Experimental design and performance analysis when using the flank milling to machine the thin wall of aluminum alloy

Thiết kế thử nghiệm và phân tích kết quả thử nghiệm khi sử dụng quá trình phay sườn để gia công thành mỏng hợp kim nhôm

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Keywords:

Surface roughness, Taguchi method, ANOVA analysis.

Abstract

This study was performed by using the flank milling process to machine the thin wall of aluminum alloy. Using Taguchi method and ANOVA analysis, the effects of milling type and cutting conditions on the surface roughness were investigated. With five controllable factors (milling type, cutting speed, feedrate, axial depth of cut, and radial depth of cut), the most suitable orthogonal array L_{18} was used and performed with one performance measurements that is the surface roughness. By using ANOVA analysis with the assistance of Intercooled Stata 8.2^{TM} software, the effect of milling type and cutting conditions on the surface roughness was analyzed and modeled. The most suitable regression of surface roughness was modeled with the confidence level is 99.14%. This model was verified by experiments with very promising results. Besides, the optimization process of surface roughness was performed by both Taguchi method and the ANOVA analysis with the same results.

Từ khóa:

Độ nhám, Phương pháp Taguchi, Phân tích ANOVA

Tóm tắt

Công trình này được thực hiện bằng việc sử dụng quá trình phay sườn để gia công thành mỏng hợp kim nhôm. Sử dụng phương pháp Taguchi và phân tích phương sai (ANOVA analysis), ảnh hưởng của dạng cắt và điều kiện cắt đến độ nhám bề mặt gia công được nghiên cứu. Với 5 nhân tố có thể điều khiển (dạng cắt, tốc độ cắt, tốc độ đẩy dao, chiều sâu cắt và chiều rộng cắt), ma trận thực nghiệm L18 được sử dụng và tiến hành thực nghiệm để đo độ nhám bề mặt gia công. Bằng phương pháp phân tích phương sai với sự hỗ trợ của phần mềm Intercooled Stata 8.2^{TM}, ảnh hưởng của dạng cắt và điều kiện cắt đến độ nhám bề mặt gia công đã được mô hình hóa với độ tin cậy là 99.14%. Mô hình này đã được kiểm chứng bằng thực nghiệm với các kết quả rất tin tưởng. Ngoài ra, việc tối ưu hóa độ nhám bề mặt cũng được thực hiện bằng hai phương pháp là phương pháp Taguchi và phương pháp phân tích phương sai với cùng một kết quả.

Received: 05/8/2018

Received in revised form: 07/9/2018

Accepted: 15/9/2018

1. INTRODUCTION

The Taguchi method and ANOVA analysis have been widely used in industrial engineering analysis. Moreover, the Taguchi method employs a special design of orthogonal array through reducing the number of experiments to investigate the effect of the entire machining parameters. Recently, this method has been widely employed in several industrial fields, and research work. Lin, Chen, Wang, Lee [1] and Lajis, Mohd Radzi, Nurul Amin [2] used Taguchi and ANOVA analysis to research the effect of main machining parameters such as machining polarity, peak current, pulse duration, and so on, on the EDM machining characteristics such as material removal rate, surface roughness. Tsoukalas [3] and Hsu, Do [4] used L27 orthogonal array of Taguchi method to determine the optimum conditions leading to minimum porosity in aluminum alloy die castings. Rao and Padmanabhan [5] applied the Taguchi method and ANOVA in optimization of process parameters for metal removal rate in electrochemical machining of Al/5%SiC composites. Besides, the Taguchi method and ANOVA analysis were also applied to investigate other machining processes such as turning [6], drilling [7], and milling [8].

The surface roughness and cutting force are important machining characteristics to evaluating the productivity of machining processes. In milling processes, by using Taguchi method and ANOVA analysis, the cutting forces and surface roughness could be investigated based on a number of factors such as depth of cut, feedrate, cutting speed, cutting time, workpiece hardness, etc. Several research works had been conducted in different conditions and had also been applied for different workpieces and tool materials such as Kıvak [9], Ozcelik, and Jayakumar [10]. However, although there were already many studies on surface roughness, it seems that the effect of cutting type and cutting conditions on surface roughness have not been mentioned when using the flank milling the thin wall.

2. EXPERIMENTAL METHOD

2.1. Setup of the experiment

The setup of the experiments in this paper includes workpiece and tool, CNC machine, and surface roughness measurement. The description of the setup is as the followings:

2.1.1. Workpiece, tool, and CNC machine

In order to investigate the effect of milling type and machining conditions on the cutting force and surface roughness, a series of end milling experiments were performed. The cutter and workpiece were chosen as follows. Cutter: a new carbide flat-end mill with number of flutes N = 2, a helix angle $\beta = 30^0$, a rake angle $\alpha_r = 5^0$, and a diameter of 10mm.

The workpiece material was Al6061-T6 and its compositionsare listed in **Table 1**. The properties of the Al6061-T6 were: Hardness 95 HB, Young's modulus = 68.9 GPa, Poisson's ratio = 0.33, tensile strength = 310 MPa.

Table 1. Chemical composites of Al6061-T6

Element	Al	Cr	Cu	Fe	Mg	Mn	Si	Ti	Zn
Composite (%)	98	≤0.3	≤0.4	≤0.7	≤1.2	≤0.15	≤0.8	≤0.15	≤0.25

The experiments were performed at a three-axis vertical machining center (Vcencter-4) (Fig 1).

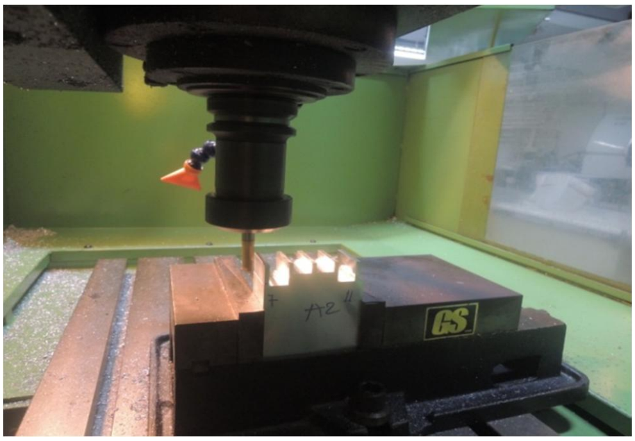

Fig. 1. Flank milling processes in a three-axis vertical machining Vcenter-4

2.1.2. Surface roughness measurement

The surface roughness (Ra) of the product was measured by Mitutoyo SJ.400 portable surface roughness tester as shown in **Fig. 2**. The cutoff length and evaluation length were fixed at 0.8mm and 4mm, respectively. The surface roughness was measured parallel to the machined surface from three different points and repeated five times following five repeated times of each cutting test. The average values of the measurements were evaluated.

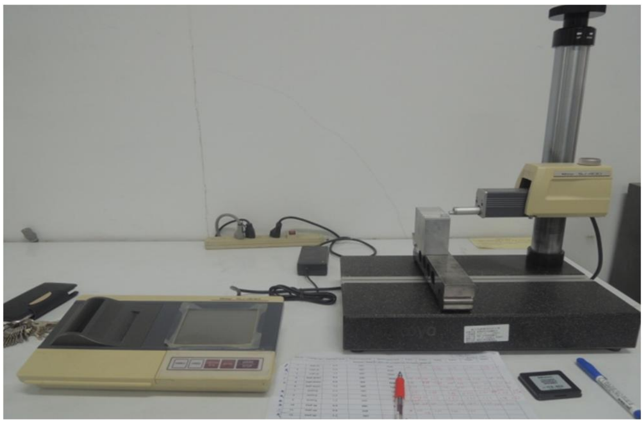

Fig. 2. Setting of surface roughness measurement

2.2. Response surface methodology and Analysis of Variance (ANOVA)

Response surface methodology is a collection of mathematical and statistical techniques that are 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 this response. Almost all Response surface methodology problems use one or both of the first-order model and second-order model of polynomial that are given by Eq. (1) and Eq. (2), respectively [11].

$$y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \varepsilon \quad (1)$$

$$y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \sum_{i}^{k} \sum_{j}^{k} \beta_{ij(i<j)} x_i x_j + \varepsilon \quad (2)$$

where k represents number of independent variables; β_0 , β_i, $\beta_{ii}\beta_{ij}$ are the constants; ε measures the experimental error (noise).

ANOVA analysis can be used to determine the effect of any given input parameter on any output parameter from a series of experimental results. Let $y_{i.}$ represent the total of the observations under the ith treatment that is given by Eq. (3) and $\bar{y}_{i.}$ represent the average of the observations under the ith treatment that is given by Eq. (4). Similarly, let $y_{..}$ represent the grand total of all the observations that is given by Eq. (5) and $\bar{y}_{..}$ represent the grand average of all the observations that is given by Eq. (6), [11].

$$y_{i.} = \sum_{j=1}^{n} y_{ij} \qquad i = 1, 2, \ldots, m \tag{3}$$

$$\bar{y}_{i.} = \frac{y_{i.}}{n} i = 1, 2, \ldots, m \tag{4}$$

$$y_{..} = \sum_{i=1}^{m} \sum_{j=1}^{n} y_{ij} \tag{5}$$

$$\bar{y}_{..} = \frac{y_{..}}{N} \tag{6}$$

Where N = (m*n) is the total number of observations.

ANOVA partitions total variation into its appropriate components. Total sum of squares term can be calculated by Eq. (7), [11].

$$SS_T = \sum_{i=1}^{m} \sum_{j=1}^{n} (y_{ij} - \bar{y}_{..})^2 \tag{7}$$

The Eq. (7) can be rewritten by Eq. (8).

$$SS_T = SS_{Treatments} + SS_E \tag{8}$$

Where $SS_{Treatments}$ is a sum of squares of differences between the treatment average and the grand average, and SS_E is a sum of squares of the differences of observations within treatments from the treatment average. $SS_{Treatments}$ and SS_E can be calculated by Eq. (9) and Eq. (10).

$$SS_{Treatments} = n \sum_{j=1}^{n} (y_{i.} - \bar{y}_{..})^2 \tag{9}$$

$$SS_E = \sum_{i=1}^{m} \sum_{j=1}^{n} (y_{ij} - \bar{y}_{.})^2 \tag{10}$$

While performing ANOVA analysis, degrees of freedom should also be considered together with each sum of squares.

2.3. The Taguchi method and experiment design

Taguchi method was developed by G. Taguchi. This is a statistical method used to improve the product quality. It is commonly used in improving industrial product quality due to the proven success. It is an experimental design and also a beneficial technique for high quality system design. In engineering analysis, the Taguchi method is a powerful method and it has been widely used in the world. This method dramatically reduces the number of tests by using orthogonal arrays and minimizes the effects of factors that cannot be controlled [12].

The parameter design study involves control and noise factors. The measurement of interactions between these factors with regard to robustness is signal-to-noise (S/N) ratio. Normally, there are three kinds of quality characteristics in the analysis of the S/N ratio, namely the bigger-the-better, the smaller-the-better, and the nominal-the-better [13, 14] that can be calculated by Eq. (11) to Eq. (13). For each level of the process parameters, the S/N ratio is calculated based on the S/N analysis.

The bigger-the-better:

$$\frac{S}{N_s} = -10\log\left[\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}\right] \tag{11}$$

The smaller-the-better:

$$\frac{S}{N_s} = -10\log\left[\frac{1}{n}\sum_{i=1}^{n} y_i^2\right] \tag{12}$$

The nominal-the-better:

$$\frac{S}{N_s} = -10\log\left[\frac{\bar{y}}{S_y^2}\right] \tag{13}$$

Where, $\bar{y}$ is the average of observed data, S_y^2 is the variance of y, and n is the number of observations.

The cutting types (A), cutting speed (B), feedrate (C), axial depth of cut (D), and radial depth of cut (E) were selected as control factors in milling processes. The cutting conditions their levels were designed and expressed in the **Table 2**.

Table 2. Milling parameters and their levels

No.	Parameters	Symbol	Level 1	Level 2	Level 3
			-1	**0**	**1**
1	Cutting type	A	Up milling	Down milling	-
2	Cutting speed [m/min]	B	30	65	100
3	Feed per tooth [mm/tooth]	C	0.04	0.10	0.16
4	Axial depth of cut [mm]	D	5	10	15
5	Radial depth of cut [mm]	E	0.2	0.6	1.0

In the experimental layout plan, with four factors and three levels, the most suitable orthogonal array (L_{18} - $2^1 3^4$) was chosen to analyze the effects of machining parameters on the cutting force and surface roughness [13-14]. The experimental plan was performed with 18 experiments and detailed as in **Table 3**.

Table 3. The experimental design with orthogonal array of Taguchi L_{18} ($2^1 3^4$)

No.	Coded factors					Actual factors				
	A	B	C	D	E	Milling type	V_c (m/min)	F_t (mm/tooth)	a (mm)	b (mm)
1	-1	-1	-1	-1	-1	Up	30	0.04	5	0.2
2	-1	-1	0	0	0	Up	30	0.1	10	0.6
3	-1	-1	1	1	1	Up	30	0.16	15	1
4	-1	0	-1	-1	0	Up	65	0.04	5	0.6
5	-1	0	0	0	1	Up	65	0.1	10	1
6	-1	0	1	1	-1	Up	65	0.16	15	0.2
7	-1	1	-1	0	-1	Up	100	0.04	10	0.2
8	-1	1	0	1	0	Up	100	0.1	15	0.6
9	-1	1	1	-1	1	Up	100	0.16	5	1
10	0	-1	-1	1	1	Down	30	0.04	15	1
11	0	-1	0	-1	-1	Down	30	0.1	5	0.2
12	0	-1	1	0	0	Down	30	0.16	10	0.6

13	0	0	-1	0	1	Down	65	0.04	10	1
14	0	0	0	1	-1	Down	65	0.1	15	0.2
15	0	0	1	-1	0	Down	65	0.16	5	0.6
16	0	1	-1	1	0	Down	100	0.04	15	0.6
17	0	1	0	-1	1	Down	100	0.1	5	1
18	0	1	1	0	-1	Down	100	0.16	10	0.2
19	**0**	**0**	**-1**	**-1**	**-1**	**Down**	**65**	**0.04**	**5**	**0.2**
20	**0**	**0**	**-1**	**-1**	**-1**	**Down**	**65**	**0.04**	**5**	**0.2**

3. ANALYSIS AND AVALUATION OF EXPERIMENTAL RESULTS

3.1. Analysis of Variance

In this study, by ANOVA analysis was used to analyze the effects of cutting type, axial depth of cut, feedrate, and spindle speed on the surface roughness. Using Intercooled Stata 8.2^{TM} software, these ANOVA results were shown in **Table 4**. This analysis was performed with 95% confidence level and 5% significance level. This indicates that the obtained models are considered to be statistically significant. The coefficient of determination (R^2), is defined as the ratio of the explained variation to the total variation and is a measure of the fit degree. When R^2 approaches to unity, it indicates a good correlation between the experimental and the predicted values. In Table 4, the contributions of each factor on the surface roughness were listed in the last column. It is clear from the results of ANOVA that the most important factor affecting on the surface roughness is radial depth of cut (factor E, 31.229%). The cause of this problem is that with the thin wall structure, changing radial depth of cut will make a great changing the structure of the machine-thin wall dynamic system and will greatly affect on the vibrations and deformations of the thin wall. So, changing radial depth of cut will much greatly affect on the surface roughness. The second factor influencing the surface roughness is feetrate (factor C, 25.56%). The third factors influencing on the surface roughness is cutting speed (factor B, 9.708%). The fourth and fifth factors influencing on the surface roughness are cutting type (factor A, 4.481%) and axial depth of cut (factor D, 1.867%), respectively.

Table 4. Results of ANOVA for surface roughness

	Factor	Sum of squares	DOF	Mean square	F-value	Percent contribution
Model		0.2945	17	0.0173	0.0000	
Cutting type	A	0.0132	1	0.0132	0.0000	4.481
Cutting speed (m/min)	B	0.0286	2	0.0143	0.0000	9.708
Feedrate (mm/tooth)	C	0.0753	2	0.03765	0.0000	25.560
Axial depth of cut (mm)	D	0.0055	2	0.00275	0.0000	1.867
Radial depth of cut (mm)	E	0.0920	2	0.046	0.0000	31.229
	BA	0.0212	2	0.0106	0.0000	7.196
	CA	0.0440	2	0.022	0.0000	14.936
	CB	0.0022	2	0.0011	0.0000	0.747
	DA	0.0109	1	0.0109	0.0000	3.700
	DB	0.0000	0	0.0000	0.0000	0.000
	DC	0.0000	0	0.0000	0.0000	0.000
	EA	0.0017	1	0.0017	0.0000	0.577
	Error	0.0000	0	0.0000		0.000
	Total	**0.2946**	**17**	**0.1602**		**100**

3.2. Regression and Verification of cutting forces and surface roughness model

The regression analysis was used to model and analyze the relationship between a dependent variable and one or more independent variables. In this study, one dependent variable is the surface roughness (R_a), whereas the independent variables are milling type (A), cutting speed (B), feedrate (C), axial depth of cut (D), and radial depth of cut (E). By using Intercooled Stata 8.2^{TM} software, the most suitable model of surface roughness was given by Eq. (14) and Eq. (15).

$$\begin{cases} R_a = 0,0502 - 0.1747A + 0.0328B + 0.2492C + 0.1085D + 0.0934E \\ -0.0138BA + 0.4120CA - 0.0882CB + 0.0054DB - 0.0292DC - 0.1482EA \\ +0.1093EB - 0.1518EC + 0.0917BB + 0.0830CC + 0.7064CC + 0.0660EE \\ \qquad R^2 = 99.14\%, \ R^2_{Ajd} = 98.46\% \end{cases} \tag{14}$$

and,

$$\begin{cases} A = \begin{cases} -1 \text{ if up milling} \\ 0 \text{ if down milling} \end{cases} \\ B = \frac{V_c - 65}{35} \\ C = \frac{F - 0.10}{0.06} \\ D = \frac{a - 10}{5} \\ E = \frac{b - 0.6}{0.4} \end{cases} \tag{15}$$

where V_c is the cutting speed; F is the feedrate [mm/tooth]; a is the axial depth of cut [mm]; b is the radial depth of cut [mm].

Here R_a was presented as the predictive equations for surface roughness. The verification result of surface roughness model was described in **Fig. 3**. As seen from these figures, the predicted results were very close to the experimental results. There is a very good relation between predicted values and test values. The R^2 value of the equations obtained by regression model for surface roughness was found to be 99.14%. These results showed that the regression model was shown to be successfully investigated of surface roughness in milling processes.

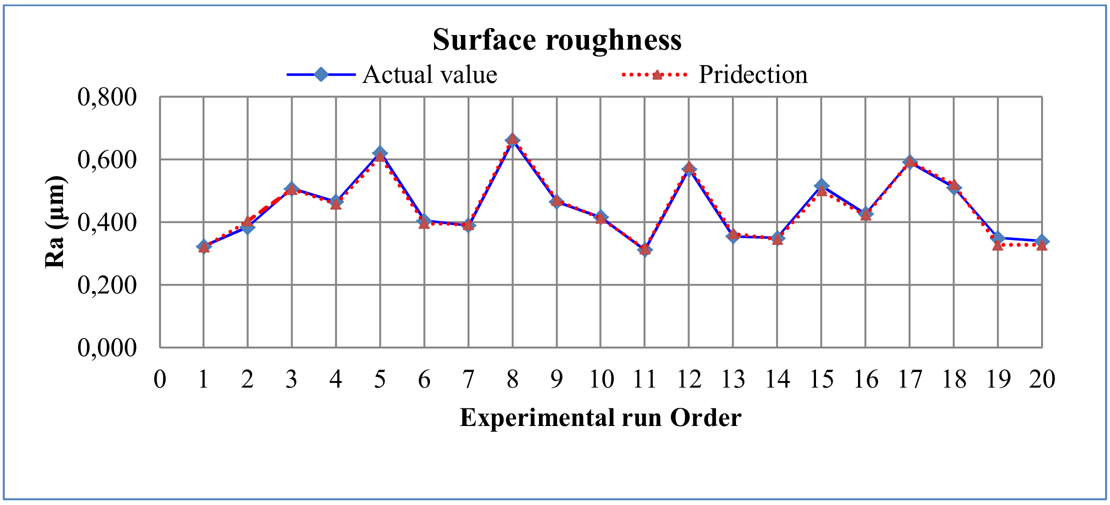

Fig. 3 Experimental and predicted values of surface roughness

3.3. Estimation of optimum surface roughness by ANOVA analysis and Taguchi method

3.3.1. The optimization parameter of milling process by ANOVA analysis

The lowest value of surface roughness is very important for quality improvement of the machining product and lowering production costs. In this study, the quadratic regression model of surface roughness as presented by Eq. (14) that was used to find the optimized values of surface roughness and machining parameters. By using MATLAB R2016a^{TM} software, the optimization process was expressed as the MATLAB algorithm and it was shown in **Fig. 4.** The optimized results of machining parameters were obtained as below.

x = [0, 0, -1, -1, -1] ⟹A = 0; B = 0; C = -1; D = -1; E = -1.

fval = 0.361

```
clc;
clear all;
close all;
f = @(x)0.0502-0.1747*x(1) + 0.0328*x(2)+0.2492*x(3) + 0.1085*x(4)...
    + 0.0943*x(5)- 0.0138*x(2)*x(1) + 0.4120*x(3)*x(1)- 0.0882*x(3)*x(2)...
    + 0.0054*x(4)*x(2)- 0.0292*x(4)*x(3) - 0.1482*x(5)*x(1)...
    + 0.1093*x(5)*x(2)- 0.1518*x(5)*x(3)+ 0.0917*x(2)*x(2)...
    + 0.0803*x(3)*x(3)+ 0.0764*x(4)*x(4)+ 0.0660*x(5)*x(5);
options = optimset('GradObj','on');
[x,fval,exitflag,output] = ...
fmincon(f,[0;0;0;0;0],[],[],[],[],[-1;-1;-1;-1;-
1],[0;1;1;1;1],[],optimset('Display','iter'));
x
fval
```

Fig. 4. .MATLAB code for optimization of machining parameters

So by ANOVA analysis, the optimal parameters of machining process were determined as below:

Milling type: down-milling

Cutting speed: V_c = 65 m/min

Feedrate: F = 0.04 mm/tooth

Axial depth of cut: a = 5 mm

Radial depth of cut: b = 0.2 mm

And the optimization value of surface roughness was: R_a = 0.361 μm.

3.3.2. The optimization parameter of milling process by Taguchi method

By using Taguchi method, the optimal values of control factor were determined by analysis of the signal-to-noise ratio. As in ANOVA analysis, the lowest value of surface roughness is very important to improve the machining product, so the smaller-the-better equation was used for calculation of the S/N ratio that was determined by Eq. (12). The values of the S/N response for observations of surface roughness were listed in **Table 5**.

Table 5. The S/N response for surface roughness

Levels	Control factors				
	A	B	C	D	E
Level 1	9.130596	8.192268	**11.866518**	**10.557418**	**12.739955**
Level 2	**10.443294**	**10.176673**	9.961999	9.170819	7.942237
Level 3	-	9.991894	7.532319	9.632599	8.678644
Delta	1.312698	1.799626	4.334199	1.386598	4.797717

The effect of cutting parameters on the surface roughness were evaluated and shown in **Fig 5.** The results from this figure show that the milling type affects on the surface roughness in which down-milling gave bester surface than up-milling. With other machining parameter, the surface roughness values exhibited decreasing tendency with decreasing of radial depth of cut and feedrate. It is seem that the tendency of surface roughness was decreased with increasing of spindle speed. So, in order to improve the surface roughness in the flank milling process, the milling type and machining conditions were proposed that were down-milling, decreasing the axial depth of cut, the feedrate, and increasing the cutting speed.

By Taguchi techniques, the best level of each control factor was determined according to the highest S/N ratio at the level of that control factor. By these techniques, from the values of Table 5 and from Fig. 5, the level and S/N ratios for the factors giving the best Ra value were specified as factor A (level 0, S/N = 10.443294 dB), factor B (level 0, S/N = 10.176673 dB), factor C (level -1, S/N = 11.866518 dB),), factor D (level -1, S/N = 10.557418 dB), and factor E (level -1, S/N = 12.739955 dB). So by Taguchi method, the optimum value of surface roughness was obtained in the down-milling (A=0), at a cutting speed of 65 m/min (B=0), a feedrate of 0.04 mm/tooth (C=-1), an axial depth of cut of 5 mm (D=-1), and a radial depth of cut of 0.2 mm (E=-1). The optimized results between ANOVA analysis and Taguchi method are the same. The difference between predicted value and measured value in experimental number 19 and 20 is smaller than 5% (this case: 3.28%).

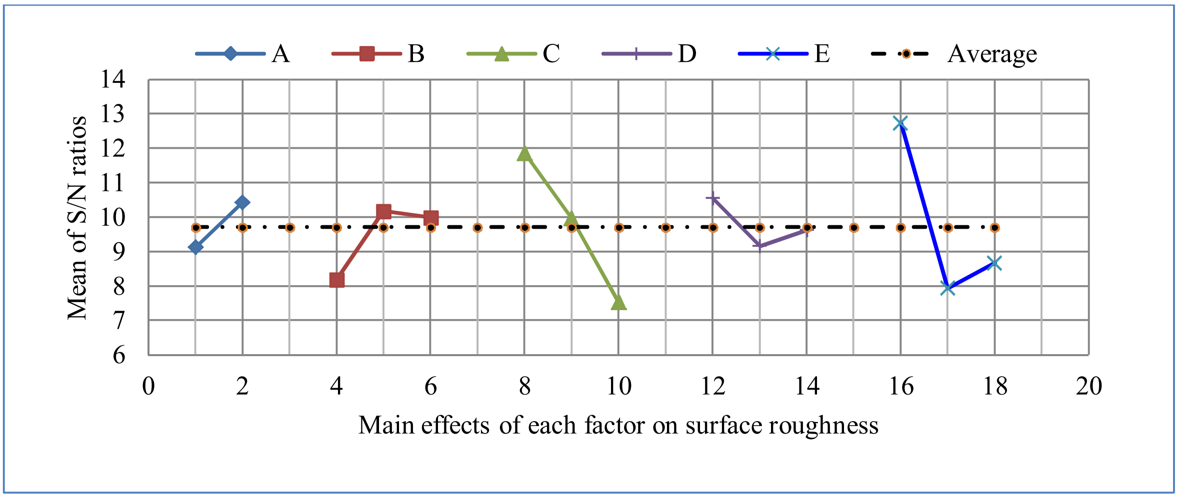

Fig. 5. Main effects of each factor on surface roughness

4. CONCLUSIONS

Depending on the analysis of experimental results, the conclusions of this study can be drawn as follows.

The milling type and milling conditions affect differently on the surface roughness; two of the most important factors affecting on the surface roughness are radial depth of cut and cutting speed. The regressions of surface roughness was modeled as given by Eq. (12) with the confidence level is 99.14%, and these models were verified by experiments with very promising results.

In flank milling processes, the cutting type affects on the surface roughness in which down-milling gave the bester surface than up-milling. Besides, the tendency of surface roughness decreases with decreasing axial depth of cut, radial depth of cut, and feedrate while the tendency of surface roughness decreases with increasing of cutting speed.

Taguchi method and ANOVA analysis can be used to analyze the effect of milling type and milling conditions on the surface roughness, and also used to find the optimal value of surface roughness. In this study, the optimized results from Taguchi method and the ANOVA analysis are the same. The optimum value of surface roughness is 0.361 μm that was obtained in the down milling, at a cutting speed of 65 m/min, a feedrate of 0.04 mm/tooth, an axial depth of cut of 5 mm, and a radial depth of cut of 0.2 mm.

ACKNOWLEDGMENTS

The authors appreciate the support from from the Advanced Institute of Manufacturing with High-tech Innovations, National Chung Cheng University, Taiwan, and Hanoi University of Industry, Vietnam.

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