MACHINABILITY ASSESSMENT OF AISI 4140 HARDENED STEEL USING CBN INSERTS IN HARD TURNING

Bhushan Nikam, Avinash Khadtare, Raju Pawade

Dr. Babasaheb Ambedkar Technical University, Department of Mechanical Engineering
Vidyavihar, Lonere, India 402103

Corresponding author: Raju Pawade, rspawade@dbatu.ac.in

Abstract: The machinability aspect of AISI 4140 steel is analyzed in this experimental study for the tool life, cutting forces, tool wear mechanism, and machined surface roughness using CBN inserts. Cutting speed and feed are selected as input variables and its range of cutting speed and feed are 150-175-200 m/min, 0.1-0.15-0.2 mm/rev respectively. All hard turning experiments were carried out using L9 factorial orthogonal array under a dry cutting environment with a fixed depth of cut of 0.25 mm. Tool wear mechanism and tool life were investigated at the optimum condition of cutting parameters using grey relation analysis (GRA). Experimental results observed that the radial force shows the highest magnitude (309.93 N) as compared to cutting and feed force components. Also, it is observed that machining forces increase as the input variables increases. As a feed increases the machined surface roughness also increases and its maximum value is observed at a higher feed (1.403 µm). Using GRA, the minimum cutting forces and lower surface roughness was observed at the combination of 200 m/min cutting speed and 0.1 mm/rev feed. There are two different types of wear mechanisms namely abrasion and oxidation was noticed on the tool face during hard turning. As the cutting length increase, flank wear increases and adversely affects the machined surface quality and cutting forces behaviour.

Key words: AISI 4140, CBN, Cutting forces, Surface roughness, Tool wear, GRA.

1. INTRODUCTION

Machinability terms related to the ease of unwanted material removal from a blank to achieve a desired geometrical shape with an acceptable machined surface quality under higher tool life conditions at a lower cost (Machado, and Diniz, 2017). Hardened steel is a class of carbon steel and it consists of a carbon percentage near about 2.1 % by weight. Besides, hardened steel has undergone different heat treatment processes to achieve desirable hardness. During the heat treatment process, the quenching process results in the formation of a metastable martensite phase in hardened steel which improves the hardness of workpiece (Chinchanikar and Choudhury, 2013, Ibrahim, 2012). The typical properties of hardened steels are resistant to wear, excellent corrosion resistance against chemical environments, higher abrasion resistance for severe sliding application, and durability (Das et al, 2015). These properties make them suitable for extensive use in many industries for making different geometrical parts such as gear shaft, main axle, valve rod, connecting rod, aircraft bearing, mandrel bars, punching, and machine tools, etc. In the advancement of machining processes, hardened steels are turned using single-point cutting inserts. Because, it replaced the finish turning and grinding process due to limited parts producing capability of grinding as well as it reduces the larger machining time. While machining of hardened steel higher cutting forces and high temperature at the machining zone is generated (More et al, 2006, de Godoy and Diniz, 2011) which reduces the tool rigidity and subsequently tool life. Thus, it pushes the various cutting inserts industries to design and supply an advanced type of cutting inserts for the ease of turning. Initially, several types of cutting inserts such as ceramic, cubic boron nitride (CBN), polycrystalline cubic boron nitride (PCBN), and diamond are used for improving the tool life by producing different shape of components. This is because of high hot hardness and resistance to corrosion ability (More et al, 2006, de Godoy and Diniz, 2011) of the tools. Besides, some of the different shapes of cutting inserts are coated with a single or multi-layer under geometrical considerations. These coatings can sustain high mechanical shocks, abrasion resistance, and high-temperature generation while turning. But, the cost involved in the production of multi-layered inserts, PCBN, and, diamond inserts are high because of that they are manufactured at limited stock and crucial for economical justification. Hence, there are two-fold challenges in hard turning such as enhance the machinability aspect and decreases in the tool cost without compromising machining performance. In this context, most of the researchers have tried to analyze machining behaviour and find optimized machining conditions using different cutting inserts. Mahfoudi et al. (2008) studied the performance of PCBN/TiC composite cutting inserts during hard turning of AISI 4140 at higher cutting speed without coolant conditions. They concluded that machining at high cutting speed was provided better surface roughness and high tool life in hard turning. Aslan et al. (2007) analyzed the effects of cutting parameters on tool wear and surface roughness using an uncoated Al_2O_3+TiCN mixed ceramic tool of hardened AISI 4140 (63 HRC) steel. They observed that tool wear progression in hard turning was mainly dependent on the variation of cutting speed than the feed and depth of cut. It was also seen that chipping off in most of the cutting inserts rather than smooth abrasive wear due to the brittle nature of ceramic tools. Chavoshi and Tajdari (2010) investigated the effect of workpiece hardness and spindle speed on surface roughness in hard turning of AISI 4140 using CBN cutting tool. They seen that machined surface roughness was dependent on workpiece hardness. Besides, with an increased hardness of material up to 55 HRC, surface roughness value decreases; however beyond that surface roughness value increases with workpiece hardness. Among all the considered hardness values of steels; 55 HRC steel showed a smooth machined surface under different spindle speeds. Derakhshan and Akbari (2009) analyzed the effect of workpiece hardness, and cutting speed on surface roughness and tool wear in hard turning of AISI 4140 with CBN tools. They considered five different workpieces based on the workpiece hardness. The best surface quality of the machined surface was observed at 55 HRC using CB50 tool however CB7020 tool for 50 HRC. Chinchanikar and Choudhury (2013) studied the machining performance of hardened AISI 4340 alloy steel using multi-layer carbide tool at a various level of hardness. They observed that cutting speed was significantly affected tool life than the feed. Besides, abrasive and adhesive two different tool wear mechanisms were observed during hard turning. Suresh et al. (2012) studied the performance of multilayer hard coatings ($TiC/TiCN/Al_2O_3$) on machining of hardened AISI 4340 steel. The feed rate showed a significant influence on machining force and surface roughness than the depth of cut and cutting speed. In addition to that as higher feed rate increases, the machining force due to more chip area was available in-front of cutting edge during turning. Besides cutting forces decreases with an increase in cutting speed due to higher temperature generation at the contact of tool-workpiece, which reduces the tool performance due to tool wear. Bouacha et al. (2010) analyzed the effect of cutting parameters on surface roughness and cutting forces using response surface methodology in hard turning of AISI 52100 bearing steel. Experimental studies revealed that the cutting forces increase with the hardness of workpiece. Moreover, the radial force was observed as the highest cutting force component and it was sensitive with the workpiece hardness variation due to workpiece resistance. Yallese et al. (2009) carried out the experimental study in hard turning of AISI 52100 bearing steel using CBN tool. They analyzed the effect of cutting parameters on tool wear, surface roughness, cutting forces, and metal volume removal rate. Experimental results showed that the cutting speed exhibits maximum influence on tool wear. Furthermore, higher feed rate and cutting time increases the cutting forces; whereas higher cutting speed reduces cutting forces due to softening phenomenon. Aouici et al. (2011) demonstrated the effect of cutting parameters on flank wear and surface roughness using CBN tool on hardened AISI H11 steel. They were observed that the flank wear increased with the cutting speed, feed rate, and cutting time. Moreover, higher tool wear was noted at higher cutting speed and moderate feed rate. Benlahmidi et al. (2017) optimized cutting parameters when turning hardened AISI H11 steel (50 HRC) with CBN7020 tools. The results indicated that surface roughness of the machined component was improved with an increasing the cutting speed and workpiece hardness. But in case of feed rate it was showing negative effects on surface roughness. The high surface finish was observed at the combination of higher cutting speed and lower feed rate. The reason behind that, higher temperature was generated during turning, which reduces the hardness of workpiece material and subsequently improves the machining performance. Poulachon et al. (2004) analyzed tool-wear mechanisms for different hardened steels in hard turning using CBN inserts. They observed that drastic changes in tool-wear phenomenon were noticed in the machining of hardened steels. Further, they correlated groove wear on the flank face with the hard particles in the workpiece. Machado and Diniz (2017) studied the tool wear analysis of hardened steels. They observed that the tool life mainly depends on the tool wear rate. In addition to that, high hardness of materials (over 35 HRC) are difficult to machine because of higher cutting forces, and heat generated during turning causes gradual tool wear. Abrasion and diffusion are the two wear mechanisms observed while turning when CBN-L tools were used. However, in the case of CBN-H tools Diffusion wear was noticed on the tool face.

From the available research articles, it is observed that the many researchers have focused on machining of hardened steels like AISI 52100, AISI 4340, AISI H11 using PCBN, ceramic, multilayered coated tool, hybrid coated and uncoated inserts. Besides, limited experimental research has been discussed on hardened steel such as AISI 4140 using CBN inserts, but their machinability aspects are not studied in detail the higher cutting speed range. Therefore, the aim of the experimental study is the machinability assessment of AISI 4140 steel in hard turning using CBN inserts. In this context, the present study is to examine the cutting force generation and machined surface roughness (R_a and R_z) with regards to the process parameters variation like cutting speed and feed. Further, input parameters are optimized for lower cutting forces generation and minimum surface roughness using Grey Relational Analysis (GRA). Finally, tool life and tool wear mechanisms are investigated at optimized machine condition with cutting force generation as well as machined surface roughness.

2. EXPERIMENTAL DETAILS

2.1 Workpiece material, cutting insert, and cutting parameters

In this work, AISI 4140 hardened steel was chosen as a workpiece material for the external turning process. The nominal chemical composition of AISI 4140 steel is reported in Table 1. A strategy of the experimental outline is as shown in Figure 1. All experimental tests were performed on AISI 4140 cylindrical rods having dimensions of Ø 86 mm and 210 mm long (See Figure 2(a)) using CNC Jobber XL lathe (Make: Micromatic - Ace) having the spindle speed range up to 5000 rpm. The hardness of the workpiece along the radial direction was measured at a specified location using Rockwell hardness tester (Figure 2(b)). The range of input variables such as cutting speed and feed were selected based on the past literature, manufacturer's catalogue, and machine tool capability [12,14], and each of them has three levels. The corresponding levels of cutting speed chosen were 150-175-200 m/min and feed as 0.1-0.15-0.2 mm/rev. Each experiment was performed under no coolant condition with a constant 0.25 mm depth of cut. A rhombus-shaped screw-type CBN insert (see Figure 2(c)) having a 0.8 mm nose radius (2NKCNGA120408) was selected as a cutting tool (Make: Rudrali Hi-Tech Ltd) for the turning process. The cutting insert was fixed on tool holder PCLNL2525M12, Make Widia (see Figure 2(d)) having tool geometry of −6° normal rake angle, and 5° clearance angle. Further, the tool holder was clamped on the Kistler dynamometer and the complete assembly was attached to the turret of CNC lathe as shown in Figure 3(a). The corresponding tool-workpiece interaction with cutting force direction is shown in Figure 3(b).

Table 1. Chemical composition of AISI 4140 (wt %)

Elements	C	S	P	Mn	Si	Ni	Mo
% wt	0.41	0.029	0.012	0.74	0.26	0.11	0.17
Elements	Cr	Fe					
% wt	1.10	Balanced					

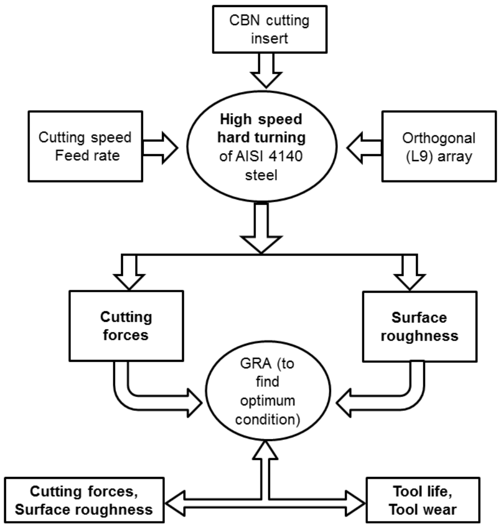

Fig. 1. Experimental scheme

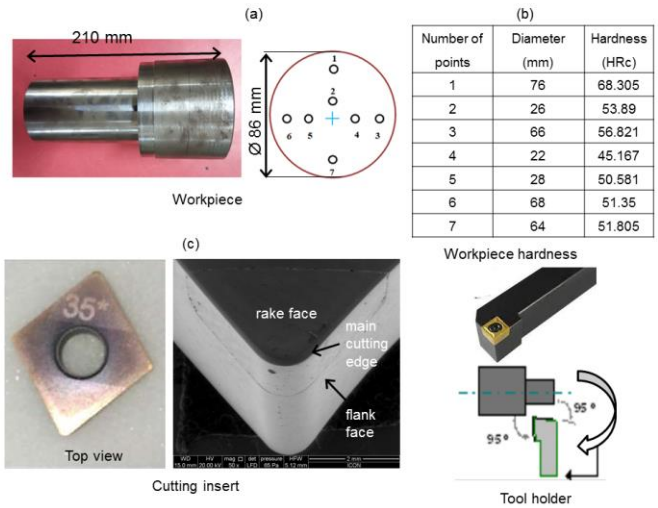

Fig. 2. Pictorial view of (a) workpiece, (b) hardness of workpiece at a specified location, (c) SEM image of cutting insert, and (d) tool holder

2.2 Design of experiments

Traditional experimental designs were based on process performance characteristics which increase the number of experiments trial when the input variable parameters are large in number. Therefore it is too complex and difficult to handle for analysis. Hence, the robust design of experiments is a reliable route to improve the product quality and machining process at a lower cost (Pawade et al.,2007). Keeping the above in mind, L_9 orthogonal array (OA) was selected in this study for the purpose of evaluating the machinability in terms of process performance as shown in Table 2.

2.3 Grey theory and Grey Relational Analysis

In Grey theory, incomplete information about data and unclear problems can be considered very accurately for analysis. In Grey relational analysis of problems if the data sequences are not in a single unit or range or scatter range of data then data pre-processing is required. In data pre-processing, the original data sequence can be converted into a comparable sequence. Therefore, data must be scaled, and polarized into a comparable sequence before proceeding to other steps. The processing is called a generation of grey relational processing. The data normalization is based on the characteristics of a data sequences, for example: If the expectancy is ‘higher-the-better’, then it can be expressed by [18].

Table 2. L_9 orthogonal array with experimental results

Expt. no.	Input Variable		Cutting speed (V) (m/min)	Feed (f) (mm/rev)	Output respounce			
					Cutting forces (N)			Surface roughness (µm) (R_a)
	Variable 1	Variable 2			Cutting force (Fc)	Radial force (Fr)	Feed force (Fa)	
1	1	1	150	0.1	77.44	299.59	145.87	0.5945
2	2	1	175	0.1	167.16	262.2	132.46	0.518
3	3	1	200	0.1	165.92	243.3	132.15	0.522
4	1	2	150	0.15	211.12	280.94	137.77	0.9355
5	2	2	175	0.15	204.15	270.91	131.61	0.7965
6	3	2	200	0.15	202.08	269.2	129.55	0.7345
7	1	3	150	0.2	250.37	304.56	138.87	1.2985
8	2	3	175	0.2	264.27	309.93	150.19	1.2425
9	3	3	200	0.2	247.05	303.91	138.05	1.403

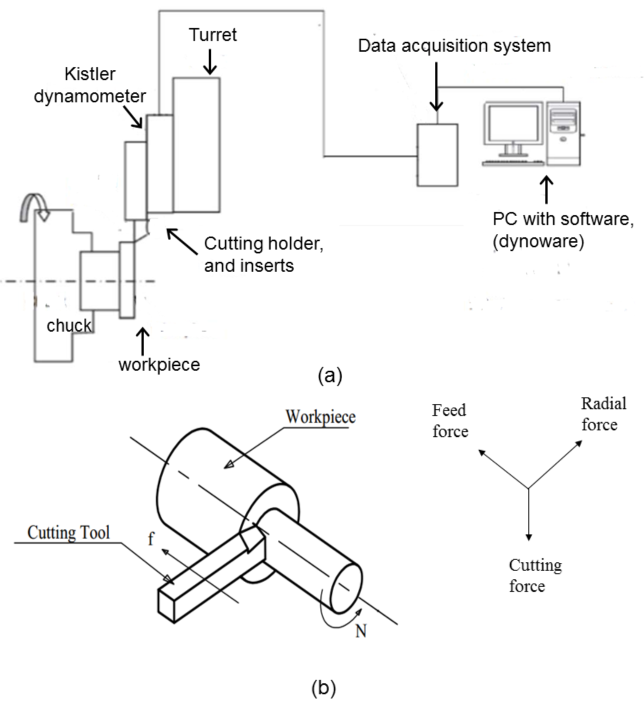

Fig. 3. Schematic diagrams of (a) experimental setup, and (b) tool-workpiece interaction and machining force directions

$$x^*(k) = \frac{x_i^0(k) - \min x_i^0(k)}{\max x_i^0(k) - \min x_i^0(k)} \quad (1)$$

If the expectancy is ‘lower-the-better’, then it can be expressed by,

$$x^*(k) = \frac{\max x_i^0(k) - x_i^0(k)}{\max x_i^0(k) - \min x_i^0(k)} \quad (2)$$

where,

i= 1,…m; k= 1,….n.

m - is number of experimental data items,

n - is the number of parameters;

x_i^o (k) - is the original sequence.

2.4 Experimental procedure

A cylindrical workpiece of AISI 4140 hardened steel was clamped on lathe spindle using a three-jaw chuck. A CBN insert was clamped on the tool holder. Further, tool holder is rest on the dynamometer for collecting the cutting force signals and corresponding magnitude as shown in Figure 3. All experimental tests were planned based on the L_9 full factorial orthogonal array and carried out accordingly to the experimental sequence (see Table 2). In each experiment, a continuous 20 mm cutting length was set for cutting forces data measurement. The cutting force signals were collected using Kistler 3-component tool dynamometer (KISTLER 9257 BA) and stored on the computer through the data acquisition unit and dynoware software. After successfully each experiment, the machined surface roughness was measured along the circumferential direction of the machined surface using a surface roughness tester (MITUTOYO SJ-301), at three different specified locations with a cut-off length 0.8

mm. The average surface roughness value was considered for the analysis purpose. After the successful completion of nine experiments, the process parameters were optimized for lower cutting forces and minimum surface roughness using GRA technique. For tool life and tool wear analysis, experiments begin with optimized variables by considering 100 mm cutting length in each cut. Tool life of cutting inserts was measured based on the VB_{max} = 0.3 mm criteria. Further after each cut, the cutting insert condition (tool wear) was analyzed under a digital USB microscope (Make- Dino-Lite; Model- AM4113 Series) to investigate tool wear mechanism. Additionally, cutting forces and machined surface roughness variation were analyzed as a function of cutting length (tool life).

3. RESULTS AND DISCUSSION

This section is separated into two parts; in the first part discusses the experimental results that were planned according to the orthogonal L_9 array and analyze the effect of input variables on output responses using the analysis of variance (ANOVA). In the second part, optimum cutting parameters combination was obtained using GRA technique. Additionally an investigation at optimized cutting condition was performed for tool wear mechanism and tool life analysis as a function of cutting length.

3.1 Analysis of cutting forces

Cutting force is a primary output response variable that helps to assess the tool life, analysis of process and its productivity, and tool wear mechanism during turning. Also, cutting forces affect the machined surface topography by appropriate selection of input variables. Therefore, the main effects of input parameters on cutting forces are presented in Figure 4 however, the corresponding cutting forces magnitude is tabulated in Table 2. Among all the cutting force recorded (Table 2) the radial force shows maximum magnitude over the feed and cutting force components. Whereas, feed force shows the minimum magnitude, and cutting force lies in between them. This observation makes the hard turning distinct from the conventional turning process. The probable reason behind the generation of higher radial force was the selection of a lower depth of cut than that of the nose radius of inserts. At this condition, specific stresses were developed and exerted on the round part of the cutting nose area which initiated the radial force that further increases with the continuous hard turning (Ibrahim,2012). Similarly, Bouacha et al. (2010) seen that the radial force component shows a higher magnitude because of the small depth of cut, low feed rate, and negative rake angle that generate higher compressive stresses in finish machining condition. Moreover, as the cutting speed increases, cutting forces tend to decrease, this is because of the softening phenomenon. At higher cutting speed, a higher cutting temperature may be developed at the machining zone because of the hardness of workpiece material gets reduced due to material removal takes place elastically rather than plastically (Bouacha et al., 2010, Pawade et al., 2007). This causes a decrease in a shearing force in the shear zone of machining and reduces the chip-tool contact length during turning. Whereas, higher cutting force components were found at lower feed and cutting speed than the higher cutting parameters. This may be due to high friction occurred between tool and chip on account of the high hardness of workpiece material (Lin, 2008). Further, it was also noticed that as the feed increases the cutting forces increased (see Figure 4). It can be correlated with the fundamental theory of the turning process; feed and depth of cut are the functions of the chip cross-sectional area (Suresh et al., 2012 Pawade et al., 2008). Thus, it can be understood that as the feed increases, the chip area (undeformed chip thickness) in the machining zone increases that contributed to the generation of higher cutting force.

Statistical analysis of cutting force

The effect of input parameters on cutting forces is analyzed using ANOVA and corresponding P and F-values are presented in Table 3. In cutting force (F_c) analysis, the effect of feed (F= 229.50) is substantial than the cutting speed (F = 2.07) and its probability (P) value is less than 0.05 at 95% confidence level. In the case of radial force, the (Fr) effect of feed (F=9.69) is the most significant than the cutting speed (F = 3.56), as its probability (P) value is less than 0.05 at 95% confidence level. Whereas, in the case of feed force (Fa), feed and cutting speed are showing the minimum effect on it because of P values are higher than 0.05.

By using the regression analysis it is possible to know the cutting force magnitude for different cutting parameters that can be formulated within the given range of input variables. From the ANOVA analysis, it is noted that the lower value of cutting force and radial force is observed at 0.1 mm/rev feed and cutting speed of 200 m/min. However, the maximum value of Fc and Fr is at 0.2 mm/rev feed and 175 m/min cutting speed. The regression equations for the three cutting force component are obtained using ANOVA is as follows:

$$F_c = 112.2 - 0.159 \times \text{Cutting Speed} + 837.2 \times \text{Feed} \quad (3)$$

$$Fr = 306.2 - 0.458 \times \text{Cutting Speed} + 378 \times \text{Feed} \quad (4)$$

$$Fa = 155.6 - 0.152 \times \text{Cutting Speed} + 55.5 \times \text{Feed} \quad (5)$$

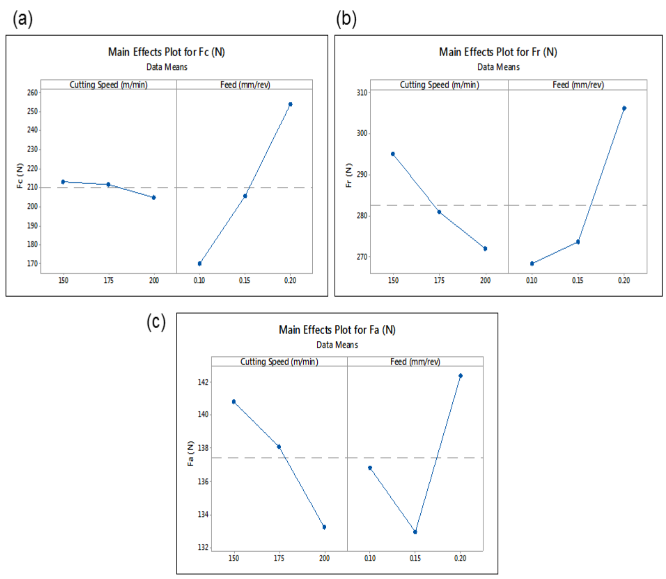

Fig. 4. Main effect plots for the effect of cutting speed and feed on cutting forces (a) cutting force, (b) radial force, and (c) feed force

Table 3. ANOVA for the cutting force components

Source	DF	Cutting force (N)			Radial force (N)		
		F	*P*	Contri	*F*	*P*	Contr.
V	2	1.24	0.382	1.04	1.69	0.293	24.14
f	2	117.49	0.000	98.95	5.31	0.075	75.85
Source	DF	Feed force (N)					
		F	*P*	Contr.			
V	2	1.24	0.420	39.92			
f	2	117.49	0.301	60.07			

3.2 Analysis of surface roughness

Surface roughness is an important aspect of machining which helps to analyze machined surface characteristics for determining the fatigue strength and corrosion resistance of the machined components. The effect of machine input variables on surface roughness is as shown in Figure 5 and the corresponding ANOVA table is represented in Table 4. It is noticed that the P-value of feed is lesser than 0.05. It indicated that the feed is a significant factor on average surface roughness (R_a) and maximum peak-to-valley height (R_z), than that of the cutting speed. The cutting speed does not have statistical importance on the obtained surface roughness (R_a, and R_z) because of their smaller F value. Thus, from this observation, it can be concluded that the surface roughness dependent only on feed than other machining input parameters. Also, in the theoretical analysis of metal cutting it is seen that surface roughness is inversely related to the feed (Chou et al., 2002). Besides, during the turning process feed generates helicoids and furrows due to the result of the plowing action of tool shape, and it is increased with feed (Aouici et al., 2011). In addition to that, it was observed that as the feed increase, the thrust force charged sharply which resulted in a chance of vibration. These vibrations reduce the cutting capability of inserts and that enhance plastic deformation while turning and thereby resulting in poor surface finish. While reducing the feed and increasing the cutting speed, the uncut chip thickness is decreasing that decreases the cutting forces, and subsequently produced good surface roughness. The higher surface roughness is observed at 0.2 mm/rev feed and 200 m/min cutting speed whereas minimum surface roughness is noticed at 0.15 mm/rev and 175 m/min (see Figure 5). It could be seen that while increasing the feed rate and decreasing cutting speed the surface roughness increased as shown in Figure 5. This may be because of lower cutting speed generates high friction which reduces the surface finish. Whereas, at higher cutting speed, surface finish improves because workpiece materials shear strength reduces due to high-temperature generation which causes easy removal of material from the workpiece. The regression equations for surface roughness analysis are as follow:

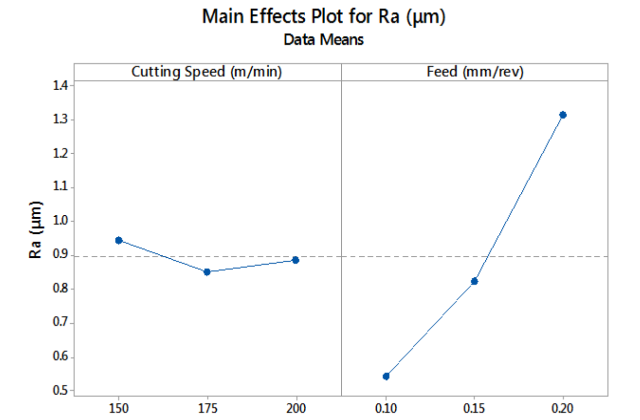

Fig. 5. Main effects plot for surface roughness

Table 4. ANOVA for surface roughness

Source	R_a (µm)			R_z (µm)		
	F-Value	P-Value	Contri	F-Value	P-Value	Contri
V	0.98	0.451	1.35	0.99	0.446	1.62
f	71.15	0.001	98.64	59.81	0.001	98.37

$$R_a = -0.064 - 0.00113\times\text{Cutting Speed} + 7.698\times\text{Feed} \quad (6)$$

$$R_z = 1.06 - 0.00778\times\text{Cutting Speed} + 31.04\times\text{Feed} \quad (7)$$

3.3 Tool life and tool wear mechanism analysis

Tool wear is the principal aspect in the metal cutting study because the good quality of machined surface depends on the tool condition. Besides, it also influences the behaviour of cutting forces that affect the tool motion while turning leading to loss of its rigidity and subsequently reduces the tool life. Tool life and tool wear mechanism were analyzed at optimum cutting parameters such as 200 m/min cutting speed, 0.1 mm/rev feed, and 0.25 mm depth of cut which are obtained from the GRA technique.

The effect of cutting length under the optimized condition on VBmax of the tool is presented in Figure 6. It is observed that, as the turning length increases, VBmax also increases, and it rapidly increased up-to cutting length of 3000 mm and thereafter steadily increased from 3000 to 5000 mm cutting length. The reason behind this is the flank wear progression of CBN tool (Aouici et al., 2011, Chou et al., 2002, Machado and Diniz, 2017). At the beginning of hard turning, the cutting edge was fresh and round off (see Figure 2(c)). As the hard turning begins and considering the early stage of hard turning (say 1000 mm cutting length) abrasion wear on the flank face and polished texture/black surface on rake face is observed. This is because of higher cutting forces generated during the turning process due to the presence of the martensite phase in the AISI 4140 material (Ibrahim, 2012). Further, on the rake face, the black surface is observed due to friction which is taking place when chips are sliding on the rake face. Thus, the friction phenomenon associated with high specific pressure occurs between chip and tool face.

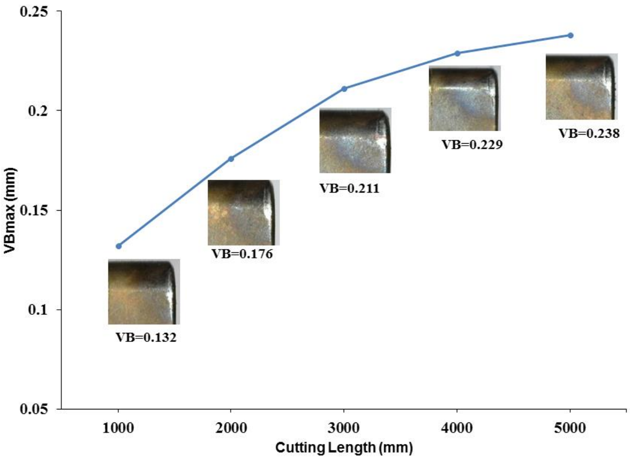

Fig. 6. Effect of cutting length on VB_{max}

This is due to high specific pressure and the presence of hardened phases in the material initiates high cutting temperature generation while turning at the tool-chip junction. Moreover, with the progress of turning with the same cutting edge, the length of VB_{max} further increases (see Figure 6 and Figure 7(d)). At this stage, higher cutting forces (see Figure 8) are generated by shearing and friction phenomenon that causes softening of the binder phase on the rake and flank face of the tool which metallic binder phase on the rake and flank face of tool which reduces the cutting edge strength. Finally, cutting edge conditions were analyzed after successful completion of the 5000 mm cutting length of a workpiece (see Figure 7(e,f)). At this stage, VB_{max} reaches near to 0.25 mm and dark black surface appeared on the rake face whereas the flank face shows loss of tool layer due to abrasion wear followed by oxidation effect. This is because of high-temperature generation at higher cutting speed (V=200 m/min) which reduces the hot hardness resistance of the tool (More et al.,2002) and gradually increasing of flank wear. On the other side, when the chips are sliding on the tool rake face that causes a decrease in the tool binder resistance and consequently loss of cohesion between CBN and binder due to friction as well as higher cutting temperature generation in the cutting region. As a consequence, crater wear and black surfaces, as well as the small groove, are noticed on the rake face. The effects of cutting length on cutting forces are presented in Figure 8. It can be seen that initially cutting edge is fresh and sharp (unused) because of that minimum tool-workpiece contact taking place at the shear plane (Machado and Diniz, 2017) and material removal occurs easily leading to lower cutting forces generated at the initial stage of hard turning. After turning of sufficient cutting length, tool wear starts to occurs on the flank face as well as rake face, which reduces the sharpness of cutting edges and increases the chip-tool interface contact length, and increased the cutting force magnitude. As the material is case hardened, hardness changes with the diameter of the material during each cut. In the case of hardened steel, the hardness of the surface is more as compared to the hardness of the inner core. Therefore, as the cutting length increases the hardness of the material decreases which causes a decrease in the cutting force magnitude. It is seen from Figure 9 that surface roughness R_a was linearly decreasing with the cutting optimized parameter at V 200 m/min and 0.1 mm/rev feed length. This is because of the decrease in hardness of material as the diameter of the workpiece decreases during each experiment. So, as the hardness of the material decreases, a better surface finish is obtained (Chavoshi and Tajdari, 2010).

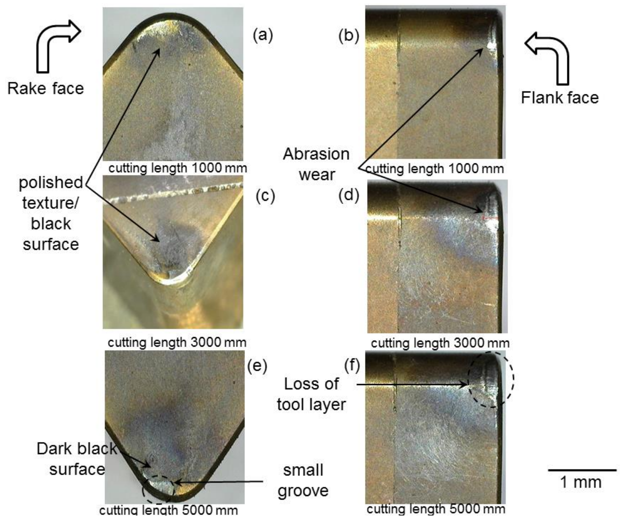

Fig. 7. Tool wear image at different cutting length

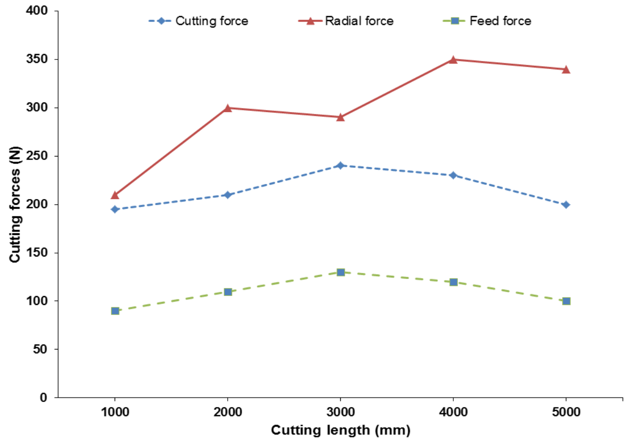

Fig. 8. Cutting force variation with cutting length under

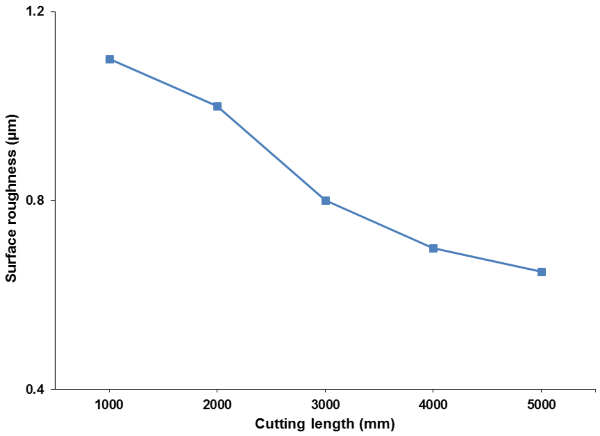

Fig. 9. Effect of cutting length on surface roughness

4. CONCLUSIONS

In this experimental study, turning of AISI 4140 steel is carried out using CBN inserts and analyzed in terms of tool life, tool wear, cutting forces, and surface roughness. Also, optimum cutting parameters are obtained using GRA for lower cutting force magnitude and minimum surface roughness. The following conclusions are drawn based on experimental results:

- Radial force shows the highest magnitude as compared to the feed and cutting force in hard turning. The machining forces decrease with increases in cutting speed and it increases with feed. The lowest cutting force (129.522 N) was observed at 200 m/min cutting speed and 0.15 mm/rev feed. However, the highest cutting force (309.93 N) was observed at 175 m/min cutting speed and 0.2 mm/rev feed.
- The feed shows the highest effect on surface roughness than the cutting speed. Surface roughness increases with the increase in feed. The lowest value of surface roughness (0.518 µm) is observed at 175 m/min cutting speed and 0.1 mm/rev feed. The highest surface roughness (1.4 µm) was observed at 200 m/min cutting speed 0.2 mm/rev feed. Using the GRA technique, optimum cutting condition was obtained at a combination of 200 m/min cutting speed and 0.1 mm/rev feed.
- Abrasion and oxidation tool wear mechanism was observed in hard turning. Polished texture, black surface, and small groove on the tool are observed at the rake face whereas abraded cutting edge and loss of tool layer are observed at the flank face during tool life analysis. As the cutting length increases cutting force increases and machined surface roughness reduces due to the tool gets worn out. The maximum tool life of 58.02 min for CBN inserts is observed at 0.1 mm/rev feed and cutting speed of 200 m/min during turning of AISI 4140 hardened steel.

5. DECLARATION /COMPETING INTEREST

The Authors warrants that the article is the author's original work that has not been published before. The authors declare that they have no competing interest pertaining to this submission.

6. DATA AVAILABILITY

The data of this study can be available from the corresponding author on request.

7. FUNDING STATEMENT

This work was supported by the MHRD of India through TEQIP III programme.

8. ACKNOWLEDGEMENT

The authors are grateful to the MHRD India to be supportive of this study under TEQIP III programme. Besides authors express special gratitude to Mayuri Jadhav, Minal Kalokhe, Koyal Mankar, and Nupoor Mirgane, undergraduate students for technical support. Finally deep appreciation to Rudrali Pvt. Ltd. for providing cutting inserts to carry out experiments.

9. REFERENCES

1. Álisson Rocha Machado, and Anselmo Eduardo Diniz, (2017). *Tool wear analysis in the machining of hardened steels.* The International Journal of Advanced Manufacturing Technology, **92**(9)-12, pp. 4095-4109.
2. Satish Chinchanikar and S. K. Choudhury, (2013). *Effect of work material hardness and cutting parameters on performance of coated carbide tool when turning hardened steel: An optimization approach.* Measurement, **46**(4), pp. 1572-1584.
3. Sadik M. Ibrahim, (2012). *Wear development and cutting forces on CBN cutting tool in hard part*

turning of different hardened steels. Procedia CIRP, **1**, pp. 232-237.
4. Sudhansu Ranjan Das, Debabrata Dhupal, and Amaresh Kumar, (2015). *Experimental investigation into machinability of hardened AISI 4140 steel using TiN coated ceramic tool.* Measurement, **62**, pp 108-126.
5. Abhijeet S. More, Wenping Jiang, W.D. Brown, and Ajay P. Malshe, (2006). *Tool wear and machining performance of cBN–TiN coated carbide inserts.* Journal of Materials Processing Technology, **180**, pp. 253–262.
6. Vitor Augusto A. de Godoy and Anselmo Eduardo Diniz, (2011). *Turning of interrupted and continuous hardened steel surfaces using ceramic*. Journal of Materials Processing Technology, **211**, pp. 1014-1025.
7. Farouk Mahfoudi, Gautier List, Alain Molinari, Abdelhadi Moufki, and Lakhdar, (2008). *High speed turning for hard material with PCBN inserts: tool wear.* International Journal of Machining and Machinability of Materials, **1-2**, pp. 62-79.
8. Ersan Aslan, Necip Camuşcu, and Burak Birgören, (2007). *Design optimization of cutting parameters when turning hardened AISI 4140 steel (63 HRC) with Al ceramic tool*. Materials & Design, **28**(5), pp. 1618-1622.
9. Saeed Zare Chavoshi, and Mehdi Tajdari, (2010). Surface roughness modelling in hard turning operation of AISI 4140 using CBN cutting tool. *International Journal of Material Forming*, **3**(4), pp 233-239.
10. E. D. Derakhshan, and A. A. Akbari, (2009). Experimental investigation on the effect of workpiece hardness and cutting speed on surface roughness in hard turning with CBN tools. *Proceedings of the world congress on engineering* **2**, pp 1-3.
11. Suresh, R., S. Basavarajappa, and G. L. Samuel, (2012). *Some studies on hard turning of AISI 4340 steel using multilayer coated carbide tool*. Measurement, **45**(7), pp. 1872-1884.
12. Khaider Bouacha, Mohamed Athmane Yallese, Tarek Mabrouki, and Jean-François Rigal, (2010). *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, **8**(3), pp. 349-361.
13. Mohamed Athmane Yallese, Kamel Chaoui, Nassereddine Zeghib, Lakhdar Boulanouar and Jean-François Rigal, (2009). *Hard machining of hardened bearing steel using cubic boron nitride tool.* Journal of materials processing technology, **209**(2), pp. 1092-1104.
14. Hamdi Aouici, Mohamed Athmane Yallese, Brahim Fnides, Kamel Chaoui, and Tarek Mabrouk, (2011). *Modeling and optimization of hard turning of X38CrMoV5-1 steel with CBN tool: Machining parameters effects on flank wear and surface roughness.* Journal of Mechanical Science and Technology, **25**(11), pp. 2843-2851.
15. S. Benlahmidi, H. Aouici, F. Boutaghane, A. Khellaf, B. Fnides, and M. A. Yallese, (2017). *Design optimization of cutting parameters when turning hardened AISI H11 steel (50 HRC) with CBN7020 tools.* The International Journal of Advanced Manufacturing Technology, **89**(1-4), pp 803-820.
16. G. B.Poulachon, (2004). *Wear behavior of CBN tools while turning various hardened steels*. Wear, **256**(3-4), pp. 302-310.
17. R.S. Pawade, Suhas S. Joshi, P.K. Brahmankar, M. Rahman, (2007). *An investigation of cutting forces and surface damage in high-speed turning of Inconel 718.* Journal of Materials Processing Technology, **192-193**, pp 139-146.
18. Sue J. Lin, I. J. Lu, and Charles Lewis, (2007). *Grey relation performance correlations among economics, energy use and carbon dioxide emission in Taiwan*. Energy Policy, **35**(3), pp. 1948-1955.
19. H. M. Lin, (2008). *Wear behavior in turning high hardness alloy steel by CBN tool*. Wear, **264**(7-8), pp. 679-684.
20. M. Shaw, (2005). *Metal Cutting Principles*, second ed., NewYork: Oxford.
21. Y. Kevin Chou, Chris J. Evans, and Moshe M. Barash, (2002). *Experimental investigation on CBN turning of hardened AISI 52100 steel*. Journal of Materials Processing Technology, **124**(3), pp. 274-283.
22. Álisson Rocha Machado, and Anselmo Eduardo Diniz, (2017). *Tool wear analysis in the machining of hardened steels.* The International Journal of Advanced Manufacturing Technology, **92**(9-12), pp. 4095-4109.

Received: February 21, 2021 / Accepted: June 15, 2021 / Paper available online: June 20, 2021