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Paper:

Investigation of the Surface Roughness in Infeed Centerless Grinding of SCM435 Steel

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This study was carried out to investigate the surface roughness in infeed centerless grinding process. The experiment was performed to determine the influence of several technological parameters on the surface roughness. The grinding wheel of Hai Duong Company, Vietnam, was used to machine the SCM435 steel. The experimental matrix was designed using central composite design (CCD). The machining parameters that were used as the input parameters in this study include the workpiece center height, dressing feed rate, regulating wheel velocity, and infeed rate. From the experimental data, an initial model of the surface roughness was built as a quadratic function. Further, a Box-Cox transformation was used to develop a new model from the initial surface roughness data with better accuracy than that of the initial model. The accuracy of the proposed model was verified by comparing the values of the mean absolute error, mean square error, and determination coefficients. This direct approach can be applied for the investigation of other factors during machining processes and can be used in the optimization of machining processes.

Keywords: surface roughness model, infeed centerless grinding, Box-Cox transformation, SCM435 steel, Hai Duong grinding wheel

1. Introduction

Centerless grinding is a machining method for high productivity and precision machining. This method is often used to machine parts in automotives, aerospace, textile industries, latching pins, and some parts of engines. This method is particularly effective when applied to large-scale production [1–4]. The centerless grinding method can be carried out by centerless grinding, infeed centerless grinding, centerless grinding using a magnetic disk, and ultrasonic centerless grinding in a surface grinder [1, 5–9].

In grinding processes, the roughness of the machining surface has a large influence on the working ability and tool life of the products [10, 11]. Particularly, in the infeed centerless grinding method, the surface roughness is often selected as an important parameter to evaluate the effectiveness of the grinding processes. Several studies have been carried out to determine the effect of machining process parameters on the surface roughness of the parts.

Kopac et al. [12] investigated the influence of some parameters on the surface roughness during the infeed centerless grinding of 9SMn28 steel (JIS Standard: SUM25). The parameters investigated include the workpiece center height, dressing feed rate, regulating wheel velocity, and infeed rate. The experimental matrix 2^k was applied with 8 experiments using a vitrified grinding wheel (22A60L6V63L).

Krajnik et al. [13, 14] carried out the infeed centerless grinding of 9SMn28 steel using a vitrified grinding wheel (22A60L6V63L). The input parameters chosen in this study include the workpiece center height, dressing feed rate, regulating wheel velocity, and infeed rate. Central composite design (CCD) was applied in the design of the experimental matrix. They found that only the feed rate of the dressing had significant influence on the surface roughness. In addition, the effect of the remaining three parameters on the surface roughness was negligible.

Siddiquee et al. [15] conducted an EN52 steel grinding (JIS Standard: SUH 1) to investigate the influence of the dressing feed rate, infeed rate, dwell time, and cycle time on the surface roughness. The experiments were conducted using aluminum oxide grinding wheels with the symbol A80N5V45. They found that the feed rate in the dressing had the greatest influence of about 84.88% on the surface roughness of the steel.

Khan et al. [16] used aluminum oxide grinding wheels with the symbol A80N5V45 to determine the influence of the grinding wheel velocity, infeed rate, and the dressing feed rate on the surface roughness of EN52 steel in the grinding process. The experimental matrix was designed using the Taguchi design with 27 experiments (L_{27}). They found that the influence of the dressing feed rate on the surface roughness much larger than the those of the grinding wheel velocity and the infeed rate.

Khoi et al. [17] and Trung et al. [18] conducted 20X steel (JIS Standard: SCr420) grinding using aluminum oxide grinding wheels with the symbol Cn80.TB1.G.V1. The input parameters used in this study include the workpiece center height angle (other determination method of the workpiece center height), dressing feed rate, infeed rate, and regulating wheel velocity. The matrix-type CCD was applied to design the experimental matrix with 29 experiments. They found that all the four examined parameters had a significant influence on the surface roughness of the part. Particularly, the dressing feed rate had the most influence, followed by the center height angle of the workpiece, the regulating wheel velocity, and the infeed rate.

Based on these studies, it can be concluded that when grinding different materials with different grinding wheels, the degrees of influence of the machining parameters on the surface roughness are different. Therefore, to apply research results to production practice, it is necessary to conduct experimental research based on specific machining conditions. SCM435 steel exhibits high hardness, high compressive strength, high impact resistance, and high thermal strength. This steel is commonly used to manufacture parts with high loads, such as spindles, transmission shafts, ring marbles, and some types of bearings. However, there are no studies on the infeed centerless grinding of this type of steel.

A grinding wheel factory in Vietnam named the Hai Duong grinding wheel factory produces grinding wheels known as the Hai Duong grinding wheel. The grinding wheels produced by this factory not only serve domestic needs, but also export to many countries in Southeast Asia. In Vietnam, these grinding wheels are frequently used to machine SCM435 steel by the infeed centerless grinding method of the shafts and bearings.

In this study, we conducted experimental research on the grinding of SCM435 steel using the Hai Duong grinding wheel to determine the influence of the workpiece center height, dressing feed rate, regulating wheel velocity, and infeed rate on the surface roughness. The surface roughness model was established based on the experimental results. Further, a Box-Cox transformation was applied to propose a new model of surface roughness to improve the model's accuracy in the prediction of surface roughness.

2. Experimental Method

2.1. Workpiece

The workpiece material used in the experiment was SCM435 steel. The equivalent signs of this steel based on some standards are presented in **Table 1**. The workpiece was heat treated for archived 60HRC in hardness. The chemical composition of the SCM435 steel is presented in **Table 2**. The diameter and length of the workpiece were 30 mm and 80 mm, respectively.

Table 1. Equivalent sign of SCM435 steel according to several standards.

SCM435	JIS	Japan
35KHM	GOST	Russia
4137	ASTM/ AISI/UN S/SAE	USA
34CrMo4	DIN	Germany
35CrM0	GB	China
34CrMo4	BS	England
34CrMo4	AFNOR	France
34CrMo4	ISO	ISO

Table 2. Chemical composition of SCM435 steel.

C (%)	Si (%)	Mn (%)	P (%)	S (%)	Cr (%)	Ni (%)	Mo (%)
0.36	0.25	0.75	< 0.03	< 0.03	1.1	< 0.02	0.2

2.2. Grinding Machine, Grinding Wheel, and Measurement System

A centerless machine with sign M1080B (**Fig. 1**) was used to conduct the experiments. The Hai Duong grinding wheel and rubber regulating wheel used in the experiment had the sign Cn100.TB1.G.V1 and RB, respectively. The external diameter, thickness, and internal diameter of the grinding wheel were 500 mm, 150 mm, and 305 mm, respectively. The corresponding dimensions of the regulating wheel were 273 mm, 150 mm, and 203 mm.

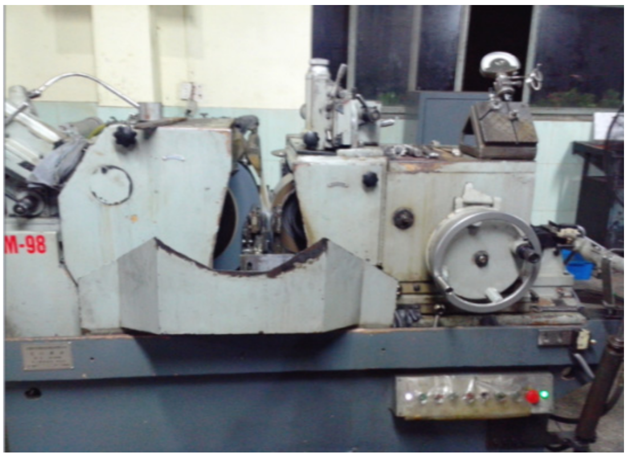

Fig. 1. Grinding machine.

A SJ401 surface tester was used to measure the surface roughness of the machined parts.

Table 3. Values and levels of the input parameters.

Input factors	Sign	Values at the experimental levels				
		-2	*-1*	*0*	*1*	*2*
Workpiece center height (mm)	h	8	10	12	14	16
Feed rate of ressing (mm/min)	f_d	80	160	240	320	400
Regulating wheel velocity (m/min)	v_r	20	25	30	35	40
Infeed rate (µm/s)	v_{fa}	2	6	10	14	18

2.3. Experimental Design

The experimental matrix was designed using the CCD. The input parameters at the experimental levels are presented in **Table 3**. The experimental matrix is presented in **Table 4**.

2.4. Experimental Conditions

Four parameters, namely, the workpiece center height, dressing feed rate, regulating wheel velocity, and infeed rate, were adjusted in each experiment, as shown in **Table 4**. The experimental process using overflow irrigation method was carried out with fixed parameter values as follows: grinding wheel velocity (34 m/s), depth of grinding wheel dressing (0.01 mm), depth of the regulating wheel dressing (0.01 mm), feed rate in the regulating wheel dressing (100 mm/min), the inclined angle of the workrest surface compared to the horizontal was 300, the cool fluid was UNIMET AS 192 oil (Oemeta, Germany) with a concentration of 4%.

3. Results and Discussions

3.1. Influence of the Input Parameters on the Surface Roughness and Prediction Model of the Surface Roughness

With each experimental sample, the surface roughness was measured following the axial direction of the workpiece at least 3 times. The average values of surface roughness were calculated and are listed in **Table 4**. The surfaces of the machined products obtained after machining are shown in **Fig. 2**. ANOVA analysis was applied for surface roughness, and the analyzed results are listed in **Table 5**. **Figs. 3** and **4** show the interactive influence of the parameters on the surface roughness.

The results from **Table 5** and **Figs. 3** and **4** indicate that:

- The dressing feed rate had a significant influence on the surface roughness. With an increase in the dressing feed rate, the surface roughness increased rapidly. The influence of the regulating wheel velocity on the surface roughness of the steel was greater than those of the workpiece center height and infeed rate. However, the degree of influence of these three parameters on the surface roughness was not significant.

- The interaction effect between the four parameters on the surface roughness was negligible. In detail, the interaction influence of each pair on the surface roughness decreased in the following order. First, the interaction between the dressing feed rate and the regulating wheel velocity. Second, the interaction between the dressing feed rate and the infeed rate. Third, the interaction between the workpiece center height and the dressing feed rate. Fourth, the interaction between the workpiece center height and the infeed rate. Next, the interaction between the regulating wheel velocity and the infeed rate. Finally, the interaction between the workpiece center height and the regulating wheel velocity.

From the experimental data, the surface roughness model was built using Eq. (1). This model was built with a determination coefficient R^2 of 0.7801.

$$\begin{aligned}R_a = {} & 0.36400 - 0.04917 \cdot h + 0.25167 \cdot f_d \\ & +0.05750 \cdot v_r - 0.02833 \cdot v_{fa} \\ & +0.09858 \cdot h^2 + 0.12108 \cdot f_d^2 \\ & +0.08608 \cdot v_r^2 + 0.04358 \cdot v_{fa}^2 \\ & -0.06875 \cdot h \cdot f_d + 0.0225 \cdot h \cdot v_r \\ & -0.06125 \cdot h \cdot v_{fa} + 0.09375 \cdot f_d \cdot v_r \\ & -0.08250 \cdot f_d \cdot v_{fa} - 0.03875 \cdot v_r \cdot v_{fa} \quad . \quad . \quad (1)\end{aligned}$$

3.2. Modeling of the Surface Roughness Using Box-Cox Transformation

The surface roughness model presented in Eq. (1) was applied to predict the surface roughness, and compare it with the experimental results. The compared results are shown in **Fig. 5**.

The results in **Fig. 5** indicates that the surface roughness of the prediction is consistent with that of the experimental results. However, to further improve the accuracy of the predicted surface roughness compared to the experimental results, the Box-Cox transformation method was applied. To use the Box-Cox transformation method, the data must have a value greater than zero. The Box-Cox transformation performs the transformations of the model

Table 4. Experimental matrix and results.

No.	Code values				Actual values				Surface roughness			
	h	f_d	v_r	v_{fa}	h (mm)	f_d (mm/min)	v_r (m/min)	v_{fa} (µm/s)	R_{a1} (µm)	R_{a2} (µm)	R_{a3} (µm)	R_a (µm)
1	1	-1	-1	1	14	160	25	14	0.73	0.79	0.79	0.77
2	0	0	-2	0	12	240	20	10	0.66	0.64	0.53	0.61
3	-2	0	0	0	8	240	30	10	0.78	0.82	0.80	0.80
4	-1	1	-1	-1	10	320	25	6	1.05	1.12	1.16	1.11
5	-1	1	-1	1	10	320	25	14	0.88	0.89	0.90	0.89
6	0	0	0	0	12	240	30	10	0.40	0.36	0.35	0.37
7	-1	-1	1	-1	10	160	35	6	0.44	0.48	0.46	0.46
8	1	-1	1	1	14	160	35	14	0.49	0.51	0.53	0.51
9	-1	-1	-1	-1	10	160	25	6	0.45	0.45	0.45	0.45
10	1	1	1	1	14	320	35	14	0.66	0.64	0.62	0.64
11	0	0	0	-2	12	240	30	2	0.55	0.57	0.56	0.56
12	-1	-1	1	1	10	160	35	14	0.40	0.44	0.42	0.42
13	-1	1	1	-1	10	320	35	6	0.99	1.02	0.96	0.99
14	1	1	1	-1	14	320	35	6	1.58	1.65	1.63	1.62
15	0	0	0	0	12	240	30	10	0.35	0.35	0.35	0.35
16	0	0	0	0	12	240	30	10	0.33	0.40	0.38	0.37
17	0	0	0	0	12	240	30	10	0.33	0.33	0.36	0.34
18	0	0	0	2	12	240	30	18	0.33	0.38	0.34	0.35
19	1	-1	-1	-1	14	160	25	6	0.28	0.25	0.25	0.26
20	1	-1	1	-1	14	160	35	6	0.52	0.51	0.47	0.50
21	1	1	-1	1	14	320	25	14	0.64	0.61	0.61	0.62
22	-1	-1	-1	1	10	160	25	14	0.52	0.50	0.48	0.50
23	-1	1	1	1	10	320	35	14	1.52	1.55	1.61	1.56
24	2	0	0	0	16	240	30	10	0.58	0.56	0.51	0.55
25	0	2	0	0	12	400	30	10	1.16	1.20	1.21	1.19
26	0	-2	0	0	12	80	30	10	0.34	0.34	0.34	0.34
27	1	1	-1	-1	14	320	25	6	0.80	0.78	0.76	0.78
28	0	0	2	0	12	240	40	10	0.64	0.66	0.62	0.64
29	0	0	0	0	12	240	30	10	0.41	0.36	0.40	0.39

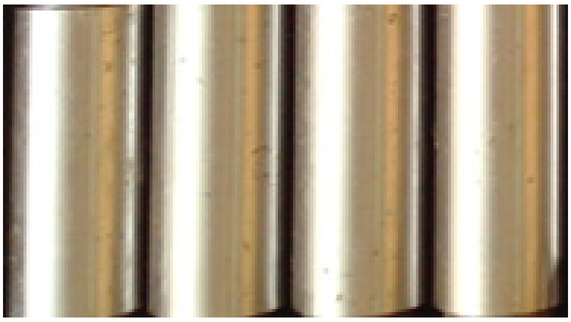

Fig. 2. The experimental products after machining.

using Eq. (2) [19, 20]:

$$\begin{cases} X' = X^{\lambda} & \text{when} \quad \lambda \neq 0 \\ X' = \ln(X) & \text{when} \quad \lambda = 0 \end{cases} \quad . . . . (2)$$

where X' is the value of new data, X is the value of the initial data, and λ is the transformation exponent number. The value of λ was determined using the detection method so that the standard error of the transformed data set is the smallest. The Box-Cox method was used to detect λ in the range of -5 to 5, then rounded to normal values, as shown in **Table 6** [19, 20].

Minitab 16 was used to perform the Box-Cox transformation for the dataset of surface roughness values in **Table 4**. The obtained results of this transformation are presented in **Fig. 6**. From the results in **Fig. 6**, the λ value was determined to be -0.5. Finally, the surface roughness value after performing the Box-Cox transformation was determined using Eq. (3).

$$\begin{aligned} \frac{1}{\sqrt{R_a}} = & \ 1.65891 + 0.04486 \cdot h - 0.21589 \cdot f_d \\ & -0.03352 \cdot v_r + 0.01555 \cdot v_{fa} \\ & -0.11913 \cdot h^2 - 0.09847 \cdot f_d^2 \\ & -0.11114 \cdot v_r^2 - 0.04911 \cdot v_{fa}^2 \\ & +0.03939 \cdot h \cdot f_d - 0.03512 \cdot h \cdot v_r \\ & -0.00825 \cdot h \cdot v_{fa} - 0.02477 \cdot f_d \cdot v_r \\ & +0.08449 \cdot f_d \cdot v_{fa} + 0.06026 \cdot v_r \cdot v_{fa} \quad . . (3) \end{aligned}$$

3.3. Evaluation of the Accuracy of the Surface Roughness Models

Table 7 presents the experimentally obtained surface roughness value, the surface roughness value predicted using model (1), and the roughness values predicted using model (3). To evaluate the accuracy of the two prediction models of the surface roughness, the mean absolute error (MAE) and the mean square error (MSE) of the results

Table 5. ANOVA for the surface roughness (R_a).

Source	Sum of quare	Degree of freedom	F-value	P-value	
Regression	2.70077	14	3.55	0.012	
Linear	1.67670	4	7.71	0.002	Significant
h	0.05802	1	1.07	0.319	Not significant
f_d	1.52007	1	27.96	0.000	
v_r	0.07935	1	1.46	0.247	
v_{fa}	0.01927	1	0.35	0.561	
Square	0.60677	4	2.79	0.068	
h^2	0.11585	1	4.64	0.049	
$f_d{}^2$	0.27859	1	7.00	0.019	
$v_r{}^2$	0.16303	1	3.54	0.081	
$v_{fa}{}^2$	0.04928	1	0.91	0.357	
Interaction	0.41730	6	1.82	0.328	
$h * f_d$	0.07563	1	1.39	0.258	
$h * v_r$	0.00810	1	0.15	0.705	
$h * v_{fa}$	0.06003	1	1.10	0.311	
$f_d * v_r$	0.14063	1	2.59	0.130	
$f_d * v_{fa}$	0.10890	1	2.00	0.179	
$v_r * v_{fa}$	0.02402	1	0.44	0.517	
Residual Error	0.76125	14			
Lack-of-Fit	0.75973	10	199.93	0.000	Significant
Pure Error	0.00152	4			
Total	3.46202	28			
Mean		0.6531	R^2		0.7801
Standard deviation		0.3106	Adjusted R^2		0.5602
PRESS		4.37844	Predicted R^2		0.00

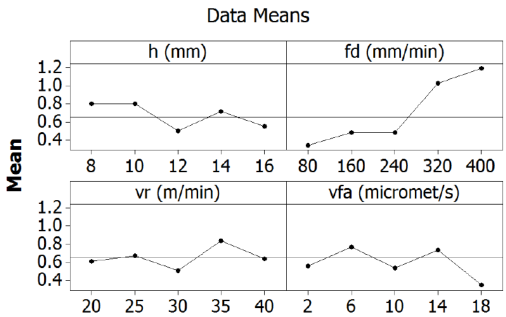

Fig. 3. Major influence of the factors on the surface roughness.

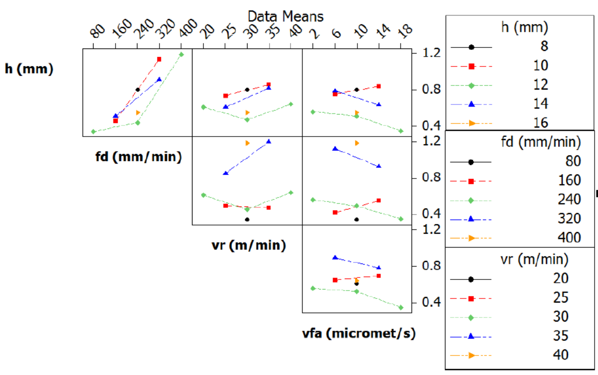

Fig. 4. Interaction influence of the factors on the surface roughness.

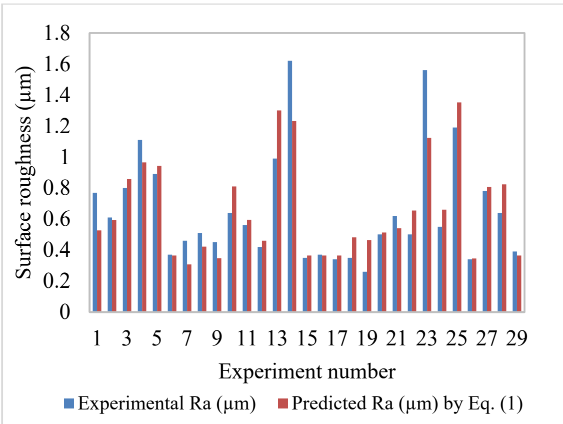

Fig. 5. Comparison of the experimental and predicted surface roughness.

were compared [21, 22]. In addition, the two determined coefficients (R^2) of the two models were compared.

$$\%\text{MAE} = \left(\frac{1}{n}\sum_{i}^{n}\left|\frac{e_i - p_i}{e_i}\right|\right)\cdot 100\% \quad \ldots\ldots \quad (4)$$

$$\%\text{MSE} = \left(\frac{1}{n}\sum_{i}^{n}|e_i - p_i|^2\right)\cdot 100\% \quad \ldots\ldots \quad (5)$$

In Eqs. (4) and (5), e is the experimental value, p is the predicted value, and n is the number of experiments.

Table 8 presents the results of the comparison of some

Table 6. Normal values of the exponential number λ in the Box-Cox transformation [19, 20].

λ values	Transformation equations
$\lambda = 2$	$X' = X^2$
$\lambda = 0.5$	$X' = \sqrt{X}$
$\lambda = 0$	$X' = \ln X$
$\lambda = -0.5$	$X' = 1/\sqrt{X}$
$\lambda = -1$	$X' = 1/X$
$\lambda = -2$	$X' = 1/X^2$

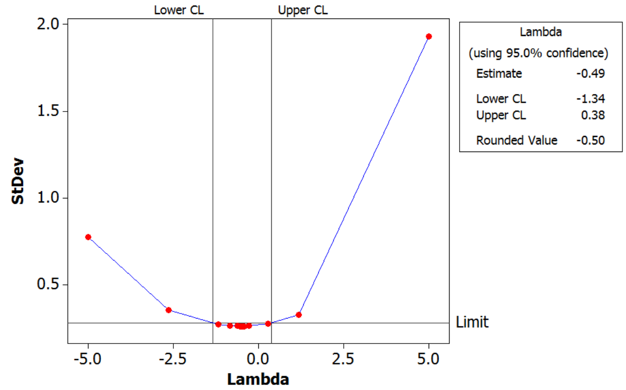

Fig. 6. Box-Cox plot for power transformation.

Table 7. Surface roughness values by the prediction of the models and their corresponding errors.

Order	Experimental surface Roughness Ra (μm)	Predicted surface roughness (μm)		% Absolute error	
		Without transformation	*With transformation*	*Without transformation*	*With transformation*
1	0.77	0.5267	0.5040	31.60	34.54
2	0.61	0.5933	0.6100	2.73	0.00
3	0.8	0.8567	0.8376	7.08	4.70
4	1.11	0.9650	1.0946	13.06	1.39
5	0.89	0.9433	0.9038	5.99	1.55
6	0.37	0.3640	0.3634	1.62	1.79
7	0.46	0.3067	0.4340	33.34	5.66
8	0.51	0.4217	0.4813	17.32	5.62
9	0.45	0.3467	0.3977	22.97	11.63
10	0.64	0.8100	0.6855	26.56	7.11
11	0.56	0.5950	0.4881	6.25	12.84
12	0.42	0.4600	0.4344	9.52	3.44
13	0.99	1.3000	1.6066	31.31	62.28
14	1.62	1.2317	1.2245	23.97	24.41
15	0.35	0.3640	0.3634	4.00	3.82
16	0.37	0.3640	0.3634	1.62	1.79
17	0.34	0.3640	0.3634	7.06	6.87
18	0.35	0.4817	0.4483	37.62	28.08
19	0.26	0.4633	0.3528	78.20	35.71
20	0.5	0.5133	0.4595	2.66	8.10
21	0.62	0.5400	0.6160	12.90	0.64
22	0.5	0.6550	0.5537	31.00	10.74
23	1.56	1.1233	0.7887	27.99	49.44
24	0.55	0.6600	0.6179	20.00	12.35
25	1.19	1.3517	1.4403	13.58	21.03
26	0.34	0.3450	0.3473	1.46	2.15
27	0.78	0.8067	0.6818	3.42	12.58
28	0.64	0.8233	0.7611	28.64	18.92
29	0.39	0.3640	0.3634	6.67	6.83

parameters when comparing the roughness model without using the Box-Cox transformation and the roughness model after using the Box-Cox transformation.

The results in **Table 8** show that when the surface roughness model was used after performing the Box-Cox transformation (model (3)), the MAE of the surface roughness between the predicted results and the experimental results was 13.66%. However, when the model was used without the Box-Cox transformation (model (1)), the MAE of the surface roughness be-

Table 8. Comparison of the surface roughness models.

Models	% Mean absolute error	% Mean square error	R^2
Without Box-Cox transformation	17.59	5.71	0.7801
With Box-Cox transformation	13.66	4.15	0.8322

tween the predicted result and the experimental result was 17.59%. For example, with experiment point No.19, when the surface roughness model was used after using the Box-Cox transformation to predict surface roughness, the MAE reduced by 42.49% (from 78.20% to 35.71%) in comparison to when the model was used without the Box-Cox transformation model.

The MSE values between the predicted value and the experimental value for the surface roughness model without using the Box-Cox transformation and surface roughness model after performing the Box-Cox transformation were 5.71% and 4.15%, respectively.

The determination coefficient (R^2) of the surface roughness model using the Box-Cox transformation was higher than that without the Box-Cox transformation.

The three quantities were compared and the results are given in **Table 8**. We confirmed that in the prediction of surface roughness, the model that was established after using the Box-Cox transformation had greater accuracy than the model established without the Box-Cox transformation.

4. Conclusions

The conclusions for the infeed centerless grinding of the SCM435 steel drawn from this study are as follows.

- The dressing feed rate has a significant effect on the surface roughness. With an increase in the dressing feed rate, the surface roughness increased rapidly. However, the workpiece center height, regulating wheel velocity, and the infeed rate, as well as the interaction between these parameters had no significant effect on the surface roughness.
- Box-Cox transformation was successfully applied to develop a model for predicting surface roughness. Using Box-Cox transformation in the model used to predict the surface roughness ensured a higher accuracy of the surface roughness value in comparison to when the model was used without the Box-Cox transformation. The MAE decreased from 17.59% to 13.66%, while the MSE decreased from 5.71% to 4.15%, and the determination coefficient R^2 increased from 0.7801 to 0.8322.
- This study only considered changes in the workpiece center height, dressing feed rate, regulating wheel velocity, and infeed rate. However, there were several parameters which affect the surface roughness that have not been considered (parameters of the grinding wheel, parameters of the regulating wheel, parameters of dressing, parameters of the cooling lubrication mode, etc.) in this study. Therefore, the proposed surface roughness model in the study cannot be used for all cases in infeed centerless grinding of the SCM435 steel. In contrast, the determination of the optimal value of the machining process was not performed in this study. We intend to explore these research directions in subsequent studies.

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