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Modeling and Analysis of High Speed Milling Ni-Based Superalloy GH3039 Surface Roughness Based on Response Surface Methodology

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Abstract

The effects of the cutting parameters on the surface roughness in machining the Ni-base superalloy GH3039 were investigated. The experimental design for surface roughness was conducted in this paper based on Taguchi's experimental. The effects of cutting parameters on surface roughness were evaluated and the optimum cutting conditions for minimizing the surface roughness were determined. The response surface methodology (RSM) was set up between the cutting parameters and surface roughness. The experimental results revealed that the feed rate is the main factor to affect surface roughness, followed by the cutting speed. The prediction of surface roughness and measured surface roughness are fairly close, which indicates that RSM model of surface roughness in machining the Ni-Base superalloy GH3039 is proved to be correct.

Keywords: *Ni-Based superalloy; surface roughness; response surface methodology*

1. Introduction

Ni-based superalloy has been widely used in the hot portions of modern aviation engine, jet turbines such as blades, vanes, and combustion chamber, attribute to their ability to work at 600℃~1000℃ in the conditions of high temperature for extended periods. As these materials possess high cutting temperature characteristics, they place the cutting tools under tremendous heat, the unit of big cutting force and serious work hardening phenomenon, leading to rapid flank wear, crater wear and tool notching at the tool nose *etc.*, and make them highly difficult to machine, which in turn, affects the dimensional accuracy and surface integrity during machining [1−2].the nickel based superalloy keep low production efficiency, which belongs to difficult to cut materials.

In the multi parameter characterization of surface topography, surface roughness is still one of the most direct measure. Surface quality has great influence on its use in the reliability and durability. The surface roughness value is high, the ability of anti-fatigue damage and anti-rot of candle ability is poor, and will decrease with the precision of workpiece.

In the present study, the effect of the cutting parameters on surface roughness during machining of the Ni-based superalloy GH3039 was studied by a PVD coated cemented carbide insert. Taguchi method was used for conducting the milling experiments, and to optimize the cutting parameters. To predict the surface finish the response surface method was adopted. Application of the response surface methodology to establish the prediction model of the surface roughness. The purpose of this study is to discuss the rationality of the analysis model, study the influence of the cutting parameters on the surface roughness, and evaluate the prediction ability of the model.

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2. Experimental

2.1. Work Material and Cutting Tool

The experimental studies were performed on a four-axis milling center of Austria EMCO FAMUP Company (MC12060). NC system for Heidenhain ITNC530. The tests were performed dry ant different cutting speeds, feed rates and depth of cut. Processing of blank dimension of 90mm×40mm×25mm. spindle speed range of 50−12000 r/min, main motor of 22.5KW, and the positioning accuracy of 0.01mm. The selected cutting tool for machining Ni-based superalloy GH3039 was of Sandvik make, with PVD coated cemented carbide inserts SANDVIK6190.Each turning trial was carried out using a fresh cutting edge so that the tool wear effect on the surface topography and roughness could be the same, and the variation due to the wear could be minimized. Surface roughness was measured by Mitutoyo SJ-201 roughness tester. 4 points were measured on the surface. The experiment setup is shown in Figure 1.

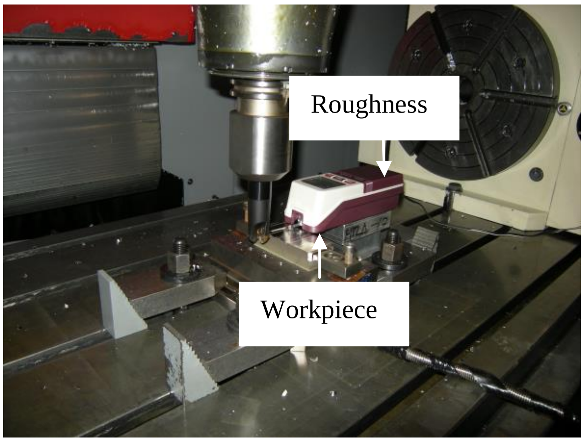

Figure 1. Experiment Setup

Ni-based superalloy GH3039 material was used for all the experiments. The chemical analysis was studied using the spark emission spectrometer. The chemical composition of the workpiece material is listed in Table 1.

Table 1. Chemical Composition of GH3039

Element	C	Cr	Fe	Si	Al	Ti
w%	≤0.080	19.000～22.000	≤3.000	≤0.800	0.350～0.750	0.350～0.750
Element	Mo	Nb	S	Mn	P	Ni
w%	1.800～2.300	0.900～1.300	≤0.012	≤0.400	≤0.020	Margin

2.2. Experimental Design

In this study, the experimental design was planned as per Taguchi's method for optimization of cutting parameters in the machining of Ni-based superalloy GH3039. This method is very attractive and effective to deal with the responses influenced by a number of variables and useful for studying the interactions between the parameters. The objective of Taguchi's quality loss function is the quantitative evaluation of quality loss due to functional variations. A quality characteristic is the object of interest of a product or process. It is called as a fundamental characteristic. The difference between the functional value and objective value is emphasized and identified as the loss function, which is given in equation (1).

$$L(y) = \frac{L(m)(y-m)^2}{2} = k(y-m)^2 = k(\sigma) \tag{1}$$

where $L(y)$ is the loss function, y is the value of the quality characteristic, m is the target value of y, k is the proportionality constant and σ is the mean square deviation. Equation (1) can be expressed by signal to noise (S/N) ratio (η) and can be rewritten as:

$$S/N\ (\eta) = -10\lg\sigma \tag{2}$$

Where η in the decibel (dB) scale measures the effect of noise.

There are three categories of quality characteristics in the analysis of the S/N ratio, (i) the-lower-the-better, (ii) the-higher-the-better and (iii) the-nominal-the-better. Regardless of the category of the quality characteristic, the process parameter settings with the highest S/N ratio always yield the optimum quality with a minimum variance. The-lower-the-better category is always preferred to calculate the S/N ratio for both the quality characteristics of surface roughness and tool wear. The equation for the calculation of the S/N ratio for the-lower-the-better characteristic can be expressed as

$$S/N = -10\lg\left(\frac{1}{n}\sum_{i=1}^{n} R_i^2\right),\ i = 1,2,\cdots,n \tag{3}$$

Where R_i is the value of the surface roughness for the i th trial in n number tests.

According to Taguchi method to optimization cutting parameters [4, 5]. Three machining parameters are considered as controlling factors (cutting speed, feed and depth of cut) and each parameter has three levels denoted by 1, 2 and 3. Table 2 shows the cutting parameters and their levels as considered for the experimentation. Table 3 shows the sets of experiments of $L_{27}(3^{13})$ orthogonal array with experimental results of surface roughness R_a and signal to noise S/N .

Table 2. Cutting Parameters and their Levels

Machining parameters	Symbol	Level		
		1	2	3
Cutting speed(m/min)	v_c	40	60	80
Feed（mm/rev）	f_z	0.05	0.06	0.07
Depth of cut(mm)	a_p	0.3	0.5	0.7

Table 3. Experimental Conditions and Results

No	Coded level			Actual setting value			Roughness R_a (μm)	S / N ratio(dB)
	1	2	3	v_c (m/min)	f_z (mm/r)	a_p (mm)		
1	1	1	1	40	0.05	0.3	0.43	7.33
2	1	1	2	40	0.05	0.5	0.41	7.74
3	1	1	3	40	0.05	0.7	0.38	7.80
4	1	2	1	40	0.06	0.3	0.48	8.40
5	1	2	2	40	0.06	0.5	0.47	6.56
6	1	2	3	40	0.06	0.7	0.45	6.94
7	1	3	1	40	0.07	0.3	0.52	5.68
8	1	3	2	40	0.07	0.5	0.55	5.19
9	1	3	3	40	0.07	0.7	0.51	5.85
10	2	1	2	60	0.05	0.5	0.40	7.96
11	2	1	3	60	0.05	0.7	0.39	8.18
12	2	1	1	60	0.05	0.3	0.37	8.64
13	2	2	2	60	0.06	0.5	0.54	5.35
14	2	2	3	60	0.06	0.7	0.46	6.74
15	2	2	1	60	0.06	0.3	0.44	7.13
16	2	3	2	60	0.07	0.5	0.50	6.02
17	2	3	3	60	0.07	0.7	0.53	5.51
18	2	3	1	60	0.07	0.3	0.47	6.56
19	3	1	3	80	0.05	0.7	0.39	8.18
20	3	1	1	80	0.05	0.3	0.36	8.87
21	3	1	2	80	0.05	0.5	0.35	9.11
22	3	2	3	80	0.06	0.7	0.44	7.13
23	3	2	1	80	0.06	0.3	0.43	7.33
24	3	2	2	80	0.06	0.5	0.42	7.54
25	3	3	3	80	0.07	0.7	0.49	6.20
26	3	3	1	80	0.07	0.3	0.48	8.40
27	3	3	2	80	0.07	0.5	0.47	6.56

2.3. Response Surface Methodology

Apart from Taguchi's design of experiment, response surface methodology was adopted to determine the relationship between the various process parameters and the response. Response surface methodology (RSM) is a collection of mathematical and statistical techniques that is useful for the modeling and analysis of problems, in which a response of interest is influenced by several variables and the objective is to optimize the response [5−6]. In order to study the effect of the process parameters on the surface roughness, a first order polynomial response surface can be fitted into following equation.

$$Y = \varphi(S, f, \alpha, \gamma) + \in \tag{4}$$

Where Y is the corresponding response, and φ is the Response function, S, f, α, and γ are milling variables, and $\in$ is the experimental error.

The first order response surface representing the surface roughness (R_a) can be expressed as a function of cutting parameters, such as the cutting speed (v), feed rate (f) and depth of cut (d). The relationship between the response (surface roughness) and the machining parameters can be expressed as equation (5) [6].

$$R_a = C a_p^{b_1} f^{b_2} v_c^{b_3} \tag{5}$$

Where R_a is roughness, and C is coefficient of correction. The terms b are the indexes.

Both sides to take the common logarithm as equation (6).

$$\lg R_a = \lg C + b_1 \lg a_p + b_2 \lg f + b_3 \lg v_c \tag{6}$$

Where $y = \lg R_a$, $b_0 = \lg C$, $x_1 = \lg a_p$, $x_2 = \lg f$, $x_3 = \lg v$. The equation (6) can be calculates as follow:

$$y = b_0 + b_1 x_1 + b_2 x_2 + b_3 x_3 \tag{7}$$

There are three independent variables in equation, and the levels of cutting parameters are different. The logarithm value of different levels in different cutting parameters was substituted, obtained the matrix of X and the matrix of Y.

The analysis was made using MATLAB software. The vector X, Y were Calculated. Using the least squares fitting in MATLAB work out the coefficient, and the undetermined coefficients in the model. The model coefficients can be achieved as follows:

$$b = \begin{bmatrix} 0.8431 \\ 0.0207 \\ 0.7834 \\ -0.1288 \end{bmatrix} \tag{8}$$

The model of Ni-based superalloy GH3039 can be obtained as follows:

$$R_a = 6.968\, a_p^{0.8431} f^{0.0207} v^{-0.1288} \tag{9}$$

3. Results and Discussion

3.1. Effect of Control Parameters on Surface Roughness

In Taguchi’s method, the terms of signal and noise represent the desirable and undesirable values. The S/N ratio indicates the degree of the predictable performance of a product or process in the presence of noise factors. The S/N ratio for each parameter level is calculated by averaging the S/N ratios obtained when the parameter is maintained at that level. The calculated S/N ratio for three factors on the surface roughness in machining the Ni-based superalloy GH3039 for each level is shown in Table 4. From Table 4, it can be seen that among the process parameters, the feed rate has the highest S/N ratio (R_B = 1.98), indicating its dominant influence on the surface roughness, compared with the cutting speed and depth of cut. The quality characteristic considered in the present study is the-lower-the-better characteristic. The surface roughness observed at low cutting speed is more than that observed at higher cutting speed.

Table 4. Responses of Signal-To-Noise Ratio

Level	S/N ratio		
	Cutting speed	Feed rate	Depth of cut
1	6.83	8.20	7.59
2	6.90	7.01	6.89
3	7.70	6.22	6.95
Difference	0.87	1.98	0.7
Rank	2	1	3

3.2. Response Surface Analysis

In order to determine the Ni-based superalloy GH3039 surface roughness model precision, absolute error between calculated data and model calculation using Matlab value. Through calculation, the maximum absolute error is 9.37%, less than 10%, so the roughness model of Ni-based superalloy GH3039 is reasonable.

4. Conclusions

Using Taguchi method helps to evaluate the effects of cutting parameters on the surface roughness, and the optimal machining conditions to minimize the surface roughness were determined. The feed rate was observed to be the main effect parameter for achieving less surface roughness, followed by the cutting speed and depth of cut. The best possible machining condition for obtaining better surface roughness was cutting speed of 80 m/min, feed rate of 0.05 mm/r and depth of cut of 0.7 mm for turning the Ni-based superalloy GH3039 with PVD coated carbide tool. The resultant deviation is reduce feed rate and reduce the surface roughness, whereas the increase of cutting speed and depth of cut cause decreases the surface roughness under all cutting conditions. The increase of feed speed will cause the surface quality of parts decrease. The response surface methodology can be used to predict the feature of surface roughness. The verification test results revealed that the determined optimal combination of the machining parameters satisfies the real requirements of the cutting operation in machining the Ni-based surperalloy GH3039.

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