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TECHNICAL PAPER

Modeling of geometrical and machining parameters on temperature rise while machining Al 6351 using response surface methodology and genetic algorithm

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Abstract This paper focused on the effect of geometrical and machining parameters such as rake angle, nose radius, cutting speed, feed rate, and depth of cut on temperature rise during end milling operation. The experiments were conducted on Al 6351 with high-speed steel end mill cutter. Central composite rotatable experimental design methodology was employed to conduct the experiments. The temperature rise during machining was measured using K-type thermocouple coupled with the thermal indicator. A prediction model was developed using response surface methodology and the adequacy of the model was verified using analysis of variance. The predictive model was used to analyze direct and interaction effect of the machining parameters on temperature rise, which helps to select proper combination of machining parameters to obtain better quality in machining. Genetic algorithm was applied to optimize the machining process parameters to obtain minimum rise in temperature. A program was developed using C language to do the optimization and the best optimal combination of machining parameters gave a value of 0.0105 °C.

Keywords Temperature rise · Mathematical model · Analysis of variance · Response surface · Genetic algorithm

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1 Introduction

In our modern manufacturing process it is important to manufacture a product with high quality at minimum expenditure and time. End milling is a commonly used metal cutting operation, frequently employed in making profiles, slots, pockets, molds, die, etc. It is used in various manufacturing industries like valve and automotive sectors, where quality is an important factor. During machining, heat generation occurs as a result of plastic deformation and friction at the tool–chip and tool–workpiece interface. The power utilized during end milling is mostly converted into thermal energy. Rise in the temperature in cutting zone affects the material behavior and mechanics of chip formation. Higher temperature leads to thermal expansion of tool which causes tool wear and degrades the work piece quality. It is very difficult to measure the temperature of an end milling cutter correctly, because the cutting tool rotates at a high speed and the area to be measured is very small. In the present research, the measurement of temperature rise was made using the tool–workpiece thermocouple technique.

The measurements of cutting temperatures are more difficult as the temperature is a scalar field which varies throughout the system and cannot be uniquely described by values at a point. The most widely used method to measure cutting temperatures is tool–work thermocouple, which measures average interfacial temperature at tool–work piece interface. Many researchers have attempted to develop a technique to measure and model the temperature distribution at the cutting zone during machining. Leshock et al. [1] demonstrated that the thermocouple can be embedded in the tool or work piece to measure the temperature accurately with less effort. Smart et al. [2] measured the cutting temperature by inserting thermocouple in the hole drilled in the work piece. Thermocouples are conductive, operate over a wide temperature range, rugged and inexpensive [3]. Pittala and Monno [4] employed infrared camera to measure the temperature rise during milling operation. They proposed a thermal model of cutting processes in order to design cutting edge, to optimize the quantity of coolant and to analyze the effects of the coatings. Masahiko et al. [5] proposed a practical method in end milling for measuring the temperature history at tool–chip interface during chip formation. An infrared radiation pyrometer with two optical fibers connected by a fiber coupler was developed and applied to the measurement of tool–chip interface temperature. Kadirgama et al. [6] proposed a first-order temperature model using response surface methodology to determine the temperature distribution on cutting tool. The experimental results were verified by applying finite element analysis.

Adeel et al. [7] determined an experimental result in which work piece surface temperature can be used as an indicator to control the cutting performance. They employed Taguchi techniques to optimize the cutting parameters using work surface temperature and surface roughness as a performance measure. They concluded that work piece surface temperature can be sensed and used effectively as an in process signal for optimizing cutting parameters. Liu et al. [8] applied the particle swarm optimization technique to develop nonlinear curve for determining cutting temperature. Liu and Wang [9] used the modified genetic algorithm for the optimization of milling parameters. They concluded that the simulation and experimental results showed an improvement in performance. Palanisamy et al. [10] determined tool–chip interface temperature for different machining using Oxley's energy partition function and Rapier's equation. They observed and concluded that the temperature increases with a rise in cutting forces during machining. Haci et al. [11] estimated the temperature generated in secondary shear zone for different cutting parameters and tool geometries in the orthogonal cutting using Kienzle approach.

The experiments conducted should provide enough information with lesser effort and time. Design of experiments is an important tool that helps the researcher to plan the experimental design to conduct the experiment and further statistical approach results in regression model. Many researchers employed response surface methodology for developing statistical model for predicting surface roughness, tool wear and cutting forces [12–14]. It has several advantages compared to other experiments which help to do analysis, to determine the influence (direct effect and interaction effect) of process parameters on the responses. Optimization of the machining parameters increases the product quality. Genetic algorithms are an adaptive search and optimization algorithm that mimics the principles of natural genetics [15]. The genetic algorithm is a very appealing optimization algorithm as it may be applied to both discrete and continuous objective functions.

The literature review reveals that developing predictive model for temperature rise has not been attempted. The high thermal conductivity of aluminum alloys contributes machining difficulty of obtaining the dimensional stability in machined parts. Further, the geometry of end mill cutter has not been considered for modeling the machining performance. The main objective of the current research work is to establish a statistical model in terms of geometrical and machining parameters such as rake angle, nose radius, cutting speed, feed rate and depth of cut to predict temperature rise during milling operation. The direct and interaction effects of these parameters on temperature rise to understand the influence of these parameters were studied. Genetic algorithm was employed to optimize these parameters to obtain minimum temperature rise during machining.

2 Response surface methodology

Response surface methodology is the most informative method of analysis of the result of a factorial experiment. In the present work, rake angle and nose radius of cutting tool, cutting speed, feed rate and axial depth of cut have been considered as the process parameters and the cutting temperature rise is taken as a response variable (Table 1).

Table 1 Parameters and their levels in end milling

Parameters	Units	Factor levels				
		−2	−1	0	1	2
Rake angle (α)	Degree (°)	4	8	12	16	20
Nose radius (n)	mm	0.4	0.6	0.8	1.0	1.2
Cutting speed (N)	m/min	1.25	1.5	1.75	2	2.25
Feed rate (Z)	mm/rev	0.02	0.03	0.04	0.05	0.06
Axial depth of cut (X)	mm	1.5	2	2.5	3	3.5

Table 2 Experimental design—central composite design matrix

Exp no.	Rake angle (°)	Nose radius (mm)	Cutting speed (m/min)	Feed rate (mm/rev)	Axial depth of cut (mm)	Temperature rise (°c)		Error (%)
						Observed	Predicted	
1	−1	−1	−1	−1	1	30.3	29.735	1.86
2	1	−1	−1	−1	−1	16.8	17.241	−2.63
3	−1	1	−1	−1	−1	11.7	12.001	−2.57
4	1	1	−1	−1	1	57.9	56.543	2.34
5	−1	−1	1	−1	−1	38.2	39.011	−2.12
6	1	−1	1	−1	1	68	69.177	−1.73
7	−1	1	1	−1	1	30.1	30.785	−2.28
8	1	1	1	−1	−1	32.3	32.667	−1.14
9	−1	−1	−1	1	−1	37.1	36.261	2.26
10	1	−1	−1	1	1	48.6	46.251	4.83
11	−1	1	−1	1	1	26.3	25.635	2.53
12	1	1	−1	1	−1	47.2	47.693	−1.04
13	−1	−1	1	1	1	42.8	41.569	2.88
14	1	−1	1	1	−1	49.1	49.251	−0.31
15	−1	1	1	1	−1	26.3	26.235	0.25
16	1	1	1	1	1	48.6	50.601	−4.12
17	−2	0	0	0	0	15.9	16.631	−4.60
18	2	0	0	0	0	49.2	48.679	1.06
19	0	−2	0	0	0	38.4	39.547	−2.99
20	0	2	0	0	0	28.9	27.963	3.24
21	0	0	−2	0	0	34.9	36.407	−4.32
22	0	0	2	0	0	56.1	53.391	4.83
23	0	0	0	−2	0	37.8	36.813	2.61
24	0	0	0	2	0	44.7	45.897	−2.68
25	0	0	0	0	−2	33.2	33.657	−1.38
26	0	0	0	0	2	53.7	56.141	−4.55
27	0	0	0	0	0	43.8	44.899	−2.51
28	0	0	0	0	0	43.6	44.899	−2.98
29	0	0	0	0	0	46.3	44.899	3.03
30	0	0	0	0	0	43.4	44.899	−3.45
31	0	0	0	0	0	46.6	44.899	3.65
32	0	0	0	0	0	47.1	44.899	4.67

The response temperature rise T can be expressed as a function of process parameters rake angle (α), nose radius (n), cutting speed (N), feed rate (Z) and depth of cut (X).

Temperature rise,

$$T = \phi\left(\alpha_{iu}, n_{iu}, N_{iu}, Z_{iu}, X_{iu}\right) + e_u, \tag{1}$$

where ϕ is the response surface, e_u is the residual, u is the no. of observations in the factorial experiment and iu represents level of the ith factor in the uth observation.

When the mathematical form of ϕ is unknown, this function can be approximated satisfactorily within the experimental region by polynomials. Box and Hunter [16] proposed central composite rotatable design for fitting a second-order response surface based on the criterion of rotatability. The selected design plan chosen consists of 32 experiments (Table 2). It is a five factors–five levels central composite rotatable design consisting of 32 sets of coded design matrix. The above design for conducting the experiment comprises a ½ replication of 2^5 (=16) factorial design, 6 center points and 10 star points. These correspond to first 16 rows, the last 6 rows and rows from 17 to 26, respectively, in the design plan shown in Table 2.

For ½ replicate the extra point included to form a central composite design, α becomes $2^{(k-1)/4} = 2$. The upper limit of the parameter is coded as 2, lower limit as −2 and the coded values for intermediate values were calculated from the following relationship [17]:

Table 3 Chemical composition of Al 6351

Percentage weight	Elements							
	Si	Fe	Cu	Mn	Mg	Zn	Ti	Al
Min	0.7	–	–	0.4	0.4	–	–	Remainder
Max	1.3	0.5	0.1	0.8	0.8	0.2	0.1	

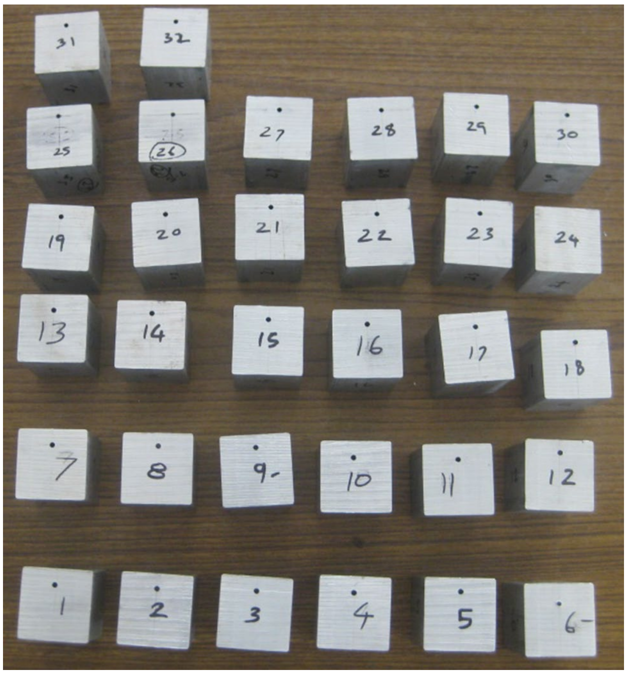


Fig. 1 Work pieces with pre-drilled holes

$$X_i = \frac{2(2X - (X_{\max} + X_{\min}))}{(X_{\max} - X_{\min})}, \quad (2)$$

where X_i is the required coded value of a variable X, X is any value of the variable from $X_{\min}$ to $X_{\max}$, $X_{\min}$ is the lower limit of the variable, $X_{\max}$ is the upper limit of the variable. The intermediate values coded as −1, 0 and 1.

3 Experimental setup

The experiments were conducted on a HAAS vertical machining center with high-speed steel end mill cutter under dry condition, which has maximum cutting speed of 2.25 m/min and minimum displacement of 0.01 mm. The workpiece material was aluminum alloy (Al 6351) which finds application in valve and automobile industries. The chemical composition of Al 6351 is given in Table 3. The dimension of the workpiece specimen was 32 × 32 mm square bar with 40 mm length. A hole of 2 mm diameter was drilled in the workpiece at about 3 mm below the machining area as shown in Fig. 1. From the previous work it has been found that radial depth of cut has no significant effect on the performance measure [18], the value for radial depth of cut was taken as 4 mm. The temperature was measured by using a CIE model 305P Thermal indicator with K-type thermocouple whose measuring range is −50 to 1300 °C with accuracy of 0.1 °C. The initial temperature and the peak temperature during machining were noted as shown in Figs. 3 and 4. The difference between the maximum and initial temperature is the temperature rise which is calculated and noted in Table 2.

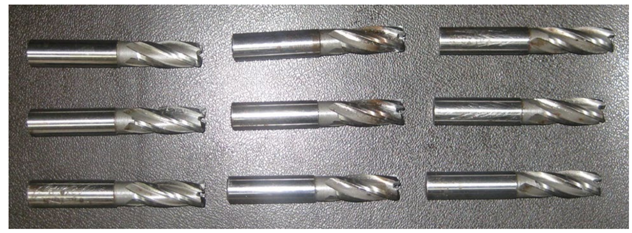


Fig. 2 HSS end milling cutter

Table 4 Geometrical combinations of rake angle and nose radius in tool

Tool number	Rake angle (degree)	Nose radius (mm)
1	8	0.6
2	16	0.6
3	8	1
4	16	1
5	4	0.8
6	20	0.8
7	12	0.4
8	12	1.2
9	12	0.8

The geometrical combination HSS end mill cutter is shown in Fig. 2 and the details are given in Table 4 (Figs. 3, 4).

Make: Addision Tools Ltd.

Tool material: high-speed steel (HSS)

Dimensions: 12 mm HSS end mill cutter with 4 flute 45° Helix angle.

4 Development of mathematical model

The general form of a quadratic polynomial which gives the relation between response surface y and the process variable x under investigation is given by:

$$\mathbf{y} = \mathbf{b}_0 + \sum_{i=1}^{k} b_i \mathbf{x}_i + \sum_{i=1}^{k} b_{ii} \mathbf{x}_i^2 + \sum_{i<j} b_{ij} \mathbf{x}_i \mathbf{x}_j, \quad (3)$$

where b_0 is the constant, b_i is the linear term coefficient, b_{ii} is the quadratic term coefficient and b_{ij} is the interaction term coefficient.

The values of the coefficients of the polynomials were calculated by multiple regression method. A statistical software QA Six Sigma DOEPC IV was used to calculate the values of these coefficients. The second-order mathematical model was developed by neglecting the insignificant coefficients of the temperature rise (T).

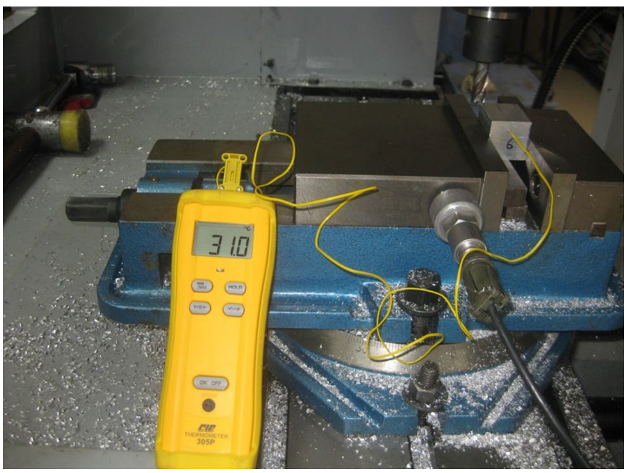


Fig. 3 Measurement of initial temperature

Fig. 4 Measurement of maximum temperature

$$\begin{aligned}\text{Temperature rise } (T) = {} & 44.899 + 8.012\,\alpha - 2.896\,n \\ & + 4.246\,N + 2.271\,Z + 5.621\,X \\ & - 3.061\,\alpha^2 - 2.786\,n^2 - 0.886\,Z^2 \\ & + 3.594\,\alpha n + 3.844\,\alpha X - 4.444\,nN \\ & - 2.769\,NZ - 5.044\,ZX, \end{aligned} \quad (4)$$

where α is the rake angle in (°), n is the nose radius in mm, N is the cutting speed in m/min, Z is the feed rate in mm/rev and X is the axial depth of cut in mm.

The adequacy of the model was tested using the analysis of variance (ANOVA) technique (Table 5). The calculated F ratio of the model does not exceed the standard value and the calculated R ratio of the model is above the standard value for a desired 95 % level of confidence. It is evident from Table 2 that the error between the experimental value and predicted value is less than 5 %.

5 Genetic algorithm

Genetic algorithm (GA) is a computerized search and optimization algorithm based on the mechanics of natural genetics and natural selection [19]. It is based on the idea of survival of the fittest, only the fittest individual of any population have most probability to reproduce and survive to the next generation. In order to solve a problem using GA, the variables are coded into some string structure. The data processed by genetic algorithm includes a set of strings or chromosomes with an infinite length in which each bit is called an allele (or a gene). The length of the string is usually determined according to the desired solution accuracy as shown in Table 6. A selected number of strings are called population and the population at a given time is known as generation. Generation of the initial population of strings are random since the binary alphabet offers the maximum number of schemata per bit of information of any coding, a binary encoding scheme is traditionally used to represent the chromosomes using either zeros or ones. Thereafter the fitness value (objective function value) of each member is computed. The population is then operated by three main operators—reproduction, cross-over, and mutation to create a new population of points. The new population is further evaluated and tested for determination. The current population is checked for acceptability or solution. The iteration is stopped after the completion of maximum number of generations or on the attainment of the best results.

Table 5 Adequacy of the model

Response	Factors *df*	Lack of fit—*df*	Pure error	F ratio		R ratio		Whether model is adequate
				Model	Standard	Model	Standard	
Temperature rise	13	13	5	1.035	4.86	124.786	4.86	Adequate

Table 6 Solution accuracy for the machining parameters

Machining parameters	Limits	Code	Decode	Range	Accuracy
Rake angle (α)	4–20 (°)	00000000	0	16	16/255 = 0.06275
		11111111	255		
Nose radius (n)	0.4–1.2 mm	00000000	0	0.8	0.8/255 = 0.00314
		11111111	255		
Cutting speed (N)	1.25–2.25 m/min	00000000	0	1	1/255 = 0.00392
		11111111	255		
Feed rate (Z)	0.02–0.06 mm/rev	00000000	0	0.04	$0.04/255 = 1.5686 \times 10^{-4}$
		11111111	255		
Axial depth of cut (X)	1.5–3.5 mm	00000000	0	2	2/255 = 0.00784
		11111111	255		

Table 7 Parameters of genetic algorithm

Number of iterations performed	100
Population	100
Cross-over probability	0.9
Mutation probability	0.01

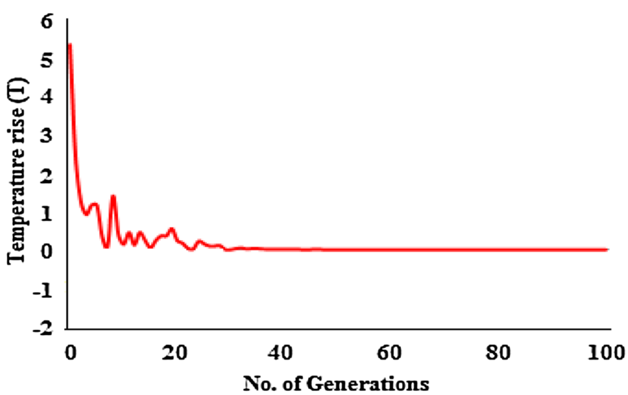


Fig. 5 Variation of fitness value with no. of generations for temperature rise

The objective function in this research is to determine optimal combination of geometrical and machining parameters to obtain minimum temperature rise during machining. The mathematical model developed using response surface methodology can be considered as an objective function with the range of the machining parameters as constraints. The number of iteration performed, population size, cross-over probability and mutation probability are shown in Table 7.

Figure 5 shows the results obtained by running the C program for minimizing temperature rise. The initial variation in the curve is due to the search for optimum solution. In Fig. 1, it is evident that the minimum temperature rise occurs at the 53rd generation and the value is 0.0105 °C. The optimum values of the machining parameters are given as: rake angle = 4.12°, nose radius = 1.03 mm, cutting speed = 1.297 m/min, feed rate = 0.036 mm/rev, axial depth of cut = 2.94 mm.

6 Results and discussion

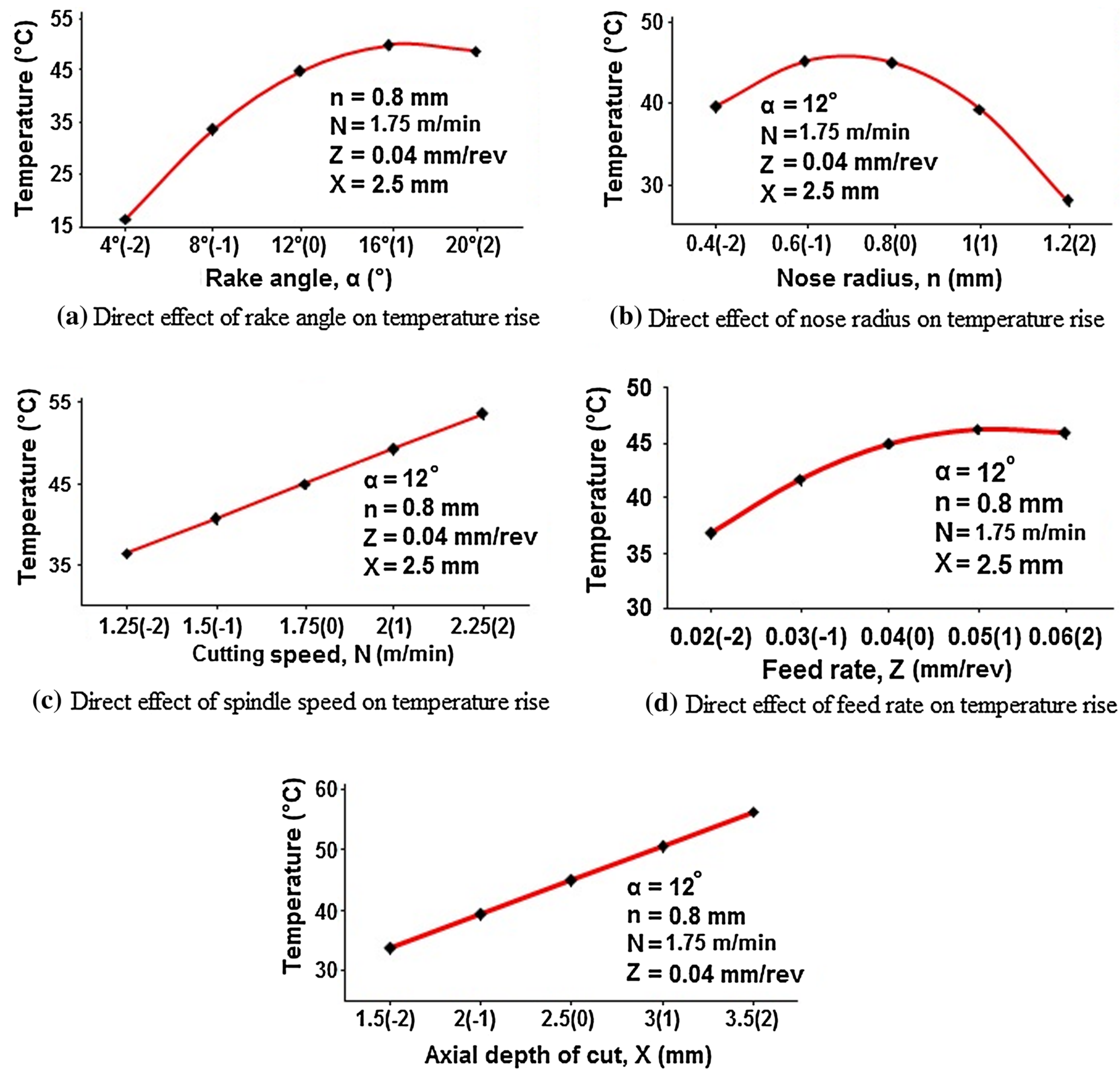
The empirical mathematical model using response surface methodology is used to predict temperature rise during machining in terms of machining parameters. The influence of each machining parameters was studied using the developed model.

6.1 Direct effect of variables

The direct effect of machining parameters was studied by changing the levels of a particular parameter whose influence on the response is to be studied, while keeping all the other parameters at the middle level. In this experimental investigation, the effects of rake angle, nose radius, cutting speed, feed rate and axial depth of cut on temperature rise were plotted graphically and analyzed. Figure 2 shows the direct effect of rake angle, nose radius, cutting speed, feed rate and axial depth of cut on temperature rise during milling operation.

6.1.1 Direct effect of rake angle on temperature rise

Figure 6a shows the direct effect of rake angle on cutting temperature. From the figure it is clear that the increase in rake angle increases the cutting temperature from 4 to 16° and reduces gradually. The reduction in the radial rake angle is beneficial in terms of tool life [20]. Increase in rake angle will increase the contact length between the chip and work piece which results in high friction. This causes an increase in the temperature of cutting zone during machining. From the figure, it is noted that the rake angle at 4° causes minimum temperature rise. It is observed decrease in the temperature rise as the rake angle increases from 16°



(a) Direct effect of rake angle on temperature rise

(b) Direct effect of nose radius on temperature rise

(c) Direct effect of spindle speed on temperature rise

(d) Direct effect of feed rate on temperature rise

(e) Direct effect of depth of cut on temperature rise

Fig. 6 Direct effect of machining parameters on temperature rise

to 20° was due to the ease of end mill ploughing the material easier, which reduces the energy required.

6.1.2 Direct effect of nose radius on temperature rise

Figure 6b depicts the direct effect of nose radius on cutting temperature. From the figure it is evident that the increase in nose radius increases the cutting temperature from 0.4 to 0.6 mm and reduces gradually. The rise in temperature is increasing with an increase in nose radius from 0.4 to 0.8 mm, due to increased vibration. When the nose radius is increased the chip formation during machining was thicker, which results in high heat dissipation resulting in lesser temperature rise.

6.1.3 Direct effect of cutting speed on temperature rise

Figure 6c shows the direct effect of cutting speed on temperature rise. From this figure, it is evident that the increase in cutting speed increases the temperature rise. When the cutting speed increases, the rate at which the energy is dissipated through plastic deformation and friction is very high. Thus, the rate of heat generation in the cutting zone increases, resulting in high cutting temperature during machining [21]. Thus an increase in cutting speed increases the temperature rise during machining. From the figure, it is noted that the cutting speed at 1.25 m/min causes minimum temperature rise.

6.1.4 Direct effect of feed rate on temperature rise

Figure 6d presents the direct effect of feed rate on temperature rise. This figure shows that the increase in feed rate resulted in temperature rise, and it is minimal at the feed rate range of 0.05–0.06 mm/rev. As feed increases, the chip formation is thicker. With larger thickness-to-surface area of the chip, there is less opportunity for the heat to be dissipated, hence temperature increases. Increase in feed rate will increase the rate of heat generation in the cutting zone. Tool–chip interface increases with the square root of the cutting speed and the third root of the feed rate [3]. Chip melting is observed when machining aluminum Al 6063 at higher feed rate.

6.1.5 Direct effect of axial depth of cut on temperature rise

Figure 6e shows the direct effect of axial depth of cut on temperature rise. From this figure it is clear that the increase in axial depth of cut increases the temperature rise. Increase in axial depth of cut causes larger amount of work

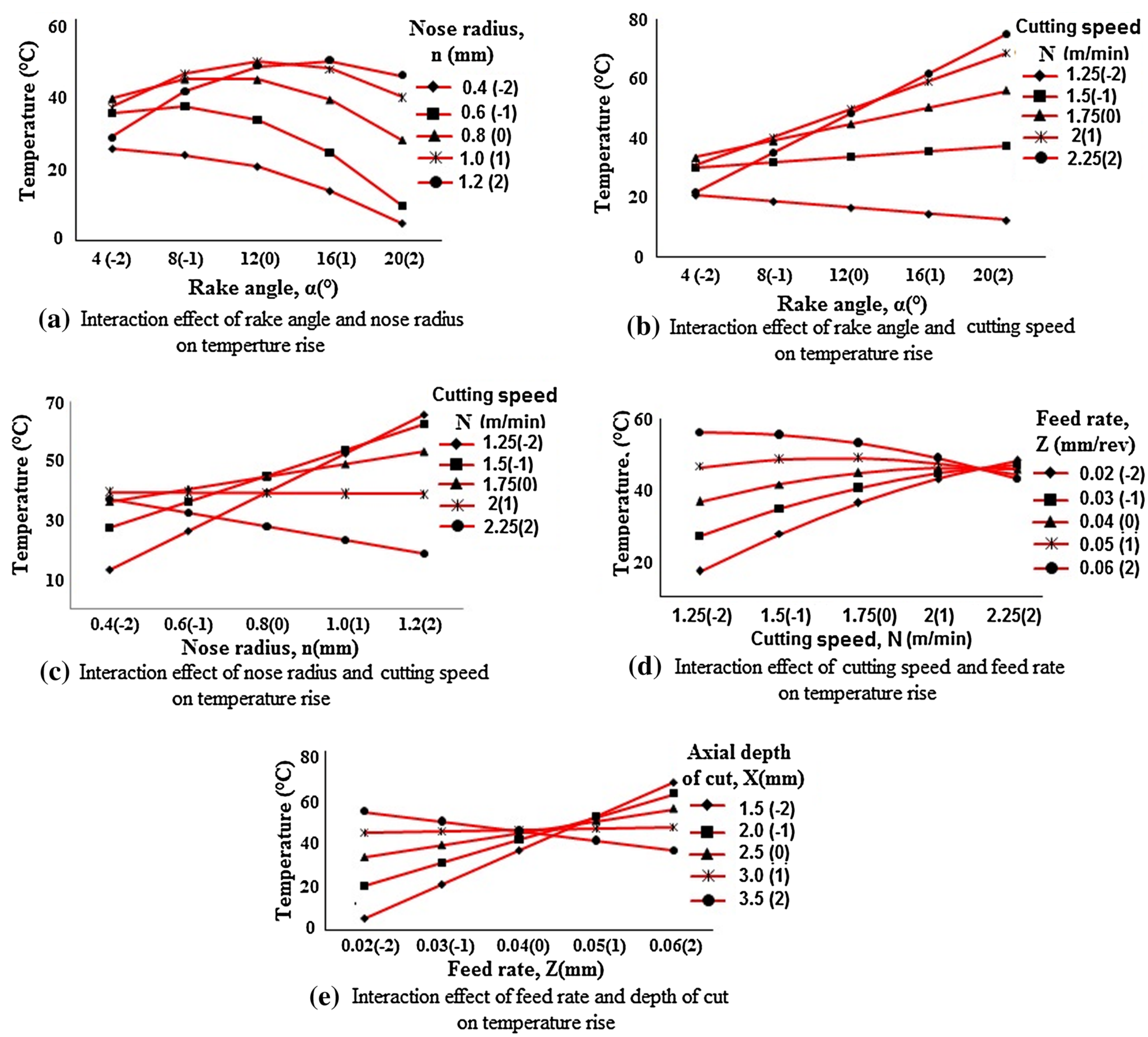


Fig. 7 Interaction effect of machining parameters on temperature rise

piece materials to be removed, which increases the cutting temperature. Temperature rise will be minimum with lower axial depth of cut, due to lesser amount of work piece material adhering on the flank of the tool than at lager depths of cut. This adhesion of work piece material on the tool flank causes an increase in temperature rise.

6.2 Interaction effects of variables

The effect of one parameter on the response with the change in the levels of other parameters is known as interaction effect. If the change of trend of one variable on a particular response gets changed significantly for the change of levels of the other parameter, strong interactions were observed. Strong interactions were observed between various machining parameters for temperature rise. The graph between the most significant parameter interactions effect of machining was plotted graphically as shown in Fig. 7.

6.2.1 Interaction effect of rake angle and nose radius

Figure 7a shows the interaction effect of rake angle and nose radius on temperature rise. From the figure it is understood that the temperature rise increases with an increase in rake angle for the change of level of nose radius from 0.4 to 0.8 mm. For the change of level of nose radius at 1.0 mm, the temperature rise increases with an increase in rake angle from 4° to 12° and then decreases from 12° to 20°. For the change of level of nose radius at 1.2 mm, the trend reverses; the temperature rise decreases with an increase in rake angle.

6.2.2 Interaction effect of rake angle and axial depth of cut

Figure 7b shows the interaction effect of rake angle and axial depth of cut on temperature rise. The figure reveals that increase in rake angle increases the temperature rise during machining. The same trend is observed for the change of levels of axial depth of cut from 3.5 to 2 mm. But the trend is reversed for the change of level of axial depth of cut at 1.5 mm, as increase in rake angle decreases the temperature rise.

6.2.3 Interaction effect of nose radius and cutting speed

Figure 7c shows the interaction effect of nose radius and cutting speed on temperature rise. From the figure it is understandable that the increase in nose radius resulted in increase of cutting temperature rise for the change of levels of cutting speed from 1.25 to 1.75 m/min. This trend gets reversed for the change of level of cutting speed at 2.25 m/min. For a cutting speed at 2 m/min, the nose radius has no effect on temperature rise.

6.2.4 Interaction effect of cutting speed and feed rate

Figure 7d shows the interaction effect of cutting speed and feed rate on temperature rise. The graph shows that the increases in cutting speed resulted in an increase in temperature rise for the change of levels of feed rate from 0.02 to 0.05 mm/rev. The trend gets reversed when the levels of feed rate change from 0.05 to 0.06 mm/rev.

6.2.5 Interaction effect of feed rate and axial depth of cut

Figure 7e shows the interaction effect of feed rate and axial depth of cut on temperature rise. The figure depicts that the temperature rise increases with increase in feed rate for the levels of axial depth of cut between 1.5 and 2.5 mm. The trend gets reversed for the levels of axial depth of cut between 2.5 and 3.5 mm, where the temperature rise decreases with the increase in feed rate. For depth of cut at 3 mm, the feed has no effect on temperature rise.

7 Conclusion

The following conclusions were arrived from the prediction and optimization of temperature rise during machining Al 6351 from the various machining parameters

- The rake angle is the most significant parameter which reduces peak temperature rise. The temperature rise is minimal at 4° rake angle.
- The increase in cutting speed, feed rate and axial depth of cut increases cutting temperature.
- The radial depth of cut does not have a significant effect on temperature rise.
- The temperature rise during machining increases with an increase in nose radius from 0.4 to 0.6 mm and thereafter reduces gradually.
- The interactions between the process parameters on temperature rise were analyzed and the most significant interaction was observed between feed rate and axial depth of cut.
- The genetic algorithm has been employed to optimize machining parameters to obtain minimum temperature rise. The optimal combination of machining parameters for minimum temperature of 0.0105 °C was found to be 4.12°, 1.03 mm, 1.297, 0.036 mm/rev and 2.94 mm for rake angle, nose radius, cutting speed, feed rate and axial depth of cut, respectively.

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