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Investigation of tool wear, surface roughness, sound intensity, and power consumption during hard turning of AISI 4140 steel using multilayer-coated carbide inserts

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ABSTRACT

The present study investigated the machinability aspects, namely, surface roughness, sound intensity, power consumption, and crater wear, during dry turning of hardened AISI 4140 steel (63 HRC) employing ($TiCN/Al_2O_3/TiN$) multilayer-coated carbide inserts under dry cutting condition. The relationship between machining parameters and output parameters was determined using the Taguchi design. The analysis of variance was employed to evaluate the contributions of input parameters on output parameters. The main effect plots illustrated the impacts of cutting speed, feed, and depth of cut on response variables. Results show that the feed was the most dominant factor that affects surface roughness. Increasing the feed value increases the surface roughness, power consumption, and sound intensity. In the other part of this study, the constant values for feed (0.3 mm/rev), depth of cut (0.7 mm), and cutting speed (150 m/min) have been selected to evaluate a tool life that has 0.3 mm crater wear criteria. The results indicated that multilayer-coated carbide inserts presented very good tool life and reached 0.3 mm in 90 min. The experimental study results showed that chipping and abrasion were found to be the significant wear mechanism during hard turning of AISI 4140 steel. The cutting speed was the most significant parameter on the tool wear, although high cutting speed results the good surface finish but adversely increases the tool crater wear.

Keywords: AISI 4140 steel; Surface roughness; Power consumption, Multilayer-coated carbide; Tool wear.

INTRODUCTION

One of the most important purposes of machining industries is to manufacture products with high dimensional accuracy and high quality by reducing the cost and process time in this competitive world. In addition, environmental pollutions are another significant aspect that should be considered by decreasing power consumption and cutting fluids that adversely affect the ecology's cleanliness. Nowadays, in most machining operations, hard turning with coating cutting inserts was established as an essential process on steels to deal with the issues mentioned above.

In hard turning applications, the metal workpieces' hardness is in the range of 40–70 HRC (Bartarya and Choudhury 2012). Hard turning is used in the production of many parts, especially in automotive industries such as gears, bearings, and shafts. The advantages of hard turning compared to conventional machining processes are higher productivity, lower energy consumption, shorter setup time, better surface quality, and lower manufacturing costs (Yallese et al., 2009; Guo and Liu 2002; Tönshoff et al., 2000). Cutting tools play a crucial role in enhancing the products' productivity and quality besides minimizing the machining process's cost. The hard turning processes are usually performed using cubic boron nitride (CBN), ceramic or multilayer-coated carbide inserts with high wear resistance and hardness. A titanium-based coated cutting tool is frequently used in hard turning due to its good wear resistance, low friction coefficient, high thermal conductivity, and corrosion properties. Chemical vapour deposition (CVD) and physical vapour deposition (PVD) techniques are applied to cutting tool materials to obtain coated cutting inserts (Das et al., 2018).

Tool wear is one of the critical issues in hard turning due to its effects on surface quality and integrity, dimensional accuracy of the component, residual stresses, and tool life. Previous studies revealed that the depth of cut and cutting speed affected tool life significantly (Rakesh and Datta 2019; Mia et al., 2018; Das et al., 2018; Salimi Asl et al., 2017). Any increase in each cutting parameter increases cutting forces and temperatures. The high temperature is one of the parameters that result in tool wear (Salimiasl and Rafighi 2017).

Surface roughness is another vital issue that affects the wear rate, fatigue strength, corrosion resistance, and tribological properties of the machined surface. Recently, many studies were performed to explore the effects of coated cutting inserts during hard turning of different steels since the tool wear modifies both the surface and tool life (Rakesh and Datta 2019; Das et al., 2018; Mia et al., 2018).

Several factors such as cutting parameters, workpiece, and tool variables affect the surface roughness and tool wear in the hard turning process (Salimiasl and Rafighi 2017; Patel and Gandhi 2019; Sarnobat and Raval 2019). Cutting parameters consist of feed rate, cutting speed, and depth of cut. Workpiece variables consist of hardness and material of the component. Tool variables consist of tool nose radius, tool material, tool point angle, cutting edge geometry, and tool coating. Previous studies have shown that coating is an effective method to increase the tool wear resistance and decrease the tool cost in machining industries (Zhao and Lio 2020; Moganapriya et al., 2018; Keblouti et al., 2017). The TiCN, Al_2O_3, and TiN are the most frequently used material for a coating with wear resistance, thermal barrier, and lubricity properties. It is important to select the most appropriate machining parameters in the hard turning operations to obtain high-quality products with minimum production cost. In past years, the optimization of cutting parameters is fulfilled by using the experimental results and developing a mathematical model to increase productivity.

In this study, the influences of process parameters such as feed, depth of cut, and cutting speed on output variables, namely, sound intensity, surface roughness, power consumption, and tool wear, are investigated. Hard turning is performed on AISI 4140 steel (63 HRC) employing multilayer-coated carbide cutting inserts under a dry cutting environment. The chemical vapour deposition (CVD) was applied to coat the carbide insert with thin layers of titanium carbide nitride (TiCN), aluminum oxide (Al_2O_3), and titanium nitride (TiN). Thin coating layers can decrease the tool wear and increase the tool life (Nouari et al., 2003; Moganapriya et al., 2018; Keblouti et al., 2017). The analysis of variance and the main effect plots are employed to evaluate the influences of machining variables on output parameters. Also, mathematical models are developed to predict the tool wear.

LITERATURE REVIEW

Many experimental works are performed to investigate the impacts of different process conditions on surface roughness and tool wear during hard turning of various steels (Das et al., 2018; Mia et al., 2018; Patel and Gandhi

2019; Sarnobat and Raval 2019; Kuntoğlu and Sağlam 2020). However, the number of studies investigating the impacts of cutting variables on power consumption and sound intensity is limited (Şahinoğlu and Rafighi 2020 a, b). The following literature review is related to the study of process conditions such as tool variables and cutting conditions on the response variables, as mentioned above.

Aslantaş et al. investigated the effects of Al_2O_3/TiCN mixed ceramic tools coated with TiN on surface roughness, tool wear, and tool life while turning hardened AISI 52100 bearing steel. The results presented that uncoated cutting tools are vulnerable to fracture; however, the more obvious damage in TiN coated inserts is crater wear (Aslantas et al., 2012).

In Huang's study, the optimization of machining parameters was performed to model the CBN inserts crater wear rate during hard turning of AISI 52100 bearing steel. The CBN cutting tools are expensive, and the need for maximizing tool life during the manufacturing process is indispensable. Therefore, the results showed that adhesion is the dominant factor for tool wear, among other factors such as diffusion and abrasion. Further, the mathematical model presents good agreement between experimental and predicted results (Huang and Dawson 2005; Huang and Liang 2004).

In other studies, the impacts of wiper-coated carbide insert on tool life and surface roughness while turning hardened AISI 420 stainless steel were investigated. The results showed that increasing the cutting speed and feed decrease tool life. Further, the fine surface quality is achieved using wiper-coated carbide inserts compared to conventional inserts (Kurniawan et al., 2010; Noordin et al., 2007).

The impacts of machining variables on the cutting forces and surface roughness during turning of hardened AISI 52100 bearing steel using cubic boron nitride cutting tools were evaluated (Bouacha et al., 2010). Results showed that feed has a dominant influence on the surface roughness. The same results were obtained for surface roughness while turning hardened AISI 4140 steel employing Al_2O_3/TiC inserts (Asiltürk and Akkuş 2011).

Motorcu reported the influences of tool nose radius and cutting parameters such as feed rate, depth of cut and cutting speed on surface quality while performing hard turning on AISI 8660 steel using physical vapour deposition coated ceramic inserts. The significant parameters on surface roughness were determined using analysis of variance (ANOVA). According to the results, feed is the dominant variable on surface roughness. Both depths of cut and tool nose radius affect surface roughness (Motorcu 2010).

Meddour et al. showed the impacts of input parameters such as feed, tool nose radius, depth of cut, and cutting speed on the cutting forces and surface roughness. The turning process was performed on hardened AISI 52100 bearing steel with 59 HRC employing the ceramic cutting inserts. Taguchi method was used to model the output parameters, while the influences of process variables on output parameters were determined using ANOVA. The results showed the maximum effect of depth of cut on the cutting forces. However, the tool nose radius and feed have a significant impact on surface roughness. A combination of low feed and large nose radius improves the surface quality dramatically (Meddour et al., 2015).

Sahoo performed a hard turning process on AISI 4340 steel by employing uncoated and multilayer-coated carbide inserts to evaluate process parameters' influences on surface roughness, cutting forces, chip morphology, and flank wear. According to this study's results, the tool operating time without failure for ZrCN and TiN coated carbide cutting tools is approximately 8 min and 19 min. Thus, the multilayer-coated insert (TiN/TiCN/Al_2O_3/TiN) exhibits excellent performance in comparison to uncoated and coated carbide insert (TiN/TiCN/Al_2O_3/ZrCN) in evaluating of the flank wear (Sahoo and Sahoo 2012).

Elbah et al. compared the effects of the conventional inserts and wiper inserts on tool wear and surface roughness during turning hardened AISI 4140 steel. The analysis of variance was used to determine the dominant factors affecting the output parameters, and the validation of the quadratic regression model was done by using response surface methodology. According to the results, the feed rate was the most important factor influencing surface roughness. Comparing conventional ceramic cutting inserts and wiper ceramic cutting insert reveals that wiper ceramic creates a better surface finish in the specimen (Elbah et al., 2013).

Although the number of studies that exhibited the impacts of various tools on surface quality and tool life and while turning hardened steels are high, a few papers are published relative to multilayer-coated carbide inserts' performance on surface roughness, sound intensity, power consumption, and tool wear simultaneously. Mainly, the number of studies that considered sound intensity as criteria for machining operation is limited. In this study, feed, depth of cut, and cutting speed are chosen as process parameters, and sound intensity, surface roughness, power consumption, and tool wear are chosen as response variables. Hard turning is performed on AISI 4140 steel employing multilayer-coated carbide inserts ($TiCN/Al_2O_3/TiN$). The results are evaluated using main effect plots, and the significant factors are determined through an analysis of variance.

EXPERIMENTAL PROCEDURES

Cutting Conditions

This experimental study is performed to evaluate surface roughness (Ra), sound intensity, tool wear, and power consumption during turning of hardened AISI 4140 steel employing multilayer-coated carbide inserts under dry cutting conditions. Three cutting parameters, namely feed (f), cutting speed (V), and depth of cut (a), were chosen according to the previous studies and manufacturer catalogue for this material and inserts. These cutting parameters are given in Table 1.

Table 1. The levels of cutting parameters.

Parameters-(symbol)	Depth of cut-(a)			Cutting speed-(V)			Feed-(f)		
Units	(mm)			(mm/min)			(mm/rev)		
Levels	0.3	0.5	0.7	100	125	150	0.1	0.2	0.3

Machine and Cutting Tool

The dry turning is performed on the TAKSAN CNC lathe (TTC-630 model). This lathe has 20 kW power and 4000 RPM spindle speed capacities.

In this test, multilayer-coated carbide inserts manufactured by Taegutec with WNMG 080408 MT TT5100 ISO designation are used. The chemical vapour deposition (CVD) is used to coat carbide inserts with TiCN/Al_2O_3/TiN layers. It has a 0.8 mm tool nose radius (r), 4.76 mm thickness (t), 12.70 mm inscribed diameter (d), and negative 80° cutting tip. Besides, the cutting tools are rigidly mounted into chuck using the MWLNR 2525 M08 tool holder.

Experiment Specimen

The AISI 4140 steel workpiece has 200 mm length and 45 mm diameter. Heat treatment is applied at 920°C to increase the hardness of material to 63 (HRC), and then it is quenched in the oil for 30 min. Moreover, the tempering process is applied for 150 min at 400°C to remove the residual stresses; hence, the homogeneous structure is obtained. Table 2 shows the chemical composition of AISI 4140.

Table 2. Chemical composition of AISI 4140 steel.

Element	C	Mn	Si	Mo	Cr	S_{max}	P_{max}	Fe
Content (%)	0.39-0.44	0.65-0.95	0.15-0.35	0.12-0.32	0.85-1.15	0.040	0.035	Balance

Measurement Devices

Mitutoyo SJ 201 portable device was employed to measure the arithmetic average surface roughness (Ra) of the test specimen. It has a cut-off length of 0.8 mm. The calibration of this device was done employing a standard calibration block. The final surface roughness value was considered the mean value of the three measured roughnesses from various locations on the workpiece.

Lutron SL-401 portable device was used to measure sound intensity. In order to avoid possible instantaneous fluctuations in the sound intensity, this device was located 1 m away from the CNC lathe machine.

UNI-T UT201 device was used to measure the machine's current. The total current value is calculated by multiplying the current value of one phase by three. Subsequently, the power consumption was obtained by multiplying the voltage by the total current value.

Optical microscope (AM4815T Dino-Lite Edge) with a magnification of 220 times equipped with digital camera and computer was used to measure the tool wear. The crater wear happens in the area of cutting edge. Therefore, the cutting edge has the maximum crater wear. The experimental setup is given in Figure 1.

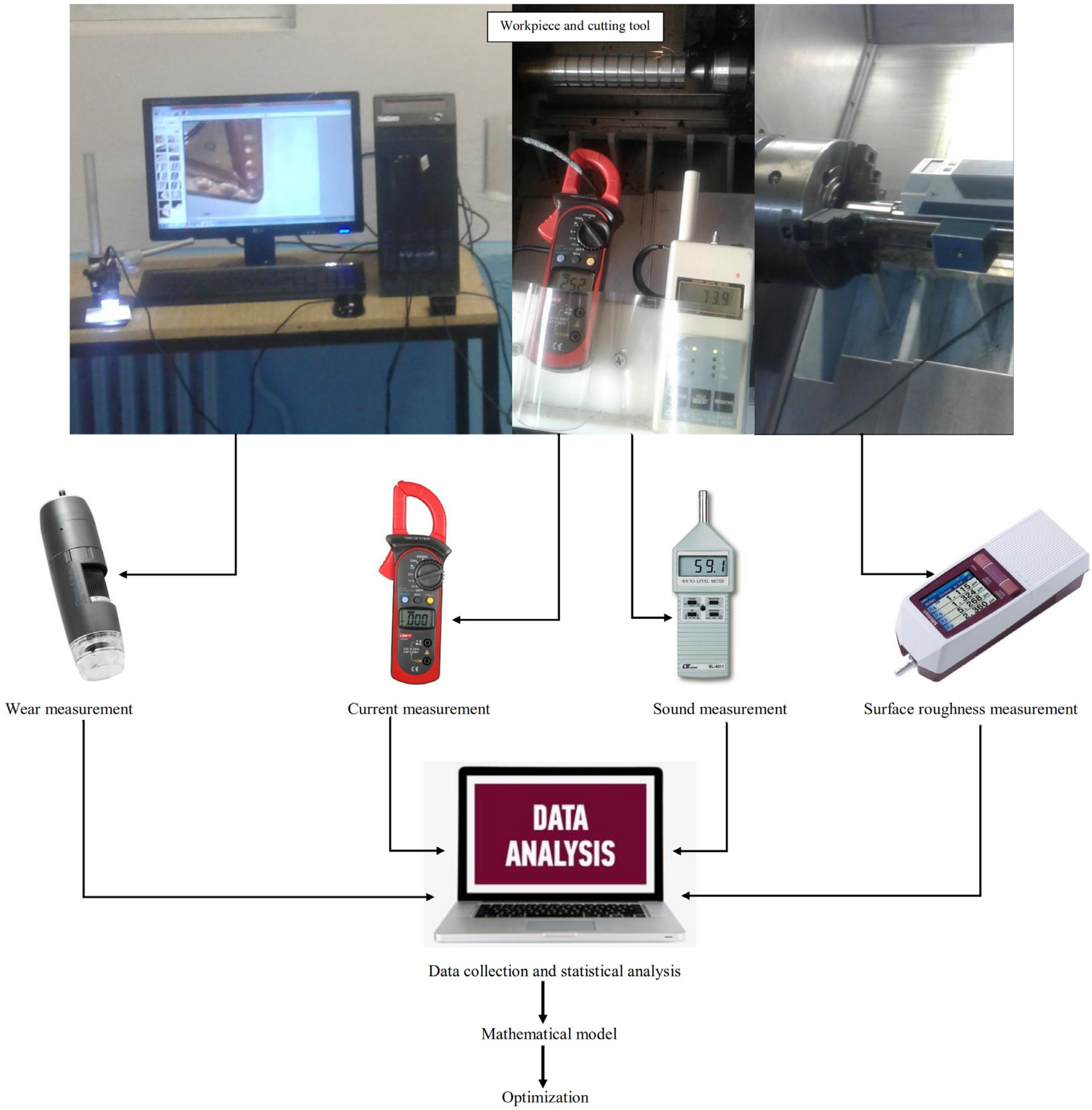


Figure 1. Schematic of the experimental setup.

RESULTS AND DISCUSSION

In this section, the effect of machining parameters on sound intensity, power consumption, and surface roughness during hard turning of AISI 4140 steel employing multilayer-coated carbide insert presented. The relation between machining parameters and output parameters is determined using the regression equation. The most significant factors that influenced the response parameters are shown using analysis of variance. The effects of machining parameters on machinability aspects are depicted using main effect plots. Finally, the regression model was developed to predict the tool wear.

Experimental Study Results

In the presented work, the L_{27} Taguchi design was utilized to create a relationship between input and output parameters. The experimental results for sound intensity, power consumption, and surface roughness for different combinations of machining parameters obtained from Taguchi design are presented in Table 3. The power consumption was obtained in the range of (1914-4560.6) W, the sound intensity was obtained in the range of (76.1-89) dB, and the range of the surface roughness was (0.375-2.49) µm. According to the results, the minimum power consumption was obtained at the combination of 0.1 (mm/rev) feed, 100 (m/min) cutting speed, and 0.3 (mm) depth of cut and. The minimum surface roughness was obtained at the combination of 0.2 (mm/rev) feed, 0.7 (mm) depth of cut, and 125 (m/min) cutting speed. The minimum sound intensity was obtained at the combination of 0.7 (mm) depth of cut, 150 (m/min) cutting speed, and 0.1 (mm/rev) feed.

Table 3. Experimental results for surface roughness, power consumption, and sound intensity.

Experiment Number	Depth of cut (mm)	Cutting speed (m/min)	Feed (mm/rev)	Ra (µm)	Power consumption (W)	Sound intensity (dB)
1	0.3	100	0.1	0.59	1914	81.6
2	0.3	100	0.2	0.75	2046	82.4
3	0.3	100	0.3	1.47	2151	83.2
4	0.3	125	0.1	0.67	1986	78
5	0.3	125	0.2	0.84	2171	80
6	0.3	125	0.3	1.46	2329	81
7	0.3	150	0.1	0.51	2171	77
8	0.3	150	0.2	0.75	2395	79.2
9	0.3	150	0.3	1.16	2620	79.6
10	0.5	100	0.1	0.6	2013	81
11	0.5	100	0.2	1.44	2244	85
12	0.5	100	0.3	2.43	2620	89
13	0.5	125	0.1	0.61	2290	80
14	0.5	125	0.2	1.33	2574	81.9
15	0.5	125	0.3	2.49	2818	85
16	0.5	150	0.1	0.55	2468	79
17	0.5	150	0.2	1.30	2778	81
18	0.5	150	0.3	1.63	3069	83
19	0.7	100	0.1	0.64	2574	82.1
20	0.7	100	0.2	1.05	2917	83.5
21	0.7	100	0.3	0.98	3234	86.6
22	0.7	125	0.1	0.39	3141	78.9
23	0.7	125	0.2	0.37	3445	76.2
24	0.7	125	0.3	0.56	3570	80.3
25	0.7	150	0.1	0.6	3491	76.1
26	0.7	150	0.2	0.56	4026	77
27	0.7	150	0.3	0.82	4560	78.9

Analysis Of Variance

Analysis of variance is performed to define the impacts of machining variables on response parameters. In this experimental work, the analysis of variance is performed using Minitab-19 software. Table 4 shows the results of ANOVA for surface roughness. According to the results, feed is the most significant factor that affects surface roughness by 42.30% contribution. Following the feed rate, depth of cut is the next critical factor on the surface roughness with a 28.70% contribution effect. The interaction of feed rate and depth of cut with 17.66% contribution is also exhibited high impact on the surface quality. Cutting speed has a minor effect on the response.

Table 4. ANOVA results for surface roughness.

Source	DOF	Seq SS	Adj SS	Adj MS	F-Value	P-Value	Contribution
a	2	2.3453	2.3453	1.17263	43.74	0.000	28.70%
V	2	0.2394	0.2394	0.11968	4.46	0.050	2.93%
f	2	3.4567	3.4567	1.72836	64.46	0.000	42.30%
a*V	4	0.3265	0.3265	0.08162	3.04	0.084	4.00%
a*f	4	1.4431	1.4431	0.36077	13.46	0.001	17.66%
V*f	4	0.1466	0.1466	0.03666	1.37	0.327	1.79%
Error	8	0.2145	0.2145	0.02681			2.62%
Total	26	8.1720					100.00%

Table 5 shows the results of ANOVA for power consumption. According to the results, the depth of cut has a significant influence on power consumption by 64.83% contribution. Following to depth of cut, cutting speed and feed are the next important parameters with 16.81% and 11.80% contribution, respectively. The interaction of depth of cut and cutting speed presents a 4.49% contribution effect on the power consumption.

Table 5. ANOVA results for power consumption.

Source	DOF	Seq SS	Adj SS	Adj MS	F-Value	P-Value	Contribution
a	2	7399480	7399480	3699740	485.80	0.000	64.83%
V	2	1918669	1918669	959334	125.97	0.000	16.81%
f	2	1346995	1346995	673497	88.43	0.000	11.80%
a*V	4	512077	512077	128019	16.81	0.001	4.49%
a*f	4	110847	110847	27712	3.64	0.057	0.97%
V*f	4	63887	63887	15972	2.10	0.173	0.56%
Error	8	60926	60926	7616			0.53%
Total	26	11412881					100.00%

Table 6 shows the ANOVA results for sound intensity. These results indicated that all cutting parameters, namely, cutting speed, feed rate, and depth of cut, are significant factors for sound intensity by 45.06%, 24.00%, and 16.97% contribution, respectively. Besides, the interaction of (a*f) also has a significant impact on the response.

Table 6. ANOVA results for sound intensity.

Source	DOF	Seq SS	Adj SS	Adj MS	F-Value	P-Value	Contribution
a	2	43.343	43.343	21.6715	25.43	0.000	16.97%
V	2	115.067	115.067	57.5337	67.50	0.000	45.06%
f	2	61.290	61.290	30.6448	35.95	0.000	24.00%
a*V	4	10.944	10.944	2.7359	3.21	0.075	4.29%
a*f	4	13.661	13.661	3.4154	4.01	0.045	5.35%
V*f	4	4.217	4.217	1.0543	1.24	0.369	1.65%
Error	8	6.819	6.819	0.8523			2.67%
Total	26	255.341					100.00%

Main Effect Plots

Figure 2 depicts the main effect plot for the surface roughness values. The plot indicated that feed is the most dominant factor that influences the surface roughness. By increasing the feed value, the surface roughness value also increases sharply. The same results were found in Bouacha, Aslitürk, Motorcu and Şahinoğlu studies (Asiltürk and Akkuş 2011; Motorcu 2010; Bouacha et al., 2010; Şahinoğlu and Rafighi 2020a). According to the main effect plot, surface roughness slightly decreases as cutting speed increases. Further, the depth of cut has a great impact on surface roughness. However, the minimum value can be obtained with a combination of high cutting speed, low feed rate and low depth of cut.

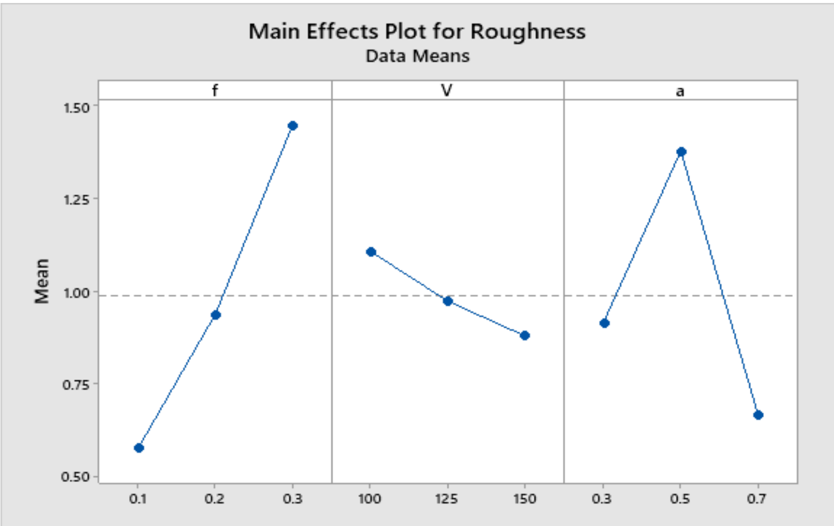


Figure 2. Main effect plot for surface roughness (μm).

Figure 3 shows the main effect plot for power consumption. Any increase in the amount of all machining parameters increases the power consumption. However, the depth of cut causes a significant increase in power consumption. This phenomenon is applying maximum load on the CNC lathe while turning the workpiece at 0.7 mm depth of cut.

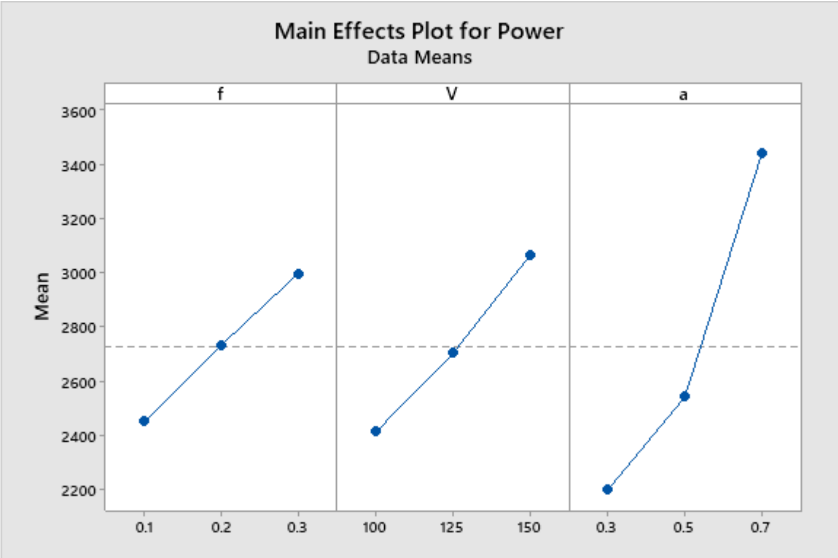


Figure 3. Main effect plot for power consumption (W).

The main effect plot for the sound intensity is illustrated in Figure 4. This plot showed that the sound intensity decreases sharply by any increase in the cutting speed. The high cutting speed reduces the cutting forces, and consequently, the load on the machine decreases, which causes a lower sound. The feed rate is the next important factor that increases the sound intensity while it increases.

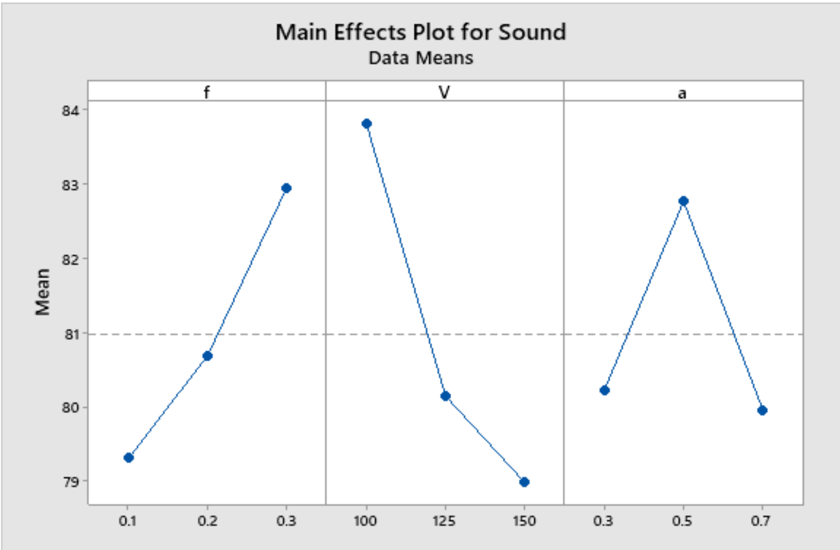


Figure 4. Main effect plot for sound intensity (dB).

Repeatability Test

Before the final run for this experimental work, three sets of cutting parameters were chosen for the repeatability test. The experimental errors for the repeating trials are presented in Table 7. According to the results, the error percentage between experimental and measurement results for surface roughness, power consumption, and sound intensity is in the range of (2.25-3.65%), (1.38-2.44%), and (0-0.13%), respectively.

Table 7. Repeatability test before the final run.

	Cutting parameters			Surface roughness (µm)			Power consumption (W)			Sound intensity (dB)		
	a	*V*	*f*	*Final run*	*Repeating test*	*Error (%)*	*Final run*	*Repeating test*	*Error (%)*	*Final run*	*Repeating test*	*Error (%)*
1	0.3	100	0.1	0.59	0.61	3.39	1914	1950	1.84	81.6	81.5	0.12
2	0.5	125	0.2	1.33	1.30	2.25	2574	2637	2.44	81.9	81.9	0
3	0.7	150	0.3	0.82	0.79	3.65	4560	4497	1.38	78.9	79.0	0.13

Optimization of Machining Parameter

The optimization of machining parameters in the manufacturing process is difficult due to the existence of many factors. However, it is essential to specify the optimum machining variables to minimize machining costs and maximize surface and tool life quality. Table 8 presents the machining parameters and their responses calculated through the mean value for each input parameter. The optimum machining parameters correspond to the lowest value for each response. For instance, the average of the surface roughness for the first level (0.1 mm/rev) of the feed rate is obtained using the Equation (1):

$$\frac{(0.59 + 0.675 + 0.51 + 0.6 + 0.61 + 0.55 + 0.64 + 0.395 + 0.6)}{9} = 0.5744\ \mu m \qquad (1)$$

Thus, minimum surface roughness and sound intensity can be obtained using the first level of feed rate (0.1 mm/rev), third level of cutting speed (150 m/min), and third level of depth of cut (0.5 mm). Minimum power consumption can be obtained using the first level of all machining parameters.

Table 8. Optimum machining parameters and their levels.

	Surface roughness (µm)			Power consumption (W)			Sound intensity (dB)		
	f	*V*	*a*	*f*	*V*	*a*	*f*	*V*	*a*
1	**0.5744**	1.1072	0.9138	**2450**	**2412**	**2198**	**79.3**	83.8	80.2
2	0.9361	0.9722	1.3772	2733	2703	2541	80.6	80.1	82.7
3	1.4467	**0.8777**	**0.6661**	2997	3064	3440	82.9	**78.9**	**79.9**

Tool Wear

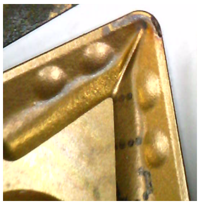
Hard turning aims to manufacture mechanical parts with good dimensional accuracy and surface quality with properties close to the grinding process. Generally, the surface roughness in the grinding process is smoother than 1.6 µm. This roughness can be used as a determining factor to evaluate crater wear. According to the previous studies (Čerče et al., 2015) and Standard ISO 3685, a crater wear depth of 0.3 mm is considered in this study as the ideal tool life criteria.

The efficiency in manufacturing can be improved by increasing the cutting speed. However, the high cutting speed generates a high temperature in the workpiece, tool and chip; hence the surface quality and the tool life are decreased.

Tool wear is a dominant parameter in the machining that affects manufactured component accuracy. The crater wear happens in the area of cutting edge. The amount of crater wear is calculated by measuring the crater wear region's width using an optical microscope having 220 times magnification. The width of crater wear is increased at the beginning of machining, and the growth of wear is decreased with time.

In order to evaluate surface roughness and crater wear during machining following cutting conditions were used; feed (0.3 mm/rev), cutting speed (150 m/min), and depth of cut (0.7 mm). The experimental results for surface roughness and crater wear with illustration at different intervals while turning hardened AISI 4140 employing multilayer-coated carbide ($TiCN/Al_2O_3/TiN$) inserts are shown in Table 9.

Table 9. Experimental results for surface roughness, crater wear, and their illustrations.

Trials	Machining duration (min)	Surface roughness (µm)	Crater wear (mm)	Crater wear illustration
1	10	0.30	0.10	
2	50	0.35	0.15	
3	90	0.38	0.30	
4	130	0.40	1.20	
5	170	0.42	1.80	

By progressing the machining, the cutting tool's sharpness degraded and resulted in a deterioration of the surface quality. The reason for the degradation of the tool sharpness and occurring the crater wear is the sliding of chips on the tool's rake surface. After 90 min, the catastrophic failure of the tool has occurred due to crater wear caused by the collapse of the cutting edge. The variation of surface roughness and crater wear by cutting time is shown in Figures 5 and 6, respectively.

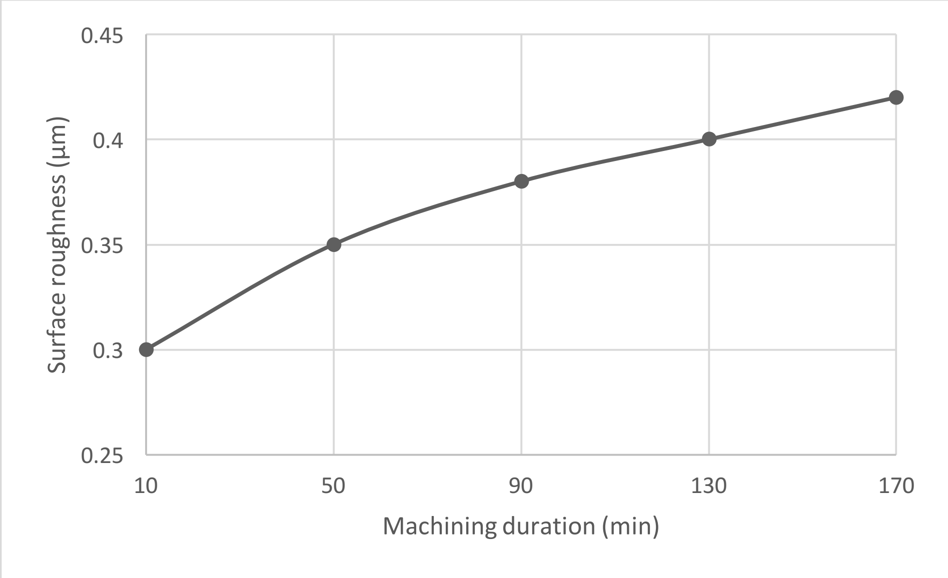


Figure 5. Variation of surface roughness with machining time.

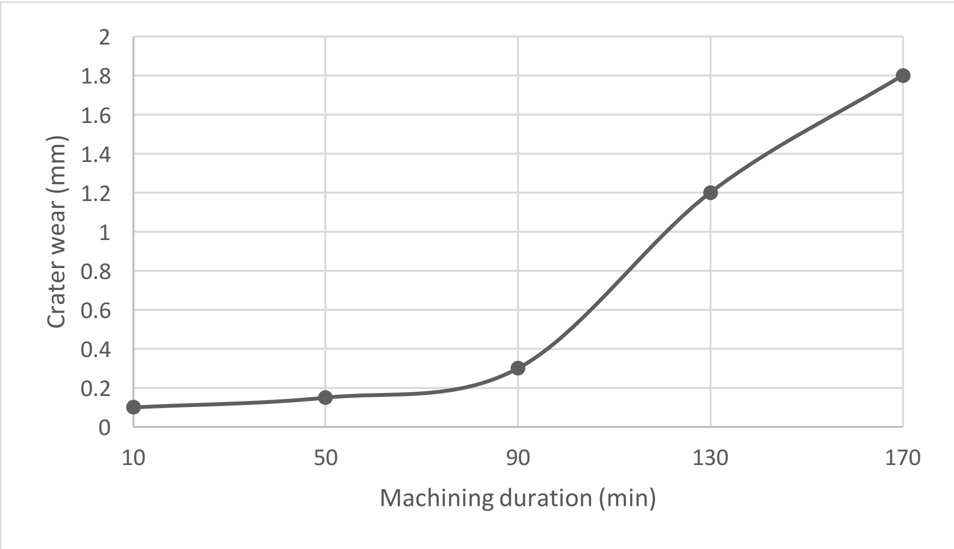


Figure 6. Variation of crater wear with machining time.

According to the results, the multilayer TiCN/Al_2O_3/TiN coated carbide insert exposes good performance during hard turning of steel at high cutting speed. The titanium nitride (TiN) coated layer has the lubricity properties that decrease the friction between cutting inserts and workpiece; hence, it prevents the enhancement of temperature at higher cutting speed and consequently lags the growth of tool wear. Therefore, the increase in temperature is prevented at the contact surface and diffusion. Aluminum oxide (Al_2O_3) layer exhibits good thermal barrier properties that decrease the tool wear. The titanium carbide nitride (TiCN) layer has good thermal stability and wear resistance. The TiN coating layer proposed good diffusion barrier properties. These properties increase the cutting tool material's chemical stability, thanks to the thermal barrier of the Al_2O_3 and diffusion barrier of the TiN while machining the hardened steel at higher cutting speed.

Figure 6 shows crater wear growth with cutting time for multilayer-coated carbide cutting tools during turning of hardened AISI 4140 under dry cutting conditions. The results showed that the crater wear creation is primarily affected by associated chemical wear and thermal conditions. The results indicated that tool wear progress by the time is due to abrasion at the rake face of the cutting tool. Any extreme crater wear causes a catastrophic failure of the tool due to the weakening of the cutting edge.

The growth of tool wear at the beginning of machining is slow due to the influence of Al_2O_3 layers as a thermal barrier, TiCN layer as wear resistance and a small amount of friction between tool and chip thanks to TiN lubricity properties. The barrier precluded heat from entering the cutting insert, and therefore a high amount of heat is dissipated by the chip.

The nature of TiN decreases the tool friction, whereas TiCN and Al_2O_3 reduce cratering. Multicoated layers present a combination of the properties of both types of coating in conjunction with various substrates. For example, the TiN layer over TiCN/Al2O3 coating remarkably enhances the coated cutting tool's crater resistance at both high and low machining speeds.

The slow growth of crater wear for multilayer-coated cutting tools presents stable machining without any premature tool failure by fracturing or chipping. According to table 8, the crater wear was 0.1 mm, nearly about 10 min. Then, wear growth gradually and reaches to 0.15 mm in 50 min. However, the tool reaches its limit value (0.3 mm) for nearly about 90 min. The figures depict three wear zones for multilayer-coated carbide; initial wear, steady wear, and rapid wear that cause tool failure.

High temperature and pressure at cutting speed equal to or greater than 150 m/min were the dominant factors in the rake face that cause the crater wear to occur near to cutting edge.

Regression Model

The mathematical models were developed for each response using a multiple linear regression model. The mathematical models for surface roughness, power consumption, and sound intensity are given in Equations 2, 3, and 4, respectively. The coefficient of determination for surface roughness is 97.38%. The power consumption and sound intensity were modelled with 99.47% and 97.33% accuracy, respectively.

$$\text{Surface roughness} = -0.89 + 1.32\ a + 0.0052\ V + 12.25\ f - 0.0049\ a{*}V - 6.65\ a{*}f - 0.0365\ V{*}f \quad (2)$$

$$\text{Power consumption} = 2353 - 2580\ a - 10.04\ V - 2180\ f + 37.9\ a{*}V + 4704\ a{*}f + 20.5\ V{*}f \quad (3)$$

$$\text{Sound intensity} = 77.3 + 16.4\ a + 0.0078\ V + 34.7\ f - 0.147\ a{*}V + 6.2\ a{*}f - 0.157\ V{*}f \quad (4)$$

According to the previous studies, multilayer-coated carbide inserts have better performance compared to uncoated carbide inserts. Thus, the first and second-order regression models were developed for tool wear at a 95% confidence level based on machining time (T) as continuous predictors. The developed mathematical models for first- and second-order models are given in Equations 5 and 6, respectively.

$$\text{Wear} = -0.291 + 0.01113 * T \qquad (5)$$

$$\text{Wear} = 0.113 - 0.00374 * T + 0.000083 * T * T \qquad (6)$$

The sufficiency of the developed regression model is confirmed through the coefficient of determination (R^2). The second-order model presents better variability of responses in predicting new results with $R^2 = 97.49\%$ compared to the first-order model with $R^2 = 86.78\%$. The second-order model has a higher R^2 that indicates the available data fits perfectly with the model. Further, the confirmation test was performed, employing a second-order model to compare the experimental value and predicted value. The minimum and maximum residuals were 0.016 and 0.171, respectively. The predicted and experimental values for tool crater wear by employing the second-order model are presented in Table 10.

Table 10. The predicted and experimental values for tool crater wear.

Time (min)	Predicted value (mm)	Experimental value (mm)	Residuals
10	0.084	0.10	0.016
50	0.134	0.15	0.016
90	0.449	0.30	-0.149
130	1.029	1.20	0.171
170	1.876	1.80	-0.076

CONCLUSION

The impacts of cutting depth, cutting speed, and feed rate on the surface roughness, power consumption, sound intensity, and tool wear are investigated in this study while turning hardened AISI 4140 using multilayer-coated carbide insert under dry cutting condition. Also, the high values of cutting depth and feed rate were selected to evaluate their effect on the sound intensity and power consumption. The results of this experimental study are presented as follows:

According to the analysis of variance, the feed rate has a dominant effect on surface roughness by 42.30% contributions. Following feed rate, depth of cut shows a significant impact on the surface roughness by 28.70% contribution. In addition, the effect of (a*f) on the surface quality is significant, with a 17.66% contribution. However, the cutting speed has a minor effect on surface roughness.

The depth of cut with 64.83% contribution considerably influences the power consumption. The motor current increases by enhancing the depth of cut; hence, the consumed energy by the lathe machine also increases. Following the depth of cut, cutting speed and feed exhibit great effect on power consumption with 16.81% and 11.80% contribution, respectively.

Cutting speed is the dominant factor that affects sound intensity by 45.06% contribution. Increasing the cutting speed decreases the sound intensity simultaneously. The feed rate is the next significant factor in sound intensity, with a 24.00% contribution. Any increase in the feed rate increases the sound intensity. Finally, the depth of cut with a 16.97% contribution presents an essential impact on the response.

Except for two combinations for multilayer-coated carbide inserts, the rest of the surface roughness values are less than 1.6 µm; this is among the recommended range for hard turning. However, for evaluating the tool wear, only a combination of (0.3 mm/rev) feed, (150 m/min) cutting speed, and (0.7 mm) depth of cut is taken into account, and the maximum surface roughness is calculated as (0.42 µm).

According to the results, multilayer-coated carbide inserts (TiCN/Al_2O_3/TiN) exhibit good performance in terms of tool wear due to the layers' good properties. TiCN layer has wear resistance, whereas Al_2O_3 layers act as a thermal barrier, and TiN presents lubricity properties that reduce friction between tool and workpiece. The experimental results show that tool crater wear for multilayer-coated carbide inserts was 0.10 mm, 0.15 mm, and 0.30 mm after 10 min, 50 min, and 90 min, respectively. The tool life criterion was assumed to be 0.30 mm based on previous studies. At higher cutting speed and as time passes, the inserts' coating is wiped out, and chipping occurs at the cutting edge and leads to tool wear. Thus, tool crater wear started to be greater than 0.30 mm after 90 min, and catastrophic failure occurred.

The results indicated that the second-order regression model exhibits better performance with R^2 = 97.49% to predict the multilayer-coated carbide tool wear during hard turning of AISI 4140 steel. Also, the second-order regression model has good adequacy due to close results between the experimental value and predicted value for the crater wear of multilayer-coated carbide inserts.

The accuracy of proposed mathematical models for predicting the power consumption, sound intensity, and surface roughness is in good agreement with actual data with R^2 = 99.47%, R^2 = 97.33%, and R^2 = 97.38%, respectively. In order to reduce power consumption, the first level of all machining parameters should be selected. Minimization of surface roughness can be done by increasing the cutting speed and decreasing the feed rate according to materials theory machining.

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