中國機械工程學刊第四十二卷第四期第 403~412 頁(民國一百一十年)
Journal of the Chinese Society of Mechanical Engineers, Vol.42, No.4, pp. 403~412 (2021)

Machinability of the AISI M2 High-Speed Steel using CBN Insert

Mohammad Rafighi*, Osman Özenç**, Mehmet Tuncay Kaya***, Mustafa Özdemir**** and Hamza Kemal Akyıldız*****

Keywords： AISI M2 high-speed steel, Material processing, Surface roughness, Cutting force components.

ABSTRACT

In this experimental study, the impact of machining parameters on surface roughness and cutting force components was investigated. The finish hard turning was carried out on the AISI M2 high-speed steel using cubic boron nitride under dry cutting conditions. Hard turning experiments were performed employing Taguchi L9 orthogonal array with three input and two output parameters. This experiment was performed using constant cutting speed (150 m·min-1), three tool nose radius (0.2, 0.4, 0.8 mm), three feed rates (0.025, 0.05, 0.075 mm·rev-1) and three depths of cut (0.05, 0.10, 0.15 mm). The analysis of variance was employed to obtain the most important machining variables. Results showed that surface roughness is primarily influenced by feed rate. Furthermore, the cutting depth mainly affected all components of cutting force, namely axial force, tangential force, and radial force. However, the nose radius was a dominant factor in the radial force. Finally, the regression analysis was performed to obtain the mathematical model between input parameters and output variables. Based on the mathematical model a strong agreement was reached between predicted and empirical values.

Paper Received September 2020 Revised January 2021, Accepted February 2021, Author for Correspondence: Rafighi M.

* *Assistant Professor, Department of Mechanical Engineering, University of Turkish Aeronautical Association, Ankara, Turkey.*

** *Research Assistant, Department of Mechanical Engineering, Yozgat Bozok University, Yozgat, Turkey.*

*** *Graduate student, Department of Mechanical Engineering, Yozgat Bozok University, Yozgat, Turkey.*

**** *Assistant Professor, Department of Machine and Metal Technology, Yozgat Bozok University, Yozgat, Turkey.*

***** *Professor, Department of Mechanical Engineering, Yozgat Bozok University, Yozgat, Turkey.*

INTRODUCTION

The hard finish turning process was applied to ferrous metal workpieces with hardness between 45-70 HRC. These materials are widely utilized in forging, high-speed steels, bearing steels, machine tools, and automotive industries (Bartarya & Choudhury, 2012b; Singh & Rao, 2007; Tönshoff, Arendt, & Amor, 2000). In the last decades, the grinding process was used to produce a good surface quality in the manufactured products. However, it has some disadvantages such as long set-up and processing time, low material removal rate, and expensive machinery. Recently, hard turning is used frequently as an alternative method for the grinding process. Hard turning has many benefits compared to the grinding process such as good dimensional accuracy, higher material removal rate, cheap machinery, producing complex shapes, shorter set-up, and cycle time that all can be performed under dry cutting conditions (Aneiro, Coelho, & Brandao, 2008; Asiltürk & Akkuş, 2011; Chou & Song, 2004).

Hard turning has become prominent due to the developments in cutting tool technology. This process is conducted using modern tooling materials, such as cubic boron nitride (CBN), polycrystalline cubic boron nitride (PCBN), coated ceramics, and multilayer-coated carbide. Due to the high cost of the CBN cutting inserts, it is of great importance to use them carefully to increase the tool life by selecting proper cutting parameters (Davim & Figueira, 2007; More, Jiang, Brown, & Malshe, 2006). Therefore, many experimental studies have been done by CBN and other advanced tool materials during the turning of hardened steels that are presented below.

The efficiency of the turning process can be measured within the selected range of machining parameters by investigating the output parameters such as cutting forces, tool wear, surface roughness, and power consumption. Thus, many researchers evaluated the surface quality and cutting force components in their studies (Aouici, Yallese, Chaoui, Mabrouki, & Rigal, 2012; Bensouilah et al., 2016; Bouacha, Yallese, Mabrouki, & Rigal, 2010; Lalwani, Mehta, & Jain, 2008). The depth of cut, which is lower than the tool nose radius, is one of the essential aspects of hard turning, hence often the thrust force is greater than the axial and tangential forces (Fnides & Yallese, 2008; Huang & Liang, 2005). This is one of the main differences between hard turning and conventional turning. In conventional turning, the thrust force is about 0.3 to 0.5 times of the tangential force.

In another study by researchers, they are indicated that the low cutting speeds result in high cutting forces due to the creation of a built-up edge at the lower temperature. A higher cutting speed is required to diminish the cutting forces. As the turning operation performs at high speeds the temperature of the machined surface region increases and this causes thermal softening at the workpiece, hence the machining operation carries out easily, and consequently, the cutting forces reduce (Ebrahimi & Moshksar, 2009; Lin, Liao, & Wei, 2008).

Jang and Hsiao studied the impacts of process parameters on cutting forces and tool wear during the hard turning of AISI M2 high-speed steel having 60 HRC hardness employing a ceramic insert. The result showed the dominant influence of the depth of cut on the cutting forces (Jang & Hsiao, 2000).

Özel et al. experimentally studied the effect of cutting edge geometry, cutting speed, feed rate, and workpiece hardness on cutting forces and surface roughness during finish turning of hardened AISI H13 steel employing CBN inserts. The findings showed that cutting force components are generally affected by the depth of cut and workpiece hardness while the surface roughness is affected by the hardness and feed rate (Özel, Hsu, & Zeren, 2005).

Lalwani et. al. (Lalwani et al., 2008) evaluated the influence of cutting parameters on the surface roughness and cutting forces in turning of hardened MDN250 steel with coated ceramic tools. The RSM was used to carry out the machining experiments. The results showed that the depth of cut with an 89.05% contribution has a dominant effect on the feed force. The thrust force was mainly affected by cutting depth and feed rate with 49.59% and 46.71% contribution, respectively. The feed rate exhibits a major role in the tangential force with 52.60% contribution, followed by the depth of cut with 41.63% contribution. Finally, the feed rate contributes an 86.03% effect on the surface roughness.

Bouacha et. al. (Bouacha et al., 2010) used CBN insert to carry out hard turning operation on AISI 52100 bearing steel. The material hardness, cutting depth, cutting speed, and feed rate were chosen as the input parameters, while the surface roughness and cutting forces were selected as response parameters. The response surface method was employed to define the relationship between the input and output parameters. The analysis of variance was used to identify the major factors that impacted the outputs. The results presented the significant impact of the feed rate on the surface quality followed by cutting speed. The cutting forces mainly affected by the hardness of the workpiece and the depth of cut, in which the thrust force was found to be the highest of the cutting force components. Finally, the optimum machining parameters (0.15 mm depth of cut, 0.08 $mm \cdot rev^{-1}$ feed rate, and 246 $m \cdot min^{-1}$ cutting speed) were determined using composite desirability and response surface.

Suresh et. al. (Suresh, Basavarajappa, & Samuel, 2012) performed a hard turning process on the AISI 4340 employing a multilayer-coated carbide insert to study the impacts of process parameters on the power consumption, surface roughness, cutting forces, and tool wear. They used the Taguchi method in their experimental design. The results showed that the combination of low feed rate and low cutting depth with high cutting speed is useful to minimize cutting forces. Also, high cutting speed and low feed rates are required to reduce the surface roughness. However, increasing the cutting speed and feed rate increased power consumption.

Bartarya et al. (Bartarya & Choudhury, 2012a) assessed the impact of machining factors on surface quality and cutting force when finishing hardened AISI 52100 steel (60 HRC) with an uncoated cubic boron nitride insert. The analysis of variance and full factorial design of the experiment was employed to identify the optimum cutting parameters. The cutting depth was identified as the most effective parameter influencing the three cutting force components. The axial, radial, and tangential forces were affected by the depth of cut with 89.7%, 74.8%, and 71.56% contribution, respectively. The feed rate with a contribution of 25.63% was determined to be the next important factor in tangential force. Besides, the axial force has not affected by the feed rate and the cutting speed. The surface quality was affected by feed rate, depth of cut, and the interaction of the depth of cut and feed rate, respectively.

Aouici et. al. (Aouici et al., 2012) experimentally evaluated the impacts of machining factors such as cutting speed, workpiece hardness, depth of cut, and feed rate on the cutting forces and surface roughness in turning of hardened AISI H11 employing CBN inserts. They employed ANOVA and RSM to analyze the experimental data. Results showed that the depth of cut and the workpiece hardness are both significant on the cutting forces. The contribution of the depth of cut on the feed, thrust, and tangential forces was 56.77%, 11.95%, and 31.50%, respectively. Furthermore, the surface quality was mainly influenced by feed rate and hardness. Consequently, the optimum machining parameters for the proposed workpiece and cutting tools were determined.

Yücel and Günay (Yücel & Günay, 2013) optimized machining parameters according to cutting force and surface roughness with CBN and ceramic inserts considering different nose radii in turning of hardened high alloy white cast iron (62 HRC). Taguchi L_{18} orthogonal array was employed for experimental design. According to the results of ANOVA, it has been seen that the surface roughness and cutting force were mainly influenced by feed rate with 75.78% and the depth of cut with 74.50% contribution, respectively. The CBN insert exhibits better performance compared to the ceramic insert.

Varma and Kaladhar (Varma & Kaladhar, 2015) determined the optimum machining parameters during the turning of hardened AISI M2 steel with cryogenically treated cutting tools. The depth of cut, feed rate, and cutting speed were chosen as input parameters, while surface roughness and power consumption were chosen as responses. The ANOVA results revealed a major impact on surface roughness and power consumption by feed rate and cutting speed.

Kumar and Chauhan (Kumar & Chauhan, 2015) statistically analyzed the influences of machining factors such as cutting speed, feed rate depth of cut, and workpiece hardness on cutting edge temperature, surface roughness, and cutting forces in finish turning of hardened AISI H13 die tool steel using CBN inserts. The design of the experiment has been generated using a central composite design and the response surface method was used to create a relation between output and input parameters. The findings of this analysis have shown that the hardness of the workpiece was the primary factor in cutting forces. Moreover, the cutting depth and the feed rate have also an important impact on the cutting forces. It has been revealed that the surface roughness reduces with enhancing the workpiece hardness and cutting speed, whilst the surface quality deteriorates with rising feed rate and cutting depth. The workpiece hardness of the 55 HRC exhibits almost three times better surface finish than 45 HRC.

Chandra et. al. (Chandra, Rao, & Kiran, 2018) researched the effects of process parameters on the surface quality and machining forces in hard turning of HCHCr and EN 24 alloy steels with multi-layer coated tungsten carbide tools. In this study, they used various feed rates and cutting speeds with a constant cutting depth. The results revealed that the surface roughness of the HCHCr steel workpiece is lower than EN 24 steel. Besides, the best surface quality and the least cutting forces were acquired at the combination of high cutting speed with low feed rate. However, the cutting forces during turning of the HCHCr steel was 35% higher than EN 24 steel due to its hardness.

Zerti et. al. (Zerti et al., 2019) used coated ceramic cutting tools to research the impacts of cutting depth, feed rate, and cutting speed on surface roughness, power consumption, cutting force, and material removal rate in hard turning of AISI 420 steel (59 HRC). The experimental tests were performed based on the Taguchi method, the Pareto chart, and ANOVA was employed to identify the most significant factors that affect response parameters. According to the findings, the feed rate has proved to be a dominant factor, impacting surface roughness by 80.71% contribution. The material removal rate, the power consumption, and the cutting force are all affected by the cutting depth with 36.45%, 37.56%, and 65.31% contribution, respectively.

Şahinoğlu and Rafighi (Şahinoğlu & Rafighi, 2020) explored the machinability of AISI 4140 material under a dry cutting environment. They used coated carbide as cutting inserts to evaluate the effect of machining factors on surface quality, current, sound, and vibration. The response surface method, analysis of variance, and regression were employed to analyze the obtained data. According to the results, it was observed that the feed rate is a dominant factor in surface quality. Also, current, vibration, and sound values increased as the feed rate and depth of cut rise.

By evaluation of the aforementioned studies, it was found that the studies relating to hard turning using CBN inserts with different nose radii are not enough. The constant radius insert was used in most of them and the influence of various nose radii on the surface roughness and cutting forces was not adequately investigated. In this study, CBN cutting inserts with three nose radii (0.2, 0.4, and 0.8 mm) were used in hard finish turning of AISI M2 high-speed steel under dry cutting conditions. The machining parameters were selected by considering the recommendations of the CBN insert manufacturer and the literature studies. The experiments were designed according to the Taguchi L_9 orthogonal array to reduce the number of trials. The contribution of the input parameters was obtained using analysis of variance and the validity was verified with the verification experiment for the input parameters. Consequently, the optimum cutting factors namely feed rate, nose radius, and depth of cut were determined based on surface roughness (Ra) and the components of cutting forces (F_x: radial force, F_y: tangential force, and F_z: axial force).

MATERIALS AND METHODS

Workpiece Material Preparation

In this work, AISI M2 high-speed steel was used as a workpiece material, which is widely used in cutting dies, punching, and machine tool manufacturing due to its good mechanical properties in recent years. The cylindrical workpiece has a 70 mm diameter and 250 mm length. This material undergoes a heat treatment process to increase the hardness. Firstly, the workpiece was preheated at 650°C in a vacuum furnace. Secondly, it was annealed at 1040°C for 45 minutes, then, it was cooled using nitrogen at 5 bar pressure. After nitrogen cooling, the second annealing was applied at 250°C for another 1.5 hours. Finally, as a result of cooling in air, 59-60 HRC hardness was obtained in this material. The chemical composition of the AISI M2 steel is presented in Table 1.

Table 1. AISI M2 steel chemical composition

C	Si	Mn	Cr	Mo	V	W
0.90	0.30	0.30	4.10	5.00	1.90	6.40

Machine Tool

All tests were carried out on GOODWAY GS-260Y CNC lathe without using coolant. It has a maximum power of 15 kW, a maximum speed of 4000 RPM, a maximum turning length of 600 mm, and a maximum turning diameter of 400 mm.

Tool Holder

In the presented experiments, ISCAR SVJCL 2525M-16 was used as a tool holder. This tool holder is left-handed with a 93° lead angle and it is used for 35° diamond inserts with a 7° clearance angle. The schematic of the tool holder is presented in Fig. 1.

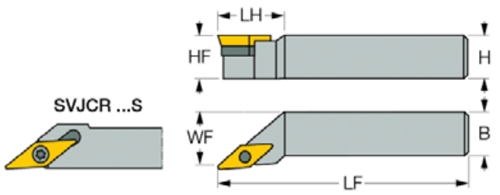

Fig. 1. Schematic of ISCAR SVJCL 2525M-16 tool holder

Cutting Inserts

The finish turning of hardened steels was performed with TAEGUTEC VBGW 160408 LS TB650, TAEGUTEC VBGW 160404 LS TB650, and TAEGUTEC VBGW 160402 LS2 TB670 CBN inserts with 0.8 mm, 0.4 mm, and 0.2 mm nose radius, respectively. The manufacturer's recommendation for cutting speed using these tools for hardened steel is 90-180 $m \cdot min^{-1}$. The CBN insert is presented in Fig. 2.

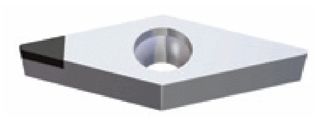

Fig. 2. TAEGUTEC VBGW CBN insert

Cutting Forces Measurement

The three cutting forces components namely axial force, tangential force, and radial force were measured using the KISTLER 9129AA dynamometer and type 5070 amplifier. This dynamometer is used to hold a 25*25 mm tool holder.

Surface Roughness Measuring

The machining length of 20 mm was considered to measure the surface roughness. Three measurements were made on the three various locations of the workpiece surface with 120° intervals and the mean Ra value was obtained by taking the arithmetic averages of these measurements. In Ra measurements, MAHR MARSURF PS10 brand and model, portable surface roughness measuring device, which complies with ISO 4287 standard, were used and the device was calibrated before measurement. The experimental setup is shown in Fig. 3.

Fig. 3. Experimental setup

Machining Parameters

In the turning process, various factors can be considered as input factors such as tool nose radius, feed rate, cutting depth, and cutting speed. In the presented work, the cutting speed was chosen to be 150 $m \cdot min^{-1}$. In addition, three cutting depths, three feed rates, and three nose radius were selected as process factors. Optimizing the machining parameters is of great importance for reducing manufacturing time and costs. The machining parameters were selected considering the literature review and manufacturer’s catalog for the AISI M2 high-speed steel and CBN inserts. The three levels of machining parameters are presented in Table 2.

Table 2. The levels of machining parameters

Factor	Symbol	Unit	Low level	Medium level	High Level
Tool nose radius	*R*	mm	0.2	0.4	0.8
Feed rate	*f*	$mm \cdot rev^{-1}$	0.025	0.05	0.075
Cutting depth	*a*	mm	0.05	0.1	0.15

Experimental Design

The efficiency of the turning tests can be increased by designing the experiment, properly. The number of experiments enhances exponentially, while the number of cutting parameters increases. Therefore, a statistical method such as Taguchi is used to reduce the number of experiments in most researches, recently (ÖZDEMİR, 2019). In the presented work, the relationship between the process factors (R, a, f) and response (Y) is presented as Equation (1):

$$Y = Ø (R, a, f) \quad (1)$$

where Y is machinability factors such surface roughness (Ra) or cutting force components (Fx, Fy, Fz), Ø is the response function, (R) is nose radius, (a) is a depth of cut, and (f) is feed rate. The analysis of the interaction between cutting parameters and response variables was done using an approximation of the Y (non-linear (quadratic) mathematical model).

RESULTS AND DISCUSSION

In this study, hard finish turning was performed on the AISI M2 high-speed steel using cubic boron nitride insert with three nose radius. The cutting factors were chosen according to previous researches and the manufacturer's catalog for CBN insert. In this experimental study, the constant cutting speed of 150 $m \cdot min^{-1}$ with three different depths of cut, feed rates, and nose radius were used to determine their effects on the output parameters namely cutting force components and surface roughness. The design of this experiment was carried out according to the Taguchi technique. The full factorial method requires 27 experiments, whereas the number of experiments was decreased to 9 using the Taguchi L_9 orthogonal array. The ANOVA was carried out to obtain the significant factor that affected responses. The mathematical equation between each output parameter and all input parameters was obtained using the regression analysis. Besides, the confirmation test was carried out to compare the experimental and predicted results. In this study, every trial was repeated three times, and the final value was considered to be the arithmetic mean. This experimental study was analyzed using Minitab 19 software. The cutting force components such as Fx: radial force Fy: tangential force and Fz: axial force were obtained in the range of (17.71-66.12) N, (5.31-46.97) N, and (25.14-52.26) N, respectively. The surface roughness was found within the (0.148-0.527) μm range. The results of this experiment are presented in Table 3.

Table 3. Experimental results for cutting force components and surface roughness

No	Cutting Parameters			Experiment results			
	R (mm)	*f (mm·rev⁻¹)*	*a (mm)*	*Fx (N)*	*Fy (N)*	*Fz (N)*	*Ra (μm)*
1	0.2	0.025	0.05	17.71	7.64	29.82	0.212
2	0.2	0.050	0.10	25.70	24.21	41.06	0.148
3	0.2	0.075	0.15	33.92	46.97	52.26	0.377
4	0.4	0.025	0.10	31.14	12.28	35.42	0.229
5	0.4	0.050	0.15	44.37	34.03	49.42	0.254
6	0.4	0.075	0.05	18.65	5.31	25.14	0.527
7	0.8	0.025	0.15	66.12	36.80	46.55	0.304
8	0.8	0.050	0.05	39.83	12.95	27.51	0.237
9	0.8	0.075	0.10	65.78	41.99	39.26	0.477

The Analysis of Variance

In the presented research, the ANOVA was employed to determine the most important input factors that influence the output factors. Therefore, the influences of feed rate, depth of cut, and nose radius on the cutting force components and the surface quality were determined. The ANOVA was performed with a 95% confidence level. The most important part of the ANOVA table is a contribution result, which indicates whether the parameters are significant or not.

The analysis of variance result for surface roughness (Ra) is presented in Table 4. According to this result, surface roughness is mainly affected by feed rate and product of feed rate with 51.74% and 30.66% contribution, respectively. It was followed by a nose radius and a product of nose radius with 7.80% and 5.29% contribution, respectively. The depth of cut has not exhibited a significant impact on the surface roughness.

Table 4. Analysis of variance result for surface roughness (*Ra*)

Source	**DF**	**Seq SS**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**	**Cont.**	**Remarks**
Regression	6	0.126	0.126	0.021	12.79	0.074	97.46%	
R	1	0.010	0.009	0.009	5.63	0.141	7.80%	**Sig.**
f	1	0.067	0.025	0.025	15.61	0.058	51.74%	**Sig.**
a	1	0.0002	0.002	0.002	1.50	0.346	0.22%	No sig.
*R*R*	1	0.006	0.006	0.006	4.16	0.178	5.29%	**Sig.**
*f*f*	1	0.039	0.039	0.039	24.14	0.039	30.66%	**Sig.**
*a*a*	1	0.002	0.002	0.002	1.38	0.361	1.76%	No sig.
Error	2	0.003	0.003	0.001			2.54%	
Total	8	0.130					100.00%	

The analysis of variance result for radial force is presented in Table 5. The finding reveals that nose radius is the most significant factor that influenced the radial forces by 63.06% contribution, followed by cutting depth with 29.75% contribution. The R*R and a*a have also a minor effect on the radial force. Feed rate has not any impact on the radial force.

Table 5. Analysis of variance result for radial force (*Fx*)

Source	DF	Seq SS	Adj SS	Adj MS	F-Value	P-Value	Cont.	Remarks
Regression	6	2511	2511	418.6	8.75	0.106	96.33%	
R	1	1644	0.83	0.834	0.02	0.907	63.06%	**Sig.**
f	1	1.90	8.74	8.743	0.18	0.711	0.07%	No Sig.
a	1	775	94.61	94.6	1.98	0.295	29.75%	**Sig.**
*R*R*	1	45.91	45.91	45.9	0.96	0.431	1.76%	**Sig.**
*f*f*	1	10.16	10.16	10.1	0.21	0.690	0.39%	No Sig.
*a*a*	1	33.73	33.73	33.7	0.71	0.489	1.29%	**Sig.**
Error	2	95.69	95.69	47.8			3.67%	
Total	8	2607					100.00%	

The analysis of variance result for radial force is presented in Table 6. The result indicates a dominant effect of cutting depth on the tangential force with a 70.81% contribution. Feed rate was the next important parameter with 11.83% contribution, followed by R*R and nose radius with 10.70% and 3.36% contribution, respectively.

Table 6. Analysis of variance result for tangential force (*Fy*)

Source	DF	Seq SS	Adj SS	Adj MS	F-Value	P-Value	Cont.	Remarks
Regression	6	1935	1935	322.6	12.46	0.076	97.39%	
R	1	66.87	175.9	175.9	6.79	0.121	3.36%	**Sig.**
f	1	235.1	0.03	0.032	0.00	0.975	11.83%	**Sig.**
a	1	1407	71.42	71.4	2.76	0.239	70.81%	**Sig.**
R*R	1	212.6	212.6	212.6	8.21	0.103	10.70%	**Sig.**
f*f	1	4.13	4.13	4.126	0.16	0.728	0.21%	No Sig.
a*a	1	9.76	9.76	9.756	0.38	0.602	0.49%	No Sig.
Error	2	51.80	51.80	25.90			2.61%	
Total	8	1987					100.00%	

The analysis of variance result for radial force is presented in Table 7. The result clearly shows the considerable impact of the depth of cut on axial force with 94.26% contribution. The R*R and nose radius have also minor effects on the axial force. However, feed rate and other interactions did not exhibit any impact on the response.

Table 7. Analysis of variance result for axial force (*Fz*)

Source	DF	Seq SS	Adj SS	Adj MS	F-Value	P-Value	Cont.	Remarks
Regression	6	759	759	126	45.57	0.022	99.27%	
R	1	10.2	24.8	24.8	8.96	0.096	1.34%	**Sig.**
f	1	3.9	4.16	4.16	1.50	0.345	0.52%	No Sig.
a	1	720	16.1	16.1	5.81	0.137	94.26%	**Sig.**
*R*R*	1	20.9	20.9	20.9	7.54	0.111	2.74%	**Sig.**
*f*f*	1	3.15	3.15	3.15	1.13	0.398	0.41%	No Sig.
*a*a*	1	0.03	0.03	0.03	0.01	0.922	0.00%	No Sig.
Error	2	5.55	5.55	2.77			0.73%	

Main Effect Plots

The main effect plots for surface roughness is illustrated in Fig. 4. According to this plot, the surface roughness rises sharply as the feed rate increases. However, it experiences small decreases while the feed rate changes from 0.025 mm·rev^{-1} to 0.050 mm·rev^{-1}. Nose radius has also a great impact on surface quality. The larger the nose radius the higher surface roughness in finish hard turning of the AISI M2 high-speed steel workpiece. In most studies, researchers emphasize the dominant influence of the feed rate on surface roughness (Bartarya & Choudhury, 2012a; Bouacha et al., 2010; Lalwani et al., 2008; Suresh et al., 2012).

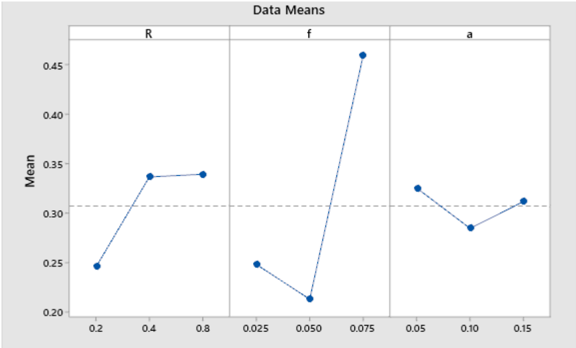

Fig. 4. Main effect plots for surface roughness

The main effect plots for radial force is illustrated in Fig. 5. It is observed that the nose radius has a dominant impact on the radial force. The radial force increases sharply as the nose radius increases. The depth of cut is the next effective factor on the radial force. Increasing the cutting depth also rises the radial force due to extensive force that occurs during the machining process. The feed rate has not any effect on the radial force.

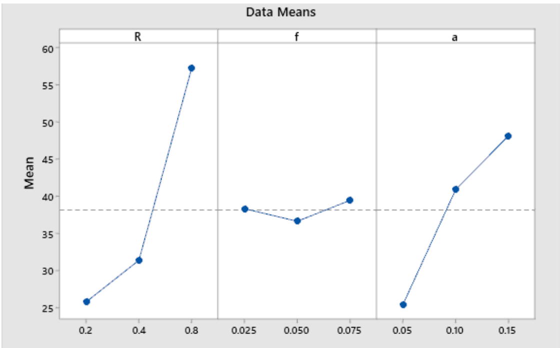

Fig. 5. Main effect plots for radial force

The main effect plots for tangential force is illustrated in Fig. 6. According to this graph, the depth of cut is a dominant factor. It is clearly seen that the tangential force rises by increasing the cutting depth. The feed rate has also a minor influence on the response factor. The tangential force maximized as the feed rate increased. Nose radius and product of it (R*R) also play a minimum effect on the tangential force.

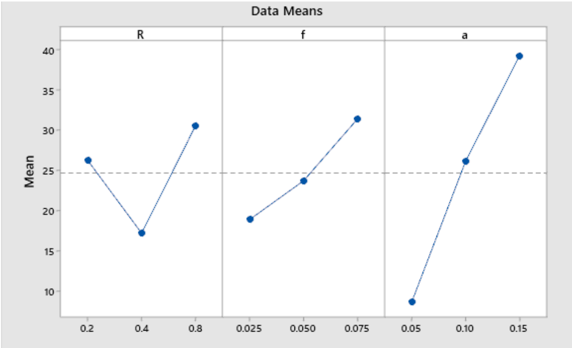

Fig. 6. Main effect plots for tangential force

The main effect plots for axial force is illustrated in Fig. 7. According to this graph, the cutting depth has a maximum effect on the axial force. Increasing the depth of the cut enhances the axial force dramatically. The other two factors did not exhibit any effect on the response. In most studies related to the cutting force components, researchers also indicated the significant influence of the cutting depth on the components of cutting force. In this study, the same results were obtained as previous studies (Aouici et al., 2012; Bartarya & Choudhury, 2012a; Lalwani et al., 2008; Yücel & Günay, 2013), which indicated the dominant effect of the cutting depth on the axial force rather than tangential and radial force. Respectively, the contribution of the depth of cut on the axial, tangential, and radial forces are 29.75%, 70.81%, and 94.26%. The combination of low cutting depth, low feed rate, and high cutting speed should be preferred for reducing the cutting force components.

Fig. 7. Main effect plots for axial force

Optimization of Cutting Parameters

The optimum cutting parameters, which result in the minimum cutting force components and minimum surface roughness are presented in Table 8. In order to obtain the minimum surface roughness in hard finish turning of the AISI M2 high-speed steel, the combination of the first level of nose radius (0.2 mm), the second level of depth of cut (0.10 mm), and the second level of feed rate (0.050 mm·rev^{-1}) is needed. The minimum radial force was obtained by the combination of the first level of nose radius (0.2 mm), the first level of depth of cut (0.05 mm), and the second level of feed rate (0.050 mm·rev^{-1}). The smallest values for tangential force and axial force were obtained by the combination of the second level of the nose radius (0.4 mm), the first level of depth of cut (0.05 mm), and the first level of feed rate (0.025 mm·rev^{-1}).

Table 8. Optimum cutting parameter for surface roughness and cutting force components

	Ra (µm)			Fx (N)		
	a	*f*	*R*	*a*	*f*	*R*
1	0.325	0.248	**0.246**	**25.40**	38.32	**25.78**
2	**0.285**	**0.213**	0.337	40.87	**36.63**	31.39
3	0.312	0.460	0.339	48.14	39.45	57.24
Level	**2**	**2**	**1**	**1**	**2**	**1**
	Fy (N)			Fz (N)		
	a	*f*	*R*	*a*	*f*	*R*
1	**8.64**	**18.91**	26.27	**27.49**	**37.26**	41.05
2	26.16	23.73	**17.21**	38.58	39.33	**36.66**
3	39.27	31.43	30.58	49.41	38.89	37.77
Level	**1**	**1**	**2**	**1**	**1**	**2**

Regression Equation

In the present study, the mathematical equations were obtained using a second order regression Equation (2).

$$Y = \alpha_0 + \sum_{i=1}^{k} \alpha_i X_i + \sum_{i=1}^{k} \alpha_{ii} X_i^2 \quad (2)$$

where

Y is the response variables such as cutting force components (Fx, Fy, Fz) and surface roughness (Ra). α_0 is the constant term of this equation, $\alpha_1, \alpha_2, \ldots, \alpha_k$ and $\alpha_{11}, \alpha_{22}, \ldots, \alpha_{kk}$ are the coefficients of the linear and the quadratic terms, respectively. X_i is the input factor namely feed rate (f), nose radius (R), and depth of cut (a).

The relation between the control factors with each response is determined using regression equations. Also, the determination coefficient (R^2) is presented for responses to suggest the best formula. In the presented work, mathematical models were presented considering feed rate, nose radius, and the depth of cut as input parameters, cutting force components, and surface roughness as output parameters in finish turning of hardened AISI M2 high-speed steel. The Equations (3-6) correspond to the developed models for each output parameter.

The regression equation for surface roughness

Ra = 0.480 + 0.903 R - 18.37 f - 2.84 a - 0.747 R*R + 226.1 f*f + 13.5 a*a (3)

R^2 = 97.46%

The regression equation for radial force

Fx = -5.0 - 8.5 R - 338 f + 556 a + 61.0 R*R + 3605 f*f - 1643 a*a (4)

R^2 = 96.33%

The regression equation for tangential force

$$Fy = 0.1 - 124.1\,R + 21\,f + 483\,a + 131.2\,R*R + 2298\,f*f - 883\,a*a \quad (5)$$

$R^2 = 97.46\%$

The regression equation for axial force

$$Fz = 20.57 - 46.7\,R + 233\,f + 229.6\,a + 41.2\,R*R - 2008\,f*f - 52\,a*a \quad (6)$$

$R^2 = 99.27\%$

Comparison of the Experimental and Predicted Values

A graphical comparison between experimental and predicted values is illustrated in Fig. 8. The results for all responses namely, surface roughness, radial force, tangential force, and axial force show very strong agreement between the experimental and the predicted values.

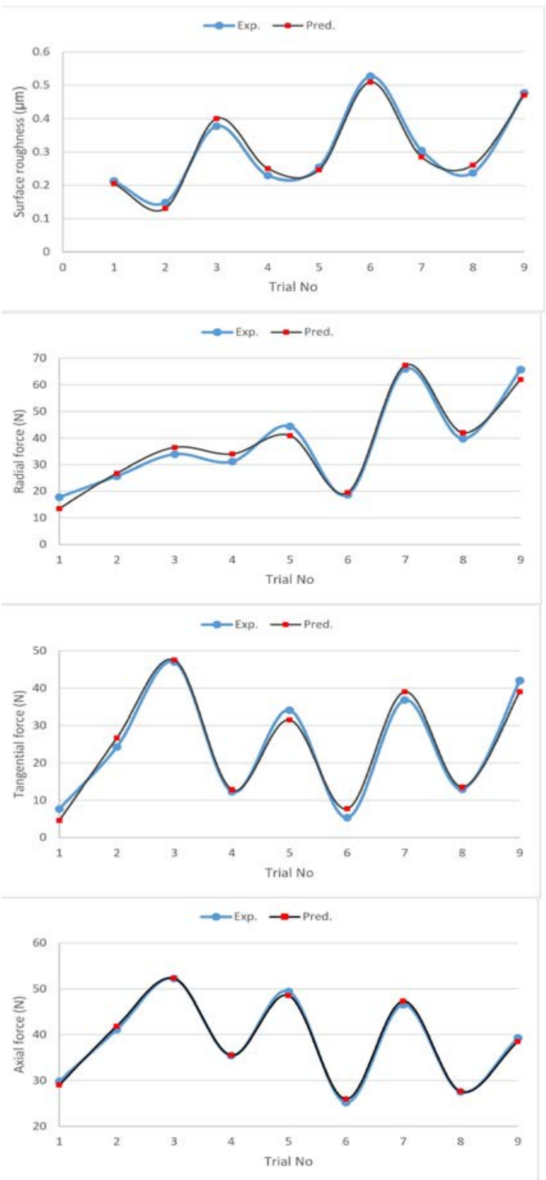

Figure 8. Comparison between experimental and predicted values

CONCLUSION

In this study, hard finish turning was carried out on AISI M2 high-speed steel with 60 HRC using CBN insert under dry cutting conditions. The constant cutting speed and three different nose radius, three depths of cut, and three feed rates were selected as input parameters, whereas cutting force components and surface roughness were chosen as output parameters. Nine tests were performed based on Taguchi L_9 orthogonal array to reduce the number of trials. The results were analyzed using ANOVA to acquire the most significant parameters that affect response variables. The optimum cutting parameters were determined for this study, and very good agreement was obtained by comparison of the experimental and predicted values.

According to the result of the analysis of variance surface roughness is majorly influenced by feed rate with 51.74% contribution. Also, the product of feed rate also provides a major impact on the surface quality with a 30.66% contribution. The nose radius exhibits a considerable impact on the surface roughness. However, the depth of cut has not exhibited any effect during the finish turning of hardened AISI M2 high-speed steel. Based on the main effect plots, the surface roughness increases considerably as the feed rate value rises. On the other hand, it increases slightly by increasing the cutting depth.

According to the ANOVA findings, the radial force affected by nose radius with 63.06% contribution. The cutting depth was the next important parameter that impacted the radial force with a 29.75% contribution. The main effect plots depicted a sharp increase in radial force as a consequence of increasing the nose radius. Furthermore, the radial force enhances by increasing the cutting depth.

The axial and tangential forces are significantly affected by the depth of cut with 94.26% and 70.81% contribution, respectively. The main effect plots illustrated that as the cutting depth increases the required load for cutting the material enhances, consequently the components of cutting force increase. Besides, the feed rate and product of nose radius have 11.83% and 10.70% contribution to the tangential force.

The optimum cutting parameters for obtaining the best surface quality and the minimum cutting force components in finish turning of the hardened AISI M2 workpiece have been determined. The comparison between predicted values and experimental value presented very good agreement, which shows the accuracy of the proposed model for output parameters. Based on the mathematical models, surface roughness, axial force, tangential force, and radial force were modeled with 97.46%, 99.27%, 97.39%, and 96.33% accuracy, respectively.

REFERENCES

Aneiro, F. M., Coelho, R. T., & Brandao, L. C. "Turning hardened steel using coated carbide at high cutting speeds". *Journal of the brazilian society of mechanical sciences and engineering,* Vol. 30, No. 2, pp. 104-109, (2008).

Aouici, H., Yallese, M. A., Chaoui, K., Mabrouki, T., & Rigal, J.-F. "Analysis of surface roughness and cutting force components in hard turning with CBN tool: Prediction model and cutting conditions optimization". *Measurement,* Vol. 45, No. 3, pp. 344-353, (2012).

Asiltürk, I., & Akkuş, H. "Determining the effect of cutting parameters on surface roughness in hard turning using the Taguchi method". *Measurement,* Vol. 44, No. 9, pp. 1697-1704, (2011).

Bartarya, G., & Choudhury, S. "Effect of cutting parameters on cutting force and surface roughness during finish hard turning AISI52100 grade steel". *Procedia CIRP,* Vol. 1, No., pp. 651-656, (2012a).

Bartarya, G., & Choudhury, S. "State of the art in hard turning". *International Journal of Machine Tools and Manufacture,* Vol. 53, No. 1, pp. 1-14, (2012b).

Bensouilah, H., Aouici, H., Meddour, I., Yallese, M. A., Mabrouki, T., & Girardin, F. "Performance of coated and uncoated mixed ceramic tools in hard turning process". *Measurement,* Vol. 82, No., pp. 1-18, (2016).

Bouacha, K., Yallese, M. A., Mabrouki, T., & 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,* Vol. 28, No. 3, pp. 349-361, (2010).

Chandra, P., Rao, C. P., & Kiran, R. "Influence Of Machining Parameter On Cutting Force And Surface Roughness While Turning Alloy Steel". *Materials Today: Proceedings,* Vol. 5, No. 5, pp. 11794-11801, (2018).

Chou, Y. K., & Song, H. "Tool nose radius effects on finish hard turning". *Journal of materials processing technology,* Vol. 148, No. 2, pp. 259-268, (2004).

Davim, J. P., & Figueira, L. "Comparative evaluation of conventional and wiper ceramic tools on cutting forces, surface roughness, and tool wear in hard turning AISI D2 steel". *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture,* Vol. 221, No. 4, pp. 625-633, (2007).

Ebrahimi, A., & Moshksar, M. "Evaluation of machinability in turning of microalloyed and quenched-tempered steels: Tool wear, statistical analysis, chip morphology". *Journal of materials processing technology,* Vol. 209, No. 2, pp. 910-921, (2009).

Fnides, B., & Yallese, M. "Cutting forces and surface roughness in hard turning of hot work steel X38CrMoV5-1 using mixed ceramic". *Mechanics,* Vol. 70, No. 2, pp. 73-78, (2008).

Huang, Y., & Liang, S. Y. "Modeling of cutting forces under hard turning conditions considering tool wear effect". *J. Manuf. Sci. Eng.,* Vol. 127, No. 2, pp. 262-270, (2005).

Jang, D. Y., & Hsiao, Y.-T. "Use of ceramic tools in hard turning of hardened AISI M2 steel". *Tribology transactions,* Vol. 43, No. 4, pp. 641-646, (2000).

Kumar, P., & Chauhan, S. "Machinability study on finish turning of AISI H13 hot working die tool steel with cubic boron nitride (CBN) cutting tool inserts using response surface methodology (RSM)". *Arabian Journal for Science and Engineering,* Vol. 40, No. 5, pp. 1471-1485, (2015).

Lalwani, D., Mehta, N., & Jain, P. "Experimental investigations of cutting parameters influence on cutting forces and surface roughness in finish hard turning of MDN250 steel". *Journal of Materials Processing Technology,* Vol. 206, No. 1-3, pp. 167-179, (2008).

Lin, H., Liao, Y., & Wei, C. "Wear behavior in turning high hardness alloy steel by CBN tool". *Wear,* Vol. 264, No. 7-8, pp. 679-684, (2008).

More, A. S., Jiang, W., Brown, W., & Malshe, A. P. "Tool wear and machining performance of cBN–TiN coated carbide inserts and PCBN compact inserts in turning AISI 4340 hardened steel". *Journal of Materials Processing Technology,* Vol. 180, No. 1-3, pp. 253-262, (2006).

Özdemir, M. "Optimization with Taguchi Method of Influences on Surface Roughness of Cutting Parameters in CNC Turning Processing". *Mechanika,* Vol. 25, No. 5, pp., (2019).

Özel, T., Hsu, T.-K., & 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". *The International Journal of Advanced Manufacturing Technology,* Vol. 25, No. 3-4, pp. 262-269, (2005).

Şahinoğlu, A., & Rafighi, M. "Investigation of Vibration, Sound Intensity, Machine Current and Surface Roughness Values of AISI 4140

During Machining on the Lathe". *Arabian Journal for Science and Engineering,* Vol. 45, No. 2, pp. 765-778, (2020).

Singh, D., & Rao, P. V. "A surface roughness prediction model for hard turning process". *The International Journal of Advanced Manufacturing Technology,* Vol. 32, No. 11-12, pp. 1115-1124, (2007).

Suresh, R., Basavarajappa, S., & Samuel, G. "Some studies on hard turning of AISI 4340 steel using multilayer coated carbide tool". *Measurement,* Vol. 45, No. 7, pp. 1872-1884, (2012).

Tönshoff, H., Arendt, C., & Amor, R. B. "Cutting of hardened steel". *CIRP Annals*, Vol. 49, No. 2, pp. 547-566, (2000).

Varma, K. R., & Kaladhar, M. "Multiple Performance Characteristics Optimization of Hard Turning Operations Using Utility Based-Taguchi Approach". *Journal of Mechanical Engineering,* Vol. 45, No. 2, pp. 73-80, (2015).

Yücel, E., & Günay, M. "Modelling and optimization of the cutting conditions in hard turning of high-alloy white cast iron (Ni-Hard)". *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*, Vol. 227, No. 10, pp. 2280-2290, (2013).

Zerti, A., Yallese, M. A., Meddour, I., Belhadi, S., Haddad, A., & Mabrouki, T. "Modeling and multi-objective optimization for minimizing surface roughness, cutting force, and power, and maximizing productivity for tempered stainless steel AISI 420 in turning operations". *The International Journal of Advanced Manufacturing Technology,* Vol. 102, No. 1-4, pp. 135-157, (2019).