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Optimization of tool geometry parameters for turning operations based on the response surface methodology

Süleyman Neşeli [a], Süleyman Yaldız [a,*], Erol Türkeş [b]

[a] Department of Mechanical Technologies, Technical Science College, Selcuk University, 42003 Konya, Turkey
[b] Department of Mechanical Engineering, Dumlupinar University, 43100 Kütahya, Turkey

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ABSTRACT

This investigation focuses on the influence of tool geometry on the surface finish obtained in turning of AISI 1040 steel. In order to find out the effect of tool geometry parameters on the surface roughness during turning, response surface methodology (RSM) was used and a prediction model was developed related to average surface roughness (Ra) using experimental data. The results indicated that the tool nose radius was the dominant factor on the surface roughness. In addition, a good agreement between the predicted and measured surface roughness was observed. Therefore, the developed model can be effectively used to predict the surface roughness on the machining of AISI 1040 steel with in 95% confidence intervals ranges of parameters studied.

1. Introduction

The surface quality of products are generally determined in terms of the measured surface roughness [1]. In order to improve the product quality and efficiency in machining, there has been recently and intensive computation focusing on surface roughness at international level. This computation can be observed in turning processes especially in plane and automotive industry by increasing the alternative solutions for obtaining more proper surface roughness. A good-quality turning surface can lead to improvement in strength properties such as fatigue strength, corrosion resistance and thermal resistance. In addition, the final surface roughness also affects several functional attributes of parts like friction, wearing, light reflection, heat transmission, coating and ability of distributing and holding a lubricant [2,3]. Right selection of tool geometry and cutting parameters that affect surface roughness are important factors especially in providing tolerance [4]. The desired finish surface is usually specified and the appropriate processes are selected to reach the required quality. Previously published studies show the tendency to seek effect of cutting conditions (like cutting speed, feed rate and depth of cut) on surface roughness (Table 1). This study seeks to find out the effect of cutting geometry parameters such as tool nose radius, rake angle and approach angle on surface roughness value.

The analysis of the data during manufacturing by using suitable statistical designs is of high importance for precise evaluation to be obtained from the process. Design and methods such as factorial design, response surface methodology (RSM) and Taguchi methods are now widely in use in place of one-factor-at-a-time experimental approach which is time consuming and exorbitant in cost [13]. Lalwani et al. [9] studied the effect of cutting parameters in turning on cutting forces and surface roughness. To this end, a number of experiments based on RSM have been carried out and linear and quadratic models have been formed to explain the relation between the parameters. Dickinson [15], Grieve et al. [16], and Fischer and Elrod [17] developed a turning model in which tool nose radius and feed rate are taken into account but cutting speed is ignored. Thomas et al. [18] used built up edge formation occurring during dry turning mild carbon steel

* Corresponding author. Tel.: +90 332 2232347; fax: +90 332 2410185.
E-mail address: syaldiz@selcuk.edu.tr (S. Yaldız).

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Table 1
Factors affecting surface roughness and major investigators.

Investigators	Major factors	Materials studied	Using methodology
Bouacha et al. [5]	Cutting speed, feed rate, depth of cut	AISI52100 hardened steel	Response surface
Kini and Chincholkar [6]	Cutting speed, feed rate, depth of cut, tool nose radius	Reinforced polymer	Response surface
Cakir et al. [7]	Cutting speed, feed rate, depth of cut	AISI P20 cold work tool steel	Regression model
Horng et al. [8]	Cutting speed, feed rate, depth of cut, tool nose radius	Hadfield steel	Response surface
Lalwani et al. [9]	Cutting speed, feed rate, depth of cut	MDN250 steel	Response surface
Sahin and Motorcu [10]	Cutting speed, feed rate, depth of cut	AISI1050 hardened steel	Response surface
Davidson et al. [11]	Cutting speed, feed rate, coolant	Flow-formed AA6061 tube	Response surface
Öktem et al. [12]	Cutting Speed, feed rate, axial deep of cut, radial deep of cut, machining tolerance	Aluminum (7075-T6)	Response surface
Noordin et al. [13]	Cutting speed, feed rate, side cutting edge angle	AISI 1045 steel	Response surface
Yang and Tarng [14]	Cutting speed, feed rate, depth of cut	S45C steel	Taguchi method

and a full factorial design, taking into account the three-level interactions between the independent variables has been conducted. Yang and Tarng [14] studied on optimal cutting parameters using Taguchi method in turning. Another study [11,10] developed the surface roughness model based on the RSM. Singh and Rao [19] studied the effects of cutting conditions and tool geometry on the surface roughness in the finish hard turning. Choudhury and El-Baradie [20] used RSM and 2^3 factorial designs to estimate the surface roughness during the turning process of high strength steel. Thiele and Melkote [21] used four-factor and two-level fractional factorial design to find out the effect of cutting edge geometry, workpiece hardness, feed rate and cutting speed on surface roughness and resultant forces in the finish hard turning of AISI H13 steel. Nian et al. [22] investigated the optimization of CNC turning operations by Taguchi method with multiple performance characteristics. On the other hand, Lin et al. [23] developed an abductive network model to estimate the surface roughness and cutting forces. Wang et al. [24] investigated the effect of tool nose vibration on surface roughness during turning theoretically and experimentally.

In this paper, the application of RSM on the turning of AISI 1040 steel with Al_2O_3/TiC tool was carried out to develop the mathematical model of the surface roughness (Ra) so as to investigate the influences of cutting tool geometry parameters. For finding optimum value of geometry parameters, the quadratic model of response surface methodology was utilized. In the end of this paper the authors examined a new approach for finish surface prediction in turning operations.

This research will be beneficial for future applications. Especially, as introduced in a real-world application, such as a manufacturing plant. Additionally, studies with wider varieties of materials, process variations, and cutting tools would demonstrate usefulness in more applications. Bringing more realistic and applicable examples of response surface methodology to light should be a goal of all researchers in this area. Finally, it is also advantageous to perform studies similar to this in academia as class learning exercises. By practicing response surface methodology projects, one can gain experience and knowledge in industrial DOE and statistics, as well as the in-depth study of manufacturing processes. Furthermore, just as is found in a production environment, this provides an efficient project in an academic environment as well.

2. Apparatus and method

2.1. Material

The sample material was AISI 1040 steel in the form of round bars with 40 mm diameter and 250 mm cutting length. The chemical composition of AISI 1040 in mass% is as follows: 0.365C, 0.247Si, 0.799Mn, 0.0166P, 0.0422S, 0.0528Cr, 0.0267Mo, 0.106Ni. This steel is especially recommended for the manufacture of transmission shaft, gear and railway. It is also suitable for a wide variety of automotive-type applications [25].

2.2. Cutting inserts and holder

In this experimental study, Al_2O_3 coated tools were used as they are generally preferred material in such experiments. The cutting tools used here are proper for the machining of low carbon steel with ISO P25 quality, which is equal to LC215 K code. The inserts were manufactured by Böhler Inc., with the ISO designation of CNMG 120404-BF, CNMG 120408-BF, CNMG 120412-BF (80° Rhombic inserts). The inserts were rigidly mounted on three different right hand style tool holders designated by ISO as PCLNR/L 2020 K12 AA9, PCLNR/L 2020 K12 AA6, and PCLNR/L 2020 K12 AA3 thus giving back rake angle of −9°, −6° and −3°, respectively. In all instances, the side rake angle is −6°.

2.3. Cutting condition and surface roughness measurements

The turning experiments were carried out in dry cutting conditions using Harrison M300 lathe, which have a maximum spindle speed of 2500 rpm and a maximum spindle power of 2.2 kW. Ranges of cutting parameters were selected as given in the tool manufacturer's catalogue [26]. In this study, three factors were studied and their low–middle–high levels are given in Table 2. However in all experiments depth of cut (1.5 mm), speed (1200 rpm), cutting speed (150 m/min), feed rate (0.15 mm/rev) were taken as fixed values.

Table 2
Independent variables and levels for model body.

Symbol	Factor	Unit	Level 1	Level 2	Level 3
r	Nose radius	mm	0.4	0.8	1.2
κ	Approach angle	Degree (°)	60	75	90
γ	Rake angle	Degree (°)	−9	−6	−3

Each tool was used for once and turned surface length was in 20 mm between centers. After the experiments, Mahr Perthometer M1 was used for measuring the surface roughness and the mean roughness values obtained from three different points of machined surface were calculated. A cut-off value of 0.8 or 2.5 was selected, depending on the magnitude of the roughness.

2.4. Response surface methodology (RSM)

RSM is a statistical technique based on simple multiple regressions. With this technique, the effect of two or more factors on quality criteria can be investigated and optimum values are obtained [27]. In RSM design, there should be at least three levels for each factor. In this way, the factor values that are not actually tested using fewer experimental combinations and the combinations themselves can be estimated [28,29]. The results are expressed in 3D series or counter map.

2.5. Experimental design

In this study, L_{27} Taguchi standard orthogonal array is adopted as the experimental design. The most suitable array is L_{27}, which needs 27 runs and has 26 degrees of freedoms (DOF). To check the DOF in the experimental design, for the three levels test, the three main factors take 6 DOFs (3×2) and the remaining DOFs are taken by interactions. The 3 level L_{27} orthogonal array is shown in Table 3, where the numbers 1, 2 and 3 stand for the values of the factors. The columns chosen for the main factors are 1, 2, and 5.

The experimental parameters used and the corresponding responses are given in Table 4. The first column of the table is assigned to the tool nose radius (r), the second to the approach angle (κ), the third to the negative back rake angle (γ). The roughness measurement results are given in the right and column.

2.6. Treatment method

In the engineering experiments, general aim is to determine the conditions that can lead to optimum results. The optimum result could be either a maximum or a minimum of a function of the design parameters. One of methodologies for obtaining the optimum result is response surface method (RSM). In most RSM problems, there is a functional relation between responses and independent variables and this relation can be explained using the model below [30].

$$\eta = \beta_0 + \sum_{i=1}^{k} \beta_i X_i + \sum_{i=1}^{k} \beta_{ii} X_i^2 + \sum_{i} \sum_{j} \beta_{ij} X_i X_j + \varepsilon \qquad (1)$$

Table 3
L_{27} orthogonal array.

Run	Column numbers												
	1	2	3	4	5	6	7	8	9	10	11	12	13
1	1	1	1	1	1	1	1	1	1	1	1	1	1
2	1	1	1	1	2	2	2	2	2	2	2	2	2
3	1	1	1	1	3	3	3	3	3	3	3	3	3
4	1	2	2	2	1	1	1	2	2	2	3	3	3
5	1	2	2	2	2	2	2	3	3	3	1	1	1
6	1	2	2	2	3	3	3	1	1	1	2	2	2
7	1	3	3	3	1	1	1	3	3	3	2	2	2
8	1	3	3	3	2	2	2	1	1	1	3	3	3
9	1	3	3	3	3	3	3	2	2	2	1	1	1
10	2	1	2	3	1	2	3	1	2	3	1	2	3
11	2	1	2	3	2	3	1	2	3	1	2	3	1
12	2	1	2	3	3	1	2	3	1	2	3	1	2
13	2	2	3	1	1	2	3	2	3	1	3	1	2
14	2	2	3	1	2	3	1	3	1	2	1	2	3
15	2	2	3	1	3	1	2	1	2	3	2	3	1
16	2	3	1	2	1	2	3	3	1	2	2	3	1
17	2	3	1	2	2	3	1	1	2	3	3	1	2
18	2	3	1	2	3	1	2	2	3	1	1	2	3
19	3	1	3	2	1	3	2	1	3	2	1	3	2
20	3	1	3	2	2	1	3	2	1	3	2	1	3
21	3	1	3	2	3	2	1	3	2	1	3	2	1
22	3	2	1	3	1	3	2	2	1	3	3	2	1
23	3	2	1	3	2	1	3	3	2	1	1	3	2
24	3	2	1	3	3	2	1	1	3	2	2	1	3
25	3	3	2	1	1	3	2	3	2	1	2	1	3
26	3	3	2	1	2	1	3	1	3	2	3	2	1
27	3	3	2	1	3	2	1	2	1	3	1	3	2

Table 4
Cutting insert geometry and average measured surface roughness values.

Trial number	Factors			Surface roughness
	r (mm)	κ (°)	γ (°)	Ra (μm)
1	0.4	60	−3	2.025
2	0.4	60	−6	2.283
3	0.4	60	−9	2.892
4	0.4	75	−3	2.358
5	0.4	75	−6	2.850
6	0.4	75	−9	3.962
7	0.4	90	−3	3.509
8	0.4	90	−6	4.099
9	0.4	90	−9	4.876
10	0.8	60	−3	4.225
11	0.8	60	−6	5.142
12	0.8	60	−9	5.692
13	0.8	75	−3	4.308
14	0.8	75	−6	6.066
15	0.8	75	−9	6.563
16	0.8	90	−3	5.010
17	0.8	90	−6	7.944
18	0.8	90	−9	7.990
19	1.2	60	−3	4.475
20	1.2	60	−6	5.650
21	1.2	60	−9	5.967
22	1.2	75	−3	4.796
23	1.2	75	−6	7.662
24	1.2	75	−9	8.000
25	1.2	90	−3	5.874
26	1.2	90	−6	8.665
27	1.2	90	−9	8.951

where η is the estimated response (surface roughness), β_0 is constant, β_i, β_{ii} and β_{ij} represent the coefficients of linear, quadratic and cross-product terms, respectively. X reveals

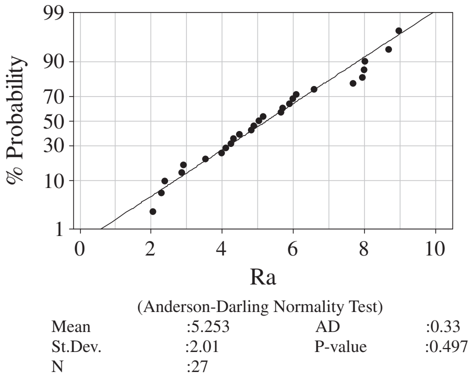

Fig. 1. Normal probability plot of surface roughness parameter Ra.

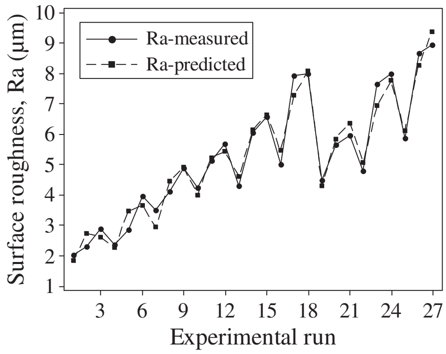

Fig. 4. Measured vs. predicted values of surface roughness.

the coded variables that correspond to the studied tool geometry parameters such as tool nose radius (r), approach angle (κ) and rake angle (γ). The relationship between the surface roughness and machining parameters are expressed as follows:

$$\mathrm{Ra} = \beta_0 + \beta_1(r) + \beta_2(\kappa) + \beta_3(\gamma) + \beta_4(r^2) + \beta_5(\kappa^2) + \beta_6(\gamma^2) + \beta_7(r\kappa) + \beta_8(r\gamma) + \beta_9(\kappa\gamma) \quad (2)$$

The tests for significance of the regression and individual model coefficients were performed to verify the goodness

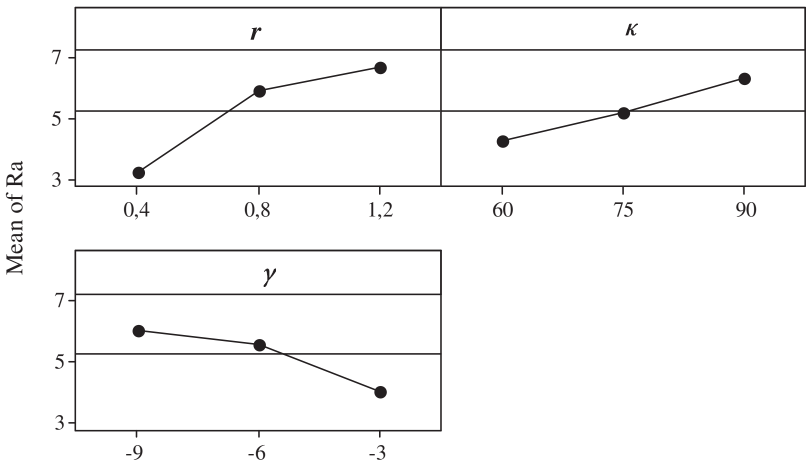

Fig. 2. Mean effects plots of surface roughness parameter Ra.

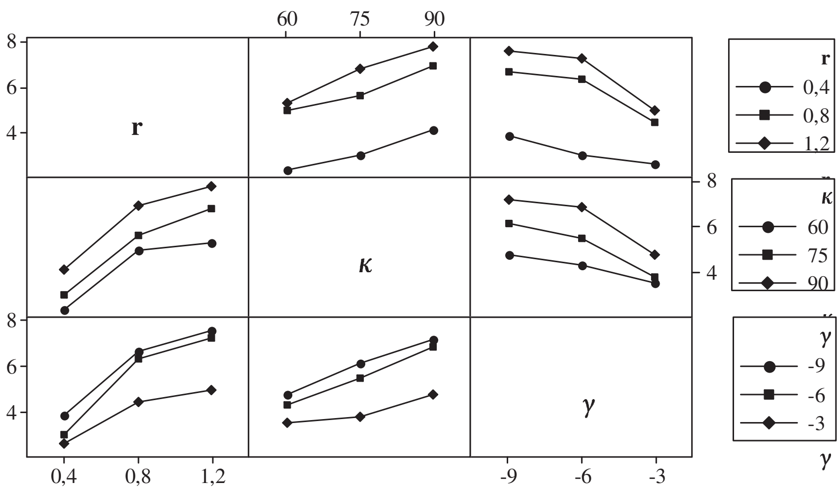

Fig. 3. Interaction plots of surface roughness parameter Ra.

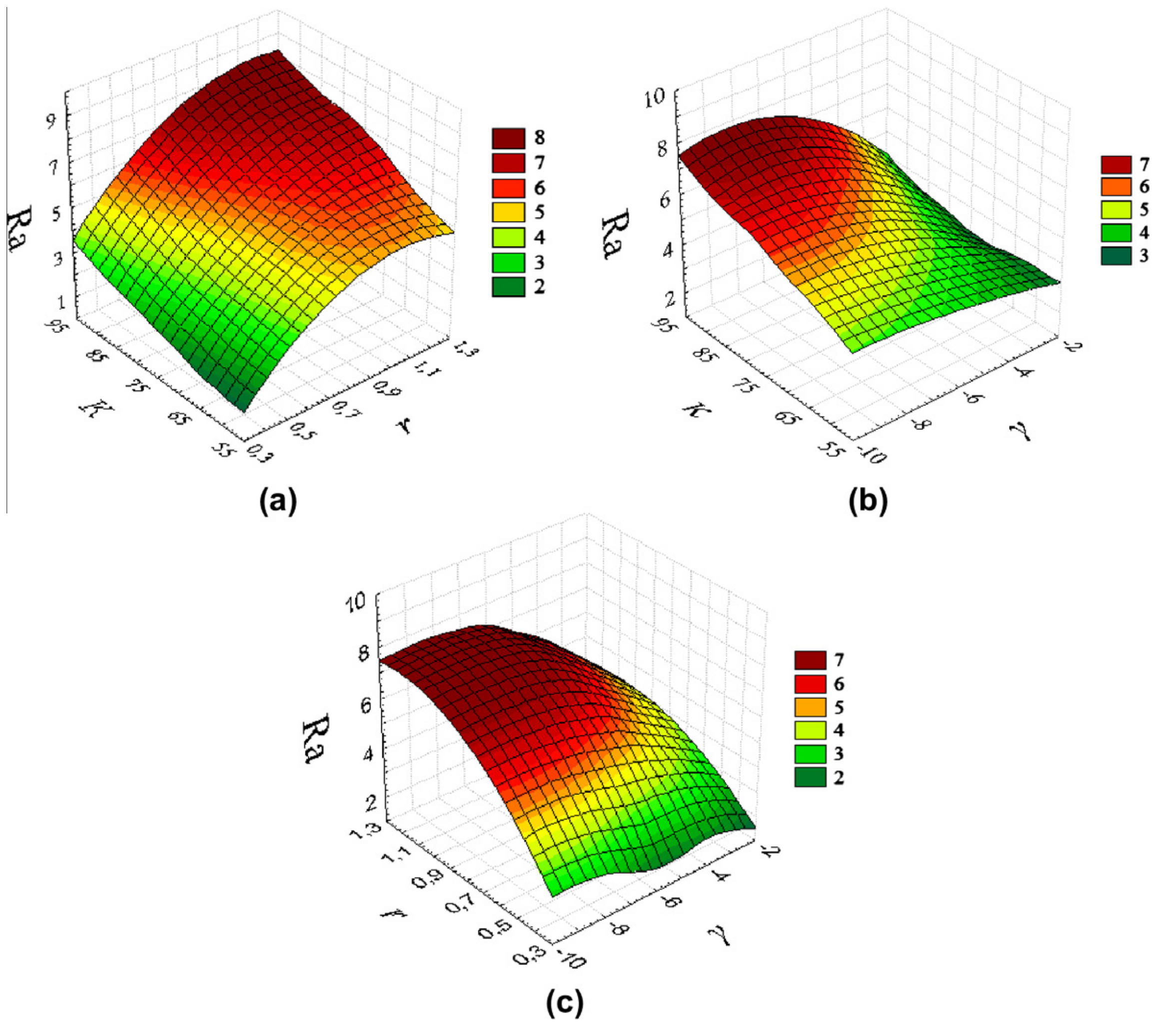

Fig. 5. Response surface of surface roughness (Ra) vs. r, κ and γ.

of fit for the obtained model. The analysis of variance (ANOVA) was applied to summaries these tests. Additionally, plot of main effects, interactions, normal probability and 3D response surface corresponding to each ANOVA analysis were constructed. These plots were used to investigate the influences of tool geometry on the surface roughness, and are illustrated in Figs. 1–6.

Analysis of variance essentially consists of partitioning the total variation in an experiment into components ascribable to the controlled factors and error. The statistical significance of the fitted quadratic models were evaluated by the *P*-values of ANOVA. Table 5 shows the results of ANOVA. In ANOVA table, the sum of squares is used to estimate the square of deviation from the grand mean. Mean squares are estimated by dividing the sum of squares by degrees of freedom. *F*-ratio is an index used to check the adequacy of the model in which calculated value of *F* should be greater than the *F*-table value. The model is adequate at 95% confidence level since the *F* calculated value is greater than the *F*-table value. When *P*-values are less than 0.05 (or 95% confidence), the obtained models are considered to be statistically significant. It demonstrates that the terms a chosen in the model have significant effects on the responses. The other important coefficient is the determination coefficients, R^2, which defined as the ratio of the explained variation to the total variation and is a measure of the degree of fit. The more R^2 approaches to unity, the better the response model fits the actual data.

3. Results and discussion

The linear r, κ, γ, quadratic r^2, γ^2 and interactive $r * \gamma, \kappa * \gamma$ factors that can affect the surface roughness parameter (Ra), the arithmetic mean of absolute roughness are given in Table 5.

The most significant factor on the parameters Ra is tool nose radius (r), which explains 51.45% contribution of total variation. The next contribution on Ra comes from the approach angle (κ) and rake angle (γ) with the contributions 18.24% and 17.74%, respectively.

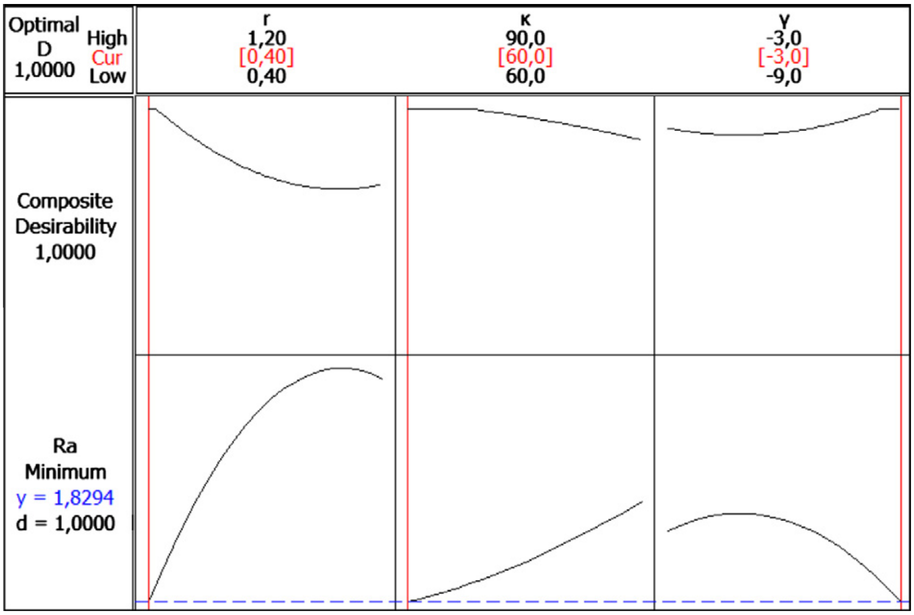

Fig. 6. Response optimization plot for surface roughness parameter components.

Table 5
Analysis of variance for surface roughness.

	SS	df	MS	F	P	PC%
r	54.031478	1	54.031478	266.901958	0.000000	51.45
κ	19.151861	1	19.151861	94.605391	0.000000	18.24
γ	18.631443	1	18.631443	92.034658	0.000000	17.74
$r*r$	5.343041	1	5.343041	26.393282	0.000082	5.09
$\kappa*\kappa$	0.084728	1	0.084728	0.418536	0.526308	0.08
$\gamma*\gamma$	1.584148	1	1.584148	7.825295	0.012374	1.51
$r*\kappa$	0.372416	1	0.372416	1.839643	0.192734	0.35
$r*\gamma$	1.290352	1	1.290352	6.374016	0.021816	1.23
$\kappa*\gamma$	1.078800	1	1.078800	5.329003	0.033811	1.03
Residual error	3.441470	17	0.202439			3.28
Total SS	105.0097	26				

For the quadratic κ and its interactions with r ($r*\kappa$) influence value is 0.08% and 0.35%, respectively. It does not have a statistical significance on Ra.

It is clearly observed that in Fig. 2, tool nose radius has biggest effect on surface roughness. Actually this case is commonly expected. A popular model [31] to estimate the surface roughness, with a tool having nonzero nose radius, is

$$\mathrm{Ra} = \frac{f^2}{32 \cdot r} \tag{3}$$

where Ra is the average surface roughness (μm), f is the feed rate (mm/rev), r is the cutting tool nose radius (mm). According to Eq. (3) the increase in tool nose radius decreases surface roughness. But, in this study, it is found out that the tool nose radius increase causes to increases of surface roughness. This case can be explained as the increase in the tool nose radius value increases contact length of tool–workpiece during cutting. This contact length causes chatter vibration and increases the value of surface roughness [32].

In Fig. 2 it can be seen that approach angle has a parallel effect on tool nose radius. The increase in approach angle increases cutting forces. The increases tool nose oscillation also increases the roughness value of machined surface.

Rake angle has the highest effect in reducing surface roughness. Positive rake angle that is specially preferred for final turning operations is a factor that facilitates the immersion between tool–workpiece during cutting. The

Table 6
Estimated regression coefficients for Ra (uncoded units).

Factors	Reg. coeff.	p	R^2
Constant	−1.29933	0.797095	96.72%
r	9.92639	0.001170	
κ	−0.07392	0.562301	
γ	−0.30591	0.380814	
$r*r$	−5.89792	0.000082	
$\kappa*\kappa$	0.00053	0.526308	
$\gamma*\gamma$	−0.05709	0.012374	
$r*\kappa$	0.02936	0.192734	
$r*\gamma$	−0.27326	0.021816	
$\kappa*\gamma$	−0.00666	0.033811	

Table 7
Response optimization for surface roughness parameter components.

Parameters	Goal	Optimum combination			Lower	Target	Upper	Pre. response	Desirability
		r (mm)	κ (°)	γ (°)					
Ra (μm)	Minimum	0.4	60	−3	2.025	2.025	8.951	1.829	1

effects of other main factors and interactions are shown in Fig. 3.

The Anderson–Darling test and normal probability plots of the residuals vs. the predicted response for the surface roughness parameter (Ra) are plotted in Fig. 1. The data closely follows the straight line. The null hypothesis is that the data distribution law is normal and the alternative hypothesis is that it is abnormal. Using the *P*-value which is greater than alpha of 0.05 (level of significance), we cannot reject the null hypothesis (i.e., the data follow a normal distribution). This implies that the models proposed are adequate.

3.1. Surface roughness quadratic model

Estimated regression coefficients for surface roughness using data in uncoded units are shown in Table 6.

The quadratic model of response equation in terms of actual factors for surface roughness (Ra) is

$$\begin{aligned} \text{Ra} = & -1.299 + 9.926 \cdot r - 0.073 \cdot \kappa - 0.305 \\ & \cdot \gamma - 5.897 \cdot r^2 + 0.0005 \cdot \kappa^2 - 0.057 \\ & \cdot \gamma^2 + 0.029 \cdot r \cdot \kappa - 0.273 \cdot r \cdot \gamma - 0.006 \cdot \kappa \cdot \gamma \end{aligned} \tag{4}$$

The empirical Eq. (4) shows greater agreement than 96% in the fit values. Hence, these equations can be used for determining the surface roughness in machining.

Fig. 4 also shows the predicted values of surface roughness from quadratic model of response equation and the measured values. The results of the comparison proves that predicted values of the surface roughness (Ra) are very close to those readings recorded experimentally.

3.2. Response surface analysis

The effect of tool nose radius (r), approach angle (κ) and tool rake angle (γ) on surface roughness is shown in Fig. 5. Fig. 5a clearly displays that the value of surface roughness (Ra) increases with increase in the effect of approach angle (κ) and tool nose radius (r). This result contradicts with common expectation. In addition to the approach given before (Unit 4.1), this result can be explained in terms of touch surface located between tool and machined material. Increasing the amount of touch surface increases the risk of excessive thermal crack and the flank wear on the surface of tools. Hence, the thermal crack and the flank wear on the surface of tools are unfavorable to the roughness of machined surface. From Fig. 5b and c it is observed that if tool nose radius, approach angle and rake angle all together are increased the surface roughness is increases too.

3.3. Optimization of response

One of the most important aims of experiments related to manufacturing is to achieve the desired surface roughness of the optimal cutting parameters [5] and tool geometry. To this end, the response surface optimization is an ideal technique for determination of the best tool geometry combination in turning. Here, the goal is to minimize surface roughness (Ra). RSM optimization result for surface roughness parameter (Ra) is shown in Fig. 6 and Table 6. Optimum cutting insert geometries obtained in Table 7 are found to be tool nose radius of 0.4 mm, approach angle of 60° and rake angle of −3°. The optimized surface roughness parameter is Ra = 1.8294 μm.

4. Conclusion

In this paper, the application of RSM on the AISI 1040 steel is carried out by turning with Al_2O_3 coated insert tools. In addition, a quadratic model is developed for the surface roughness (Ra) so as to investigate the influence of cutting insert geometry factors. The results of the research are as follows:

(1) The result of ANOVA proved that the quadratic mathematical models allow prediction of surface roughness parameter with a 96% confident interval.
(2) Tool nose radius is the most significant factor on surface roughness with 51.45% contribution in the total variability of model. The quadratic effect of tool nose radius little provides little contribution to the model.
(3) Also, approach angle and rake angle are significant factors on surface roughness with 18.24% and 17.74% contribution in the total variability of model, respectively.
(4) It can be said that the interaction between all factors has no significant effect on surface roughness.
(5) Using response optimization show that the optimal combination of machining parameters are (0.4 mm, 60°, −3°) for tool nose radius, approach angle and rake angle, respectively.

Therefore, the approach presented experimentally and statistically in this study can be regarded as a proper method for the optimization of turning process. This method can also be applied safely for the experiments where cutting parameters are to be used.

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