



Modelling and Optimization of the Surface Roughness in High Speed Hard Turning with Coated and Uncoated CBN Insert

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Received: 22/06/2016 Revised: 10/10/2016 Accepted: 17/10/2016

ABSTRACT

This study focuses on predictive model for Ra and optimization of cutting conditions in high speed hard turning of X40CrMoV5-1 steel by CBN insert. Cutting speed, feed rate, depth of cut and coating condition have been considered as cutting parameters. The experiments have been performed in CNC lathe according to Taguchi L_{32} orthogonal array. The first order mathematical model for the Ra has been developed with multiple regression analysis. Optimization study with analysis of signal-to-noise (S/N) ratios has indicated that feed rate is the negatively most significant factor for Ra under dry cutting conditions. The best surface roughness has been achieved by the lower feed rate and uncoated CBN insert.

Keywords: *Taguchi method; Regression analysis; Hard turning; CBN; Surface roughness*

1. INTRODUCTION

The machine parts required to be high strength and hardness due to their operating conditions have been made to their final geometry by conventionally operated in soft form. The final geometries and required surface topography of these machine parts were provided with grinding. The machining of hardened steel in their final geometry with conventional machining operations (turning, milling, etc.) was possible especially in the

result of developments in cutting tools area [1,2]. Hard turning is a type of machining performed with hardened materials above 45 HRC in low depth of cut. This method has a lot of advantages such as low machining cost, short machining time, high metal removal rate, high fatigue strength, needless of cutting fluid. Therefore, it is commonly preferred in manufacturing of bearings,

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die/mold components, shafts, gears and various engine parts [3,4].

Nowadays, hardened steels are preferred due to their high wear resistance and strength in many industrial applications. Hot work tool steels having high thermal strength, high toughness and high resistance to thermal fatigue, softening and thermal shock gain a place in hardened steel categories [5]. Especially X40CrMoV5-1 steel exists in class of materials hard to machining due to the mechanical properties mentioned above and aggressive cutting conditions after hardening [6]. Recently, there are performed numerous statistical and experimental researches based on design and analysis of experiment methods for determining the influences of cutting conditions on the surface roughness occurred in hard or finish turning of hardened materials.

In these studies, usually ceramic and rarely CBN cutting tool performance have been assessed with the help of various experiment design techniques in different cutting conditions. Moreover, the effects of cutting conditions on tool wear, surface roughness and cutting forces have been determined by statistical methods. In this regard, it is possible to say that these studies based on especially experimental design great contribute to manufacturing industry in terms of sustainable machining and manufacturing. Kacal and Yıldırım [7] investigated on optimization of finish turning of hardened AISI D6 tool steel with ceramic and CBN cutting tools using grey relational analysis. The feed rate is the most significant factor based on analysis of variance results. Flank and crater wears were the prominent wear types on the ceramic and CBN inserts. Gaitonde et al. [8] investigated on machinability of AISI D2 steel by using CC650, CC650WG and GC6050WH coded ceramic inserts in their different study. They also specified that CC650WG wiper ceramic tools are convenient with regard to surface roughness and tool wear while CC650 conventional ceramic tools are convenient for machining force, power and specific cutting force according to experimental and statistical results [8]. Boy et al. [9] focused on optimizing the cutting conditions to minimize the surface roughness, inner-diameter error and roundness in bearing rings produced by hard turning of AISI 52100 with TiN coated CBN insert. The hard turning experiments were carried out via the L9 orthogonal array. The cutting speed, feed rate and number of the machined part were selected as cutting factors. The ANOVA results showed that the feed rate is the major factor for the surface roughness while the cutting speed is the major factor for the roundness and inner-diameter error. The authors reported that the optimum conditions for the surface roughness were found as cutting speed of 140 m/min, feed rate of 0.04 mm/rev and the machined part of 4th in confidence interval of 95%. Aouici et al. [10] conducted response surface methodology in hard turning of DIN 1.2343 steel with CBN tool in order to obtain mathematical models for the cutting force components and surface roughness. They reported that the depth of cut and workpiece hardness are the most important factor on cutting force components while the feed rate and workpiece hardness have the most significance on surface roughness. Asiltürk and Akkuş [11] used Taguchi method in order to minimize the surface roughness (Ra and Rz) in turning of hardened AISI 4140 with coated carbide cutting tools. It was

indicated that the feed rate has the most significant effect on Ra and Rz according to the ANOVA results. They also reported that the metal machining industries can utilize the optimum cutting parameters were determined by using Taguchi method. Chinchankar and Choudhury [12] reviewed experimental and statistical studies on machining of hardened steel in recent years. It was concluded that minimizing machining force and surface roughness have been required the optimal combination of high cutting speed with lower feed rate and depth of cut. Additionally, optimization researches and predictive models obtainable during turning of hardened steels with using CBN, ceramic and coated carbide tools were mostly carried out. The authors detected that there is a dissimilarity between the researchers in terms of usage of coolant fluids in hard turning.

The factors affecting the surface roughness can be stated as cutting parameters, mechanical properties of workpiece material, non-rigidity of machine tools, cutting tool and tool holder, tool positioning, tool wear and environmental effects. The controlling of surface roughness may be primarily ensured by choosing suitable values of cutting speed, feed rate and depth of cut [13]. The required dimension of precision and surface roughness can be obtained by hard turning which is machining process increasing the productivity. Meanwhile, unsuitable cutting parameters have negative effects on the machinability criteria such as cutting time and cost. By the way, optimization of these parameters is necessary to minimize machining time and cost. By the way, optimization of these parameters is necessary to minimize machining time and cost [14,15]. Recently, various statistical methods such as response surface methodology, Taguchi method and genetic algorithms are used in order to optimize of cutting parameters. The most important advantage of Taguchi method is to finish all experiment process in minimum time by decreasing the cost with less number of experiments [16]. Moreover, the mathematical models for predicting the surface roughness have been performed for increasing the fabrication volume uncompromising the required surface roughness. The models identified the relationships between cutting conditions and machining outputs has been developed by using the techniques such as regression analysis, fuzzy logic and artificial neural networks etc. In this regard, some of modelling studies on surface roughness based on experimental data have been given below.

Gaitonde et al. [17] studied on the performance of three different ceramic inserts as conventional CC650 and wiper inserts of CC650WG and GC6050WH. Also, ANN models were performed to examine the effect of cutting parameters in addition to study the performance of wiper and conventional ceramic insert. The researchers concluded that CC650WG wiper ceramic inserts are useful for better surface roughness and tool wear. Kacal and Gülesin [18], studied influence of cutting speed, federate, austempering temperature and tool type on machinability of austempered ductile iron by means of Taguchi methodology. According to results, feed rate with 69.5% PCR and austempering temperature with 12% PCR were found main parameters on surface roughness. The authors also suggested finish turning by using of ceramic tools and suitable cutting parameters without cylindrical grinding process of austempered ductile iron.

Özel and Karpat [19] investigated the effects of machining parameters on surface roughness and tool wear in hard turning of AISI H13. It was reported that decreasing the feed rate led to improved surface roughness but slightly quicker tool wear development while increasing cutting speed caused to major increase in tool wear development but led to improved surface roughness. Kırık [20] conducted regression analysis and Taguchi method in order to evaluate the machinability of Hadfield steel with coated carbide inserts under milling conditions. It was indicated that the major factor affecting surface roughness is the feed rate with a percentage contribution of 82.38% according to ANOVA results. The researcher suggested CVD-TiCN/Al₂O₃ coated tool for the machining of Hadfield steel. It was also pointed out that quadratic regression models demonstrate a very good relationship to predict the machining outputs. Bouacha et al. [20] investigated the relationships between cutting parameters and tool wear, surface roughness, cutting force and chip volume by using variance analysis in turning of AISI 52100 steel with CBN insert. It was determined that the depth of cut affects the cutting force but does not affect the surface roughness. In addition, response surface methodology, genetic algorithm and Grey-Taguchi methods has been applied in order to optimize the performance characteristics, and so the results were found similar with the optimization approaches. Agrawal et al. [22] developed a new modelling approach in order to predict the machined surface roughness during hard turning of AISI 4340 steel with a CBN cutting tool. It was showed that the feed rate is the most important factor on surface roughness followed by the cutting speed and depth of cut. Three different regression models such as multiple, random forest, quantile were applied to predict the surface roughness on this material. Novel modelling approach, i.e. random forest regression, has been presented and applied to the machining process for the first time.

Earlier literatures above clearly indicate that although a great number of study have been reported in hard turning of hardened steels with ceramics insert, the combination of optimization and modelling studies on coating condition of CBN insert has not been studied during high speed hard turning of X40CrMoV5-1 tool steel. This study aims to obtain predictive modelling and the optimal cutting conditions (cutting speed, feed rate, depth of cut and coating condition) for surface roughness during the hard turning of the workpiece material. Firstly, experimental design and analysis based on Taguchi method has been used to reach this aim. Secondly, multiple regression analysis were applied to predict surface roughness under these cutting conditions. Finally, the analysis of variance in order to determine the significance level of cutting conditions and optimization studies has been performed at confidence level of 95%.

2. MATERIALS AND METHOD

2.1. Cutting Conditions and Equipment

In this study, the workpiece material was used X40CrMoV5-1 tool steel with the following chemical composition: 0.4% C; 5.1% Cr; 0.4% Mn; 1% Si; 1.3% Mo; 0.28%; 1% V and balance Fe. The workpiece material was commonly used in forging, injection and extrusion molds of light metal, hot cutting and deburring

tools, plastic injection mold applications in which wear resistance and high number of cycles required. The experiment samples having dimension of Ø40x200 mm has been hardened. The hardening process of the samples was performed in two steps that are vacuum hardening and then tempering for stress relieving. Consequently, the hardness of experiment samples was reached approximately to 54±1 HRC.

Hard turning experiments were carried out on Johnford TC 35 CNC Fanuc-OT having 20 HP motor. The low-content uncoated (KBN510) and mega coated CBN tools (KBN10 grade) with the code of DNGA 150404S01225 from KYOCERA have been used as cutting tools in machining experiments. Tool holder used was DDJNR 2525M-12 coded external tool holder clamping cutting tools strictly. The combination of tool holder and cutting tool has effective rake angle (γ)= -31°, clearance angle (α)= -6°, inclination angle (λ)= -6° and approaching angle (χ_r)=93°. The surface roughness measurements were done by using a Mahr Perthometer M1 with 0.8 mm cut-off length and 5 mm sampling length. The surface roughness values after hard turning process have been determined by taking arithmetic average of three measurements taken from three positions of 120°. The steps of experimental and statistical studies is shown in Fig. 1.

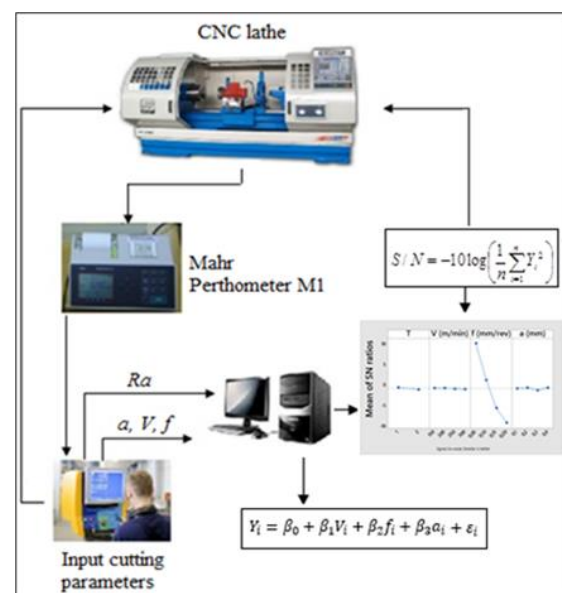


Figure 1. The steps of measurement and analysis.

2.2. Experimental Design and Optimization

The cutting conditions directly affecting the average surface roughness (R_a) have been determined in experimental design according to Taguchi method. In this regard, four factors have been chosen as A-cutting tool, B-cutting speed (m/min), C-feed rate (mm/rev) and D-depth of cut (mm). The levels of these factors have been determined by considering cutting tool company and hard turning in literature. The experiments of hard turning were performed according to Taguchi L₃₂ orthogonal array. Statistical analysis and design of experiment were performed by the help of Minitab software. In this study,

cutting conditions (factors) were optimized for Ra during the hard turning of X40CrMoV5-1 hot work tool steel. Four different levels of cutting speed (V), feed rate (f) and depth of cut (a), and different cutting tools are selected as factors for L_{32} orthogonal array. The factors and their levels are given in Table 1. The smaller-the-better performance characteristic were applied for obtaining the optimal cutting conditions. S/N ratio is defined as:

$$S/N = -10 \log \left(\frac{1}{n} \sum_{i=1}^n Y_i^2 \right) \quad (1)$$

Where Y_i is the value of quality characteristic at the experiment and n is the number of experiments. The S/N ratios for Ra were calculated using Eq. (1). The variance analysis was applied with confidence level of 95% for determining the importance levels of factors on Ra .

Table 1. Factors and levels.

Factors	Levels			
	1	2	3	4
A-Tool, T (CBN)	Uncoated	Coated	-----	-----
B-Cutting speed, V (m/min)	150	200	250	300
C-Feed rate, f (mm/rev)	0.05	0.1	0.15	0.2
D-Depth of cut, a (mm)	0.1	0.2	0.3	0.4

2.3. Modelling of Surface Roughness

The surface integrity determines the surface quality of machined components. The machined surface characteristics are important in determining the functional performance such as corrosion resistance, fatigue strength and tribological properties of machined components. Surface integrity involves the surface texture and surface metallurgy. The surface texture is primarily described by measures of the surface topography like surface roughness. The surface metallurgy is defined by probable surface changes due to plastic deformation, phase transformations, micro cracking, hardness variations, laps, tears, build-up edge formation and residual stress distribution [23,24]. The surface topography or roughness is highly affected by tool geometry, cutting conditions, fixture stiffness, loadings, contact interactions between workpiece-tool position and the workpiece-tool material properties.

The theoretical surface roughness in turning with a single-point cutting tool is highly specified by the well-known relationship between the feed rate and nose radius. Thus, the cutting edge geometry has great effects in these machining processes. However, surface roughness is usually determined by finish machining characterized by high cutting speeds and low feed rates in many industrial practices [25]. The desired surface quality depends on

many factors in the hard turning process. Cutting conditions (cutting speed, feed rate, depth of cut, clamping, coolant), tool variables (tool material, nose radius, rake angle, geometry, vibration) and workpiece variables (material, hardness and other mechanical properties) are the most important factors having major role in generation of surface quality [13,26,27]. Therefore, the selection of appropriate model in machining of hard materials is required for the better surface roughness. In this study, mathematical model has been developed by multiple regression analysis for the Ra in high speed hard turning with two different grade CBN inserts.

Regression analysis is a statistical method that allows us to determine the correlation between independent variables (input) and dependent variables (output). For this purpose, the cutting conditions and surface roughness are considered as inputs and output, respectively. Here, it is possible to acquire a linear, quadratic or exponential equation representing the relationship between the inputs and output. The dependent variable Ra can be designed as a linear combination of the independent variables, namely cutting speed, feed rate and depth of cut, etc. The least square method is utilized in regression analysis to find the coefficients of equation when considering the experimental data. The following equation can be acquired:

$$Y_i = \beta_0 + \beta_1 V_i + \beta_2 f_i + \beta_3 a_i + \beta_4 T_i + \varepsilon_i \quad (2)$$

Where Y_i is the estimated surface roughness and V_i , f_i , a_i and T_i are the cutting speed, feed rate, depth of cut and cutting tool material for the i^{th} experimental observation, respectively. β_0 is the intercept of the plane which is called constant and symbols represented by β_1 - β_4 are regression coefficients. As a result, this equation is a multiple linear regression model with four independent variables. The term R^2 called as coefficient of determination is usually utilized in order to demonstrate the efficiency of developed regression models. When R^2

value approaches to 1, it can be said as better prediction of responses and fitting of the model with the data.

3. RESULTS AND DISCUSSION

3.1. The Analysis of Experimental Results

The total of 32 experiments have been performed by using four different levels of feed rate, cutting speed and depth of cut with two different cutting tool materials in turning of hardened X40CrMoV5-1 tool steel. The experimental results and *S/N* ratios calculated based on the smaller-the-better performance criteria are given in Table 2.

Table 2. Experimental results and *S/N* ratios.

Exp. No	A	B	C	D	<i>Ra</i> (µm)	<i>S/N</i> (dB)
1	1	1	1	1	0.28	11.0568
2	1	1	2	2	0.87	1.2096
3	1	1	3	3	1.73	-4.7609
4	1	1	4	4	2.94	-9.3669
5	1	2	1	1	0.29	10.7520
6	1	2	2	2	0.8	1.9382
7	1	2	3	3	1.89	-5.5292
8	1	2	4	4	2.81	-8.9741
9	1	3	1	2	0.29	10.7520
10	1	3	2	1	0.88	1.1103
11	1	3	3	4	1.86	-5.3903
12	1	3	4	3	2.79	-8.9121
13	1	4	1	2	0.28	11.0568
14	1	4	2	1	0.85	1.4116
15	1	4	3	4	1.75	-4.8608
16	1	4	4	3	2.83	-9.0357
17	2	1	1	4	0.29	10.7520
18	2	1	2	3	0.86	1.3100
19	2	1	3	2	1.99	-5.9771
20	2	1	4	1	2.9	-9.2480
21	2	2	1	4	0.28	11.0568
22	2	2	2	3	0.87	1.2096
23	2	2	3	2	1.92	-5.6660
24	2	2	4	1	2.92	-9.3077
25	2	3	1	3	0.35	9.1186
26	2	3	2	4	0.82	1.7237
27	2	3	3	1	1.96	-5.8451
28	2	3	4	2	2.7	-8.6273
29	2	4	1	3	0.4	7.9588
30	2	4	2	4	0.89	1.0122
31	2	4	3	1	1.95	-5.8007
32	2	4	4	2	2.73	-8.7233

The changes of surface roughness according to cutting parameters (cutting speed, feed rate, depth of cut) for uncoated and coated CBN tools in hard turning of tool steel are shown in Fig. 2. The *Ra* variations with regards to cutting parameters have similar tendency for coated and uncoated CBN inserts. The surface roughness increases with increasing feed rate depending on that surface roughness is mainly a function of the feed rate as shown in many investigations. On the other hand, it can clearly be seen that depth of cut and cutting speed have negligible effect on surface roughness. These result is consistent with numerous studies in the literature [7-15] and confirms that feed rate is the most important factor on surface roughness in hard turning. *Ra* values measured with uncoated and coated CBN tools are very similar to each other and surface roughness in uncoated tools has been measured average 2.98% lower than that of coated tools as differently stated from earlier researches. This result can be explained with two reasons. Firstly, cutting process has become unstable in the existence of ploughing effect, because coated thickness increase cutting edge hone width [23] which has linear relationship with strength of cutting edge and chattering. Therefore, it can be concluded that cutting edge geometry is a significant factor on surface roughness during high speed hard turning. Secondly, this tendency of *Ra* value is based on the distribution of the depth of cut due to mixed-level orthogonal array. In the light of all results, use of uncoated CBN tool is suggested for machine parts where surface roughness is important in high speed hard turning.

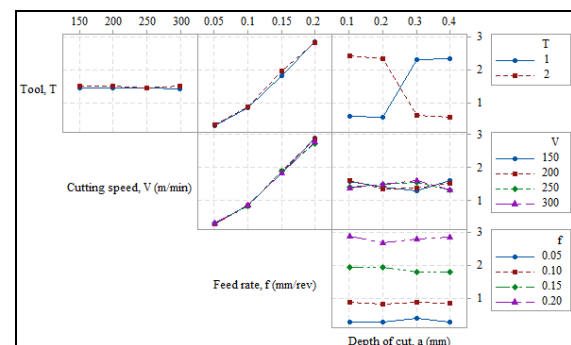


Figure 2. Interaction plot for surface roughness.

The experimental results were evaluated with analysis of variance (ANOVA) which is used for determining the factors significantly affecting the *Ra*. The results of the ANOVA were obtained for the *Ra*. Here, the probability (P) values indicating the importance level of each factor, degree of freedom (DF), the sum of squares (SS), mean square (MS), F values and the percent contribution ratio (PCR) is shown in Table 3. P value should be lower than 0.05 in 95% confidence level in order to determine that any factor acting on the force is effective on it [14]. This analysis was applied for a significance level of $\alpha=0.05$, i.e. for a confidence level of 95%. The PCR of 99.32 for the feed rate is the most important factor in respect of the surface roughness (Table 3). The cutting tool has a small influence of 0.10%. The other factors have not a statistical significance from the point of surface roughness because their P values are higher than 0.05.

Table 3. Analysis of variance for *S/N* ratios of *Ra*.

Factors	DF	SS	MS	F ratio	P value	PCR (%)
Tool	1	1.76	1.763	4.71	0.042	0.10
Cutting speed	3	0.45	0.151	0.4	0.753	0.03
Feed rate	3	1741.48	580.49	1550.61	0.000	99.32
Depth of cut	3	1.77	0.590	1.58	0.225	0.10
Error	21	7.86	0.374			0.45
Total	31	1753.33				100.00

3.2. The Analysis of Signal-to-Noise (S/N) Ratios

Optimal level of factors according to the signal-to-noise (*S/N*) ratio was determined by Taguchi method as seen Ref. [15]. The mean values of *S/N* ratios (η) of the factors for each levels are given in Table 4. Furthermore, the difference of values (Δ) of *S/N* ratios between maximum and minimum can be seen in Table 4. The maximum value of that is showed the most significance factor. The maximum value coincides with the best performance

based on Taguchi method irrespective of the performance criteria. As can be seen from Table 4 and Fig. 3 that the optimal conditions for surface roughness were: A1 (uncoated CBN), B2 (cutting speed of 200 m/min), C1 (feed rate of 0.05 mm/rev) and D2 (depth of cut of 0.2 mm). Average of experimental results performed at optimal levels are evaluated by Eq. (3) to forecast the mean for the treatment condition. Eq. (1) which is the expression of calculated surface roughness (Ra_{cal}) is derived from Eq. (4).

$$\eta_G = \bar{\eta}_G + (\bar{A}_o - \bar{\eta}_G) + (\bar{B}_o - \bar{\eta}_G) + (\bar{C}_o - \bar{\eta}_G) + (\bar{D}_o - \bar{\eta}_G) \tag{3}$$

$$Ra_{cal} = 10^{-\eta_G / 20} \tag{4}$$

Where, η_G is the *S/N* ratio calculated at the optimum levels of factors (dB), $\bar{\eta}_G$ is the mean *S/N* ratios of all factors (dB), \bar{A}_o , \bar{B}_o , \bar{C}_o and \bar{D}_o are the mean *S/N* ratios once tool material, cutting speed, feed rate and depth of cut are at optimum levels, and Ra_{cal} is the calculated *Ra* value. Consequently, η_G and Ra_{cal} for optimal cutting conditions have been determined as 10.89 dB and 0.286 μ m, respectively. Lastly, confirmation experiments have been performed by using the optimum cutting conditions after the determination of these conditions for *Ra* and so consistency of the optimization has been confirmed. The experiments conducted by considering the confidence interval (CI) calculated from Eq. (5) and (6) [15].

freedom of the error, V_e is the error variance, n_{eff} is the effective number of replications, r is the number of replications for the verification test. In Eq. (6), N is the total number of experiments and ν_T is the total main factor of the degree of freedom. Measured surface roughness (Ra_{exp}), calculated surface roughness (Ra_{cal}), and *S/N* ratios (n_{exp} and n_{cal}) for *Ra* are given in Table 5 by comparing between results of experiments and calculated values.

$$CI = \sqrt{F_{\alpha,(1,\nu_e)} V_e \left(\frac{1}{n_{eff}} + \frac{1}{r} \right)} \tag{5}$$

$$n_{eff} = \frac{N}{1 + \nu_T} \tag{6}$$

Where; $F_{\alpha,(1,\nu_e)}$ is the F ratio at the 95 % confidence level, α is the significance level, ν_e is the degree of

Table 4. *S/N* ratio (η) values for *Ra*.

Levels	T	V (m/min)	f (mm/rev)	a (mm)
1	-0.4714	-0.6280	10.3130	-0.7338
2	-0.9408	-0.5650	1.3657	-0.5046
3		-0.7587	-5.4788	-1.0801
4		-0.8726	-9.0244	-0.5059
Δ	0.4694	0.3076	19.3374	0.5755

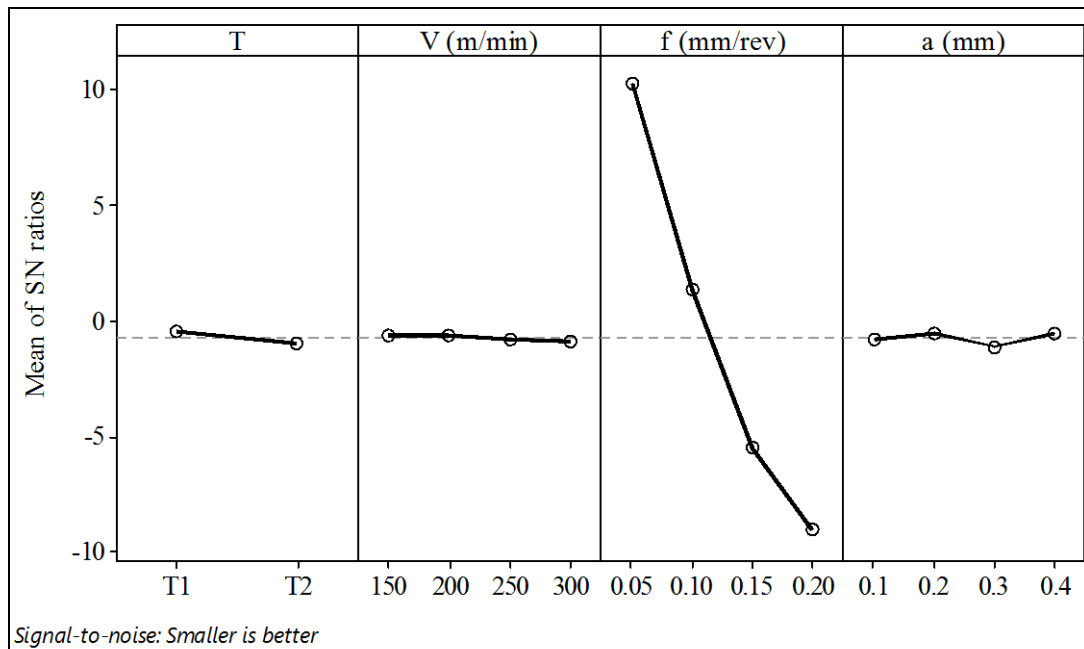


Figure 3. Main effect plot for S/N ratios of Ra.

The variances between the values of verification experiments and the calculated values by Eq. (3) of the S/N ratios. The difference of 0.354 dB can be seen under than confidence interval of 1.032 dB for main cutting force. Thus, the optimal levels of cutting conditions for Ra were confirmed as confident.

Table 5. Comparison between confirmatory experiment results and calculated values.

Experimental results		Calculated values		Differences	
Ra _{exp} (µm)	η _{exp} (dB)	Ra _{cal} (µm)	η _{cal} (dB)	Ra _{exp} - Ra _{cal}	η _{exp} - η _{cal}
0.274	11.244	0.286	10.89	0.012	0.354

3.3. The Analysis of Regression Modelling

A predictive model of surface roughness has been performed with multiple regression analysis which define the relationship between independent variables (T, V, f, a) and dependent variable (Ra) in high speed hard turning. The regression analysis was made by using Minitab statistical software. The predictive Ra model acquired in the result of regression analysis applied to experimental data has been given in Eq. (7).

$$Ra = -0.674 + 0.0431 \times T - 0.000167 \times V + 17.172 \times f - 0.129 \times a \tag{7}$$

The coefficient of determination (R²) showing the relationship between independent variables and Ra has been found as 97.87%. This value demonstrate the efficiency of multiple regression model stated the linear relationship between dependent and independent variables. Factor of feed rate with value of the 17.172 coefficient is most important term in the Ra model. Also, the comparison of experiment and predicted values in reference to number of experiments has been given in Fig. 4. Hence, it is possible to say that predictive mathematical models developed with multiple regression analysis can be used as a good estimator model in hard machining processes.

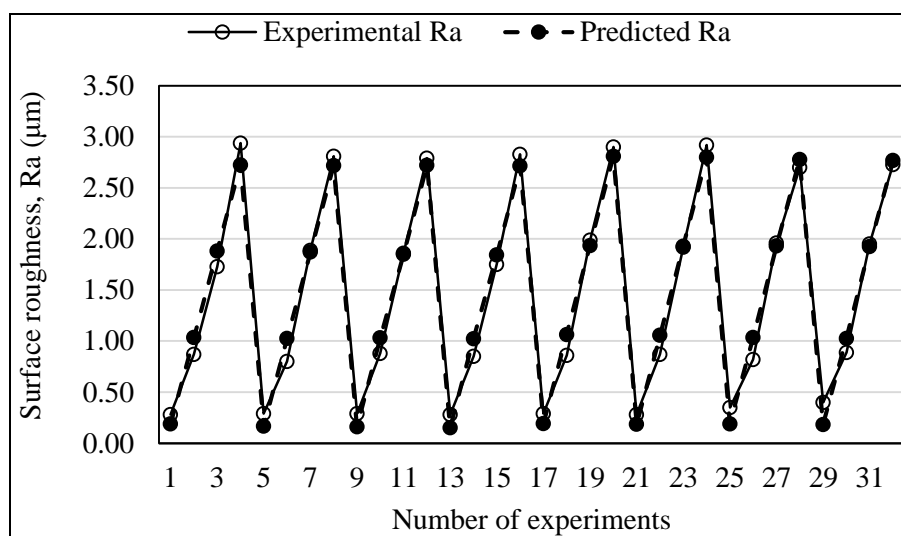


Figure 4. Comparison between experimental and predicted results for R_a .

4. CONCLUSIONS

This study presents optimum level of the factors and mathematical model to predict the R_a during hard turning of X40CrMoV5-1 steel with uncoated and coated CBN inserts. For this purpose, R_a values have been determined by high speed hard turning performed according to Taguchi L_{32} orthogonal array. Besides, a first order mathematical model was developed based on multiple regression analysis for predictive R_a . The statistical analysis and optimization studies were conducted at confidence level of 95%. The most important results from this study and future studies have been summarized below:

1. According to ANOVA result, it was found that the feed rate plays a major role on surface roughness while the cutting speed and depth of cut have a minor role on surface roughness.
2. The optimum level of the factors were determined as A1 (T=uncoated CBN), B2 ($V=200$ m/min), C1 ($f=0.05$ mm/rev) and D2 ($a=2$ mm).
3. Uncoated CBN tools exhibited better performance than coated CBN tools in terms of surface roughness and could be recommended for use in the high speed hard turning of hardened steels. Further, an economical study for energy consuming depending on cutting forces and for determining effects on tool life of cutting conditions may be conducted.
4. A strong linear relationship were found between the factors and surface roughness with coefficient of regression by $R^2=97.87\%$. The regression analysis is a safety tool for predicting the surface roughness due to its simplicity and speed in respect of the performance criterion. Thus, the proposed models can be used effectively to predict the surface roughness in hard turning process.

ACKNOWLEDGMENT

This study is supported by Scientific Research Project Unit of Karabük University (KBÜ-BAP-13/1-YL-014) and the authors express their appreciation for this support.

CONFLICT OF INTEREST

No conflict of interest was declared by the authors.

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