Surface Roughness Modeling of Hard Turning 080A67 Steel

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ABSTRACT

Surface roughness is an important parameter to evaluate the quality of a machining process in mechanical manufacturing. The construction of a surface roughness model of a machining process is the basis for predicting surface roughness corresponding to each certain case. This paper presents the construction of a surface roughness model in 080A67 steel turning. An experimental process was carried out with a total of 15 experiments, designed according to the Box-Behnken matrix. The cutting speed, feed rate, and cutting depth were changed in each experiment, and surface roughness values were measured to build a model that showed the mathematical relationship between surface roughness and the three cutting parameters. A second surface roughness model was also constructed using the Box-Cox transformation. The accuracy of these two models was compared through five coefficients: R^2, $R^2(pred)$, $R^2(adj)$, Percentage Absolute Error (PAE), and Percentage Square Error (PSE). The results showed that all these coefficients of the model using the Box-Cox transformation were better than those of the first one. In detail, the values of R^2, $R^2(pred)$, $R^2(Adj)$, *PAE*, and *PSE* of the first model were 94.55%, 12.79%, 84.74%, 8.79%, and 1.42%, while for the second model were 99.09%, 85.42%, 97.44%, 2.26%, and 0.18%, respectively, showing that the accuracy of the surface roughness model was improved by using the Box-Cox transformation.

Keywords-hard turning; 080A67 steel; surface roughness; Box-Cox transformation

I. INTRODUCTION

Steel of the 080A67 type is manufactured using the UK standard and is equivalent to some steel types from other countries, such as 65G steel in Bulgaria and Poland, 66Mn4, Ck67 in Germany, 65Mn in China, 1066, 1566, and G15660 in the USA [1]. This type of steel has the advantage of high wear resistance and is used to manufacture parts that require wear resistance in the cement industry, thermoelectricity, sliding plates, etc. [2]. Some studies were carried out to evaluate the characteristics of this steel type such as evaluating the degree of deformation when hot rolling [3], and evaluating friction coefficient [4]. Many studies have been carried out to improve the advantages of this type of steel, such as improving wear resistance by the heat treatment method [5-8], improving compressive residual stress in magnetic processing [9], developing technical solutions to produce high-quality products from the casting process [10], investigation of solutions to reduce microcracking on the surface [11], studies on the solutions to increase the hardness of the surface [12-13], etc.

This type of steel is increasingly used to manufacture parts with high-quality requirements, which usually need some finished faces to assemble with other parts. Therefore, ensuring that the surfaces used for assembling have small roughness is often a requirement when machining this type of steel. However, the number of published studies on surface roughness and, in particular, on the machining process of this type of steel is quite small. The surface roughness with flat grinding was studied in [14], the surface roughness and the productivity of the machining when grinding the outer round was investigated in [15], the change of hardness of the surface layer when grinding was studied in [16-19], the cutting force when milling was evaluated in [20], and the surface hardening phenomenon when spark machining was studied in [21]. The turning method, and the hard turning method in particular, are increasingly used to machine products with high accuracy requirements [22-24]. So, this study aims to cover the lack of published studies on the hard turning of 080A67.

While several different criteria can be used to evaluate a turning process, surface roughness is the most frequently used parameter [25-26]. The reason behind this is possibly that surface roughness has a direct influence on wear resistance, fatigue strength, and chemical corrosion resistance of the product surface [27]. In addition, measuring the surface roughness in an experimental process is easier than measuring other cutting parameters such as cutting force, cutting heat, etc.

[28]. A commonly used method to study surface roughness in the turning process is the construction of a model to predict it under certain conditions. However, as the accuracy of the predicted surface roughness results relies on the accuracy of the model, it is necessary to improve it. So, this study also aims to improve the accuracy of the surface roughness model.

II. EXPERIMENTAL PROCESS AND RESULTS ANALYSIS

This study used 080A67 steel in the experimental process. The steel samples had a length and diameter of 300 and 30mm, respectively. The steel workpieces were heat treated through two steps of quenching and tempering. When quenching, the steel workpieces were heated to 830°C and then cooled in an oil medium. When tempering, the steel workpieces were heated to 540°C and then cooled in an oil medium. A Metrology VHT-A0950D instrument was used to test the hardness of the steel workpieces. All the steel workpieces had a similar hardness, at around 52HRC. Table I shows the percentages by mass of the main chemical elements in steel, which were analyzed using a GNR S3 Mililab 300 emission spectrometer.

TABLE I. CHEMICAL ELEMENTS OF 080A67 STEEL

Element	C	Si	Mn	P	S	Cr	Ni
%	0.67	0.24	1.02	0.002	0.002	0.24	0.22

A Doosan Lynx 220L lathe was used for the experiments. A TiN-coated Kyocera TNMG160404GP was used as a cutting tool in the experimental process. This cutting piece is commonly used in the hard-turning process [29]. The cutting piece parameters, provided by the manufacturer, were: 12º front angle, 6.5° back angle, and 0.4mm tip radius. Straight oils were used in the experimental process, mixed with water to a concentration of 4%, and brought into the cutting zone with a flow rate of 8lt/min, and 2.6atm pressure, according to the oil manufacturer.

Surface roughness was measured by an SJ301 gauge. To reduce the influence of random errors on the precision of the experimental process, each experiment was carried out with 3 steel samples, and the surface roughness was measured on each steel sample at least 3 times in succession. So, the surface roughness value in each experiment was the average of at least 9 measurements. The experimental matrix was designed according to the Box-Behnken form, which is the most commonly used type of matrix to construct the relationship between input and output parameters [30]. The values of cutting speed, feed rate, and cutting depth were altered in each experiment. These parameters can be quickly adjusted by the machine operator [31-32]. Three values were chosen for each cutting parameter, corresponding to the encoding levels -1, 0, and 1. Table II shows the parameter values chosen for each level. Table III shows the experiment matrix for the fifteen experiments, built according to the Box-Behnken method.

TABLE II. VALUES OF CUTTING PARAMETERS AT LEVELS

Parameter	Unit	Code symbol	Actual symbol	Value at levels		
				–1	0	1
Cutting speed	**m/min**	x_1	v_c	140	180	220
Feed rate	**mm/tooth**	x_2	f_z	0.25	0.45	0.65
Depth of cut	**mm**	x_3	a_p	0.3	0.4	0.5

The experimental process was carried out according to the sequence of the experiments, as shown in Table III. The surface roughness of each steel sample was measured at least 3 times, and the average value of the measurements was taken. The average surface roughness of the 3 steel samples is denoted as Ra_1, Ra_2, and Ra_3, respectively. Table III summarizes the mean of the surface roughness in each experiment.

TABLE III. EXPERIMENT MATRIX AND RESULTS

Exp.	Code value			Actual value			Response			
	x_1	x_2	x_3	*v* (m/min)	*fd* (mm/rev)	*ap* (mm)	Ra_1 (μm)	Ra_2 (μm)	Ra_3 (μm)	*Ra* (μm)
1	-1	-1	0	140	0.25	0.4	0.728	0.801	0.865	0.798
2	1	-1	0	220	0.25	0.4	1.055	1.026	1.210	1.097
3	-1	1	0	140	0.65	0.4	0.922	0.966	1.010	0.966
4	1	1	0	220	0.65	0.4	1.547	1.602	1.513	1.554
5	-1	0	-1	140	0.45	0.3	1.392	1.422	1.386	1.400
6	1	0	-1	220	0.45	0.3	2.224	2.432	2.331	2.329
7	-1	0	1	140	0.45	0.5	0.886	0.853	0.874	0.871
8	1	0	1	220	0.45	0.5	1.378	1.378	1.378	1.378
9	0	-1	-1	180	0.25	0.3	1.101	1.082	1.108	1.097
10	0	1	-1	180	0.65	0.3	1.623	1.499	1.387	1.503
11	0	-1	1	180	0.25	0.5	0.801	0.703	0.860	0.788
12	0	1	1	180	0.65	0.5	1.171	1.182	1.160	1.171
13	0	0	0	180	0.45	0.4	0.882	0.884	0.883	0.883
14	0	0	0	180	0.45	0.4	0.879	0.901	0.875	0.885
15	0	0	0	180	0.45	0.4	0.886	0.892	0.883	0.887

The Minitab v.16 software was used to analyze the experimental data in Table III. The surface roughness model was constructed according to (1). The commonly used coefficients to evaluate the accuracy of a regression model, such as the surface roughness model, are R^2, $R^2(pred)$ and $R^2(adj)$. The closer these coefficients are to 1, the higher the accuracy of the regression model [30].

$$R_a = 0.8850 + 0.2903 \cdot x_1 + 0.1767 \cdot x_2 - 0.2651 \cdot x_3 + 0.2867 \cdot x_1^2 - 0.0680 \cdot x_2^2 + 0.3227 \cdot x_3^2 - 0.0722 \cdot x_1 \cdot x_2 - 0.1055 \cdot x_1 \cdot x_3 - 0.0057 \cdot x_2 \cdot x_3 \quad (1)$$

Equation (1) had R^2, $R^2(pred)$ and $R^2(adj)$ of 94.55%, 12.79%, and 84.74%, respectively. Thus, although R^2 has a quite large value, the other coefficients have quite small values, especially the coefficient $R^2(pred)$. This means that if (1) is used to predict the surface roughness, the prediction results will be much different from the experiment results [30]. Therefore, the accuracy of the regression model to predict surface roughness should be increased.

III. IMPROVING THE ACCURACY OF THE SURFACE ROUGHNESS MODEL

Two commonly used methods to increase the accuracy of regression models are converting data according to Box-Cox and Johnson [33, 34]. In this study, the Box-Cox transformation was used to improve the precision of the surface roughness model, as it was also used in several studies, such as the 65G steel surface grinding [14], SCM435 steel centerless grinding [33], 3X13 steel milling [34], and EN 353 steel milling [35]. The condition to perform the Box-Cox transformation was that the surface roughness values in the experiment were not normally distributed [30]. Therefore, it is necessary to check the distribution rules of the surface roughness values when testing. Figure 1 shows a distribution chart of surface roughness values.

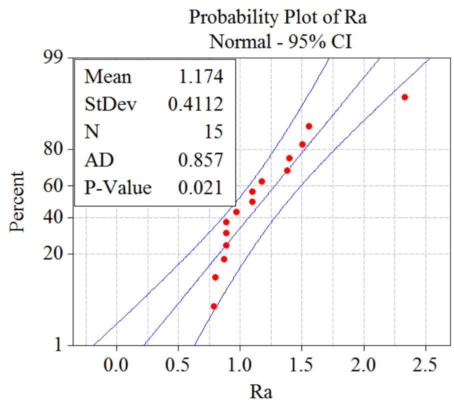

Fig. 1. The distribution rule of surface roughness values.

In Figure 1, the red dots represent the surface roughness values and the blue lines represent the normal distribution. It can be seen that the red dots lie far away from the center line and there are red dots outside the limits of the normal distribution. This proves that the set of surface roughness values was not distributed according to the normal rule. On the other hand, the probability value *P-value* was 0.021, which is lower than the significance level (the significance level is usually chosen as 0.05). This also confirms that the set of surface roughness values was not distributed according to the normal rule [31], meaning that the set of surface roughness data was eligible to perform the Box-Cox transformation. Figure 2 shows the Box-Cox transformation graph. It can be noted that the converted coefficient lambda (λ) equals -1.00, which means that the relationship between the surface roughness before and after the transformation is represented by [30]:

$$R_a(Box.) = (R_a)^{\lambda} = \frac{1}{R_a} \quad (2)$$

where R_a and $R_a(Box.)$ are the values of surface roughness before and after the Box-Cox transformation, respectively. Table IV shows the surface roughness values before and after the Box-Cox transformation.

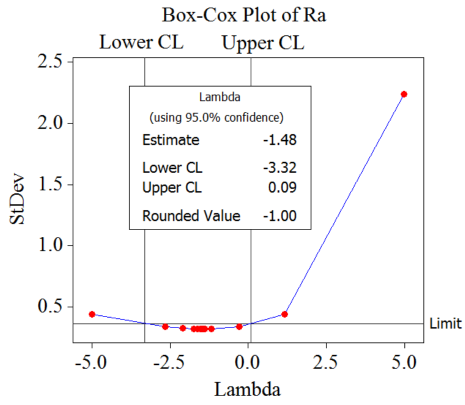

Fig. 2. Box-Cox transformation model of surface roughness

TABLE IV. SURFACE ROUGHNESS VALUES BEFORE AND AFTER BOX-COX TRANSFORMATION

Exp.	R_a(μm)	R_a(Box.) (dimensionless)
1	0.798	1.253
2	1.097	0.912
3	0.966	1.035
4	1.554	0.644
5	1.400	0.714
6	2.329	0.429
7	0.871	1.148
8	1.378	0.726
9	1.097	0.912
10	1.503	0.665
11	0.788	1.269
12	1.171	0.854
13	0.883	1.133
14	0.885	1.130
15	0.887	1.127

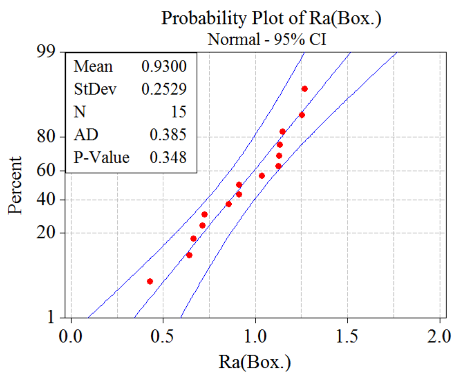

Fig. 3. Distribution rule of surface roughness data after the Box-Cox transformation.

Figure 3 shows the distributions of the surface roughness values after the Box-Cox transformation. It can be noted that all the red dots lie inside the limits of the distribution rule. The probability value *P-value* was 0.348, which was a lot larger than the significance level. This also confirms that these data were distributed according to the normal rule.

The following equation can be constructed from the surface roughness dataset after the Box-Cox transformation:

$$R_a(Box.) = 1.1299 - 0.1800 \cdot x_1 - 0.1434 \cdot x_2 + 0.1595 \cdot x_3 - 0.1698 \cdot x_1^2 + 0.0007 \cdot x_2^2 - 0.2057 \cdot x_3^2 - 0.0125 \cdot x_1 \cdot x_2 - 0.0343 \cdot x_1 \cdot x_3 - 0.0422 \cdot x_2 \cdot x_3 \quad (3)$$

Combining (2) and (3) gives the following surface roughness model:

$$R_a = \frac{1}{R_a(Box.)} \quad (4)$$

where $R_a(Box.)$ is given by (3). Equation (4) has R^2, $R^2(pred)$ and $R^2(adj)$ coefficients of 99.09%, 85.42%, and 97.44%, respectively. These values are very close to 1, proving that (4) can be used to predict surface roughness with high accuracy. The two models were used to predict surface roughness. Note that the model given by (1) is the one without data transformation, and the model given by (4) is the one after the Box-Cox transformation. The value of surface roughness when predicted using (1) is denoted $R_a^{(1)}$, and the surface roughness value predicted using (4) is denoted as $R_a^{(2)}$. Table V shows the results of surface roughness when testing and predicting according to these two models.

TABLE V. SURFACE ROUGHNESS VALUES WHEN TESTING AND PREDICTING ACCORDING TO 2 MODELS

Exp.	R_a (measured)	$R_a^{(1)}$ (1)	$R_a^{(2)}$ (4)
1	0.798	0.565	0.786
2	1.097	1.290	1.068
3	0.966	1.062	0.990
4	1.554	1.499	1.600
5	1.400	1.364	1.350
6	2.329	2.155	2.226
7	0.871	1.045	0.886
8	1.378	1.414	1.429
9	1.097	1.222	1.154
10	1.503	1.587	1.506
11	0.788	0.704	0.787
12	1.171	1.046	1.113
13	0.883	0.885	0.885
14	0.885	0.885	0.885
15	0.887	0.885	0.885
PAE		8.79%	2.26%
PSE		1.42%	0.18%

The *PAE* and *PSE* parameters were used to evaluate the accuracy of the two models, and the smaller their values, the higher the accuracy of the model. *PAE* and *PSE* were calculated according to [31]:

$$PAE = \frac{1}{N}\left|\frac{R_{a(measured)} - R_{a(predicted)}}{R_{a(measured)}}\right| * 100 \quad (5)$$

$$PSE = \frac{1}{N}\left(R_{a(measured)} - R_{a(predicted)}\right)^2 * 100 \quad (6)$$

where N is the number of experiments (N=15).

Equations (5) and (6) were used to calculate *PAE* and *PSE* according to the data in Table V, and Table VI presents the results. The R^2, $R^2(pred)$, and $R^2(Adj)$ of the two models given by (1) and (4) are summarized in this table.

TABLE VI. PARAMETERS OF THE SURFACE ROUGHNESS MODELS

Model	R^2	R^2 (pred)	R^2 (Adj)	PAE	PSE
Without transformation (1)	94.55%	12.79%	84.74%	8.79%	1.42%
Using Box-Cox transformation (4)	99.09%	85.42%	97.44%.	2.26%	0.18%

According to the data in Table VI, the coefficients R^2, $R^2(pred)$, and $R^2(Adj)$ of the model using the Box-Cox transformation (4) were higher than those of the model without data transformation (1). On the other hand, both *PAE* and *PSE* of the model using the Box-Cox transformation were smaller than those of the model without data transformation. This shows that the model with the Box-Cox transformation had a higher accuracy than the other model.

IV. CONCLUSION

The construction of a regression model representing the relationship between input and output data is a method usually used in experimental studies in general and in the field of machine building in particular. These regression models are used to predict the output parameters that correspond to certain inputs, and the prediction accuracy relies a lot on the accuracy of the regression model. Therefore, the accuracy of the regression model must be improved. This study built a regression model for surface roughness in 080A67 steel hard turning, using the Box-Cox transformation. Accordingly, the surface roughness model when using the Box-Cox transformation had higher accuracy than the one without data transformation. The improved model, given by (4), provided very high accuracy in surface roughness prediction, as its *PAE* and *PSE* were only 2.26% and 0.18%. In the future, it is necessary to investigate a comparison of the accuracy of surface roughness prediction between the Box-Cox and Johnson transformations.

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