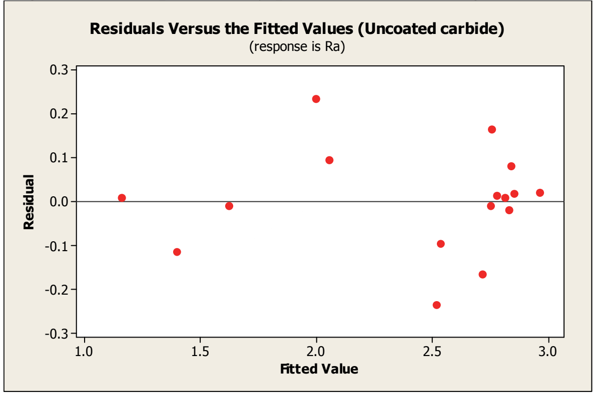


Fig. 11. Residuals vs. fitted values for surface roughness

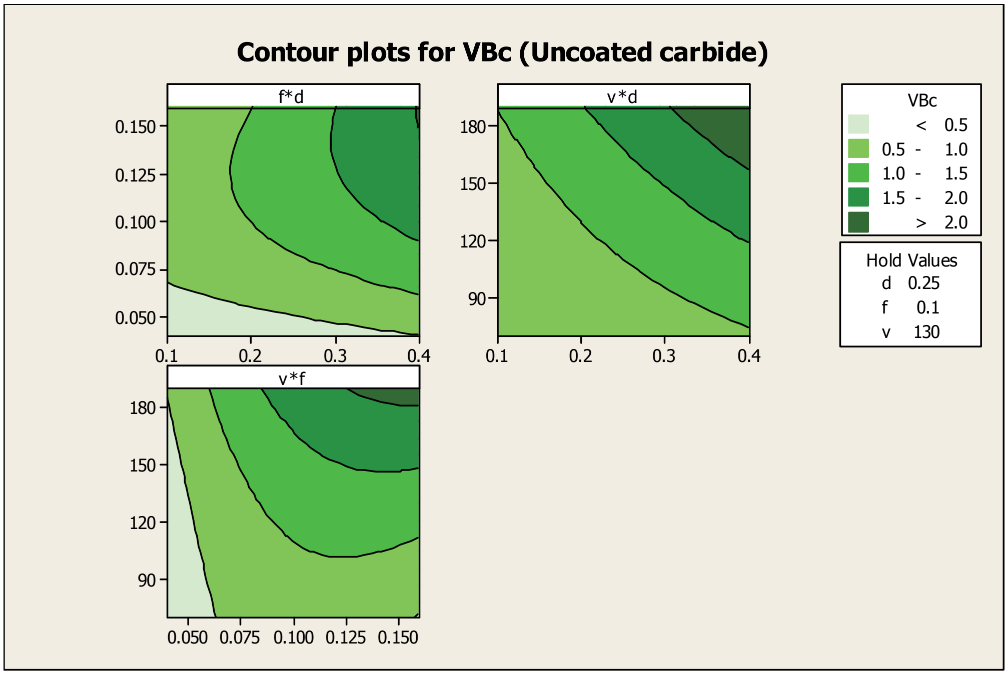


Fig. 12. Contour plots for flank wear (VBc)

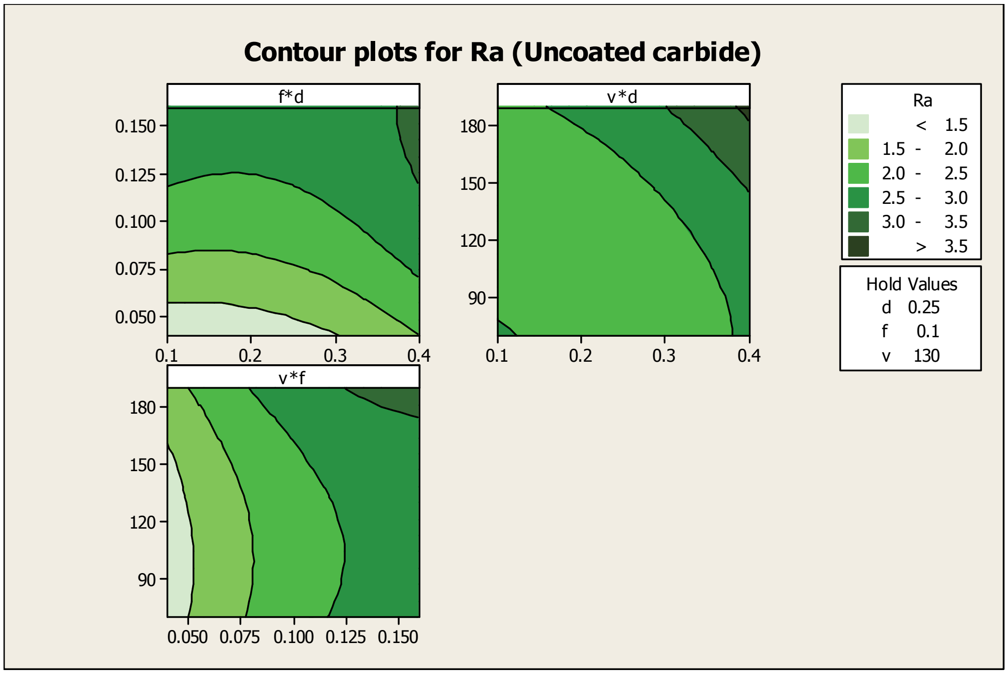


Fig. 13. Contour plots for surface roughness (Ra)

5. Conclusions

The feasibility of utilization of uncoated cemented carbide inserts in turning hardened AISI 52100 steel (55 ± 1 HRC) has been investigated with respect to machinability and regression modeling study. Study revealed that abrasion and chipping was the dominant wear mechanisms in machining hardened steel. Failure of tool tip, abrasive scars, adhesion of metal and cutting edge deformation and catastrophic failure are seen from the captured images of worn out inserts resulting rapid tool wear. Progress of flank wear degrades the surface quality.

However, uncoated cemented carbide insert performs well at run 1, 5 and 9 respectively which indicates its potential at higher cutting speed range from 70 m/min to 150 m/min but at lower feed range only (0.04 mm/rev) and flank wear and surface roughness values are well within the recommended range. This shows its feasibility for hard turning applications.

Prediction model developed using quadratic regression approach has been found to be statistically significant. Optimized parametric combinations such as cutting speed (70 m/min), feed rate (0.04 mm/rev) and depth of cut (0.1 mm) have been obtained. At optimized parametric cutting conditions, flank wear of 0.218 mm and surface roughness of 1.28 microns are obtained which is well within the recommended range and may be considered in hard turning.

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