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Original Article

Analysis and Predict Surface Roughness in the Hard Turning of Hardened SKD11 Steel using Mixed Ceramic Inserts

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Abstract *- SKD11 steel is a high-carbon and high-chromium alloy tool steel used to do cold work or hot work dressing dies, sides of rollers, and screw heading molds. The hardened SKD11 steel has a high hardness of 58-62HRC, good wear resistance, and good toughness. Hard turning is an important process because manufacturers continually seek ways to manufacture their parts with lower cost, higher quality, rapid setups, lower investment, and smaller tooling inventory while eliminating non-value-added activities where Surface roughness is an important parameter determining the accuracy and quality of parts. In this paper, an analysis of the surface roughness of SKD11 steel in hard turning with mixed ceramic inserts is performed based on variables like cutting speed, feed, and depth of cut. The feed rate is the most significant parameter affecting the surface roughness in the machining process. Prediction of surface roughness considering the simultaneous effect of cutting parameters is very difficult. Here, a mathematical model is developed based on the simultaneous effect of depth, cutting speed, and feed rate. Moreover, the developed model is validated using different sets of cutting conditions and found in close agreement with experimental results.*

Keywords *- Ceramic insert, Hard turning, SKD11, Surface roughness.*

1. Introduction

With many outstanding advantages, hard turning is a finishing method applied more and more widely in industries. In the hard-turning process, selecting cutting tool material and grade is the most important thing. Basic knowledge of each cutting tool material and its performance is important when making the correct selection. Recently, with the development of cutting tool materials, some new tool materials have been used in the hard turning process, such as CBN, PCBN, and ceramic [1]. Ceramics are widely used for the continuous hard-turning process because all ceramics used for cutting tools have excellent wear resistance at high cutting speeds. There is a range of ceramic grades available for a variety of applications.

Oxide ceramics are aluminum oxide-based (Al2O3), with added zirconia (ZrO2) for crack inhibition. This generates a chemically very stable material that lacks thermal shock resistance. Ceramic grades can be applied in a broad range of applications and materials, most often in high-speed turning operations but also in grooving and milling operations. The specific properties of each ceramic grade enable high productivity when applied correctly. Knowledge of when and how to use ceramic grades is important for success. Ceramics are very hard and refractory materials, withstanding more than 1500°C without chemical decomposition. These features recommend that they be used for machining metals at high cutting speeds and in dry machining conditions. Ceramic tools are based primarily on alumina (Al2O3), silicon nitride (Si3N4), and sialon (a combination of Si, Al, O, and N). Alumina tools can contain titanium, magnesium, chromium, or zirconium oxides distributed homogeneously into the alumina matrix to improve toughness [2]. Several researchers have been done to study the effect of hard turning on different types of ceramics tools. Junfeng Yuan et al. (2018) in their research provided a novel strategy to enhance the efficiency of machining processes that operate under extreme tribological conditions of the hard turning of AISI D2 hardened tool steels using uncoated ceramic (mixed alumina and TiCN) insert [3].

Sarmad Ali Khan et al. (2018) analyzed the effects of the cutting parameters, workpiece hardness and the tool edge geometry on machinability aspects such as material removed, surface roughness, and tool wear during turning of high chromium AISI D2 cold work tool steel with TiN PVD coated mixed alumina inserts [4]. From their analysis, it was revealed that the Wiper configuration is seen to be overriding the effect of tool edge preparation, as no difference in terms of tool wear and surface roughness is noticed between chamfered wiper insert and the chamfer plus hone wiper insert. Gaitond et al. (2009) analyze the effects of depth of cut and machining time on machinability aspects such as machining force, power, specific cutting force, surface roughness, and tool wear using second-order mathematical models during turning of high chromium AISI D2 cold work tool steel with ceramic inserts [5]. Tugrul et al. (2007) stated the effect of cutting parameters on the cutting force, surface roughness, and flank wear in the hard turning of AISI D2 steel with ceramic wiper inserts [6].

Muhammad Aftab Ahmad et al. (2018) explored the effect of the nose radius and feed rate on the surface roughness in the hard turning of AISI D2 steel using mixed alumina TiN-coated ceramic inserts [7]. Ramon et al. (2008) investigated two models that were adjusted to predict tool wear of the hard turning D2 steel using the ceramic inserts for different values of cutting speed, feed, and time, one of them based on statistical regression, and the other based on a multilayer perceptron neural network [9].

Gaitonde et al. (2009) used the response surface methodology-based mathematical model to analyze the effects of the cutting parameters on machinability during the turning of high chromium AISI D2 cold work tool steel using ceramic wiper inserts [10]. Sarmad Ali Khan et al. (2016) analyzed the tool wear/life, material removed and workpiece surface roughness during the hard turning D2 steel with the multi-radii mixed alumina TiN coated tool inserts [11].

The surface roughness in the hard turning process has been studied by many researchers. The hard turning process is a complex machining process. It is difficult to investigate the effect of all possible factors on the surface roughness in the hard-turning process. Some researchers analyze the effect of workpiece hardness on surface roughness. Others have analyzed the effect of cutting tool geometry on surface roughness. This study analyzed the effect of all three cutting parameters on surface roughness when hardening steel SKD 11 with 60HRC hardness. The predicting surface roughness model was developed based on the influence of all three cutting parameters.

2. Experimental Setup

In order to analyze the effect of the cutting parameters on the surface roughness in the hard turning process, an experimental model was set up with devices as the Figure 1. The workpiece made by cold work tool steel SKD11 with dimensions 60mm diameter and 110 mm length with hardness 60-62 HRC was used in this experiment.

The ceramic AB30 inserts of Taegutec with Al2O3 70% and TiC 30% (CNMG120404S01020) were used as a cutting tool. Surface roughness is measured using the surface roughness tester SJ210 of Mitutoyo (Mitutoyo Corporation, Kawasaki, Kanagawa, Japan), having a trace length of 5 mm and cut-off length of 0.8 mm. The hard turning process was performed in the CNC machine of Mazak at the Thai Nguyen University of Technology – Viet Nam.

Table 1. Experimental results

Run Order	DOC	CTS	FR	MeRa	PreRa
1	0.1	180	0.05	0.195	4.62
2	0.15	100	0.1	0.528	0.09
3	0.2	180	0.05	0.236	0.76
4	0.15	100	0.05	0.235	3.86
5	0.15	180	0.05	0.23	1.26
6	0.1	140	0.15	0.656	6.57
7	0.2	140	0.15	0.622	10.70
8	0.2	140	0.05	0.256	0.05
9	0.15	180	0.1	0.388	8.10
10	0.2	180	0.1	0.635	16.41
11	0.2	140	0.1	0.446	4.98
12	0.15	180	0.15	0.622	6.76
13	0.1	100	0.1	0.714	18.82
14	0.1	140	0.1	0.528	3.72
15	0.2	100	0.15	0.842	6.11
16	0.15	100	0.15	0.736	4.17
17	0.15	140	0.1	0.618	12.43
18	0.2	180	0.15	0.706	1.35
19	0.15	140	0.15	0.843	11.70
20	0.1	180	0.1	0.562	9.57
21	0.1	180	0.15	0.723	3.74
22	0.2	100	0.1	0.538	0.69
23	0.2	100	0.05	0.288	1.33
24	0.1	100	0.05	0.277	0.50
25	0.1	140	0.05	0.198	5.59
26	0.15	140	0.05	0.191	6.44
27	0.1	100	0.15	0.722	5.11
28	0.1	100	0.05	0.29	1.80
29	0.15	140	0.15	0.8055	7.95
30	0.15	100	0.05	0.241	3.26
31	0.2	180	0.1	0.438	3.29
32	0.2	180	0.05	0.251	0.74
33	0.2	140	0.1	0.496	0.02
34	0.15	180	0.1	0.37	9.90
35	0.15	140	0.1	0.58	8.63
36	0.15	140	0.05	0.194	6.14
37	0.15	100	0.1	0.562	3.31
38	0.1	180	0.05	0.188	5.32
39	0.2	180	0.15	0.713	2.05
40	0.1	140	0.1	0.434	5.68
41	0.2	100	0.05	0.262	1.27
42	0.15	100	0.15	0.749	2.87
43	0.2	100	0.15	0.864	8.31
44	0.2	140	0.05	0.265	0.85
45	0.1	100	0.1	0.516	0.98
46	0.2	140	0.15	0.627	10.20
47	0.15	180	0.05	0.252	0.94
48	0.1	180	0.15	0.747	6.14
49	0.1	180	0.1	0.594	12.77
50	0.1	140	0.15	0.668	5.37
51	0.2	100	0.1	0.512	1.91
52	0.1	140	0.05	0.206	4.79

A full factorial design using two replicates with 54 experiments was selected for analyzing the effect of depth of cut, cutting speed, and feed rate on the surface roughness. Experimental design and measured surface roughness are shown in Table 1.

The surface roughness tester SJ210 of Mitutoyo

The turning CNC machine of Mazak

Hardened SKD11 (60-62 HRC) and AB30 insert

Fig. 1 The experimental devices

3. Results and Discussion

3.1. Surface Roughness Analysis

The Minitab 18 software was used to analyze ANOVA to investigate the cutting parameter's effect on the surface roughness. ANOVA analysis results are shown in Table 2. These results indicated that two linear parameters (CTS and FR) and three interaction parameters (DOC*CTS, DOC*FR, and DOC*CTS*FR) significantly influence the surface roughness in the hard-turning SKD11 steel process using ceramic inserts.

These points are distributed very randomly around the 0 line, which proves that the imported Ra data is not affected by any rule control factors other than the input variables. The Versus Order graph represents the relationship between the residuals and the order of data points. These points are distributed randomly around the 0 line, which proves whether the imported Ra is not affected by the time factor.

The residual plots for surface roughness (Figure 2) show that the Normal Probability Plot compares the probability of distribution of the residual values displayed in points with the normal distribution displayed as a straight line. The residual values fit well into the normal line. The Histogram graph shows the frequency of residual values centered around the center of the distribution, which can be considered according to the normal distribution law. Versus Fit graph represents the relationship between the residuals and their respective values of the regression model.

Table 2. Analysis of variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	26	2.33095	0.08965	48.04	0.000
Linear	6	2.15974	0.35996	192.90	0.000
DOC	2	0.00163	0.00082	0.44	0.650
CTS	2	0.03829	0.01915	10.26	0.000
FR	2	2.11982	1.05991	568.00	0.000
2-Way Interact.	12	0.08427	0.00702	3.76	0.002
DOC*CTS	4	0.06537	0.01634	8.76	0.000
DOC*FR	4	0.01629	0.00407	2.18	0.098
CTS*FR	4	0.00262	0.00065	0.35	0.841
3-Way Interact.	8	0.08694	0.01087	5.82	0.000
DOC*CTS *FR	8	0.08694	0.01087	5.82	0.000
Error	27	0.05038	0.00187		
Total	53	2.38134			

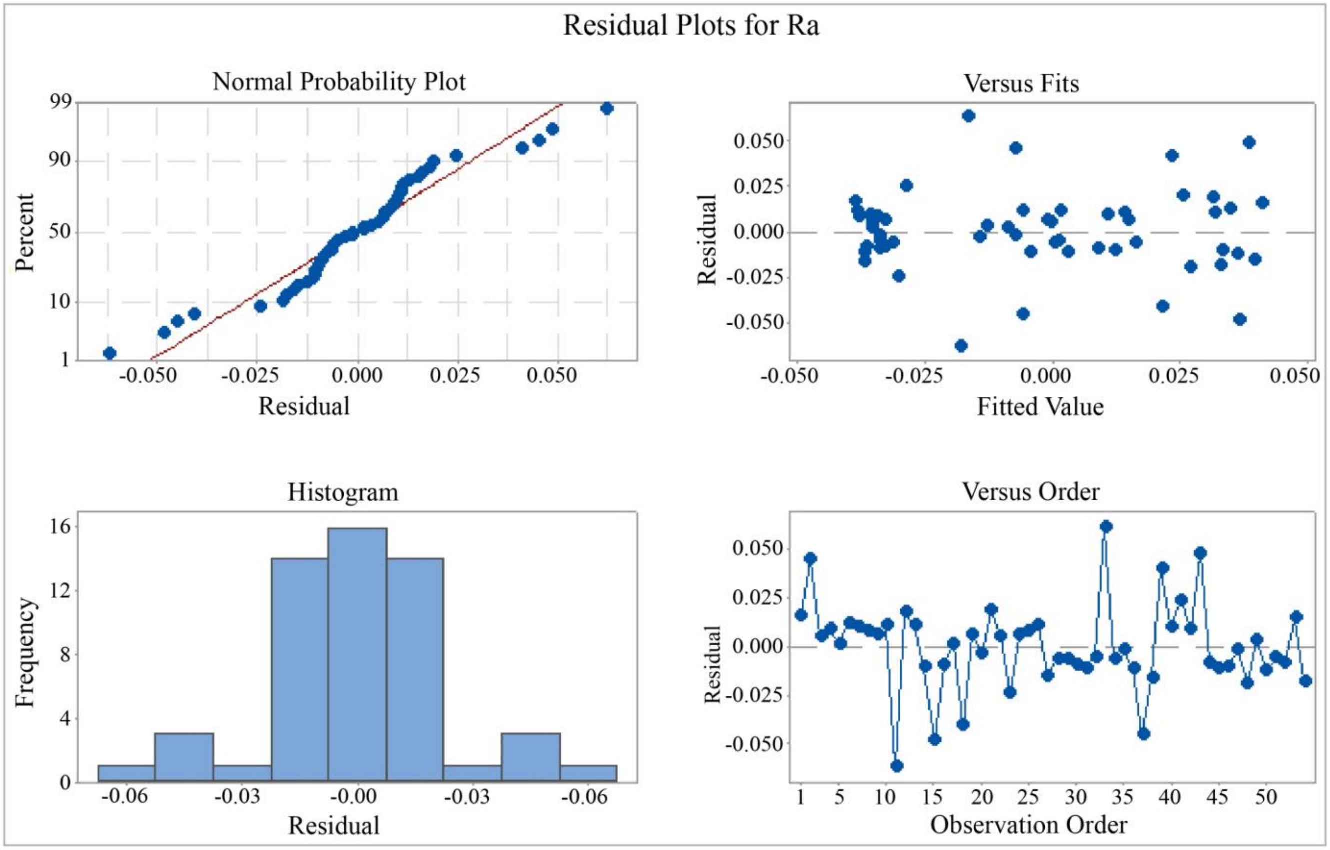

Fig. 2 The residual plots for surface roughness

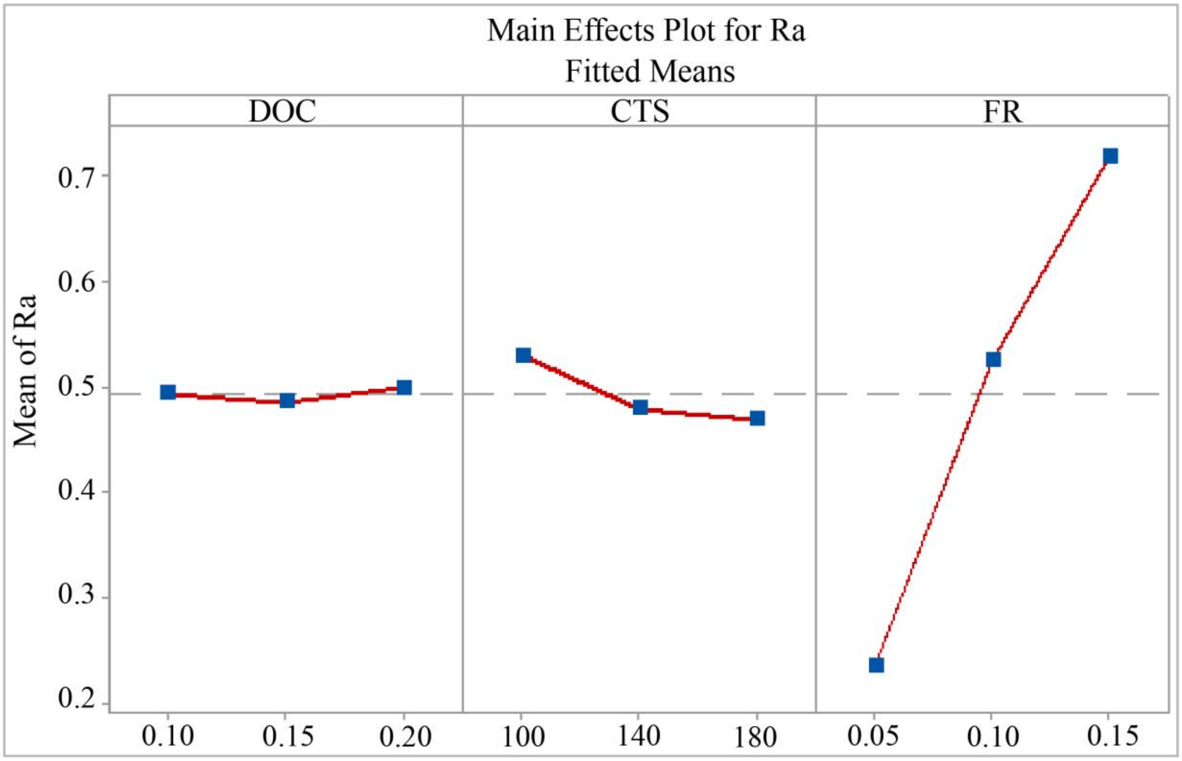

Fig. 3 Effect of cutting parameters on the mean of surface roughness

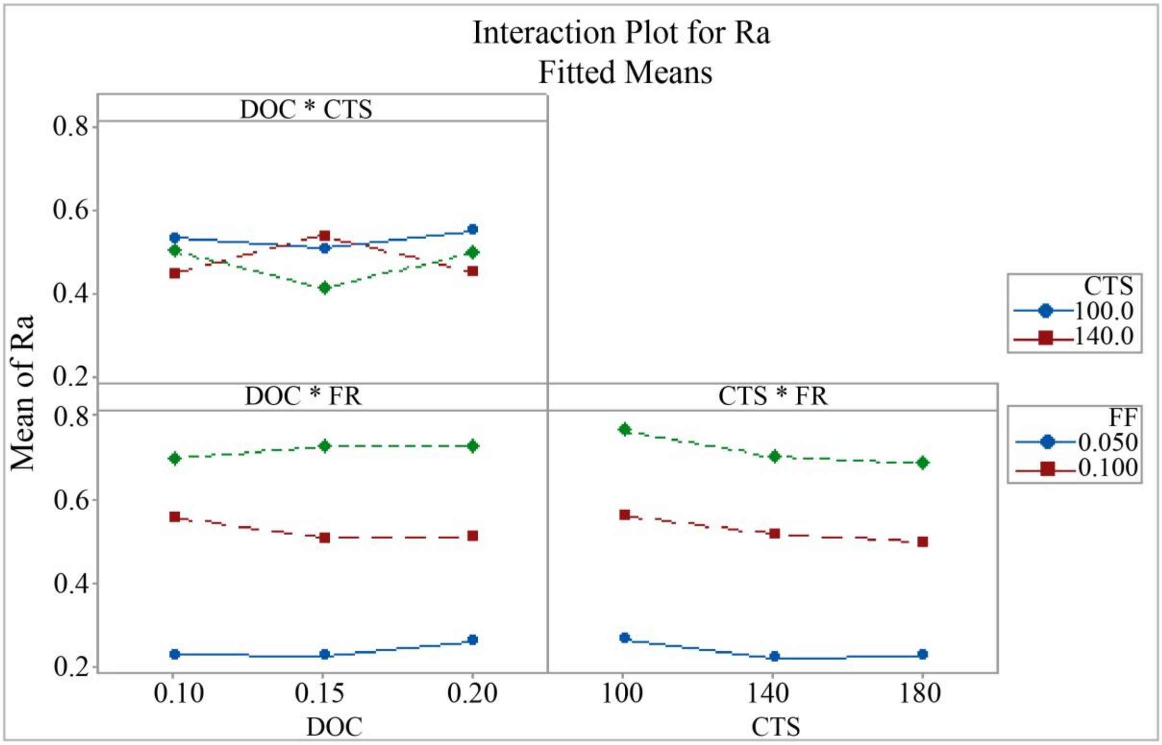

Fig. 4 Interaction plot of surface roughness

Figure 3 shows the mean surface roughness of SKD11 steel having 60 HRC hardness with the different values of cutting parameters (Depth of cut, cutting speed, and feed rate) in the hard turning process. The main effect plots investigated that the feed rate is the most powerful factor affecting the surface roughness, the surface roughness increase with increasing the feed rate. This is in accordance with previous studies that increasing the cutting feed rate increases the main cutting force, causing vibration and increasing the cutting temperature, thereby causing elastic deformation and leading to increased surface roughness. In addition, figure 3 also shows that in the survey area, the cutting depth does not affect the surface roughness. The cutting speed is the parameter that weakens the surface roughness; when the cutting speed increases, the surface roughness decreases.

Figure 4 shows the interactive effect of the cutting parameters on the surface roughness in the hard-turning process using mixed ceramic inserts. The analysis results show that the interaction between cutting depth and cutting speed affects the average surface roughness. With a cutting depth of 0.15 mm, the roughness reaches the smallest value with a cut velocity of 180 m/ph. While surface roughness reaches the smallest value of the cutting velocity, 140 m/ph in both cases, with cutting depth of 0.1 and 0.2 mm.

3.2. Modeling of Surface Roughness

Surface roughness is an important characteristic in determining the quality of the machined part, especially in the hard-turning process. The construction of mathematical models to predict surface roughness was studied and established by many researchers. Singh and Rao [13] investigated the effects of cutting conditions, radius and rake angle on surface roughness. Aouici built a mathematical model describing the effects of cutting parameters and the workpiece hardness on the surface roughness [14]. Some researchers [15, 16] established models showing the relationship between surface roughness and cutting parameters. It was found that variable cutting conditions affect the surface finish of the machined part. Surface roughness can be formulated as a function of independent parameters like cutting speed (v), feed (f), depth of cut (d), and nose radius (r). In this research, the exponential function is used to predict the effects of cutting parameters on the surface roughness in the hard-turning SKD11 60HRC process using the mixed ceramic inserts as equation (1).

$$Ra = a_1 . d^{a_2} . v^{a_3} . f^{a_4} \tag{1}$$

In where: a1, a2, a3, a4 are constant coefficients

d (mm) is the cut of depth (DOC)

v (m/min) is the cutting speed (CTS)

f (mm/rev) is the feed rate (FR)

The mathematical model was determined by using Minitab software and is shown in equation (2):

$$Ra = 0.2388 . d^{-9.79672} . v^{-9.8961} . f^{-7.71143} \tag{2}$$

The difference between the measured surface roughness value in the hard turning process and the predicted surface roughness using equation (2) is analyzed and shown in Figure 5. The results indicated that results the predicted surface roughness (Prt *Ra)* using the exponential function are very close to the measured surface roughness in the experiment (M Ra).

In order to determine the appropriateness of the predictive model with the experimental data, the standard error (SE) of the surface roughness prediction was calculated using equation (3) which is 0.07. The lower the value of S, the better the model describes the response.

$$SE = \sqrt{\frac{\sum(PrRa-MeRa)^2}{n-2}} \qquad (3)$$

In where: SE is the standard error

PrRa is the predicted surface roughness

MeRa is the measured surface roughness

n is the experiment number

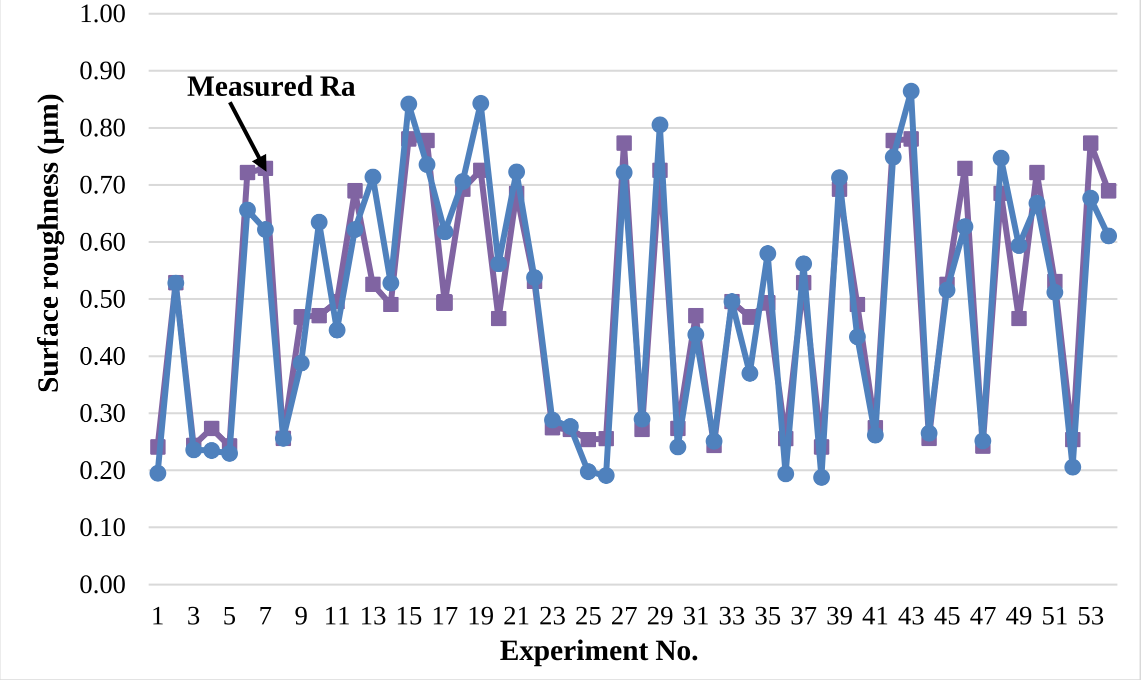

Fig. 5 Comparison of the measured surface roughness and predicted values

4. Conclusion

The effects of cutting parameters on the surface roughness in the hard-turning process of hardened SKD11 (60HRC) using mixed ceramic inserts have been analyzed. The predicted surface roughness model has also been built. The feed rate is the most powerful factor affecting the surface roughness; the surface roughness increase with increasing the feed rate. While the value of surface roughness decreases with increasing the cutting speed from 100 m/min to 180 m/min. A mathematical model shows the functional relationship of cutting depth, cutting speed, feed rate, and surface roughness. Surface roughness values are predicted by the model and compared with the experimental work, and the following conclusions are drawn. The surface roughness prediction was very close to the experimental surface roughness values.

Acknowledgments

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