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HARD TURNING OF HIGH-CARBON HIGH CHROMIUM TOOL STEEL USING CBN TOOLS UNDER DIFFERENT LUBRICATING/COOLING CONDITIONS

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ABSTRACT

The application of environment friendly cutting fluid in machining processes can strongly influence the wear on the cutting tools and the surface finish on work piece materials. This is only possible, when the cutting fluid provides better penetration into the cutting zone, thereby providing a better cooling and lubricating effect. Therefore, this study aims to show the effect of various cutting fluid cooling conditions and machining parameters on tool flank wear (VB) and surface roughness (Ra) of work piece while turning AISI D2 steel with coated CBN tools. Response surface methodology (RSM) and analysis of variance (ANOVA) were used to check the validity of quadratic regression model and to determine the significant parameters affecting the desired responses. The results showed that machining time was the most dominant parameter influencing both tool wear and surface roughness. Moreover, cutting fluid conditions also showed considerable contribution towards decreasing tool wear rate and increasing surface finish. In addition, the cutting tools were examined under scanning electron microscope (SEM) together with EDS. It was observed that abrasion along with BUE formation were the most dominant wear mechanism modes at low cutting speeds. However, at higher cutting speed and feed combinations, abrasions followed by diffusion and adhesion were the dominant form of wear mechanisms. Suppression of BUE was observed at higher cutting speeds of CBN tools. Finally, desirability function approach (DFA) was used to find out the optimal cutting parameters for minimum tool wear with maximum surface finish.

Keywords: Hard turning, RSM, CBN tools, Tool wear, Surface Roughness

1. INTRODUCTION

Machining of hardened materials having hardness greater than 45 HRC has become possible due to the recent advancement in cutting tool materials. Advanced cutting tools such as PCBN and ceramic tool materials have made it possible to machine difficult to cut materials under high cutting speed with or without the aid of cutting fluids. This process is replacing traditional and expensive finish machining process i.e. grinding process, because of the ability to machine complex work-piece geometries in single step with greater process flexibility, increased MRR and decreased set up times [1-2]. PCBN tools are widely used for machining tool steels, high speed steels, bearing steel and cast iron by the manufacturing industry and the researchers.

Within the frame-work of the comprehension of the phenomena occurring during the process of hard turning, various studies were carried out on different materials. However, the existing information or data in this field does not allow to generalise the obtained results and to predict the behavior of other materials. Therefore, the research on machining of these materials is continued. For example, Aouici et al. [3], Benlahmidi et al. [4], De Oliveira et al., [5], Ozel et al., [6], Sadik [7] performed hard turning of different steel grades and identified various parameters influencing tool wear, cutting forces and surface roughness using CBN tools. Also, Chou et al. [8] compared the performance of different CBN tools while finish hard turning of bearing steel. It was reported that the performance of low content CBN in terms of surface finish and tool wear was better than that of high content ones. Moreover, de Oliveira, [9] experimentally investigated the performance of CBN and ceramic tools while hard turning of AISI

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4340 with continuous and interrupted surfaces. Similarly, Godoy et al., [10] performed experiments on interrupted and continuous turning on AISI 4340 hardened steel surfaces using ceramic and CBN cutting tools. It was concluded that PCBN tools performed better than ceramic tools in terms of work-piece roughness and tool life for both the conditions. Another, Poulachon et al., [11] investigated the wear mechanism of CBN cutting tools while finish hard turning different hardened steels.

In order to establish relationship between cutting parameters and responses and to optimize the solutions, it is necessary to use a plan of experimentation, for example, Taguchi techniques or the RSM. Boucha et al., [12] studied and correlated the influence of process parameters on the surface roughness and cutting forces on 52100 hardened steel with CBN tools using RSM approach. It was revealed that depth of cut was the most influential parameter on cutting force components, whereas feed rate dominated surface roughness among all the parameters used in the study. Similarly, Gaitonde et al., [13] used RSM approach to study the effect of machining parameters on surface roughness and tool wear while turning AISI D2 steel with wiper ceramic tools. It was concluded that combination of low feed rate and low machining time with highest cutting speed reduces surface roughness, whereas machining time is the most important factor for tool wear. Aslan et al. [14] implemented Taguchi technique and ANOVA to study the influence of cutting parameters for optimizing flank wear and surface roughness during machining of AISI 4140 hardened (63 HRC) steel using mixed ceramic inserts. The results revealed that, flank wear (VB) value deceased with the increased cutting speed. Conversely, the surface finish was improved with increase in cutting speed and impaired with feed. Aouici et al., [15] experimentally investigated the effect of machining parameters and work-piece hardness on surface roughness and cutting forces during hard machining of AISI H11 steel with CBN tools using RSM and ANOVA techniques. It is concluded that feed rate influenced both surface roughness and cutting force components among all the parameters used. Similarly, modelling of machining parameters for tool wear and surface roughness has also been done by the several authors[16-19]. However, most of the research work in hard turning using any of the advanced cutting tool have be performed mainly under dry cutting conditions. Moreover, it will be advantageous to know the interaction of advanced cutting tool material like CBN with different cooling/lubricating conditions in terms of surface roughness, tool wear and wear mechanism while hard turning of AISI D2 steel.

In this framework, the present study is focused on evaluating the turning performance of CBN inserts while hard turning AISI D2 steel using RSM approach. The influence of the flow rate and cutting fluid velocity directed at the chip-tool interface is investigated. The tests were carried out using an environment–friendly Blasocut 2000 universal cutting fluid. The parameters including cutting speed, feed rate, machining time and cutting fluid conditions were considered for the present study. The study of worn tool surfaces was done using scanning electron microscope and corresponding wear mechanisms have been discussed.

2. METHODOLOGY

2. 1. Materials and Methods

The test material was AISI D2, cold work steel, which is popularly known as High chromium tool steel. Its chemical composition, as determined by Atomic emission spectrometer (in wt %) is given as C 1.70, Cr 12.0, V 0.10, Si 0.30, Mg 0.30, W 0.50, Mo 0.60 and Fe balance. The workpiece was through-hardened steel with hardness value of 442 HV (~45.1HRC). The cutting inserts used in the present study is a CBN-L tool coated by TiN. These cutting inserts are removable type and offered four squared with ISO code-CNGA 120408 T01020 were locked in a right-hand tool holder with ISO designation PCLNR 2525 M12 having −6° rake angle, −6° clearance angle and 95°approach angle.

Straight turning tests were carried out in wet conditions on AISI D2 steel shafts of 55 mm diameter and 200 mm in length using a 5.2 kW centre lathe. The L/D ratio of the work-piece was maintained as per ISO 3685 standards i.e. less than 10. A water based emulsion was made by adding Blasocut 2000 universal concentrate (7-10%) to water. The flow rate (Q) of cutting fluid was measured by using a stop-watch and measuring beaker. In order to calculate the flow rate (Q) of cutting fluid, the valve was opened to 45 degrees and cutting fluid was allowed to flow for 15s. The recorded flow rate (Q) was measured to be 74 ml/s. Following the same procedure, the valve was now fully opened for another 15s, and the flow was measured to be 140 ml/sec. In the last step, the valve was also kept opened fully for another 15s, however at this instant a small diameter tube of 6 mm was used instead of previously used 9.6 mm diameter tube. The final flow rate (Q) was measured as 97 ml/s. The flow rate and relative velocity of cutting fluid are tabulated in Table 1. Hommel Etamic, Jenoptik, Germany, (Model W5) contact stylus profilometer with a stylus tip radius of 2 µm was used for Ra measurement. The transverse length was 3.2 mm with basic span of 0.8 mm over five sampling lengths. Average of these Ra values were used to determine the surface roughness achieved on the machined surfaces. Leica DM 6000 microscope with image characterization software was used for tool flank wear measurement. Furthermore, Scanning Electron Microscopy (SEM) has been used to study the wear mechanism of cutting tools.

Table 1. Cutting fluid flow specifications

Flow rate, Q (ml/s)	Diameter of tube, D (mm)	Velocity of cutting fluid (m/s)	Lubricating or Cutting fluid condition, Q_C
74	9.6	1.022	Low flow rate low velocity (LFLV)
140	9.6	1.92	High flow rate low velocity (HFLV)
97	6	3.43	Low flow rate high velocity (LFHV)

2.2. Design of Experiment

A total of 81 experiments are needed when we consider a full factorial design with four parameters at three levels each. However, this experimental study is time-consuming and expensive. Consequently, Response Surface Methodology (RSM) with FCCD was used to plan the experiments for each parameter. Accordingly, only 30 experiments are required on the work material, to investigate the effect of four factors (cutting speed, machining time, feed rate, and cutting fluid conditions) on the desired outputs (Tool flank wear and Ra). The designed levels are shown in Table 2.

Table 2. Design of factors and parameter

Factors	Control Parameters	Parameter range		
	Level	-1	0	+1
A	Cutting speed (m/min)	110	150	190
B	Feed (mm/rev)	0.05	0.75	0.15
C	Machining (mins.)	2	4	6
D	Cutting fluid conditions	LFLV	HFLV	LFHV

3. RESULTS AND DISCUSSION

Table 3 shows the values of the desired response, surface roughness (Ra) and flank wear (VB). The Ra and VB were obtained in the range of (0.47–1.48) µm and (0.064–0.224) mm, respectively. The VB and Ra values were plotted for individual and interaction effects. 3D view plots were obtained based on the four independent factors. The empirical model was fitted to found the relationship between input factors and desired responses. Finally in this section, the wear mechanisms of the cutting inserts are discussed.

Table 3: The relationships between input parameters and responses

Run	A:Vc	B:f	C:T	D:Qc	Ra	VB
1	190	0.1	2	1	0.58	0.095
2	150	0.1	4	0	0.976	0.139
3	110	0.05	6	1	0.68	0.106
4	150	0.075	4	0	0.82	0.123
5	150	0.075	4	0	0.77	0.113
6	150	0.075	4	0	0.76	0.112
7	150	0.075	4	0	0.79	0.119
8	190	0.1	6	1	1.09	0.180
9	190	0.1	2	-1	0.79	0.105
10	110	0.1	2	-1	0.78	0.083
11	190	0.05	2	-1	0.56	0.103
12	190	0.05	6	1	0.89	0.163
13	150	0.075	4	1	0.67	0.107
14	150	0.075	4	0	0.72	0.113
15	150	0.05	4	0	0.62	0.099
16	150	0.075	2	0	0.71	0.086
17	110	0.1	6	-1	1.29	0.161
18	110	0.05	2	1	0.49	0.064
19	190	0.075	4	0	0.78	0.140
20	110	0.1	6	1	0.99	0.137
21	110	0.075	4	0	0.84	0.090
22	110	0.1	2	1	0.71	0.067
23	190	0.05	6	-1	0.88	0.173
24	190	0.05	2	1	0.47	0.086
25	150	0.075	4	0	0.68	0.112
26	110	0.05	2	-1	0.65	0.072
27	150	0.075	6	0	0.92	0.164
28	190	0.1	6	-1	1.48	0.224
29	150	0.075	4	-1	0.88	0.128
30	110	0.05	6	-1	0.78	0.148

3.1. Analysis of Variance

Analysis of variance of Ra and VB were made in order to analyze the influence of cutting speed (Vc), machining time (T), feed rate (f) and cutting fluid conditions (Qc) on the results. Tables 4–5 show the results of ANOVA, respectively for Ra and VB. The analysis was out for a 5% significance level, i.e., for a 95% confidence level. The last column of the tables shows the parameter contribution (Percentage Cont. %) on the total variation, which indicate the degree of influence on the results. From Table 4, T, f, Q*c*, interaction effect of Vc × T, f × T and f × Q_c all have significant effect on the Ra. But the effect of Machining time (T) is the most significant factor associated with surface roughness with 44.38% contribution to the model followed by feed rate (29.32%). Feed rate is found to be an important parameter affecting Ra. Because with the increase in feed, deeper and broader helicoid furrows are generated thus increasing the surface roughness. Similar results were observed by Bouacha et al., [12] and Aouici et al., [15] while turning hardened steel with steel using CBN tools. Similarly, cutting fluid condition (9.78%) considerable contribution towards surface roughness.

Figure 1 shows the main effect plots for surface roughness. In these plots, the greater influence is represented by a line having a steep slope for long-range change as compared with the influence contributed by less significant factors. The plots for Ra against machining time (T), feed rate (f) and cutting speed (Vc) shows increasing trend from a low level to high level i.e., positively significant effects. Conversely, the slope of cutting speed (Figure 1a) and feed rate plots (Figure 1b) was less than machining time plot (Figure 1c), which indicate that the machining time (T) parameter is more significant than cutting speed (Vc) and feed rate(f) parameters. The plot for Ra against cutting fluid conditions showed (Figure 1d) that the value of Ra considerably decreased from 0.844 to 0.67 (µm) i.e., negatively significant effects, which indicate that the LFHV cutting fluid conditions is capable of increasing surface finish.

Table 4. ANOVA table for Ra

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob> F		PC%
Model	1.26	14	0.090	19.81	< 0.0001	significant	94.73
A-Vc	5.339E-003	1	5.339E-003	1.17	0.2956		0.40
B-f	0.39	1	0.39	86.86	< 0.0001		29.32
C-T	0.59	1	0.59	129.88	< 0.0001		44.38
D-Qc	0.13	1	0.13	28.24	< 0.0001		9.78
AB	5.625E-005	1	5.625E-005	0.012	0.9129		0.00
AC	0.043	1	0.043	9.47	0.0077		3.23
AD	1.563E-004	1	1.563E-004	0.034	0.8554		0.01
BC	0.054	1	0.054	11.89	0.0036		4.06
BD	0.025	1	0.025	5.46	0.0338		1.88
CD	3.906E-003	1	3.906E-003	0.86	0.3686		0.29
A^2	1.352E-003	1	1.352E-003	0.30	0.5936		0.01
B^2	3.046E-004	1	3.046E-004	0.067	0.7993		0.00
C^2	2.008E-003	1	2.008E-003	0.44	0.5163		0.01
D^2	3.830E-004	1	3.830E-004	0.084	0.7756		0.00
Residual	0.068	15	4.546E-003				5.11
Lack of Fit	0.056	10	5.566E-003	2.22	0.1959	not significant	
Pure Error	0.013	5	2.507E-003				
Cor Total	1.33	29					100

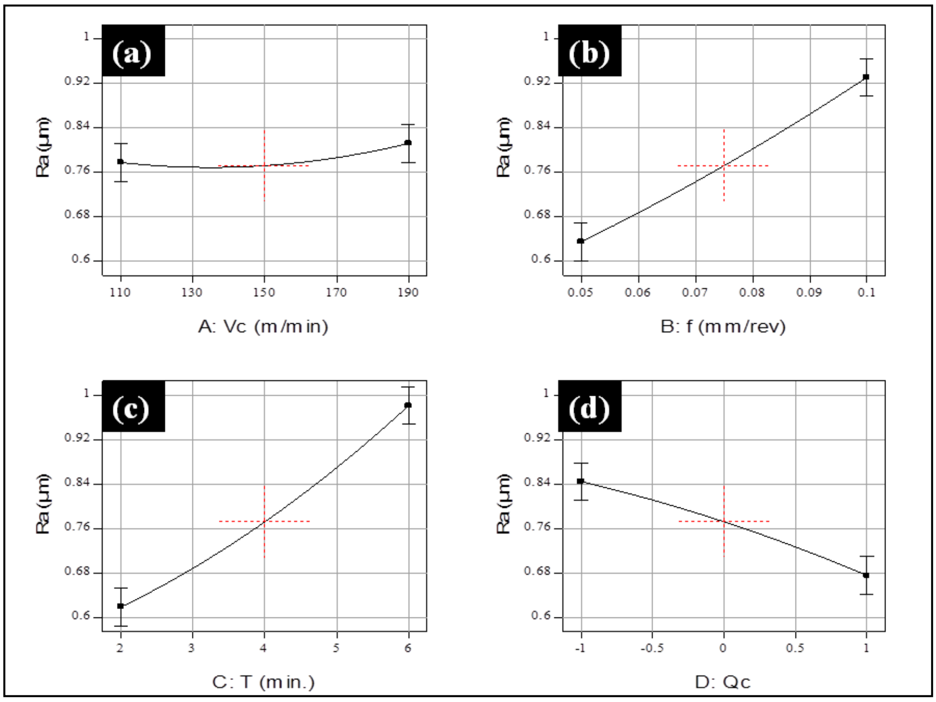

Figure 1. Ra versus (a) cutting speed (b) Feed rate (c) Machining time (d) Cutting fluid conditions

ANOVA results for VB are indicated in Table 5. It can be noted that Vc, T, f, Q_c, Vc ×T, f ×T, T ×Q_C are the parameters which significantly affect VB. However machining time is the most dominant factor contributing approx 67.5% of total contribution. The cutting speed (VC), cutting fluid conditions (Q_c) and feed rate (f) also have significant contribution respectively, their contributions are (16.35; 5.09 and 4.43) % respectively. Similar results were reported by Bouzid et al., [17] when turning AISI 304 steel. Bouzid et al., [17] found that the cutting time and cutting speed have the major statistical significance as regards tool wear.

Table 5. ANOVA table for VB

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob> F		PC%
Model	0.039	14	2.770E-003	48.09	< 0.0001	significant	97.5
A-Vc	6.539E-003	1	6.539E-003	113.52	< 0.0001		16.35
B-f	1.774E-003	1	1.774E-003	30.80	< 0.0001		4.43
C-T	0.027	1	0.027	465.74	< 0.0001		67.5
D-Qc	2.034E-003	1	2.034E-003	35.31	< 0.0001		5.09
AB	2.621E-005	1	2.621E-005	0.46	0.5102		0.065
AC	4.495E-004	1	4.495E-004	7.80	0.0136		1.12
AD	5.288E-006	1	5.288E-006	0.092	0.7661		0.01
BC	4.718E-004	1	4.718E-004	8.19	0.0119		1.17
BD	1.099E-005	1	1.099E-005	0.19	0.6685		0.028
CD	2.938E-004	1	2.938E-004	5.10	0.0393		0.73
A^2	1.632E-005	1	1.632E-005	0.28	0.6023		0.040
B^2	6.278E-006	1	6.278E-006	0.11	0.7459		0.01
C^2	1.348E-004	1	1.348E-004	2.34	0.1469		0.34
D^2	3.559E-007	1	3.559E-007	6.179E-003	0.9384		0.00
Residual	8.641E-004	15	5.761E-005				2.2
Lack of Fit	7.660E-004	10	7.660E-005	3.90	0.0729	not significant	
Pure Error	9.809E-005	5	1.962E-005				
Cor Total	0.040	29					100

Figure 2 shows the main influence (individual) of cutting parameters on VB. Machining time (Figure 2c) has the most influential factor relationships among the main input parameters, followed by cutting speed (Vc), cutting fluid condition (Qc) and at last by feed rate (f). The plots for tool wear against T, f and Vc shows increasing trend from a low level to high level i.e., positively significant effects. However the plot of T, shows a much steeper plot than other parameters used. Conversely, the slope of Vc (Figure 2a) and f (Figure 2b) was less than machining time (T) plot, which indicate that the machining time(T) parameter is more significant than cutting speed and feed rate parameters. The plot for tool wear against cutting fluid conditions showed (Figure 2d) that the value of tool wear considerably decreased from 0.127 to 0.106 (mm) i.e., negatively significant effects. This indicates that the effect of cutting fluid condition at high level are capable of reducing tool wear considerably.

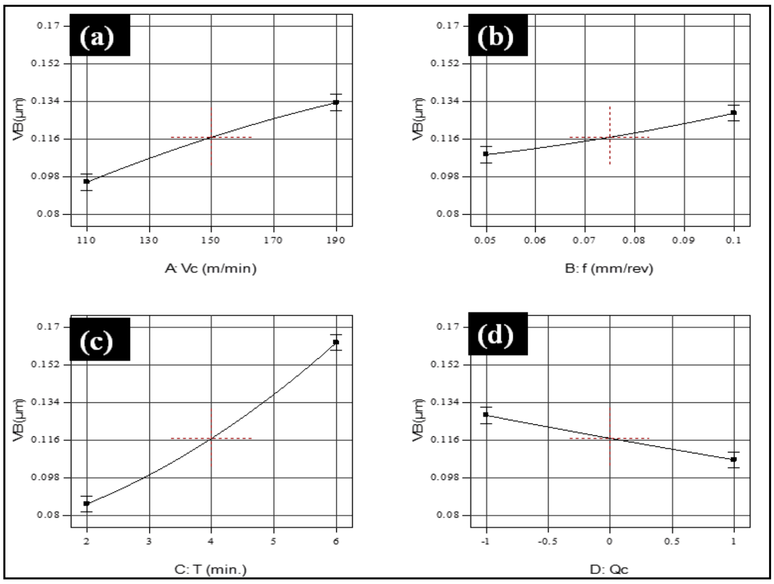

Figure 2. Flank wear versus (a) cutting speed (b) Feed rate (c) Machining time (d) Cutting fluid conditions

3.2. Regression Equations

The relationship between the input parameters (Vc, f, T and Q_c) and performance measures (Ra and VB) was modelled by quadratic regression equations. The different quadratic models attained from statistical analysis can be helpful to predict the tool flank wear and Ra according to the studied parameters. The models are presented in Eqs. (1-2) respectively.

The roughness Ra model is given below in Eq. (1). Its coefficient of determination (R^2) is 94.87%.
The tool wear VB model is given below in Eq. (2). Its coefficient of determination (R^2) is 97.82%

Final Equation in Terms of Actual Factors:

$$\mathbf{Ra} = +1.14766 - 1.04641f - 0.14958T + 0.076649Q_c + 6.48438\text{E-}004 * Vc * T + 1.16250 * f * T - 1.57500 * f * Qc \tag{1}$$

Final Equation in Terms of Actual Factors:

$$\begin{aligned}\mathbf{VB} = {} & +0.032662 + 5.86073\text{E-}004Vc - 0.60288\text{f} - 0.013208T - 1.72916\text{E-}003\ Q_c \\ & + 0.00000662578\ Vc * T + 0.10860 * f * T - 2.14250\text{E-}003 * T * Qc\end{aligned} \tag{2}$$

The normal probability plots and measured vs predicted plots for surface roughness and tool wear are shown in Figures 3 and 4. Figure 3(a) and 4(a) shows the normal probability plot for Ra and tool wear. The plots indicate that the deviations of residuals from the line were minor, which specifies that the model prediction as accurate. Figure 3(b) and 4(b) presents the actual versus predicted plot for Ra and tool wear. The plot indicates that the points are falling or approximating a straight line, which reveals that the accuracy of experimental values and predicted values are acceptable.

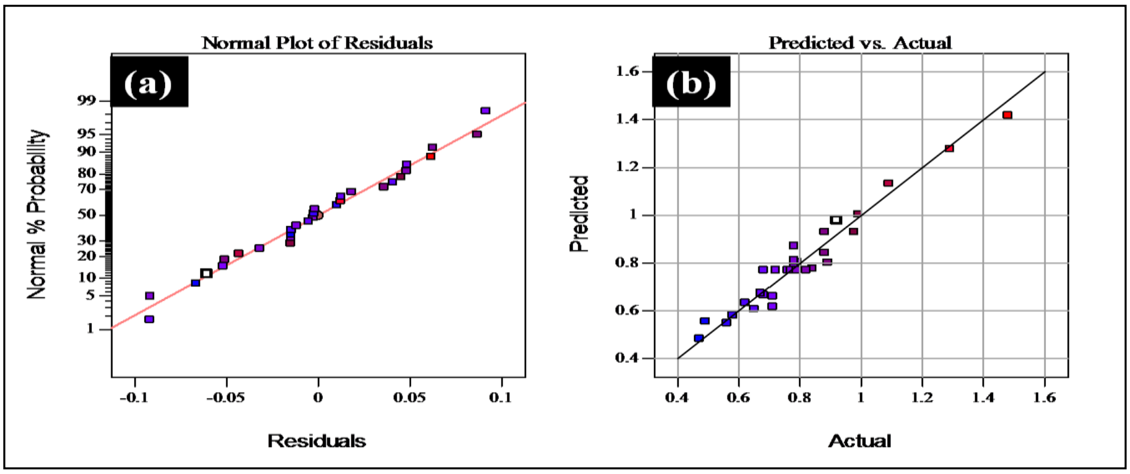

Figure 3. Comparison between (a) normal probability plot (b) measured and predicted values for Ra

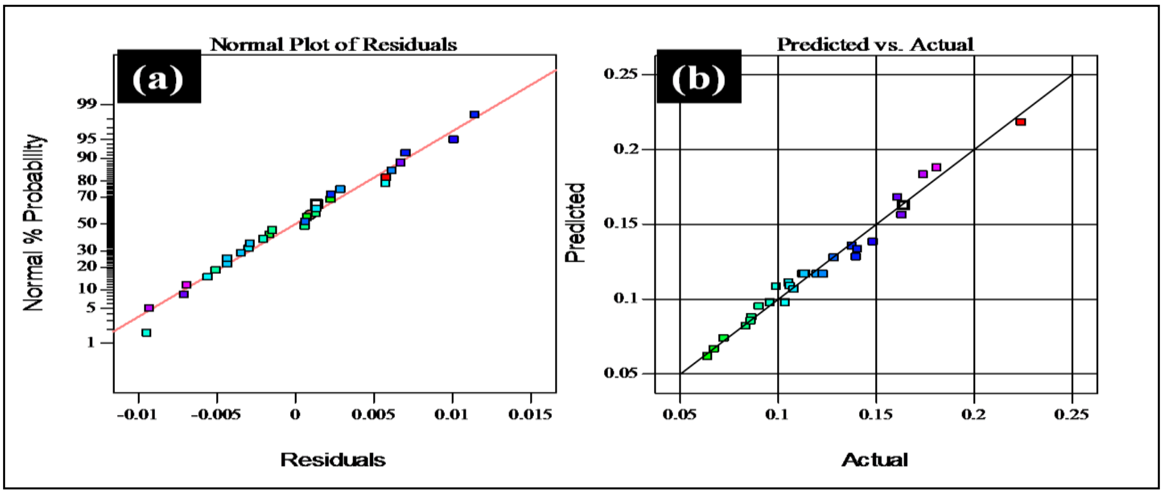

Figure 4. Comparison between (a) normal probability plot (b) measured and predicted values for tool wear

3.3. Effect of Parameters on Surface Roughness

With the aim of investigating the effect of machining parameters on the surface roughness (Ra), 3D plots are drawn in Figure 5. Figure 5 depicts the influence of Vc, f, T and Qc on the surface roughness (Ra). From Figure 5(a), at lower values of feed rates, surface roughness value slightly reduces up to 150 m/min of cutting speed beyond which it continuously increases and can be explained either by the possibility of chatter marks due to vibration, tool wear or material side flow [19-20]. As can be depicted from the plot 5(a) that higher feeds rates together with higher cutting speed considerably affects the Ra. This can be explained in terms of higher thrust force involved during cutting at higher feeds and cutting speeds, resulting into more vibrations.

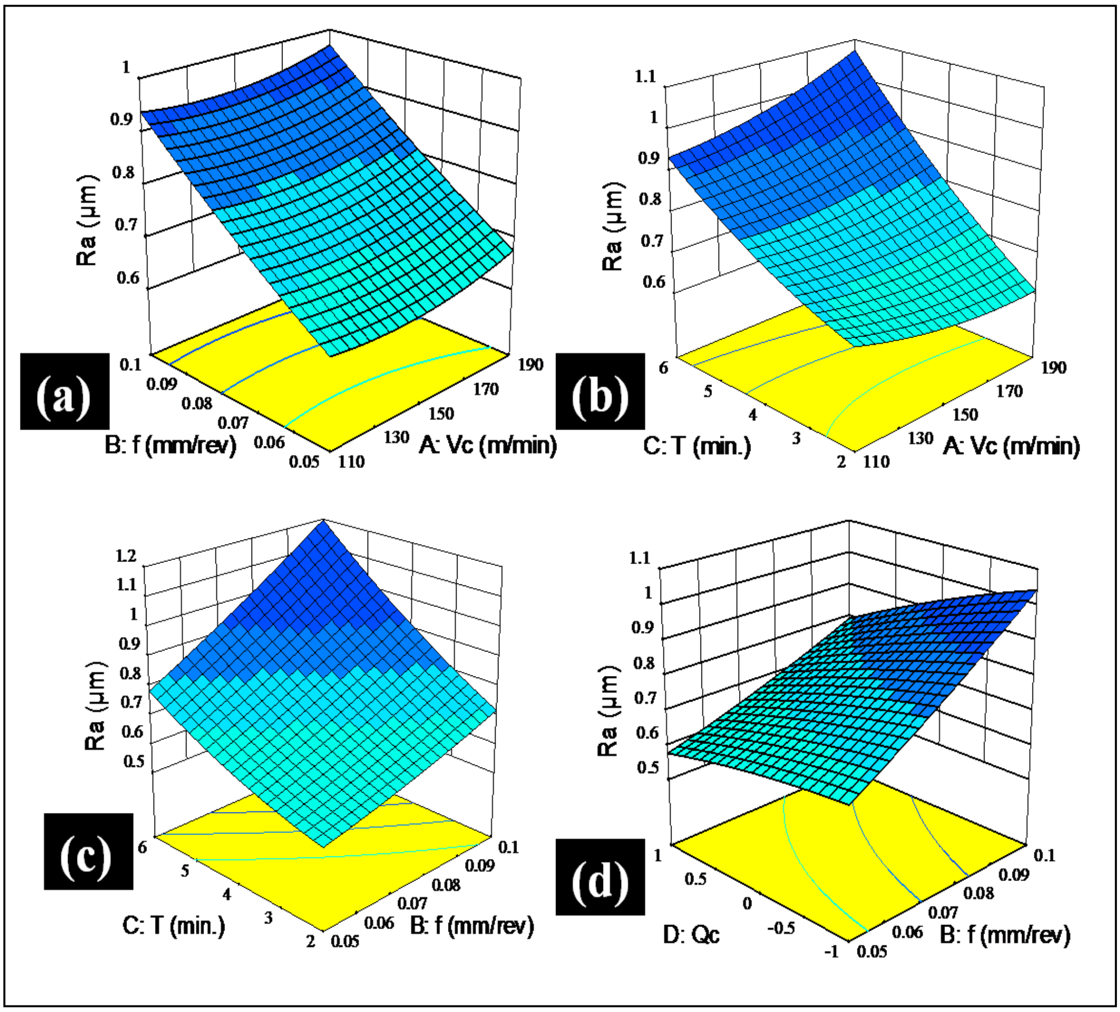

Figure 5. 3D surface plots of Ra (a) Effect of Vc and f (b) Effect of Vc and T (c) Effect of f and T (d) Effect of Q_c and f

From, Figure 5 (b) and (c), at the lowest machining time, the Ra is at a lesser level and is attributed to less tool wear on the cutting tool edge. However, at a higher machining time, the Ra values increases severely with increase in both feed rate and cutting speed. This may be due to steady increases in tool wear and following vibrations [21]. It can be also observed from figure that best surface finish is obtained by the combination of lowest feed rate and minimum machining time. According to Figure 5 (d), it can be recognized that the Ra values increases considerably with increasing in feed rate and decreases with increase in cutting fluid condition. Moreover, it can be observed from figure 5(d) that an improvement in Ra value is achieved with highest level of cutting fluid conditions. This improvement can be explained by the penetration of lubricant into the work-piece and tool interface, which reduces the friction and hence improves surface finish.

3.4. Effect of Parameters on Tool Wear

Figure 6 shows the 3D graphs for tool flank wear which help to understand the interaction between parameters and responses. Tool wear displayed minimum value when the values of machining time and cutting speed were at their lowest during cutting. The 3D plot, shows that the increasing effect of machining (T), cutting speed (Vc), cutting fluid condition (Q_c) and feed rate (f) on tool wear. Cutting speed has the second largest effect on tool flank wear, however with simultaneous increase of feed rate and cutting speed, the forces, heat generation and speed of MRR increases, which subsequently increase temperature at the interface [22]. This increased temperature at the flank face softens the cutting tool edge and wear occurs rapidly. From Figure 6(b) and (c) it is evident that tool wear increases considerably with the increase in cutting speed and feed rate, however machining time has the most dominant effect on increasing tool wear among all the parameters used. Moreover the combination of highest level of cutting speed with highest level of machining time produces maximum tool wear. Similar result was reported by Bouzid et al. [17], while machining AISI 304 stainless steel.

It can also be observed from Figure 6(d) that highest level of cutting fluid condition is capable of reducing tool flank wear at the highest levels of cutting speeds. The decrease in flank wear in combination with LFHV condition can be attributed to the high speed of cutting fluid which possibly penetrates the tool work-piece interface and removes heat from interface and hence reduces the tool wear. Moreover, the emulsion is water-miscible and has better cooling properties at high speed operations [23].

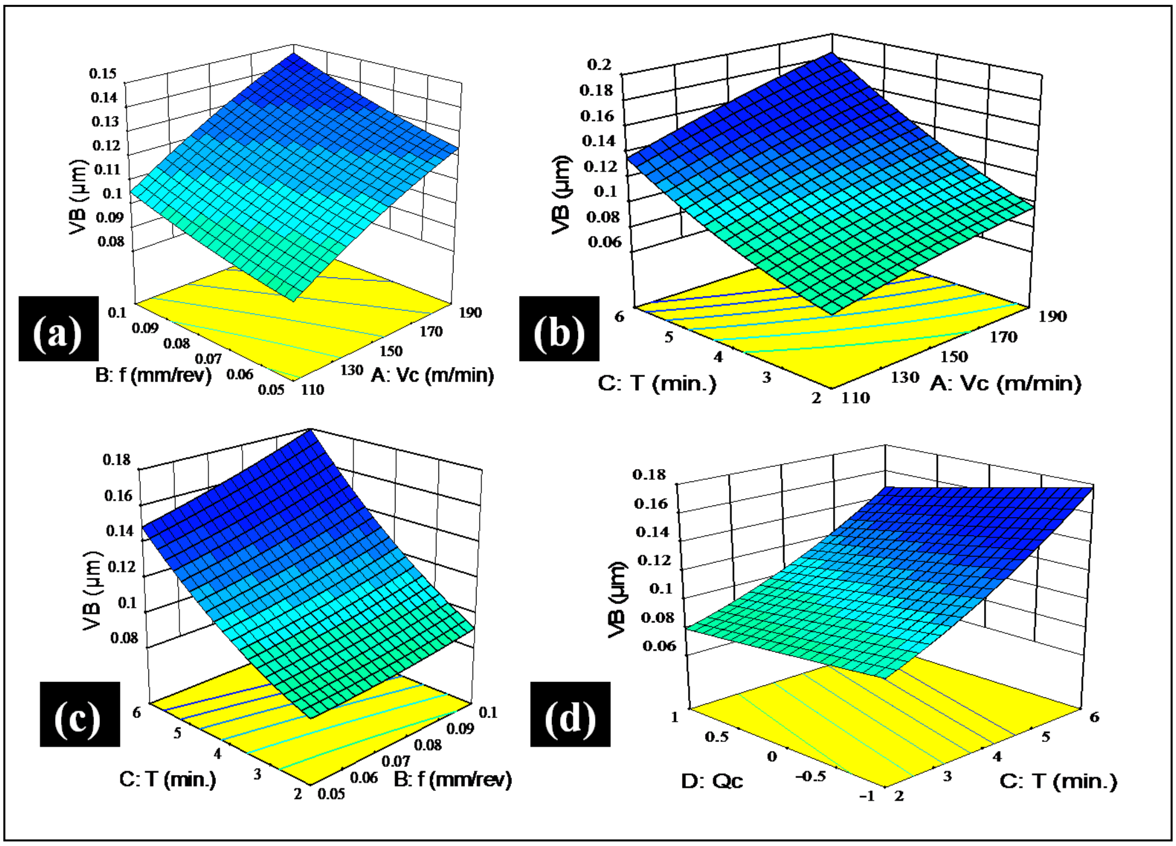

Figure 6. 3D surface plots of flank wear (a) Effect of Vc and f (b) Effect of Vc and T (c) Effect of f and T(d) Effect of Q_c and T

3.5. Wear Mechanism

Figure 7 shows the optical micrographs and Figure 8 the SEM images of worn out tools at various cutting speeds, feed rates and cutting fluid conditions. It can be seen from all the optical micrographs and SEM images that no chipping or fracture of cutting edge is observed, demonstrating that the cutting factors were adequate and the rigidity of the workpiece and tool fixture systems was appropriate for the operation. According to optical image 7(a) and SEM image 8(a), evidence of abrasive wear mechanism, identified by parallel scratches or grooves in the direction of cutting speed along with some smooth regions is observed for PCBN tools at low speed (110 m/min), feed rate at 0.1 mm/rev and using LFLV conditions. These evident thin parallel scratches or grooves formed on flank face of the CBN tools are mainly caused by direct contact of hard particles (carbides) and impurities like chromium present within the work-piece material, as well as, due to built-up fragments [24-25].

The smooth regions observed on the CBN tools suggest that the wear mechanism also occurred by diffusion wear [10, 26]. Furthermore, the sticking of work-piece material on the tool edge has caused the formation of huge built of layer on the cutting edge, which is clearly evident in Figure 7a. In addition to these wear mechanisms, crater wear was also observed on the rake face of CBN inserts. Other wear mechanisms such as chip sticking and adhesion were also observed on the cutting tools.

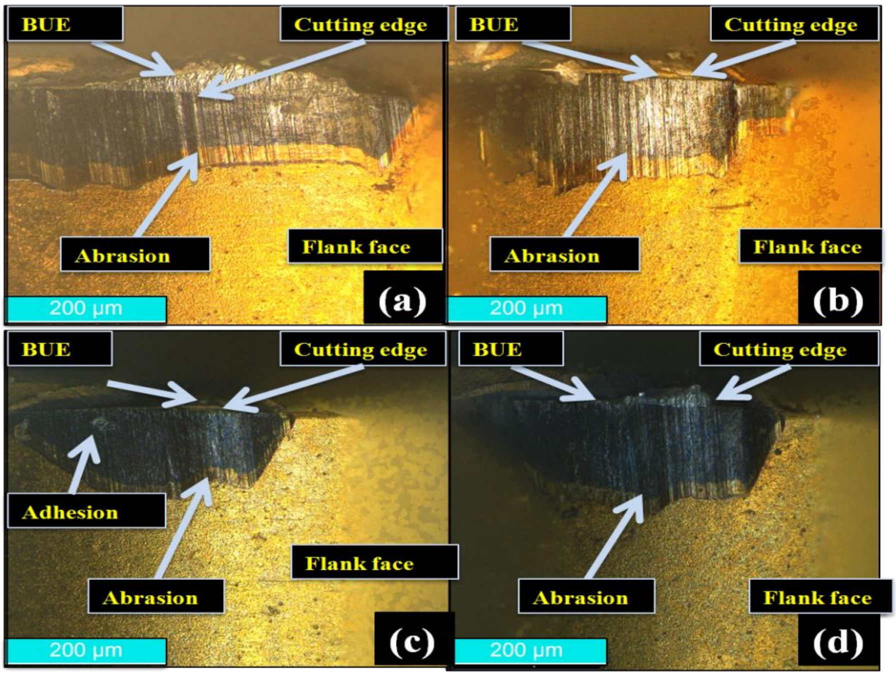

Figure 7. Optical micrograph of the worn CBN cutting tool at, **(a)** Vc=110 m/min, f = 0.1 mm/rev, T= 6 mins, Qc= LFLV **(b)** Vc=190 m/min, f = 0.1 mm/rev, T= 6 mins, Qc = LFLV **(c)** Vc=110 m/min, f = 0.5 mm/rev, T= 6 mins, Qc= LFLV **(d)** Vc=110 m/min, f = 0.1 mm/rev, T= 6 mins, Qc= LFHV

Figure 7b and 8b shows the optical and SEM images of CBN inserts when the the speed was increased from 110 to 190 m/min, keeping rest of parameters same, the wear mechanisms seen for this cutting insert was similar to those observed at Vc = 110 m/min and a feed rate of 0.1 mm/rev using LFLV conditions, i.e. Abrasion (ploughing and scratches) along with diffusion becomes the dominant wear mechanism. However at this speed, adhesion wear is also prominent on flank face. The cause of adhesion or welding of work-piece material on the clean or fresh face of the tool is possibly because of elevated temperature and pressures generated during cutting. However at this cutting speed, less BUE was observed on the cutting insert, which is possibly due to the high cutting speed involved. Figure 7(c) shows the optical image and 8(c) SEM micrographs of the cutting inserts when the feed rate employed to machine the steel was reduced to 0.05 mm/rev, the wear mechanism observed at this feed was found similar to the earlier observations at higher feed rates. Figure 7d and 8d indicates the flank wear at higher cutting speed (190 m/min) with low flow high-velocity lubricant supply (LFHV) and keeping feed rate at 0.1 mm/rev. The wear mechanism observed at this condition was mainly by abrasion, identified by grooves on the cutting tool flank face. Moreover, small clusters of adhered material can also be found on the tool face. Furthermore, it can be observed from SEM image (Figure 8d), no adherences of chip material is seen, which can be attributed to the effectiveness of coolant. When applying LFHV in the process, it allowed better penetration and access to cutting fluid into the cutting region. This effectiveness of the cutting fluid condition may be recognized by the less adhesion of chips on the insert. Other wear mechanisms such as crater formation, BUE were also observed on the cutting tools.

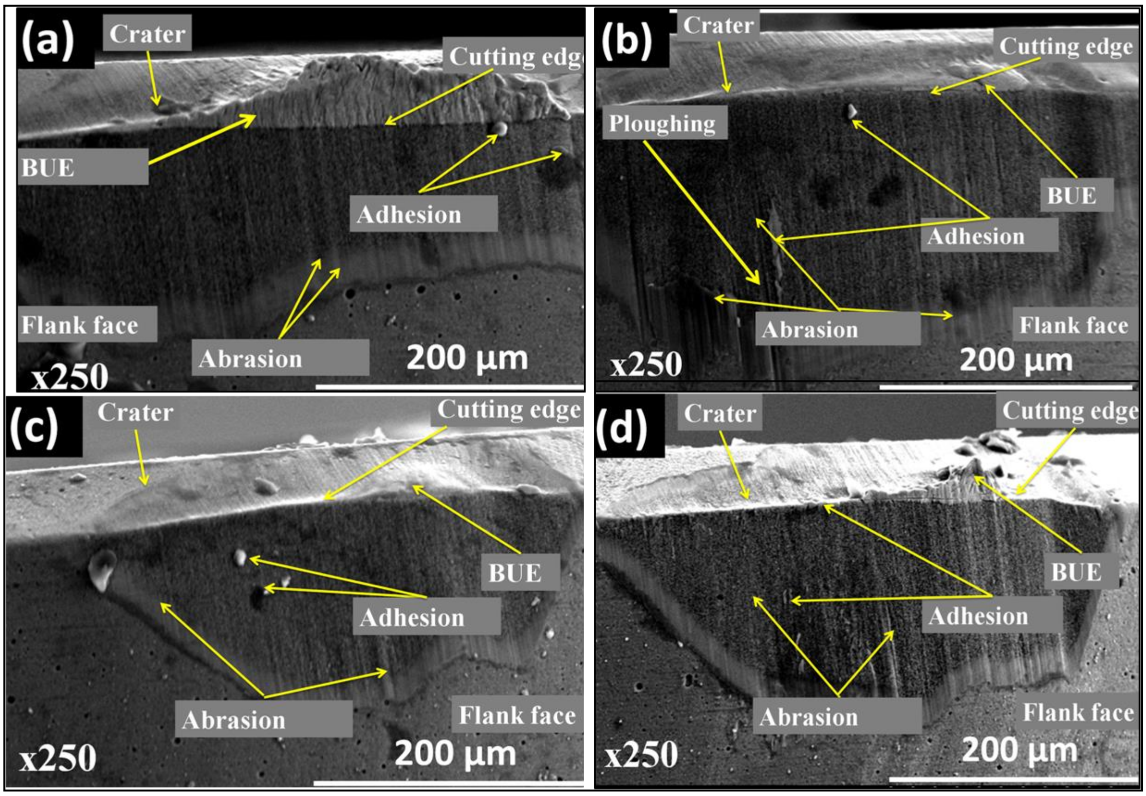

Figure 8. SEM images of the worn CBN cutting tool at, **(a)** Vc=110 m/min, f = 0.1 mm/rev, T= 6 mins, Qc= LFLV **(b)** Vc=190 m/min, f = 0.1 mm/rev, T= 6 mins, Qc = LFLV **(c)** Vc=110 m/min, f = 0.5 mm/rev, T= 6 mins, Qc= LFLV **(d)** Vc=110 m/min, f = 0.1 mm/rev, T= 6 mins, Qc= LFHV

3.6. Multiple Response Optimizations by Desirability Approach

In the present study, numerical optimization is carried out with desirability function approach (DFA). DFA is usually used to find the optimal parametric combinations for single and multiple objective optimizations [18, 27]. The constraints along with their goals used during numerical optimization process are enlisted in Table 6. During the optimization process, the aim is to find the optimal values of machining factors in order to produce the lowest tool wear and minimize surface roughness. The RSM optimization results for VB and Ra are defined in Table 7, in sequence of their declining desirability levels. The optimized tool wear (VB) and surface roughness (Ra) results are (0.064-0.067) µm and (0.535-0.547) µm, respectively. Figure 9(a) shows the ramp plots, which indicate the input parameter ranges, the output parameters and the optimum values. The optimum input factors for multi-response optimization is cutting speed of 115.0543 m/min, f= 0.050 mm/rev, T = 2.002 min. and using LFHV conditions. Figure 9(b) shows the bar charts of desirability for the cutting parameters and the desired responses together with a combined desirability of 0.961.

Table 6. Constraints for optimization of cutting conditions

Name	Goal	Lower Limit	Upper Limit	Lower Weight	Upper Weight	Importance
A:Vc	is in range	110	190	1	1	3
B:f	is in range	0.05	0.1	1	1	3
C:T	is in range	2	6	1	1	3
D:Qc	is in range	-1	1	1	1	3
Ra	minimize	0.47	1.48	1	1	5
VB	minimize	0.06405	0.22403	1	1	5

Table 7. Response optimization for Ra and VB

Number	Vc	f	T	Qc	Ra	VB	Combined Desirability
1	115.085	0.050	2.002	1.000	0.547	0.064	0.961
7	117.550	0.050	2.000	1.000	0.542	0.065	0.960
8	114.750	0.050	2.009	0.980	0.548	0.064	0.960
9	114.277	0.050	2.072	1.000	0.548	0.064	0.960
11	113.605	0.050	2.130	1.000	0.550	0.064	0.960
12	119.801	0.050	2.000	1.000	0.538	0.066	0.960
17	121.342	0.050	2.001	0.999	0.535	0.067	0.959
18	121.774	0.050	2.000	1.000	0.535	0.067	0.959

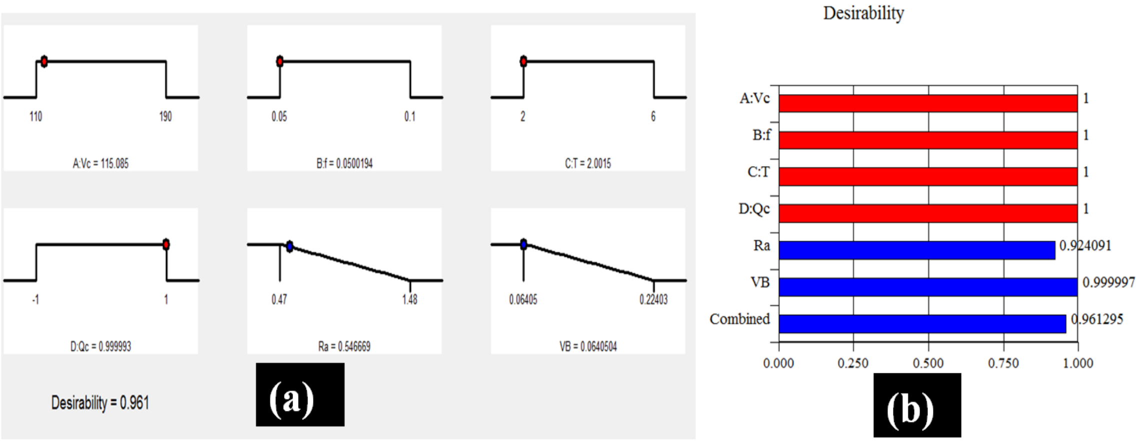

Figure 9. (a) Ramp plot **(b)** Bar graph for combined objective with desirability of 0.961

4. CONCLUSION

Based on the results of this work in the hard turning of AISI D2 steel with coated CBN inserts under different cutting conditions, it can be concluded that:

1. Quadratic model was selected as regression model of both desired outputs, namely tool flank wear and surface roughness. It was found that there was a good conformity between experimental and predicted values by quadratic models.
2. Machining time was the most dominant factor (67.5%) on tool wear followed by cutting speed (16.35%).While as machining time (44.38%) followed by feed rate (29.3%) contributed the most to surface roughness.
3. Cutting fluid conditions showed a negatively significant effect to tool wear (~5%) as well as to surface roughness (~9.77%). LFHV condition was the most efficient cutting fluid condition in reducing tool wear rate and decreasing surface roughness.
4. At low speed, high feed rate and using LFLV condition, abrasion dominated the tool wear, followed by BUE formation. Additionally, crater formation was the other wear mechanism observed at this combination.
5. Abrasion followed by diffusion, were the main form of wear mechanisms at high cutting speed and feed combination. Suppression of BUE was observed at higher cutting speeds. However under LFHV conditions, abrasion followed by adhesion was found to be the main wear mechanisms.
6. The optimum values of cutting conditions are achieved with the overall desirability function. The optimum cutting conditions for minimum tool wear with maximum surface finish are in the region of cutting speed = 115.085 m/min, Machining time of 2 min., feed rate of 0.050 mm/rev and using LFHV condition.

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REFERENCES

[1] Lawani DI., Mehta NK, Jain PK. Experimental investigations of cutting parameters influence on cutting forces and surface roughness in finish hard turning of MDN250 steel. J Mater Process Technol 2009; 209:1092–1104

[2] Zhou JM., Walter H, Andersson M, Stahl JE. Effect of chamfer angle on wear of PCBN cutting tool. J Mach Tools Manuf 2003; 43: 301–305

[3] Aouici H., Fnides B., Elbah M., Benlahmidi S., Bensouilah H., and Yallese M. Surface roughness evaluation of various cutting materials in hard turning of AISI H11. International Journal of Industrial Engineering Computations 2016;7(2): 339-352.

[4] Benlahmidi S., Aouici H., Boutaghane F., Khellaf, A., Fnides, B., and Yallese, M. A. Design optimization of cutting parameters when turning hardened AISI H11 steel (50 HRC) with CBN7020 tools. The International Journal of Advanced Manufacturing Technology 2017; 89(1-4), 803-820.

[5] De Oliveira A.J., Diniz A.E. and Ursolino D.J. Hard turning in continuous and interrupted cut with PCBN and whisker-reinforced cutting tools. Journal of Materials Processing Technology2009; 209(12), 5262-5270

[6] Ozel T, Hsu TK, Zeren E. Effects of cutting edge geometry, workpiece hardness, feed rate and cutting speed on surface roughness and forces in finish turning of hardened AISI H13 steel. Int J Adv Manuf Tech 2000;25(3–4):262–269

[7] Sadik M.I. Wear development and cutting forces on CBN cutting tool in hard part turning of different hardened steels. Procedia CIRP;2012: 1, 232-237.

[8] Chou Y.K., Evans C.J., and Barash M.M. Experimental investigation on CBN turning of hardened AISI 52100 steel. Journal of Materials Processing Technology 2002;124(3), 274-283.

[9] de Oliveira A.J., Diniz, A.E., and Ursolino, D.J. Hard turning in continuous and interrupted cut with PCBN and whisker-reinforced cutting tools. Journal of Materials Processing Technology, 2009;209(12-13), 5262-5270.

[10] De Godoy, V.A. A., and Diniz A. E. Turning of interrupted and continuous hardened steel surfaces using ceramic and CBN cutting tools. Journal of Materials processing technology 2011; 211(6), 1014-1025.

[11] Poulachon G., Bandyopadhyay B.P., Jawahir I.S., Pheulpin, S. and Seguin E. Wear behavior of CBN tools while turning various hardened steels. Wear 2004;256(3-4), 302-310.

[12] Bouacha K., Yallese M.A., Mabrouki T.sand Rigal J.F. Statistical analysis of surface roughness and cutting forces using response surface methodology in hard turning of AISI 52100 bearing steel with CBN tool. International Journal of Refractory Metals and Hard Materials 2010; 28(3), 349-361.

[13] Gaitonde V.N., Karnik S.R., Figueira L. and Davim J.P. Analysis of machinability during hard turning of cold work tool steel (type: AISI D2). Materials and Manufacturing Processes 2009; 24(12), 1373-1382.

[14] Aslan E., Camuşcu, N and Birgören, B. Design optimization of cutting parameters when turning hardened AISI 4140 steel (63 HRC) with Al2O3+ TiCN mixed ceramic tool. Materials and design 2007; 28(5), 1618-1622.

[15] Aouici H., Yallese M.A., Chaoui K., Mabrouki T. and Rigal J.F. (2012). Analysis of surface roughness and cutting force components in hard turning with CBN tool: Prediction model and cutting conditions optimization.Measurement, 45(3), 344-353.

[16] Mir M. and Wani M. Modelling and analysis of tool wear and surface roughness in hard turning of AISI D2 steel using response surface methodology. International Journal of Industrial Engineering Computations 2018;9(1), 63-74.

[17] Bouzid L., Berkani S., Yallese M., Girardin F. and Mabrouki T. Estimation and optimization of flank wear and tool lifespan in finish turning of AISI 304 stainless steel using desirability function approach. International Journal of Industrial Engineering Computations 2018; 9(3), 349-368.

[18] Chinchanikar S. and Choudhury S.K. Effect of work material hardness and cutting parameters on performance of coated carbide tool when turning hardened steel: An optimization approach. Measurement 2013;46(4), 1572-1584.

[19] Das S.R., Dhupal D. and Kumar, A. Experimental investigation into machinability of hardened AISI 4140 steel using TiN coated ceramic tool. Measurement 2015;62, 108-126.

[20] Kishawy H.A. and Elbestawi M.A. Tool wear and surface integrity during high-speed turning of hardened steel with polycrystalline cubic boron nitride tools. Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture 2001; 215(6), 755-767.

[21] Seeman M., Ganesan G., Karthikeyan R. and Velayudham A. Study on tool wear and surface roughness in machining of particulate aluminum metal matrix composite-response surface methodology approach. The International Journal of Advanced Manufacturing Technology 2010; 48(5),613-624

[22] Suresh R., Basavarajappa S. and Samuel G. L. Some studies on hard turning of AISI 4340 steel using multilayer coated carbide tool. Measurement 2012; 45(7), 1872-1884.

[23] Sharma V.S., Dogra M. and Suri N.M. Cooling techniques for improved productivity in turning. International Journal of Machine Tools and Manufacture 2009;49(6), 435-453

[24] Mir M.J. and Wani M.F. (2017). Performance evaluation of PCBN, coated carbide and mixed ceramic inserts in finish-turning of AISI D2 steel. Jurnal Tribolog 2018; 14, 10-31.

[25] Kumar A.S., Durai A.R. and Sornakumar T. The effect of tool wear on tool life of alumina-based ceramic cutting tools while machining hardened martensitic stainless steel. Journal of Materials Processing Technology 2006; 173(2), 151-156.

[26] Sobiyi K., Sigalas I., Akdogan G. and Turan Y. Performance of mixed ceramics and CBN tools during hard turning of martensitic stainless steel. The International Journal of Advanced Manufacturing Technology 2015, 77(5-8), 861-871.

[27] Berkani S., Yallese M., Boulanouar L. and Mabrouki T. Statistical analysis of AISI304 austenitic stainless steel machining using Ti (C, N)/Al2O3/TiN CVD coated carbide tool. International Journal of Industrial Engineering Computations 2015;6(4), 539-552.