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RESEARCH

Influence of Cutting Parameters on Surface Roughness in Grinding of 65G Steel

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A B S T R A C T

This article presents an experimental research in the grinding the 65G steel. The workpiece velocity, feed rate, and cutting depth are selected as the input parameters for each experiment. The experiments were performed according to a Box-Behnken matrix consisting of 15 experiments. ANOVA analysis results have determined the influence of the input parameters and the interaction between them on the surface roughness. A surface roughness model in the form of quadratic polynomial was constructed. Two data transformations including Box-Cox and Johnson were applied to construct two new surface roughness models. The comparison of three surface roughness models was conducted. The comparison results show that the model using the Johnson transformation has the highest accuracy, the model using the Box-Cox transformation has the accuracy ranked the second position and the model without data transformation had the lowest accuracy.

1. INTRODUCTION

During the machining of mechanical products, grinding that is one of the most machining methods is commonly used for surface finishing machining. The grinding method can machine a workpiece surface with a high demand for accuracy and small surface roughness. Surface roughness greatly affects on the product performance and shelf life of the workpiece through wear resistance, fatigue strength and accuracy of joints [1]. Many researches have been done to ensure that the workpiece surface roughness has a small value. Among them, a large number of researches investigated the influence of machining parameters on the surface roughness. In reference [2], when grinding the SUJ2 steel by a CBN grinding wheel, the authors founded that the feed rate and the workpiece velocity have a significant influence on the surface roughness, while the cutting depth has a negligible influence on the surface roughness. The results in reference [3] showed that when grinding the AISI 1080 steel using a A60V5V aluminum oxide grinding wheel, the influence of the input parameters on surface roughness gradually decreases in the order of cutting depth, feed rate, and depth of dressing. When grinding silicon carbide (SiC) advanced ceramic material by metallic bonded diamond grinding wheel, if the feed rate and the cutting depth increase, the surface roughness will increase, while if the workpiece velocity increases, the surface roughness will decrease [4]. The reference [5] showed that when grinding Inconel 718 steel by a CBN grinding wheel, the feed rate has a significant influence on the surface roughness, while the cutting depth and number of pass have a negligible influence on the surface roughness. In reference [6], it was concluded that when grinding the stainless steel by an aluminum oxide grinding wheel, the influence of the cutting velocity on surface roughness is greater than that one of the grain size, while the cutting depth has a negligible influence on surface roughness. When grinding 3X13 steel using a CBN grinding wheel, the influence of the workpiece velocity on surface roughness is greater than that one of the feed rate while the cutting depth has a negligible influence on surface roughness [7]. When grinding EN-18 steel by an aluminum oxide grinding wheel, all three parameters including workpiece velocity, feed rate, and cutting depth have a significant influence on surface roughness, when the values of three parameters increase, the surface roughness will increase [8]. Reference [9] showed that when grinding 52100 steel by a GC100K05V5 silicon carbide grinding wheel, the feed rate and cutting depth have a significant influence on surface roughness, while the cutting velocity has a negligible influence on surface roughness.

The researches that are mentioned above show that there are many factors influencing on the surface roughness when grinding. Among them, the cutting parameters are often selected as the parameters to survey their influence on surface roughness. This is also easy to explain that because the operator can adjust these parameters more conveniently than other parameters such as type of grinding wheel, parameters of cooling and lubricating technology, etc. However, some researches that mentioned above also show that the influence of cutting parameters on surface roughness when grinding different materials with different wheels is not the same. Since then, it is necessary to have specific experimental researches for each different materials and grinding wheels.

65G steel is a manganese steel with high wear resistance, this steel is often used to fabricate workpieces such as dowel pins, dowel plates, sliding surfaces, workpieces in cement and thermal power industries, etc., in which the grinding method is often selected as the final machining method for surfaces requiring small roughness. Some researches on grinding this steel (or a steel with equivalent symbol) were published such as research of the change in surface hardness when grinding [10-14] and research of cutting force [15]. However, up to now, there has not been any published research on investigating the influence of cutting parameters on surface roughness when grinding this steel.

In this research, the experimental researches will be conducted to investigate the influence of workpiece velocity, feed rate, and cutting depth on surface roughness when grinding the 65G steel. A surface roughness model that shows the relationship between surface roughness and these three cutting parameters was also constructed. Box-Cox and Johnson transformations were also applied to propose two new surface roughness models. The evaluation of the accuracy of three surface roughness models when using them to predict surface roughness compared to the test results was also carried out.

2. GRINDING EXPERIMENT

2.1 Grinding material

Tests were carried out for 65G steel. Table 1 shows equivalent symbols of this steel by some countries. The test sample sizes of length, breadth and height are 60mm, 40mm, and 10mm, respectively. The steel sample is heat-treated to achieve 62 HRC hardness and its chemical composition is shown in Table 2.

2.2 Grinder and grinding wheel

Tests were performed with an APSG-820/2A surface grinder (Taiwan). The WA46J7V1A aluminum oxide grinding wheel was used in this research. The outside diameter, hole diameter and stone thickness are 180mm, 31.75mm, and 13mm, respectively.

2.3 Design of experiment

Three parameters that were selected as the input parameters when designing the testing matrix include workpiece velocity, feed rate, and cutting depth. The testing matrix is designed in the form of Box-Behnken, in which each input parameter will have three values corresponding to three coding levels -1, 0 and 1. In Fig. 1, the Box-Behnken testing diagram is presented for three input parameters, where each black point represents a test, the number of testing points at the center point (point C) is chosen as 3 [16, 17]. The values of the parameters at all levels are presented in Table 3. The distribution law of the input parameters has been verified that they are distributed according to the standard law. The testing matrix consisting of 15 tests is presented in Table 4.

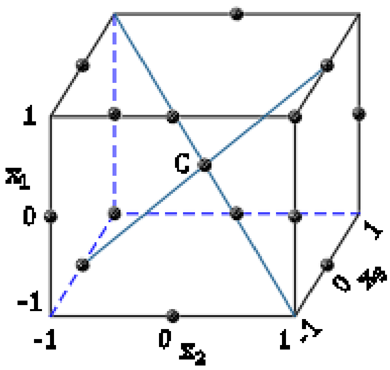

Fig. 1. Box-Behnken testing diagram for three input parameters [16, 17].

Table 1. Equivalent symbols of 65G steel by some countries.

Country	Bulgari	Poland	Germany	United Kingdom	China	United States
Notation	65G	65G	66Mn4; Ck67	080A67	65Mn	1066; 1566; G15660

Table 2. Chemical composition of 65G steel.

Element	C	Si	Mn	P	S	Cr	Ni
%	0.68	0.25	1.05	0.002	0.002	0.25	0.22

Table 3. Values of input parameters at the levels.

Parameter	Symbol	Unit	Code	Value at levels		
				-1	0	1
Workpiece velocity	v	m/min	x_1	6	10	14
Feed rate	f	mm/stroke	x_2	4	6	8
Depth of cut	t	mm	x_3	0.005	0.01	0.015

Table 4. Testing matrix and results.

No.	Code value			Actual value			Ra (μm)
	x_1	x_2	x_3	v (m/min)	f (mm/stroke)	t (mm)	
1	-1	-1	0	6	4	0.01	0.907
2	1	-1	0	14	4	0.01	1.247
3	-1	1	0	6	8	0.01	1.098
4	1	1	0	14	8	0.01	1.766
5	-1	0	-1	6	6	0.005	1.591
6	1	0	-1	14	6	0.005	2.647
7	-1	0	1	6	6	0.015	0.990
8	1	0	1	14	6	0.015	1.566
9	0	-1	-1	10	4	0.005	1.247
10	0	1	-1	10	8	0.005	1.708
11	0	-1	1	10	4	0.015	0.895
12	0	1	1	10	8	0.015	1.331
13	0	0	0	10	6	0.01	1.003
14	0	0	0	10	6	0.01	1.006
15	0	0	0	10	6	0.01	1.008

2.4 Surface roughness measuring device

SJ-301 roughness tester of Mytutoyo brand (Japan) was used to measure surface roughness (Fig. 2). It is necessary to measure at least 3 times at each sample with a standard length of 0.8 (mm), and the measuring direction is perpendicular to the cutting velocity. The surface roughness value at each test is the average value of the successive measurements.

Fig. 2. SJ-301 roughness tester.

2.5 Grinding conditions

The tests were carried out under the conditions of other parameters with constant values as follows: cutting velocity 26 m/s, depth of dressing 0.01mm, dressing feed rate 150 mm/ min, metalworking fluid used is Emulsion 10% with a flow of 4.6 liter/ min.

3. RESULTS AND DISCUSSION

The test results have been shown in Table 4. The results of ANOVA analysis were presented in Table 5. This analysis was performed with significance level α = 0.05, ie for 95% confidence level.

The results of variance analysis in Table 5 shows:

- The P probability value of the workpiece velocity, feed rate and cutting depth are 0.075, 0.497 and 0.040, respectively, it proves that the cutting depth is the parameter that has the greatest influence on surface roughness, followed by the workpiece velocity, and the feed rate has a negligible influence on surface roughness.

- The P probability values of the squared quantities of factors v2, f2 and t2 with values of 0.019, 0.453 and 0.012, respectively also show that the influence of these quantities on surface roughness is similar to that one of the first-order quantities of those factors.

- The interaction between the parameters has a P probability value much greater than the significance level, so it can be confirmed that the interaction between the parameters has a negligible influence on surface roughness.

Table 5. Results of ANOVA analysis for Ra.

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	9	2.89141	2.89141	0.321268	9.64	0.011
Linear	3	1.92062	0.45278	0.150926	4.53	0.069
v (m/min)	11	0.87120	0.16817	0.168166	5.05	0.075
f (mm/stroke)	1	0.3228	0.01788	0.017884	0.54	0.497
t (mm)		0.72662	0.25413	0.254134	7.63	0.040
Square	3	0.88614	0.88614	0.295379	8.87	0.019
v (m/min)*v (m/min)	1	0.34811	0.39250	0.392504	11.78	0.019
f (mm/stroke)*f (mm/stroke)	1	0.04128	0.02201	0.022010	0.66	0.453
t (mm)*t (mm)	1	0.49675	0.49675	0.496749	14.91	0.012
Interaction	3	0.08465	0.08465	0.028217	0.85	0.525
v (m/min)*f (mm/stroke)	1	0.02690	0.02690	0.026896	0.81	0.410
v (m/min)*t (mm)	1	0.05760	0.05760	0.057600	1.73	0.246
f (mm/stroke)*t (mm)	1	0.00016	0.00016	0.000156	0.00	0.948
Residual Error	5	0.16658	0.16658	0.033316		
Lack-of-Fit	3	0.16657	0.16657	0.055523	8766.80	0.000
Pure Error	2	0.00001	0.00001	0.000006		
Total	14	3.05799				

4. SURFACE ROUGHNESS MODEL

4.1 Surface roughness model without using transformation

From the testing results in Table 4, a surface roughness model has been constructed as in Equation (1), in which the input parameters are calculated according to the encoded values.

$$R_a = 1.00587 + 0.330 \cdot x_1 + 0.20083 \cdot x_2 - 0.3015 \cdot x_3 + 0.32599 \cdot x_1^2 - 0.07701 \cdot x_2^2 + 0.36665 \cdot x_3^2 + 0.08192 \cdot x_1 \cdot x_2 - 0.11992 \cdot x_1 \cdot x_3 - 0.00625 \cdot x_2 \cdot x_3 \quad (1)$$

This model has R-Sq = 94.55%, R-Sq (adj) = 84.74%. The significance of these values has been discussed in many documents [17, 18], the closer their value is to 1, the more accurate the model is. The value of R-Sq in this model is 94.55% and we can increase its value by adding into the model more input quantities such as cubic quantities of input parameters (xi3) or the interaction between the three parameters (x1×x2×x3). However, this will make the model more complicated. Parameter R-Sq (adj) with a value of 84.74% shows that the change of surface roughness is only determined by the change of the input parameters at 84.74% level. Therefore, the problem here is that it is necessary to construct the model with higher values of these two parameters (R-Sq and R-Sq (adj)) without adding input parameters to the model. Box-Cox and Johnson data transformations are used to transform non-normally distributed datasets into normally distribution datasets [16]. The Box-Cox transformation was successful in improving the accuracy of the surface roughness model when milling EN 353 steel [19] and AISI 1019 steel [20]. The Johnson transformation was also successfully applied to improve the accuracy of surface roughness model when turning 3X13 steel [21], and when miiling AISI 1045 steel [22]. In this research, these two transformations will also be applied with the desire to improve the accuracy of the surface roughness model when grinding 65G steel.

4.2 Distribution law of surface roughness

The distribution law of surface roughness values in Table 4 is presented in Fig. 3. This figure shows that the surface roughness values deviate quite far from the base line, on the other hand, P-value = 0.021 is smaller than the significance level. Therefore, we can confirm that the surface roughness dataset is not distributed normally. This is the necessary condition to perform data transformation [16].

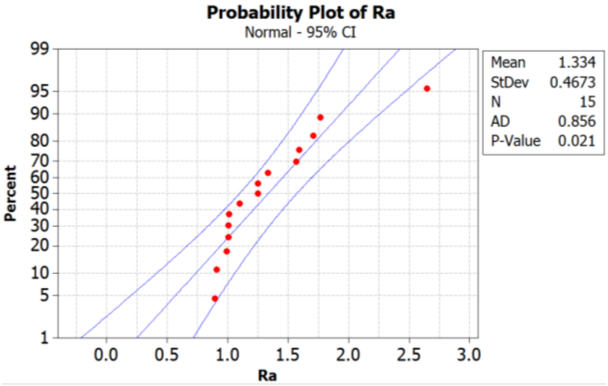

Fig. 3 Distribution law of surface roughness.

4.3 Construction of a surface roughness model using Box-Cox transformation

Box-Cox transformation was used to transform the surface roughness dataset. The Box - Cox transformation performs transformations in the form [16, 23]:

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

In which, X' is the new data value; X is the old data value; λ is the transformed exponent. The value λ is determined by detection so that the standard deviation of the transformed dataset is minimum. Box-Cox method performs detection of λ in the range of -5 to 5, then round to one of common values as shown in Table 6 [16, 23].

Table 6. Common values for the exponent λ in the Box - Cox transformation [16, 23].

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

The dataset on surface roughness after transformation is shown in Table 7. This dataset has the law of distribution as shown in Fig. 4. This figure shows that the dataset is quite close to the base line, at the same time P-value = 0.339 is much larger than the significance level, which confirmed that the data set after Box-Cox transformation was distributed normally. Fig. 5 shows the graph of the Box-Cox transformation, in this case λ = -2 has been determined. Thus, surface roughness model after the Box-Cox transformation is determined as in Equation (3). This model has R-Sq = 99.08% and R-Sq (adj) = 97.42%.

$$R_a = (0.98855 - 0.24323 \cdot x_1 - 0.21148 \cdot x_2 + 0.21481 \cdot x_3 - 0.22236 \cdot x_1^2 - 0.01443 \cdot x_2^2 - 0.27455 \cdot x_3^2 + 0.01591 \cdot x_1 \cdot x_2 - 0.09002 \cdot x_1 \cdot x_3 - 0.09696 \cdot x_2 \cdot x_3)^{-0.5} \quad (3)$$

Table 7. Surface roughness of the test and its value after transformation.

No.	Ra (μm)	After Box-Cox transformation (dimensionless)	After Johnson transformation (dimensionless)
1	0.907	1.21469	-1.51170
2	1.247	0.64274	0.10927
3	1.098	0.82896	-0.24916
4	1.766	0.32064	0.83145
5	1.591	0.39506	0.62748
6	2.647	0.14272	1.83561
7	0.990	1.02099	-0.69112
8	1.566	0.40777	0.59634
9	1.247	0.64274	0.10927
10	1.708	0.34265	0.76648
11	0.895	1.24840	-1.83183
12	1.331	0.56447	0.26010
13	1.003	0.99337	-0.61762
14	1.006	0.98811	-0.60416
15	1.008	0.98419	-0.59424

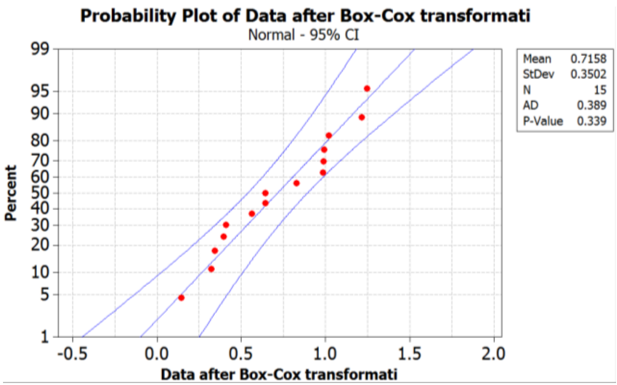

Fig. 4. Distribution law of dataset after Box-Cox transformation.

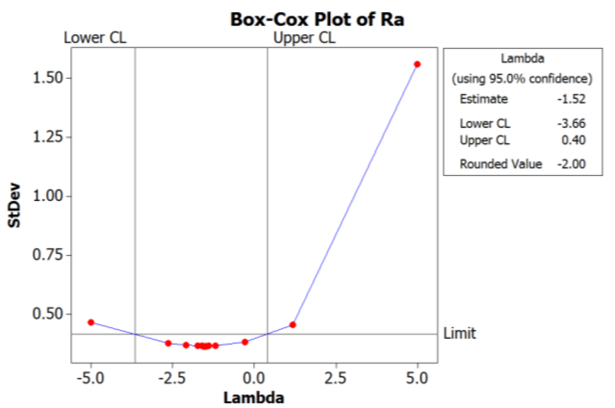

Fig. 5. Box-Cox transformation graph.

4.4 Construction of a surface roughness model using the Johnson transformation

The graph of the data transformation is shown in Fig. 6. The upper left corner of this figure shows the distribution law of surface roughness before data transformation. This issue has been discussed in Section 4.2. The lower left corner shows the distribution law of the dataset after using Johnson transformation. This figure shows that the dataset, after transformation, is quite close to the base line, and the P-value = 0.698 is also much larger than the significance level. Therefore, we have confirmed that the dataset after using Johnson transformation was distributed normally. This statement is also relevant when observing the lower right figure. The lower right figure shows the relationship between the dataset before and after performing the data transformation. The values of dataset after using Johnson transformation were also shown in Table 7. From this result, a new surface roughness model is proposed as shown in Equation (4). This model has R-Sq = 99.37% and R-Sq (adj) = 98.23%.

$$1.12008 + 0.609215 \cdot Ln\,\frac{R_a - 0.876921}{3.19391 - R_a} = -0.60534 + 0.64965 \cdot x_1 + 0.59173 \cdot x_2 - 0.62567 \cdot x_3 + 0.58319 \cdot x_1^2 - 0.18288 \cdot x_2^2 + 0.61423 \cdot x_3^2 + 0.13509 \cdot x_1 \cdot x_2 + 0.01983 \cdot x_1 \cdot x_3 + 0.35868 \cdot x_2 \cdot x_3 \quad (4)$$

or:

$$R_a = \frac{0.876921 + 3.19391 \cdot e^A}{0.876921 + e^A} \quad (5)$$

with

$$A = -2.83220 + 1.06637 \cdot x_1 + 0.97130 \cdot x_2 - 1.02701 \cdot x_3 + 0.95728 \cdot x_1^2 - 0.30019 \cdot x_2^2 + 1.00823 \cdot x_3^2 - 0.22174 \cdot x_1 \cdot x_2 + 0.03255 \cdot x_1 \cdot x_3 + 0.58876 \cdot x_2 \cdot x_3$$

4.5 Comparison of surface roughness models

Surface roughness models in equations (1), (3) and (5) are used to predict surface roughness with values of selected input parameters as shown in Table 4, the results are presented in Table 8. The percentage absolute error (PAE) between the predicted result and the testing result is calculated using the equation (6), the percentage square error (PSE) between the predicted result and the testing result is calculated using equation (7).

$$PAE = \left|\frac{R_{a(measured)} - R_{a(predicted)}}{R_{a(measured)}}\right| \cdot 100 \quad (6)$$

$$PSE = \left(R_{a(measured)} - R_{a(predicted)}\right)^2 \cdot 100 \quad (7)$$

Where $R_{a(measured)}$ and $R_{a(predicteed)}$ are the values of surface roughness when tested (measured) and predicted, respectively. From these values, a percentage mean absolute error (% MAE) and percentage mean square error (% MSE) can be calculated. Values of parameters R-Sq, R-Sq (adj), MAE and MSE were used to compare three surface roughness models, the results are presented in Table 9.

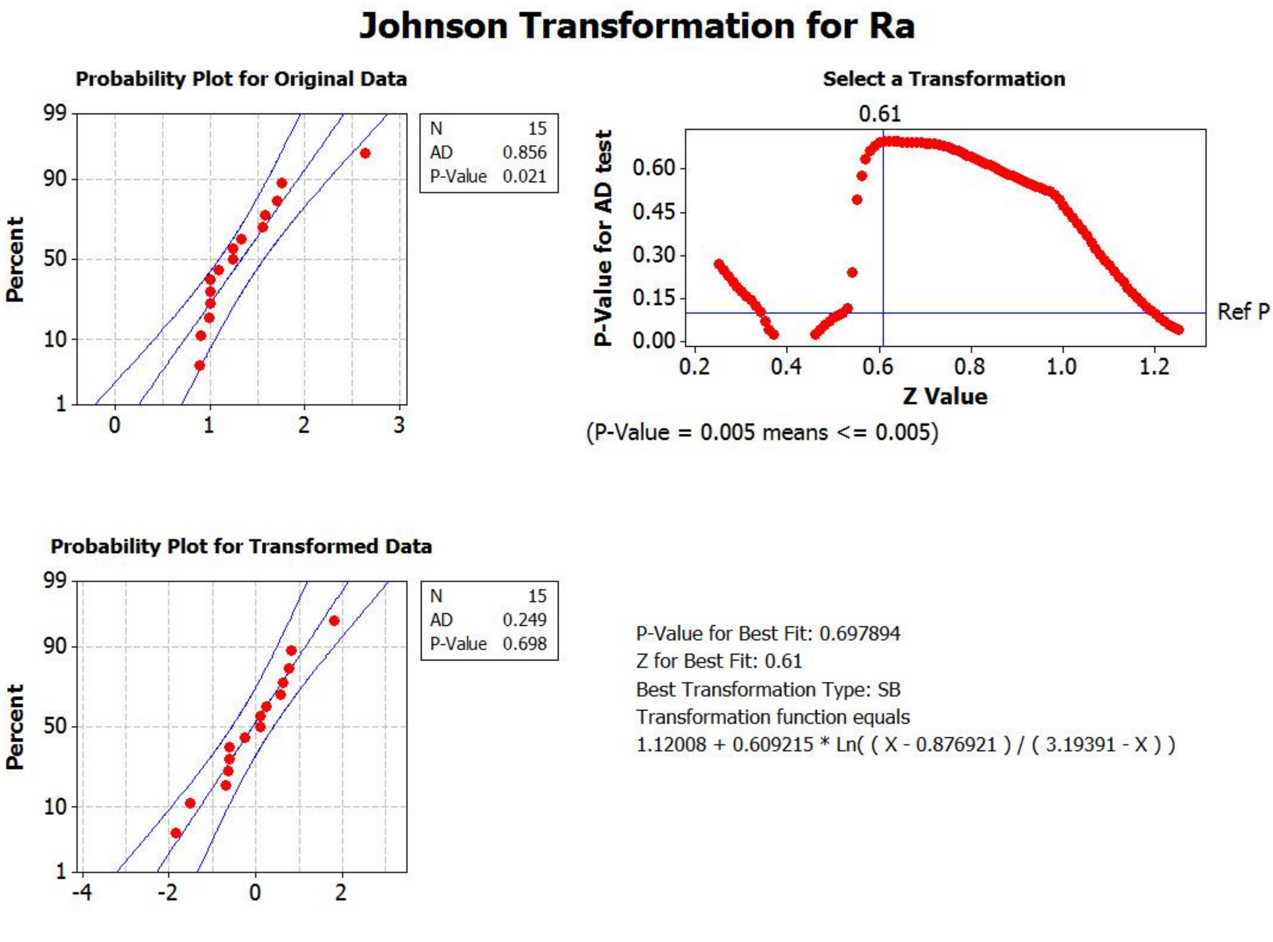

Fig. 6. Johnson transformation graph.

Table 8. Surface roughness when predicted by models and deviation value compared with the testing results.

No.	Surface roughness				MAE			MSE		
	Measured	Without transformation	Box-Cox transformation	Johnson transformation	Without transformation	Box-Cox transformation	Johnson transformation	Without transformation	Box-Cox transformation	Johnson transformation
1	0.907	0.80594	0.90448	0.904072	11.14%	0.28%	0.32%	1.02%	0.00%	0.00%
2	1.247	1.30210	1.19174	1.189389	4.42%	4.43%	4.62%	0.30%	0.31%	0.33%
3	1.098	1.04376	1.14139	1.141462	4.94%	3.95%	3.96%	0.29%	0.19%	0.19%
4	1.766	1.86760	1.78754	1.829274	5.75%	1.22%	3.58%	1.03%	0.05%	0.40%
5	1.591	1.55009	1.52527	1.559124	2.57%	4.13%	2.00%	0.17%	0.43%	0.10%
6	2.647	2.44993	2.84187	2.654613	7.45%	7.36%	0.29%	3.88%	3.80%	0.01%
7	0.99	1.18693	0.98063	0.987547	19.89%	0.95%	0.25%	3.88%	0.01%	0.00%
8	1.566	1.60709	1.63737	1.597612	2.62%	4.56%	2.02%	0.17%	0.51%	0.10%
9	1.247	1.38993	1.29069	1.306529	11.46%	3.50%	4.77%	2.04%	0.19%	0.35%
10	1.708	1.80409	1.64568	1.638003	5.63%	3.65%	4.10%	0.92%	0.39%	0.49%
11	0.895	0.79943	0.90468	0.897567	10.68%	1.08%	0.29%	0.91%	0.01%	0.00%
12	1.331	1.18859	1.28359	1.268898	10.70%	3.56%	4.67%	2.03%	0.22%	0.39%
13	1.003	1.00587	1.00577	1.005726	0.29%	0.28%	0.27%	0.00%	0.00%	0.00%
14	1.006	1.00587	1.00577	1.005726	0.01%	0.02%	0.03%	0.00%	0.00%	0.00%
15	1.008	1.00587	1.00577	1.005726	0.21%	0.22%	0.23%	0.00%	0.00%	0.00%

Table 9. Comparison of models.

Model	R-Sq	R-Sq (Adj)	MAE	MSE
Without transformation	94.55%	84.74%	6.52%	1.11%
Using Box-Cox transformation	99.08%	97.42%	2.61%	0.41%
Using Johnson transformation	99.37%	98.23%	2.09%	0.16%

The data in Table 9 show that:

- With both parameters R-Sq and R-Sq (Adj), the surface roughness model using the Johnson transformation has the highest values, these values of the model using the Box-Cox transformation are in second position, and these values of the model without using transformation have the smallest values.

- The model using the Johnson transformation has an R-Sq (Adj) of 98.23%, this shows that 98.23% of the change in surface roughness can be explained by the change of the input parameters. Similarly, for a model using Box-Cox transformation, the change of the input parameters determines 97.42% of the change in output parameters, and this value is only 84.74% for the model without using transformation.

- For two parameters MAE and MSE, the surface roughness model using the Johnson transformation has the smallest value, these values of the model using the Box-Cox transformation are in the second position. The model without using data transformation has the maximum values.

The comparisons mentioned here show that the surface roughness model using the Johnson transformation has the highest accuracy, the model using the Box-Cox transformation are in the second position, and the model without using data transformation has the lowest accuracy.

5. CONCLUSION

In this research, we have conducted the grinding the 65G steel by an aluminum oxide grinding wheel, analyzed the influence of some parameters on surface roughness, and constructed three surface roughness models with and without using data transformations. Some conclusions are drawn as follows:

- Cutting depth that is a parameter has the greatest influence on surface roughness, followed by the workpiece velocity, while the feed rate has a negligible influence on surface roughness.

- Interaction between parameters has a negligible influence on surface roughness.

- The surface roughness model using the Johnson transformation has the highest accuracy, followed by the model using the Box-Cox transformation. The surface roughness model without using transformation has the lowest accuracy.

- Box-Cox and Johnson transformations have been successfully applied not only to improve the accuracy of surface roughness model when grinding in this research, but also to improve the surface roughness model when milling [19, 20, 22], turning [21], and they also promise to be successfully applied to improve the accuracy of the models in various researches.

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