Machinability of Hardened AISI S1 Cold Work Tool Steel using Cubic Boron Nitride

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Abstract

Recently, hard turning became an interesting method to the manufacturers as an alternative to the grinding process due to its superior features such as good surface quality, good productivity, lower production costs, lower power consumption, and shorter processing time. Despite its considerable benefits, hard turning is a difficult process that needs advanced cutting inserts such as ceramics and cubic boron nitride. However, these cutting inserts are costly and should be used properly by choosing appropriate machining parameters.

In the presented work, the hard turning process was performed to investigate the machinability of AISI S1 cold work tool steel using a cubic boron nitride insert. The relation between machining parameters namely, depth of cut, cutting speed, and feed rate on the responses such as power consumption, surface roughness, and machining sound was found using a full factorial orthogonal array of response surface methodology. In addition, analysis of variance was used to identify the most important machining parameters that influence output parameters. Based on the results, surface roughness was dominantly affected by feed rate, whereas, sound and power consumption were influenced by all machining parameters especially cutting speed and feed rate. A good agreement between the experimental and the predicted values were observed.

Keywords: AISI S1 steel, hard turning, surface roughness, machining sound, power consumption, response surface methodology
1. Introduction

In the last decades, hard turning is used as an alternative method to the grinding operation due to its superior properties such as shorter machining time, good surface finish, machining without coolant, lower manufacturing power, and cost. Further, hard turning allows good flexibility in the manufacturing of intricate geometries with good surface quality and dimensional accuracy [1-3]. Smaller feed rate and cutting depth are needed to remove much more material in hard turning compared to grinding, hence, a good material removal rate is one of the notable characteristics of hard turning [4, 5]. Hard turning is performed on various materials with hardness larger than 45 Rockwell using single-point cutting tools such as ceramics and cubic boron nitride (CBN) due to their remarkable properties namely high strength, high wear resistance, and high hardness [6-9]. These cutting inserts produce good surface quality and smaller flank wear during the turning of hardened steel [10]. Many studies have been done related to the effect of cutting parameters and workpiece materials on the power consumption [11, 12], tool wear [13, 14], cutting forces [15, 16], and surface roughness [17, 18] during hard turning.

The cold work tool steels such as AISI S1 [19] and AISI D3 [20] contain a high amount of carbon. Besides, they have a low amount of molybdenum, silicon, chromium, manganese, vanadium, and tungsten in their chemical composition. The carbon element of cold work tool steel increases the wear resistance of the workpiece, while other elements increase the toughness and hardenability [21, 22]. The AISI S1 cold work tool steel material is used in many applications as cutting tools for cold cutting, cold shear blades, blanking dies, cold piercing punches, woodworking tools, scrapping scissors, industrial knives, shear blades, and ejectors.

Machinability can be defined as the ease of the metal removal process by using proper cutting tools and machining parameters. Many criteria affect machinability, however, power consumption [11], tool wear [13], cutting forces [16], surface quality [18], tool life [23], are the most important ones [24]. Surface finish is used to evaluate the machined surface quality and productivity of machine tools. Therefore, it is of great importance to investigate the surface quality of the machined workpiece in order to express machining performance.

Chou et al. [25] studied tool flank wear and surface finish during hard turning of 62 Rockwell AISI 52100 steel using various CBN cutting tools. Scanning electron microscopy (SEM) was used to characterize the wear behavior of CBN inserts. According to the
results, the low cubic boron nitride content tools (CBN-L) exhibited better performance than high content cubic boron nitride tools. The flank wear has a direct proportion with cutting speed, increasing the cutting speed increased the flank wear. In most studies, the surface roughness was mainly affected by the feed rate. However, in this study, the feed rate was kept constant and the depth of cut was effective, the low depth of cut produced a good surface in low content CBN.

Devim and Figueira evaluated the effect of input parameters on surface quality during hard turning of AISI D2 tool steel having a hardness of 60 Rockwell using ceramic cutting tools. ANOVA was utilized to detect the most important parameters that influence surface quality. The results indicated that the tool wear is greatly affected by cutting speed by 57% contribution. As the cutting speed increases the tool wear also increases. Also, the feed rate was found as a dominant factor that influenced surface roughness.

In another experimental study by Isik [27], the machinability of various cold work tool steels such as AISI H10, AISI O2, and AISI 420 was evaluated. The workpiece materials, cutting parameters, and cutting tools coating were considered as input parameters, while the surface roughness, tool flank wear, and cutting forces were considered as responses. The results indicated that tool life was mainly influenced by cutting speed and feed rate, whereas the tool nose radius was a significant factor in the surface roughness.

Bouacha et al. [28] presented an experimental study related to the hard turning of AISI 52100 bearing steel (64 Rockwell) using cubic boron nitride (CBN) cutting tools. The depth of cut, feed rate, and cutting speed were selected as cutting parameters, the tool wear, cutting forces and surface roughness were chosen as response parameters. The most effective cutting parameters on output parameters were found by using the analysis of variance. The relation between machining parameters and the responses such as surface roughness and cutting forces were chosen using RSM. According to the results, the feed rate and cutting speed were the most important factors that affected surface quality. In addition, the cutting forces were mainly influenced by workpiece hardness, negative rake angle and tool wear, respectively.

Lima et al. [29] investigated the machinability of hardened AISI D2 cold work tool steel (58 HRC) and hardened AISI 4340 high strength low alloy steel (42 and 50 HRC) using mixed alumina, polycrystalline cubic boron nitride (PCBN), and coated carbide cutting inserts, respectively. In this experimental study, input parameters include feed rate, depth of cut, and cutting speed, while output parameters were surface roughness, tool wear, cutting forces, and tool life. Based on the results of this study, good surface quality was obtained during the turning of hardened AISI D2 tool steel employing a low feed rate and
high cutting speed. However, increasing the cutting speed caused tool flank wear in mixed alumina inserts. Besides, during the turning of hardened AISI 4340 high strength low alloy steel (50 HRC), the cutting forces were reduced by increasing the cutting speed due to increasing the temperature in the shear zone that eased the material removal process. Finally, the main reason for flank wear during the hard turning of 42 HRC steel was an abrasion.

Gaitonde et al. [30] stated that hard turning with ceramic tools provide many advantages over to grinding process such as decreasing manufacturing cost, improving surface quality, reducing power consumption, and enhancing productivity. Therefore, they investigated the turning of hardened high chromium AISI D2 cold work tools using various ceramic cutting tools such as GC6050WH, CC650WG, and CC650. They considered machining time and depth of cut as input parameters and tool wear, surface roughness, cutting force, and power consumption as responses. The results indicated that the CC650WG wiper insert produced good surface quality and less tool wear. However, the cutting forces and power consumption were decreased using CC650 conventional inserts.

Bensouilah et al. [31] presented an experimental study to explore the effects of input parameters such as cutting speed, depth of cut, and feed rate on the cutting forces and surface roughness during turning of hardened AISI D3 tool steel by employing CC6050 and CC650 ceramic inserts. The Taguchi method, ANOVA, RSM, and linear regression model were employed to evaluate the machinability of the workpiece material. The results showed that the CC6050 ceramic insert exhibited 1.6 times better surface quality than uncoated CC650 ceramic inserts. The feed rate was the dominant factor that affects surface roughness followed by cutting speed. Moreover, the cutting forces were greatly affected by the depth of cut. The uncoated ceramic insert showed good performance in decreasing the cutting forces.

Aouici et al. [32] presented the impacts of the depth of cut, feed rate, and cutting speed on the cutting forces, power consumption, and surface roughness during turning of hardened AISI D3 cold work tool steel (60 HRC) employing ceramic cutting inserts. The response surface methodology was used to obtain the optimum cutting parameters and the analysis of variance was employed to determine the most significant parameter. The results showed that the feed rate was the most important factor that affected the surface quality and power. In order to obtain the best surface quality, minimum power consumption, and cutting forces, the workpiece should be machined with a low depth of cut, high cutting speed, and low feed rate.
Şahinoğlu and Rafighi [33] investigated the effects of cutting parameters on surface roughness, vibration, sound intensity, and current values during turning of AISI 4140 steel using coated carbide cutting inserts. They employed RSM and ANOVA to find out the relationship between machining parameters-response variables and the significant factors that affect the outputs, respectively. The results revealed that surface roughness was mainly influenced by the feed rate. The other responses namely, current, sound intensity, and vibration were affected by both feed rate and depth of cut. As the aforementioned machining parameters increase the responses also increase. Finally, good agreement was obtained between experimental and predicted data.

In another study by Şahinoğlu and Rafighi [34], the effect of machining parameters and workpiece hardness was investigated during turning of AISI 1040 steels. According to the results, the feed rate is the most significant factor in power consumption and surface roughness.

In the last four decades, many experimental studies have been conducted to investigate the machinability of hardened steels using different cutting inserts such as cubic boron nitride, coated carbide, and ceramic. However, the number of studies that focused on the machinability of the hardened cold work tool steels considering sound and power consumption is limited. The goal of this study is to explore the effects of machining parameters such as feed rate, depth of cut, and cutting speed on the machinability factors, namely power consumption, surface roughness, and sound during turning of hardened AISI S1 cold work tool steel employing CBN cutting inserts. This study is performed by applying the response surface methodology (RSM) to determine the relationship between input and output parameters. In addition, the analysis of variance (ANOVA) was used to determine the most important factor that affects the response parameters and multiple linear regression equations were established to determine the response variables numerically by using the correlation between input and output parameters.

2. Materials and Methods

2.1. AISI S1 properties and applications

In the presented work, hard turning was performed on AISI S1 cold work tool steel utilizing cubic boron nitride inserts to explore the effects of input parameters such as depth of cut, cutting speed, and feed rate on output parameters such as sound, power consumption, and surface roughness. The notable properties of AISI S1 steel are good toughness, good shock resistance, and good hardenability. This material is appropriate for cold work tools subjected to high shock. The AISI S1 steel can be used for cutting tools, shear knives,
and ejector pins. The designation related to this material for DIN standard is 1.2550, for EN standard is 60WCrV8 and for AISI/ASTM standard is S1.

2.2. Workpiece material
In this study, AISI S1 cold work tool steel bar was used as a workpiece material with a 50 mm diameter and a 200 mm length. The length to diameter ratio of this cylindrical workpiece was kept as 4 to maintain the stiffness of the workpiece, chuck, and cutting tool. The heat treatment was performed at 860°C for two hours, then it was quenched in the oil for 30 minutes and finally, it was tempered for 1 hour at 200°C, to remove residual stresses and obtain 60 HRC hardness. The machining time for each pass was almost one minute and the measuring period for surface roughness was almost two minutes. The chemical composition of AISI S1 cold work tool steel is presented in Table 1.

2.3. Cutting conditions
Generally, the turning process on the lathe is performed using three main parameters namely, cutting speed (\(V\)), feed rate (\(f\)), and depth of cut (\(a\)). Determining the optimum machining parameters considering output parameters is very important to reduce the cost of manufacturing. The machining parameters are chosen based on previous studies and the manufacturer’s handbook (considering the workpiece material and cutting insert). In the presented work, the hard turning was performed on AISI S1 tool steel using CBN cutting inserts. The cutting parameters for the presented work are shown in Table 2. The turning tests were carried out on the TAKSAN TTC-630 model CNC lathe having a maximum power of 20 kW and a maximum speed of 4000 rpm under dry cutting conditions.

2.4. Cutting inserts
In this experimental study, cubic boron nitride (CBN) inserts manufactured by the Sandvik company with DCGW11T304S01020FWH 7015 ISO designation were used due to their high thermal and abrasion resistance. The recommended cutting parameters for this insert according to the manufacturer’s catalog are: cutting speed (160-250 m/min), feed rate (0.05-0.25 mm/rev), and depth of cut (0.05-0.40 mm). The physical vapor deposition (PVD) is applied to coat carbide inserts with TiN layer. It has a 3.969 mm thickness, 0.40 mm tool nose radius, negative 55° cutting tip, and 9.525 mm inscribed diameter. Furthermore, the MWLNR 2525 M08 tool holder was used to mount the cutting inserts. The cubic boron nitride (CBN) insert is shown in Figure 1.

2.5. Measuring devices
Firstly, the instantaneous current and sound values were measured during the turning operation. Then surface roughness value was measured after each turning process. The
Lutron SL-401 device was employed to measure the sound of the process during the turning operation. There are instantaneous fluctuations in the sound during a turning process that affects the sound measuring process negatively. In order to avoid these fluctuations, Lutron SL-401 portable device was located at a distance of 900 mm from the CNC lathe.

The UNI-T UT201 device was used to measure the machine current. The total current value was calculated by multiplying the current value of one phase by three. Therefore, the total power consumption of the CNC lathe machine for each turning process was obtained by multiplying the voltage (380 V) by the total current value. The Lutron SL-401 and UNI-T UT201 devices are shown in Figures 2 (a) and 2 (b), respectively.

The surface roughness (Ra) was measured using a Mitutoyo SJ 201 portable device. The surface roughness value for each turning test was measured considering the mean value of three measurements from three different locations of the outer diameter of the workpiece. The measuring process on the machined surface is shown in Figure 3. The experimental setup is given in Figure 4.

2.6. Response surface methodology (RSM)

This method is used to determine the relationship between cutting parameters and response variables. In addition, the RSM is a good method to develop, improve, and optimize the processes besides identifying the significant input factors on responses within the design layout. The formula between independent input factors and desired response is given in Equation (1).

\[ Y = \varnothing(a, V, f) \]  

Where Y is the desired output parameter and \( \varnothing \) is the output parameter function.

In this experimental study the following steps are performed:

1. Defining the cutting parameters and response variables
2. Adopting full factorial orthogonal array experimental design layout
3. Developing the regression equations and calculating the coefficient of determination \( (R^2) \) based on RSM
4. Performing the ANOVA for cutting parameters to identify the dominant parameter that influences the responses
5. Obtaining the interaction plots, surface plots, residual graphs, normal plots, and Pareto charts of the standardized effects
6. Validating the mathematical model by performing the confirmation test
7. Analyzing the results of the response surface methodology
3. Results and Discussion

In this study, the impacts of machining parameters such as cutting speed, depth of cut, and feed rate on the machinability of hardened AISI S1 tool steel were investigated using cubic boron nitride inserts under dry cutting conditions. The results of the presented work were analyzed using analysis of variance, response surface methodology, and regression equations. The Minitab 19 software was employed to analyze the obtained data. The results were divided into five parts. First, the results of the analysis of variance for response variables were investigated to identify the most important factor. Second, the interaction plots, the normal plots, and Pareto charts for input and output parameters were presented. Third, the surface plot for the effect of the combination of input parameters on outputs was provided. Fourth, the regression equations were provided and the coefficients of determination were presented. Finally, the confirmation test was carried out to check the reliability of the proposed mathematical models.

3.1. Experimental results

In this study, the L_{27} full factorial orthogonal array was chosen that contains \((3^3 = 27)\) trials regarding the combination of three cutting speeds, three depths of cut, and three feed rates. The first three columns were assigned to the machining parameters including cutting speed \((V)\), depth of cut \((a)\), and the feed rate \((f)\). The next three columns were assigned to the response parameters, namely, power consumption \((P)\), surface roughness \((Ra)\), and sound \((S)\). The design of the experiment and the results of the responses are given in Table 3.

3.2. Surface roughness \((Ra)\)

The ANOVA results for surface roughness are presented in Table 4. In this table, \(F\) is the variance ratio, \(P\) is the significant factor and DF is the degree of freedom. The significance level of \(\alpha=0.05\) was chosen to perform this analysis. It means that the machining parameter is statistically significant while the \(P\)-value is smaller than 0.05.

The analysis of variance result showed that the feed rate is the most influential parameter that affects surface roughness by 91.77% contribution. The same results were obtained in [26-29] studies that indicated the effect of feed rate on surface roughness. The reason for this phenomenon is the direct relation of feed rate and surface roughness based on Equation (2). Here, \(Ra\) is the arithmetic surface roughness, \(f\) is the feed rate and \(r\) is the tool nose radius. Another reason for bad surface quality is enhancing the cutting force as a result of a high feed rate. Therefore, the high cutting forces generate heats that deteriorate the surface quality. Also, the square of feed rate \((f^2)\) and the interaction of depth of cut-feed \((a*f)\) rate have a minor impact on surface quality by 2.41% and 1.54%
contribution, respectively. Based on the results, the cutting speed has no important impact on surface quality in contrast with [28, 29] studies.

\[ Ra = \frac{f^2}{32r} \]  

(2)

The Pareto chart and the normal plot of standardized effects for surface roughness are presented in Figures 5 and 6, respectively. The Pareto chart shows that the feed rate is the dominant factor that imprints surface quality. Other parameters such as \((f^2)\), \((a*f)\), and \((a)\) have minimum influence on the surface. In the normal plot for alpha=0.05, those significant parameters that have a positive effect on response variables are placed at the right side of the distribution fit line. The normal plot also shows that the surface roughness is mainly affected by the feed rate followed by \((f^2)\). It means that by increasing the feed rate the surface roughness is also increased. The \((a*f)\) and \((a)\) have also a minimum negative effect on surface quality. It means that by increasing the cutting depth the surface roughness decreases.

The surface plots for surface roughness are provided in Figure 7. The surface plot for the interaction of \((V-a)\) with surface roughness (hold value: \(f=0.1\) mm/rev) shows that surface roughness is slightly decreased by increasing the cutting depth, whereas the cutting speed almost exhibits no impact on surface quality. The surface plot for the interaction of feed rate-depth of cut \((f-a)\) with surface roughness (hold value: \(V=200\) m/min) shows that surface roughness is significantly affected by feed rate. The surface roughness increases by increasing the feed rate. The depth of cut has a minor impact on surface quality. Finally, the surface plot for the interaction of feed rate-cutting speed \((f-V)\) with surface roughness (hold value: \(a=0.1\) mm) indicates that cutting speed has no impact on surface quality; however, surface roughness is sharply increased by increasing feed rate.

3.3. Power consumption (PW)

Table 5 shows the results of the ANOVA for power consumption. It is of great importance for a company to reduce power consumption due to the high cost of electricity and also some environmental problems. Therefore, the influences of cutting parameters are investigated on the power consumption to find out the effective parameters in this study. According to the results, all three machining parameters namely, feed rate, cutting speed, and depth of cut have a great impact effect on the power consumption by 43.61%, 30.71 %, and 19.78% contribution, respectively. Gaitonde [30] and Aouici [32], found the same result in their study that verifies the influence of feed rate on power consumption as a dominant factor. Increasing each cutting parameters result in an increase in cutting forces and consequently high power consumption. Furthermore, the interaction of \((f-a)\) with
(2.51%) and (f-V) with (1.39%) contribution have a minor effect on power consumption. The \( (a^2) \) and \( (V^2) \) have a totally 1.54% contribution on power.

The Pareto chart and the normal plot of standardized effects for power consumption are presented in Figures 8 and 9, respectively. The Pareto chart shows that power consumption is mainly affected by \( (f) \), \( (V) \), and \( (a) \), respectively. The interaction of \( (a^{*}f) \), \( (a^{*}V) \) and a square of cutting speed and depth of cut have also a minimum impact on response. The normal plot of the standardized effects shows the positive influence of all machining parameters on the power consumption except \( (a^2) \). Thus, as the level of the cutting parameter enhances the more power is consumed.

The surface plots for power consumption are provided in Figure 10. In these plots the hold value for a-V is \( (f=0.1 \text{ mm/rev}) \), for a-f is \( (V=200 \text{ mm/min}) \) and for V-f is \( (a=0.15 \text{ mm}) \). The surface plot for the interaction of a-V with PW indicates that power consumption is sharply increased by increasing both the depth of cut and cutting speed. However, the cutting speed is dominant in comparison to the depth of cut. The surface plot for the interaction of a-f with PW indicates that power consumption is considerably affected by feed rate followed by the depth of cut. As the feed rate increases the power consumption also enhances. Finally, the surface plot for the interaction of V-f with power consumption exhibits the same effect as the a-f plot.

3.4. Sound (S)

The results of the ANOVA for sound are presented in Table 6. Another way to investigate the machinability of the materials is by detecting the sound fluctuations during the machining operation. In this study, cutting speed was a dominant factor that affected sound by 44.10% contribution. The square of \( (a) \) and \( (V) \) are the next important parameters by 19.42% and 10.35% contribution, respectively. The other two machining parameters namely, depth of cut and feed rate were also effective on sound by 8.41% and 7.55% contribution, respectively. Finally, the interaction of cutting depth and cutting speed has a minor influence on sound by 1.97% contribution.

The Pareto chart and the normal plot of standardized effects for sound are presented in Figures 11 and 12, respectively. The Pareto chart shows that the sound is significantly influenced by cutting speed. The squares of \( (a) \) and \( (V) \) are the next effective parameters on sound. The depth of cut and feed rate have also affected the sound. According to the normal plot of standardized effects, the cutting speed has a positive impact on sound followed by \( (a^2) \), \( (V^2) \), and feed rate. It means that as the aforementioned parameters increase the sound also increases. However, the cutting depth and \( (a^{*}V) \) have a negative influence on the sound, thus, as the cutting depth increases the sound decreases.
The surface plots for sound are illustrated in Figure 13. The surface plot for the interaction of (a-V) with the sound indicates that the sound is sharply increased by increasing the cutting speed at f=0.1 mm/rev and a=0.1 mm. However, as the depth of cut increases from 0.1 mm to 0.15 mm the sound slightly decreases and after that increases. The same phenomenon happens in the surface plot for the interaction of depth of cut and feed rate with sound. The sound decreases by increasing the depth of cut until 0.15 mm, then it increases. According to this plot, sound enhances as the feed rate increases. Finally, the surface plot for feed rate and cutting speed shows that the sound elevated sharply by increasing the cutting speed and the feed rate. Increasing the feed rate at V=220 m/min and a=0.15 mm enhances the sound.

3.5. Regression equations

The multiple regression analysis is utilized to find the relationship between machining parameters and responses. The response surface methodology based second-order polynomial equations were developed for surface roughness (Ra), power consumption (PW), and sound (S) based on machining factors namely, feed rate (f), cutting speed (V), and depth of cut (a) during turning of hardened AISI S1 tool steel employing CBN cutting tools. The main formula for predicting responses according to cutting parameters is given in Equation (3).

\[ Y = b_0 + b_1a + b_2V + b_3f + b_4a^2 + b_5V^2 + b_{12}aV + b_{13}af + b_{23}fV^2 + b_{123}afV + b_{132}a^2f + b_{122}af^2 + b_{133}V + b_{233}Vf + b_{1323}afVf \]  

(3)

Where Y is the desired output parameter, \( b_0, b_1, ..., b_{33} \) regression coefficient to be determined for each output parameter. The mathematical models for (Ra), (PW), and (S) are presented in Equations 4, 5, and 6, respectively.

In addition, the coefficient of determination \( (R^2) \) that is the ratio of the explained variation to the total variation is presented. The presented mathematical model is significant when the \( R^2 \) tends to 100%. In this case, the predicted data fits the actual data. The coefficient of determination for surface roughness is 97.41%, which indicates the accuracy of the proposed model. The \( R^2 = 99.52\% \) shows that the proposed mathematical model can accurately predict power consumption. Finally, the \( R^2 \) of 92.89% indicates that the sound of the machining process can be predicted through the mathematical model.

A mathematical model for surface roughness (Ra)

\[ Ra = -1.285926 + 3.111111a + 0.013833V - 0.333333f - 2.222222a^2 - 0.000039V^2 + 53.111111f^2 - 0.003333aV - 30a f + 0.183333V f \]  

\( R^2 = 97.41\% \)
A Mathematical model for power consumption (PW)

\[
PW = 4317.01 + 3787.33a - 19.92V - 4553.66f - 13173.33a^2 + 0.0554V^2 - 3293.33f^2 + 1.9a \cdot V + 14820a \cdot f + 27.55V \cdot f
\]

\( R^2 = 99.52\% \)

A Mathematical model for sound (S)

\[
S = 112.081481 - 45.555556a - 0.370972V - 16.611111f + 222.22222a^2 + 0.001014V^2 + 22.22222f^2 - 0.125a \cdot V - 3.333333a \cdot f + 0.083333V \cdot f
\]

\( R^2 = 92.89\% \)

3.6. Optimization of output parameters

In manufacturing processes, one of the most important goals is to minimize surface roughness and power consumption to obtain the best surface quality and to reduce the processing cost. Response surface methodology optimization is used to obtain the optimum machining parameters based on the output parameters.

In the hard turning of AISI S1 steel, response optimization was utilized to determine the optimum cutting parameters that minimize the surface roughness, power consumption, and sound. The desirability (d) value is used to measure the impact of each response and the composite desirability is a considerable criterion for all responses. Composite desirability is the arithmetic mean of each response desirability and it ranges from zero to one. If the composite desirability value tends to zero, in this case the responses are not optimized well, whereas if it tends to one the optimized value for responses obtained.

Figure 14 shows the optimization plot for the responses. According to this figure, the optimum cutting parameters for the minimum responses are obtained as a (0.13 mm), V (180.4 m/min), and f (0.05 mm/rev). In addition, the optimized response for surface roughness is 0.319 µm with \( d = 0.917 \), for power consumption 2952 Watt with \( d = 0.867 \), and for sound 72.999 dB with \( d = 1 \). Finally, the composite desirability for this study is obtained as 0.926.

3.7. Confirmation test

The confirmation test was carried out on all sets of input factors to verify the validity of the proposed mathematical models. The experimental results, the predicted results, the absolute error (AE%), and the average of absolute errors (AAE%) for the responses are presented in Table 7. The absolute error (AE%) for each test is calculated using Equation 7.

\[
AE(\%) = \left[ \frac{|\text{experimental} - \text{predicted}|}{\text{experimental}} \right] \times 100
\]
According to the result, the AAE for sound, power consumption, and surface roughness is 0.11%, 0.23%, 5.46%, respectively. These results show that the presented model can predict the response with very good accuracy.

In addition, the comparison between experimental and predicted values for responses namely, surface roughness, power consumption, and sound is illustrated in Figures 15, 16, and 17, respectively. These graphs show good agreement between experimental and predicted values for output parameters.

4. Conclusion

In the presented work, the hard turning is performed on AISI S1 cold work tool steel using cubic boron nitride inserts to investigate the machinability factors such as surface roughness, power consumption, and sound. The cutting speed, depth of cut, and feed rate are chosen as machining parameters and RSM is employed to create the experimental design. The ANOVA is used to detect the most important factors that influence the responses. Finally, the mathematical models are proposed for each output parameter and the confirmation test is performed to compare the results of experimental and predicted values. The outcomes of this study are listed below:

Based on the ANOVA results, feed rate has a dominant effect on surface roughness by 91.77% Contribution. The product of feed rate and interaction of (a*f) have a minor impact on the (Ra) by 2.41% and 1.54% contribution, respectively. According to the surface plots, surface roughness has a direct relation with the feed rate. The surface quality deteriorates as the feed rate increases. According to the metal cutting theory, the feed rate is the most significant parameter that affects surface roughness. The feed rate has a direct relation with surface roughness and nose radius has an indirect relationship. Thus, as the feed rate increases the cutting forces increases, hence, vibration creates and results in chatter on the machined surface that adversely affects the surface quality and deteriorates the surface of the workpiece. According to workpiece material, the hardness of the workpiece, cutting tools type, machining parameters, and other criteria cutting speed could also have an important effect on the surface quality. However, in this study, the depth of cut and cutting speed do not exhibit any considerable effect on the surface quality. In some cases, the combination of low feed rate value and high cutting speed should be selected to minimize the surface roughness. Also, the normal plot and the Pareto chart of standardized effects show the same results for surface roughness. The surface roughness is modeled with a 97.41% coefficient of determination. Therefore, the experimental results and the predicted results through a mathematical equation are so
Determining the optimum cutting parameters for minimizing the power consumption and consequently reducing the cost of manufacturing is inevitable. In this study, the results of the analysis of variance for power consumption show that feed rate is the most important parameter by 43.61% contribution. Following the feed rate, cutting speed and depth of cut have also significant with 30.71% and 19.78% contribution. The other factors such as machining parameters 2-Way interaction and squares have 3.91% and 1.50% contribution on the power consumption. The normal plot of standardized effect shows that all machining parameters have a positive impact on power consumption. Based on the surface plots, by increasing the value of feed rate, cutting speed, and depth of cut the power consumption sharply increases. The $R^2$ for power consumption is 99.52% and the comparison between the predicted values from the mathematical model and experimental values exhibit almost identical results for both.

Optimization of cutting parameters based on sound is another method to determine the machinability of the workpiece. The ANOVA results showed that cutting speed is a significant factor that affected sound by 44.10% contribution. The $(a^2)$ and $(V^2)$ have also a great impact on the sound by 19.42% and 10.35% contribution, respectively. The cutting depth and feed rate have 8.41% and 7.55% contribution on the sound, respectively. The Pareto chart and the normal plot of standardized effects for sound are presented in Figures 9 (a) and (b), respectively. The Pareto chart shows that the sound is significantly influenced by cutting speed. The squares of the cutting depth and cutting speed are the next effective parameters on sound. The depth of cut and feed rate have also affected the sound. According to the normal plot of standardized effects, the cutting speed has a positive impact on sound followed by $(a^2)$, $(V^2)$, and feed rate. It means that if the aforesaid parameters increase the response (sound) also increases. The surface plots for sound shows that increasing the cutting speed and feed rate increases the sound. However, increasing the depth of cut from 0.10 mm to 0.15 mm decreases the sound. The coefficient of determination ($R^2 = 92.89\%$) indicates a good agreement between experimental and predicted results.
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**Biography of the authors**

Dr. Şahinoğlu was born in Malatya (Turkey) in 1981. He completed his undergraduate and graduate education at Gazi University in manufacturing engineering. He works in the field of machine manufacturing and design. He has three patents in machine design and manufacture. One of them is the “intelligent tool machining design” which determines the cutting parameters according to the sound and vibration analysis. He has published some papers related to the machining operation. He has worked at Çankırı Karatekin University, department of mechanical and metal technology as an instructor from 2012-2020. Since 2020, he has been working at Manisa Celal Bayar University, department of mechanical and metal technology as an assistant professor.

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## Tables

### Table 1

|        | Si (%) | C (%) | P (%) | Mn (%) | Cr (%) | S (%) | W (%) | V (%) |
|--------|--------|-------|-------|--------|--------|-------|-------|-------|
|        | 0.55-0.70 | 0.55-0.65 | 0.30  | 0.15-0.45 | 0.90-1.20 | 0.30  | 1.70-2.20 | 0.10-0.20 |

### Table 2

| Cutting parameters | Units | Levels |
|--------------------|-------|--------|
| Feed rate (f)      | mm/rev| 0.05 0.10 0.15 |
| Cutting speed (V)   | m/min | 180 200 220 |
| Depth of cut (a)    | mm    | 0.10 0.15 0.20 |

### Table 3

| Trial no | Input parameters | Output parameters |
|----------|------------------|-------------------|
|          | a (mm) | V (m/min) | f (mm/rev) | Ra (µm) | PW (Watt) | S (dB) |
| 1        | 0.1    | 180      | 0.05      | 0.29    | 2861.4    | 73.4   |
| 2        | 0.1    | 180      | 0.10      | 0.86    | 2975.4    | 73.6   |
| 3        | 0.1    | 180      | 0.15      | 1.26    | 3032.4    | 73.7   |
| 4        | 0.1    | 200      | 0.05      | 0.22    | 2964.0    | 73.5   |
| 5        | 0.1    | 200      | 0.10      | 0.76    | 3043.8    | 73.8   |
| 6        | 0.1    | 200      | 0.15      | 1.33    | 3123.6    | 74.0   |
| 7        | 0.1    | 220      | 0.05      | 0.25    | 3055.2    | 74.8   |
| 8        | 0.1    | 220      | 0.10      | 0.72    | 3169.2    | 75.0   |
| 9        | 0.1    | 220      | 0.15      | 1.42    | 3271.8    | 75.2   |
| 10       | 0.15   | 180      | 0.05      | 0.28    | 2986.8    | 73.1   |
| 11       | 0.15   | 180      | 0.10      | 0.67    | 3078.0    | 73.2   |
| 12       | 0.15   | 180      | 0.15      | 1.20    | 3157.8    | 73.3   |
| 13       | 0.15   | 200      | 0.05      | 0.30    | 3032.4    | 73.1   |
| 14       | 0.15   | 200      | 0.10      | 0.72    | 3169.2    | 73.0   |
| 15       | 0.15   | 200      | 0.15      | 1.35    | 3283.2    | 73.2   |
| 16       | 0.15   | 220      | 0.05      | 0.29    | 3123.6    | 73.3   |
| Source       | DF | Seq SS   | Adj SS  | Adj MS  | F-Value | P-Value | Contribution | Remarks |
|--------------|----|----------|---------|---------|---------|---------|--------------|---------|
| Model        | 9  | 4.27073  | 4.27073 | 0.47453 | 71.10   | 0.000   | 97.41%       |         |
| Linear       | 3  | 4.09165  | 4.09165 | 1.36388 | 204.37  | 0.000   | 93.33%       |         |
| a            | 1  | 0.06722  | 0.06722 | 0.06722 | 10.07   | 0.006   | 1.53%        | Not Sig.|
| V            | 1  | 0.00109  | 0.00109 | 0.00109 | 0.16    | 0.691   | 0.02%        | Not Sig.|
| f            | 1  | 4.02334  | 4.02334 | 4.02334 | 602.87  | 0.000   | 91.77%       | Significant |
| Square       | 3  | 0.10742  | 0.10742 | 0.03581 | 5.37    | 0.009   | 2.45%        |         |
| a²           | 1  | 0.00019  | 0.00019 | 0.00019 | 0.03    | 0.870   | 0.00%        | Not Sig.|
| V²           | 1  | 0.00145  | 0.00145 | 0.00145 | 0.22    | 0.647   | 0.03%        | Not Sig.|
| f²           | 1  | 0.10578  | 0.10578 | 0.10578 | 15.85   | 0.001   | 2.41%        | Significant |
| 2-Way Interaction | 3   | 0.07167  | 0.07167 | 0.02389 | 3.58    | 0.036   | 1.63%        |         |
| a*V          | 1  | 0.00013  | 0.00013 | 0.00013 | 0.02    | 0.889   | 0.00%        | Not Sig.|
| a*f          | 1  | 0.06750  | 0.06750 | 0.06750 | 10.11   | 0.005   | 1.54%        | Significant |
| V*f          | 1  | 0.00403  | 0.00403 | 0.00403 | 0.60    | 0.448   | 0.09%        | Not Sig.|
| Error        | 17 | 0.11345  | 0.11345 | 0.00667 | 1.14    | 0.257   | 2.59%        |         |
| Total        | 26 | 4.38419  | 4.38419 | 4.38419 | 1.14    | 0.257   | 100.00%      |         |

| Source       | DF | Seq SS   | Adj SS  | Adj MS  | F-Value | P-Value | Contribution | Remarks |
|--------------|----|----------|---------|---------|---------|---------|--------------|---------|
| Model        | 9  | 652406   | 652406  | 72490   | 387.62  | 0.000   | 99.52%       |         |
| Linear       | 3  | 616920   | 616920  | 205640  | 1099.61 | 0.000   | 94.10%       |         |
| a            | 1  | 129642   | 129642  | 129642  | 693.23  | 0.000   | 19.78%       | Significant |
| V            | 1  | 201359   | 201359  | 201359  | 1076.71 | 0.000   | 30.71%       | Significant |
| f            | 1  | 285919   | 285919  | 285919  | 1528.88 | 0.000   | 43.61%       | Significant |
| Square       | 3  | 9863     | 9863    | 3288    | 17.58   | 0.000   | 1.50%        |         |
| a²           | 1  | 6508     | 6508    | 6508    | 34.80   | 0.000   | 0.99%        | Significant |
| V²           | 1  | 2948     | 2948    | 2948    | 15.76   | 0.001   | 0.45%        | Significant |
| f²           | 1  | 407      | 407     | 407     | 2.17    | 0.159   | 0.06%        | Not Sig.|
| 2-Way Interaction | 3   | 25624   | 25624   | 8541    | 45.67   | 0.000   | 3.91%        |         |
| a*V          | 1  | 43       | 43      | 43      | 0.23    | 0.636   | 0.01%        | Not Sig.|
| a*f          | 1  | 16472    | 16472   | 16472   | 88.08   | 0.000   | 2.51%        | Significant |
| V*f          | 1  | 9108     | 9108    | 9108    | 48.70   | 0.000   | 1.39%        | Significant |
| Error        | 17 | 3179     | 3179    | 187     | 0.48    | 0.48    | 0.48%        |         |
| Total        | 26 | 655586   | 655586  | 655586  | 100.00% | 100.00% | 100.00%      |         |

| Source       | DF | Seq SS   | Adj SS  | Adj MS  | F-Value | P-Value | Contribution | Remarks |
|--------------|----|----------|---------|---------|---------|---------|--------------|---------|
| Model        | 9  | 8.85611  | 8.85611 | 0.98401 | 24.67   | 0.000   | 92.89%       |         |
| Linear       | 3  | 5.72722  | 5.72722 | 1.90907 | 47.87   | 0.000   | 60.07%       |         |
| a            | 1  | 0.80222  | 0.80222 | 0.80222 | 20.12   | 0.000   | 8.41%        | Significant |
| V            | 1  | 4.20500  | 4.20500 | 4.20500 | 105.44  | 0.000   | 44.10%       | Significant |
| Trial No | Ra (μm) | PW (Watt) | S (dB) |
|----------|---------|-----------|--------|
|          | Exp.    | RSM       | AE (%) | Exp.    | RSM       | AE (%) | Exp.    | RSM       | AE (%) |
| 1        | 0.29    | 0.30      | 3.40   | 2861.4  | 2873.7   | 0.41   | 73.4    | 73.5      | 0.13   |
| 2        | 0.86    | 0.78      | 9.30   | 2975.4  | 2963.3   | 0.40   | 73.6    | 73.6      | 0.0    |
| 3        | 1.26    | 1.35      | 7.14   | 3032.4  | 3016.5   | 0.52   | 73.7    | 73.7      | 0.0    |
| 4        | 0.22    | 0.24      | 9.09   | 2964.0  | 2947.7   | 0.57   | 73.5    | 73.6      | 0.13   |
| 5        | 0.76    | 0.70      | 7.89   | 3043.8  | 3044.9   | 0.03   | 73.8    | 73.8      | 0.0    |
| 6        | 1.33    | 1.38      | 3.75   | 3123.6  | 3125.6   | 0.06   | 74.0    | 74.0      | 0.0    |
| 7        | 0.25    | 0.25      | 0.0    | 3055.2  | 3046.1   | 0.09   | 74.8    | 74.6      | 0.26   |
| 8        | 0.72    | 0.69      | 4.16   | 3169.2  | 3170.8   | 0.04   | 75.0    | 74.8      | 0.26   |
| 9        | 1.42    | 1.39      | 2.11   | 3271.8  | 3279.1   | 0.21   | 75.2    | 75.2      | 0.0    |
| 10       | 0.28    | 0.30      | 7.14   | 2986.8  | 2972.6   | 0.46   | 73.1    | 72.9      | 0.27   |
| 11       | 0.67    | 0.65      | 2.98   | 3078.0  | 3079.2   | 0.03   | 73.2    | 73.0      | 0.27   |
| 12       | 1.20    | 1.23      | 2.50   | 3157.8  | 3169.5   | 0.38   | 73.3    | 73.2      | 0.13   |
| 13       | 0.30    | 0.31      | 3.33   | 3032.4  | 3028.4   | 0.13   | 73.1    | 72.9      | 0.27   |
| 14       | 0.72    | 0.66      | 8.33   | 3169.2  | 3162.7   | 0.22   | 73.0    | 73.0      | 0.0    |
| 15       | 1.35    | 1.26      | 6.66   | 3283.2  | 3280.5   | 0.09   | 73.2    | 73.3      | 0.13   |
| 16       | 0.29    | 0.27      | 6.89   | 3123.6  | 3128.6   | 0.16   | 73.3    | 73.5      | 0.27   |
| 17       | 0.57    | 0.62      | 8.77   | 3294.6  | 3290.5   | 0.12   | 73.6    | 73.8      | 0.27   |
| 18       | 1.23    | 1.25      | 1.62   | 3431.4  | 3435.8   | 0.11   | 74.3    | 74.3      | 0.0    |
| 19       | 0.39    | 0.36      | 7.69   | 2998.2  | 2985.5   | 0.43   | 73.2    | 73.3      | 0.13   |
| 20       | 0.51    | 0.55      | 7.84   | 3135.0  | 3129.3   | 0.19   | 73.3    | 73.4      | 0.13   |
| 21       | 1.14    | 1.10      | 3.50   | 3249.0  | 3256.6   | 0.21   | 73.5    | 73.6      | 0.13   |
| 22       | 0.31    | 0.32      | 3.22   | 3032.4  | 3043.3   | 0.36   | 73.3    | 73.3      | 0.0    |
| 23       | 0.52    | 0.56      | 7.69   | 3203.4  | 3214.6   | 0.34   | 73.4    | 73.4      | 0.0    |
| 24       | 1.16    | 1.12      | 3.44   | 3374.4  | 3369.5   | 0.14   | 73.7    | 73.6      | 0.13   |
| 25       | 0.39    | 0.36      | 7.69   | 3146.4  | 3145.4   | 0.03   | 74.1    | 74.0      | 0.13   |
| 26       | 0.45    | 0.49      | 8.88   | 3340.2  | 3344.3   | 0.11   | 74.2    | 74.2      | 0.0    |
| 27       | 1.14    | 1.11      | 2.63   | 3545.4  | 3536.7   | 0.25   | 74.5    | 74.5      | 0.0    |

| AAE (%)  | 5.46 | 0.23 | 0.11 |

Table 7

| 2-Way Interaction | 3 | 0.27167 | 0.27167 | 0.09056 | 2.27 | 0.117 | 2.85% |
|-------------------|---|---------|---------|---------|------|-------|------|
| a^V               | 1 | 0.18750 | 0.18750 | 0.18750 | 4.70 | 0.045 | 1.97% |
| a^f               | 1 | 0.00083 | 0.00083 | 0.00083 | 0.02 | 0.887 | 0.01% |
| V^f               | 1 | 0.08333 | 0.08333 | 0.08333 | 2.09 | 0.166 | 0.87% |

Error 17 0.67796 0.67796 0.03988 7.11%

Total 26 9.53407 100.00%

Significant
Not Sig.
RSM
PW (Watt)
Exp. 74.5 74.1 73.7 73.3 73.5 73.3 73.2 73.1 73.0 73.9 73.8 73.7 73.6 73.5 73.4 73.3 73.2 73.1 73.0 73.9 73.8 73.7 73.6 73.5 73.4 73.3 73.2 73.1 73.0
AE (%) 74.5 74.2 73.6 73.4 73.6 73.4 74.3 73.8 73.5 72.9 75.2 74.8 74.6 74.3 73.7 73.6 73.5 73.4 73.3 73.2 73.1 73.0 73.9 73.8 73.7 73.6 73.5 73.4 73.3 73.2 73.1 73.0
Not Sig.
Significant
Not Sig.