Jurnal Polimesin
Department of Mechanical Engineering
State Polytechnic of Lhokseumawe
http://e-jurnal.pnl.ac.id/polimesin
e-ISSN : 2549-1999 No. : 4 Month : August
p-ISSN : 1693-5462 Volume : 21 Year : 2023

Article Processing Dates: Received on 2023-06-29, Reviewed on 2023-07-08, Revised on 2023-07-31, Accepted on 2023-08-22 and Available online on 2023-08-25

Optimization of CNC machining parameters to improve surface roughness quality of the AL6061 material using the Taguchi method

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Abstract

Surface quality is an important variable of a milling machining process. Therefore, choosing the best machining parameters is very important to arrange so that the best surface quality can be obtained. The purpose of this research is to optimize machining parameters by using surface roughness as a performance indicator variable. This research was carried out by making 9 surface roughness test specimens through a facing process on a TU-3A CNC milling machine. Each test specimen is made with a different level of machining parameters. Machining parameters used in this research are spindle speed, feed rate, and depth of cut. Surface roughness values obtained from 9 test specimens were analyzed using the Taguchi method, signal-to-noise ratio, and Analysis of Variance (ANOVA). The Taguchi approach is also used to predict the best machining parameter configurations. The results of the signal-to-noise ratio analysis show that the surface quality is affected by spindle speed, depth of cut and feed rate, respectively. The results of measurements on 9 test specimens showed the best roughness values were 0.275 µm. While the results of the Taguchi analysis show that the optimal surface roughness value can be obtained at 0.267 µm for machining conditions with the parameters spindle speed 1100 rpm, feed rate 85 mm/min and depth of cut 0.25 mm. Furthermore, ANOVA yielded contribution values from spindle speed, feed rate and depth of cut to the surface roughness values of 51.80%, 36.88% and 10.72%, respectively.

Keywords:
Taguchi orthogonal array, signal to noise ratio, milling proses, machining parameters, surface roughness.

1 Introduction

Currently, Computer Numerical Control (CNC) machines are widely used in the manufacturing industry. CNC machines are usually used for various purposes to manufacture a product. The advantage of the CNC machine itself is its ease of operation and programming according to needs. Detailed and complicated specimens can be easily performed on a CNC machine using only the NC programming facilities found on all CNC machines. CNC machines can also be used to produce mass products with the same quality and can be done efficiently.

Along with increasing human needs which are very diverse, the manufacturing industry in Indonesia is also growing, one of them is the machining process industry. The machining process is a general term used to describe a group of processes consisting of removing material and modifying the surface of the specimen with a variety of processing methods [1]. The main objective of this manufacturing industry is to produce high-quality products in a short time with low production costs. To improve the quality of machine products and reduce machine costs, it is necessary to select optimal machining parameters [2].

The quality of the results of a good machining process can be seen, one of which is the level of surface roughness of the material produced by the machining process. Surface roughness is one of the most common ways to assess a product's quality [3][4]. The surface roughness of a mechanical component can affect performance related to the functional aspects of the product. Research has been carried out to see the effect of four machining parameters on surface roughness. The selected machining parameters include spindle speed, feed rate, depth of cut and coolant flow. The experimental design was based on the Taguchi technique including the orthogonal array L9 with four factors and three levels for each variable and studied the contribution of each factor to the surface roughness. Experiments were carried out on EN31 material on a CNC vertical milling machine using carbide inserts. Taguchi analysis results show that spindle speed is a parameter that significantly affects the surface roughness value followed by the depth of cut, feed speed and coolant flow respectively [5].

Optimized cutting conditions are determined by choosing the appropriate machining process parameters [6]. The relationship between the feed rate and product surface roughness is direct. Additionally, cutting settings have a direct impact on tool life and cutting tool performance [7]. Factors affecting surface roughness are analyzed to determine the optimal cutting combination [8]. The metal removal rate in the milling process is influenced by the machining parameter values. The irregularities found on the work surface are observed in the form of contour heights of valleys and hills.

Some components require a high level of surface smoothness to prevent friction between components, for example in mechanical components of machine elements that require high smoothness to prevent friction between engine components, this is very important because it will affect engine performance.

Machining of each mechanical component can be done using different techniques with results that are not much different, but each technique does not have the same efficiency [9]. The choice of processing technique depends on the goals to be achieved. Based on the machining purpose, there are different parameter combinations, such as spindle speed, feed rate and depth of cut to obtain different surface quality results. These three parameters contribute to the surface quality of the product resulting from the machining process. The magnitude of the contribution of each of these parameters is not the same. To find out the magnitude of the contribution of each of these parameters, it is necessary to do research. In this research, machining parameters such as spindle speed, cutting speed and depth of cut will be analyzed to see their effect on the surface quality of the resulting product.

The contribution of machining parameters to the aluminum alloy machining process are cutting speed, feed rate and depth of cut, respectively. The research was carried out using HSS End Mill cutting tool with 2 cutting edges and without using coolant. The Taguchi method combined with the experimental design was applied to obtain the optimum surface roughness level response characteristics [10]. Research on the surface roughness of aluminum Al6061 has also been carried out with various feed rates of 200, 400, 600, 800 and 1000 mm/min as the tested factor [11]. Based on the research results, it was found that the level of surface roughness of aluminum was affected by the speed of ingestion. The results showed that the lowest surface roughness of 0.31 µm was obtained at the smallest feed rate machining conditions of 200 mm/minute and the highest surface roughness value of 0.75 µm was obtained at machining conditions with a feed rate of 1000 mm/minute. From these results it can be concluded that the lower the feed rate used, the lower the Ra value produced and the higher the feed rate used, the higher the Ra value produced.

Research on the milling process of aluminum alloy 6061 has been carried out with the hss cutting tool under minimum lubrication conditions [12]. This study gives the result that the interaction between cutting speed and feed rate has a large influence on surface roughness. The effect of cutting speed on surface roughness is greater than that of the feed rate.

This research aims to determine the optimum machining parameters of Al6061 aluminum alloy material to obtain the optimum surface roughness level in the Al6061 for milling process with HSS End Mill.

2 Research Methods

The data analysis method used in this study is a quantitative descriptive method. The Taguchi method approach is used to examine the data obtained from the surface roughness test results, where the results are in the form of quantitative data. The Taguchi design analysis was chosen on the condition that smaller is better. There are 9 test specimens in this research. Each test specimen was made by machining process with different levels of spindle speed, cutting speed and depth of cut. The roughness value used is the average of three measurements for each test specimen.

The material used in this study is aluminum alloy Al-6061 with dimensions of 50×50×50 mm as shown in Fig. 1. Aluminum 6061 is a precipitation-hardening alloy, which combines magnesium and silicon as its main alloying elements. The nominal composition of type 6061 aluminum is 97.9% Al, 0.6% Si, 1.0% Mg, 0.2% Cr and 0.28% Cu. The density of aluminum alloy 6061 is 2.7 g/cm^3 (0.0975 lb/in^3). This material has good mechanical properties, is lightweight, durable and has a high degree of corrosion resistance. Details of the mechanical properties of these materials are shown in Table 1.

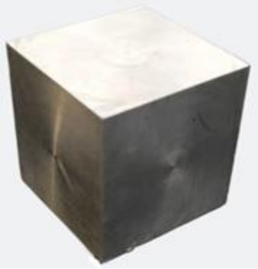

Fig. 1. Aluminium alloy Al-6061.

Table 1. Mechanical properties of aluminum alloy Al-6061

Mechanical proporties	Metric	British
Ultimate tensile strength	310 Mpa	45000 psi
Tensile yield strength	276 Mpa	40000 psi
Shear strength	207 Mpa	30000 psi
Fatique strength	96.5 Mpa	14000 psi
Modulus of elasticity	68.9 Mpa	10000 psi
Shear modulus	26 Gpa	3770 ksi

Nine specimens of aluminum alloy Al-6061 were used in this research. Each specimen is machined for the facing process using a TU-3A CNC milling machine with different machining parameters for each specimen. All specimens were machined with an HSS End Mill cutting tool with a diameter of 10 mm and 2 cutting edges as shown in Fig. 2. Each cutting tool is only used for machining one specimen. The trajectory of the cutting tool for machining each specimen is shown in Fig. 3.

Fig. 2. Cutting tool.

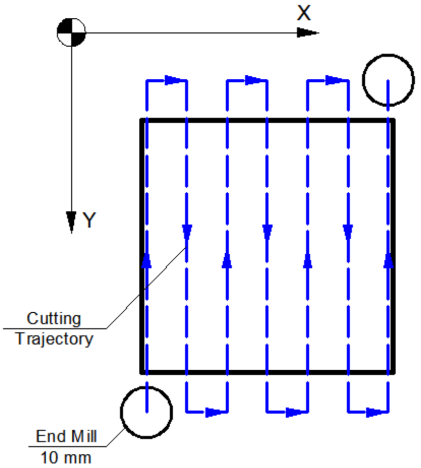

Fig. 3. Cutting tool trajectory.

The machine used in this research is a type of CNC Milling TU-3A. The TU-3A CNC machine was produced by the EMCO Industrial Training - EMCO MAIER GmbH in 1982. At present, the TU-3A CNC machine has undergone the process of changing from EMCO controller to the Mach-3 controller type as shown in Fig. 4. The machining process for Al6061 material is carried out using a TU 3A CNC machine. The surface roughness value of the product resulting from this machining process is measured using a surface roughness measuring instrument.

Fig. 4. CNC TU-3A milling machine.

Surface roughness measurement/testing was carried out using the Mitutoyo type SJ-310 surface roughness tester as shown in Fig. 5. Each variation of the experiment was carried out by measuring the surface roughness with three replications to minimize disturbance parameters that might occur during the machining process. The distance between the first measurement line and the next measurement line is 10 mm with the second test point being on the center line of the test specimen. The stroke of each measurement is 8 mm.

Fig. 5. Surface roughness tester.

Work steps of this research are described in diagrammatic form in Fig. 6. The variables used in this research are the variables contained in the CNC milling machine which are then used to see the effect on the surface roughness of objects. The variables used in this research are independent variables and dependent variables. Independent variables are variables that affect the variables to be observed, namely spindle speed, feed rate and depth of cut. Then the dependent variable is the variable that is influenced by the independent variable. In this research, the dependent variable studied was surface roughness. By using the recommendation cutting condition catalog reference, the parameter level values are designed as shown in Table 2.

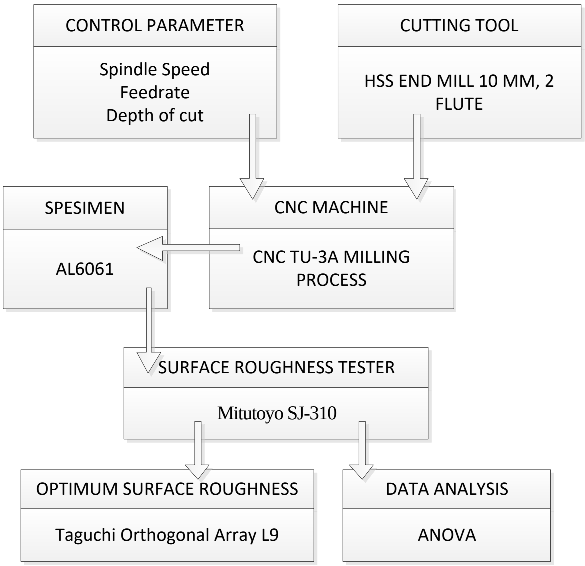

Fig. 6. Research flow.

Table 2. Machining parameter level

Machining parameters	Parameter level		
	1	2	3
Spindle speed (rpm)	600	900	1100
Feed rate (mm/min)	55	70	85
Depth of cut (mm)	0.25	0.50	0.75

Various approaches and techniques, including artificial intelligence or soft computational methods, the Taguchi method, response surface methodology, machining theory, conventional experimental designs, and artificial neural networks, have been used in surface roughness studies to predict surface roughness quality [13][14]. The experimental design method (DOE) has been used for many years in various industries to improve production processes and products [15]. The effect of feed rate, cutting speed, nose radius, depth of cut, and cutting environment on power consumption during machining of AISI P20 tool steel has been studied using the Taguchi approach [16].

This research was conducted by providing three test parameters with three different levels for each test. The test design is shown in Table 3. The test method used is a factorial design with 3 levels and 3 factors, so the number of experimental variations is 3^3 or 9 experimental variations. The experimental design was determined using the Taguchi method (orthogonal array L9) [17].

Table 3. Design of machining parameters

Experimen run	Spindel speed (rpm)	Feed rate (mm/min)	Depth of cut (mm)
Run-1	600	55	0.25
Run-2	600	70	0.50
Run-3	600	85	0.75
Run-4	900	55	0.50
Run-5	900	70	0.75
Run-6	900	85	0.25
Run-7	1100	55	0.75
Run-8	1100	70	0.25
Run-9	1100	85	0.50

The quality characteristic of the response used in this experiment is the smaller is better for surface roughness response. Calculation of the value of the signal-to-noise ratio for the surface roughness response was carried out using statistical computational tools. The signal-to-noise ratio for this characteristic is calculated using the formula in Eq. 1 [18].

$$\eta = -10log\left(\frac{1}{n}\sum_{i=1}^{n} y_i^2\right) \qquad (1)$$

where:
η = signal to noise ratio
n = number of sample
y_i = observed data

The calculation of the signal-to-noise ratio is performed to analyze the influence of machining parameters to make them more accurate. The experimental results were analyzed analytically and graphically. Analysis of Variance (ANOVA) was then performed to determine the percentage contribution of all parameters in each response. The two analytical methods above are very important to determine the parameters that significantly affect the level of surface roughness.

3 Results and Discussion

The machining of the surface roughness test specimens was carried out using a TU-3A CNC milling machine with machining parameters referring to the research design according to Table 3. The surface roughness value of each test specimen shown in Table 4 is the average surface roughness value of three measurements for each test specimen.

Table 4. Surface roughness of the spesimens

Experiment run	Spindle speed (rpm)	Feed rate (mm/min)	Depth of cut (mm)	Ra (μm)
Run-1	600	55	0.25	0.484
Run-2	600	70	0.50	0.506
Run-3	600	85	0.75	0.537
Run-4	900	55	0.50	0.418
Run-5	900	70	0.75	0.442
Run-6	900	85	0.25	0.298
Run-7	1100	55	0.75	0.476
Run-8	1100	70	0.25	0.275
Run-9	1100	85	0.50	0.337

Ra = surface roughness

Signal-to-noise ratio analysis is then performed using the Taguchi method. Signal-to-noise ratio response tables are used to analyze the impact of each machining parameter (spindle speed, feed rate, and depth of cut) on the surface roughness. Table 4, shows the response of the signal-to-noise ratio for surface roughness. This table shows the signal-to-noise ratio at each machining parameter level and how it changes when the machining parameter values are changed from one level to another.

Signal-to-noise ratio response graphs shows the impact of each machining parameter more clearly. Fig. 7 displays the response graph for each machining parameter. The slope of the line connecting the levels shows the strength of the effect of each machining parameter.

The magnitude of the signal-to-noise ratio for each research condition was obtained through analysis using the Taguchi method (orthogonal array L9). In addition to the signal-to-noise ratio of each design, condition was also calculated. The results of the analysis for each experiment are shown in Table 5. The delta value which is the difference between the highest and lowest signal-to-noise values at all different levels is also shown. The magnitude of the rank value of each factor parameter depends on the magnitude of the delta value of each factor. From the delta and rank values shown in Table 6, it is known that the factor with the highest delta value is the factor that most significantly influences the surface roughness value. Based on the order ranking, it can be seen that spindle speed is a parameter that significantly affects surface roughness, followed by depth of cut and feed rate. These results are consistent with the results of research conducted by M. P. Londhe where the order of parameters that affect the surface roughness value from highest to lowest is spindle speed, depth of cut, feed rate and coolant flow.

Table 5. Surface roughness relation with signal-to-noise ratio

Experiment run	Ra (µm)	SNRA1
Run-1	0.484	6.3031
Run-2	0.506	5.9170
Run-3	0.537	5.4005
Run-4	0.418	7.5765
Run-5	0.442	7.0916
Run-6	0.298	10.5157
Run-7	0.476	6.4479
Run-8	0.275	11.2133
Run-9	0.337	9.4474

Table 6. Signal-to-noise ratio response: smaller is better

Level	Spindle speed	Feed rate	Depth of cut
1	5.874	6.776	9.344
2	8.395	8.074	7.647
3	9.036	8.455	6.313
Delta	3.163	1.679	3.031
Rank	1	3	2

The graph of the main effect on the signal-to-noise ratio clearly shows the response trend of each machining parameter to surface roughness with the characteristic smaller is better. This condition is shown in Fig. 7. Fig. 8 shows the interaction between all machining parameters on surface roughness.

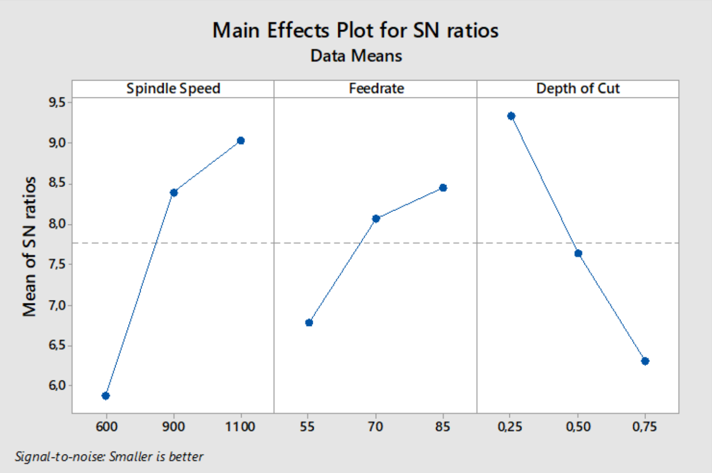

Fig. 7. Graph of the main effects for signal to nose ratio.

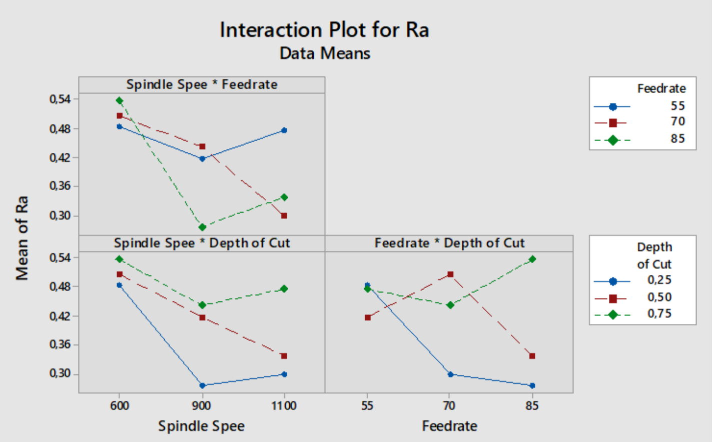

Fig. 8. Graph of interaction machining parameter for surface roughness.

Analysis of Variance (ANOVA) was carried out to determine the contribution of each machining parameter to the surface roughness of Aluminum Al6061 material resulting from the milling process. Analysis was performed using a 95% confidence level and a significance level of 0.05. The results of the ANOVA analysis of surface roughness are shown in Table 7. This table shows that the P-values for spindle speed, feed rate and depth of cut are 0.011, 0.053 and 0.016, respectively. The P-value for spindle speed and depth of cut is smaller than the confidence level used in the ANOVA analysis, which is 95% or 0.05. This shows that these two parameters have a significant effect on the surface roughness value of the workpiece with contributions of 51.80% and 36.88%, respectively. Meanwhile, the P-value for the feed rate is 0.053 or slightly above the confidence value, which means that the feeding speed parameter does not significantly affect the surface roughness value of the workpiece, which only contributes 10.72%. This condition is also in line with the results of the signal-to-noise ratio analysis carried out using the Taguchi method and produces the parameters that have the most influence on the roughness value are spindle rotation followed by depth of cut and feed speed.

Table 7. ANOVA table for the surface roughness

Source	DF	Seq SS	Contri-bution	Adj SS	Adj MS	F-Value	P-Value
Spindle speed	2	0.0371	51.80%	0.0371	0.0185	86.07	0.011
Feed rate	2	0.0077	10.72%	0.0077	0.0036	17.81	0.053
Depth of cut	2	0.0264	36.88%	0.0264	0.0132	61.28	0.016
Error	2	0.0004	0.60%	0.0004	0.0002		
Total	8	0.0716	100.00%				

Finally, a mathematical model was derived for the optimum surface roughness criteria on the Aluminum Al6061 milling process. The analysis was carried out by considering the parameters that contribute to surface roughness, namely spindle speed, feed rate, and depth of cut with the notations v, f, and t respectively, and with the help of the surface roughness test results of Al6061 material. ANOVA table for the linear regression is shown in Table 8 while the mathematical model for Ra uses multiple linear regression and correlation analysis is shown in Eq. 2.

$$Ra = 0.7157 - 0.00029\, v - 0.00254\, f + 0.2656\, t \qquad (2)$$

Table 8. ANOVA table for linear regresion

Term	Coef	SE Coef	T	P
Constant	0.71570	0.076200	9.39	0.000
Spindle speed	-0.00029	0.000049	-5.93	0.002
Feed rate	-0.00254	0.000821	-3.09	0.027
Depth of cut	0.26560	0.049200	5.39	0.003

From Eq. 2 it can be seen that the spindle speed, feed rate and depth of cut parameters contribute to the surface roughness value, Ra. The first two parameters, namely spindle speed and depth of cut, are negative. This shows that the value of spindle speed and feed rate is inversely proportional to the value of surface roughness, which means that the value of surface roughness will tend to decrease if there is an increase in one or both of these parameters. And vice versa, the value of surface roughness will tend to increase if the value of the spindle speed and/or feed rate decreases. In contrast the depth of cut parameter has a directly proportional relationship to the surface roughness value where the surface roughness value will increase with increasing depth of cut value.

The residual graph plot is used to check the validation of research data. If the residual plot is around the normal line, then normality is assumed to be satisfactory. Examination of the residual vs normal probability graph (Fig. 9) shows that the residuals lie close enough to the straight line to imply that the errors are normally distributed and provide the support that the normality of the data is satisfactory. Furthermore, the graph of residual vs fitted value is shown in Fig. 10. The standard residue is in the range of 3 to -3 therefore no unusual structure is seen.

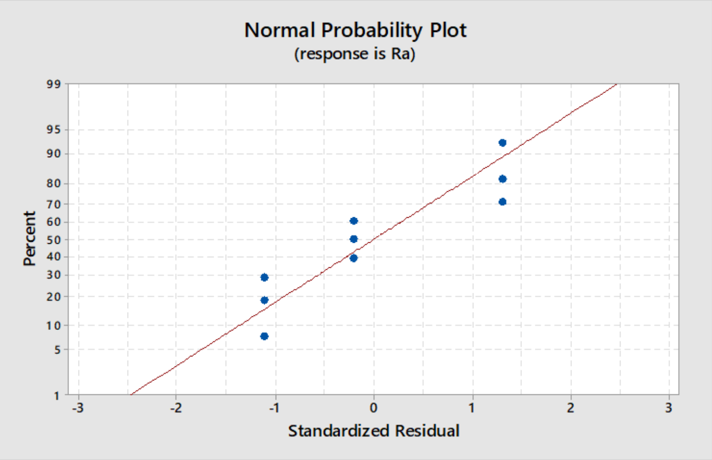

Fig. 9. Graph of residual vs normal probability.

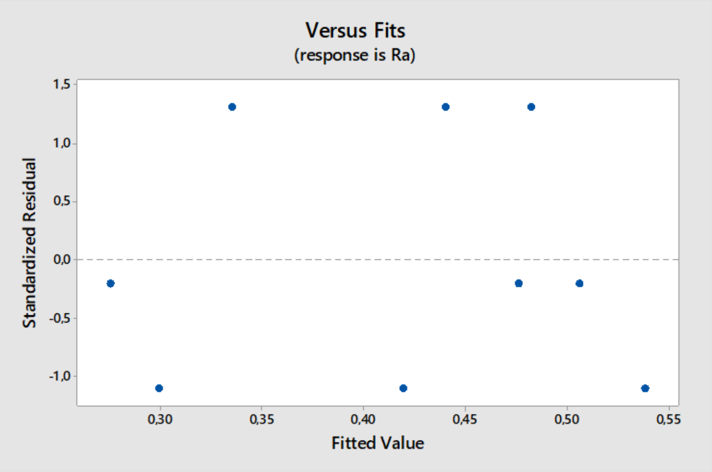

Fig. 10. Graph of residual vs fitted value.

The graph of residuals vs order data shows the residuals for running the trial sequence. In this graph, the residues must be random and do not show any pattern to the trial order. Furthermore, Fig. 11 shows that there is no particular pattern or unusual structure seen in the data. This implies that the regression model made is good.

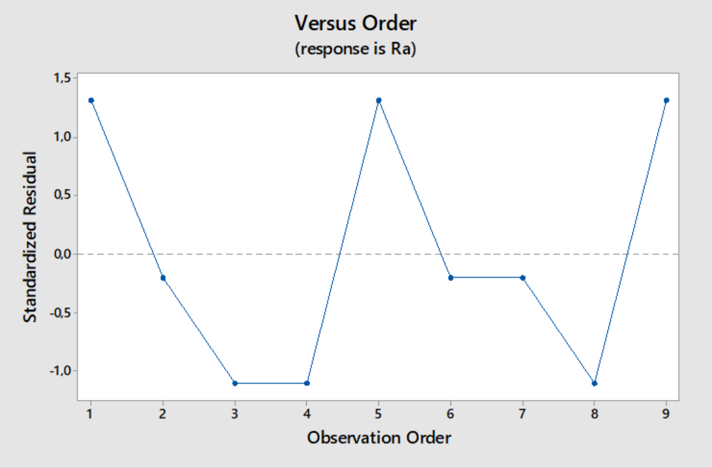

Fig. 11. Graph of residual vs observation order.

Referring to Table 6, the machining parameter with the highest delta value is the most effective and significantly affects the surface roughness value of the test specimens resulting from the milling machining process. Based on the sequence, it can be seen that the spindle speed is the most important machining parameter which has a significant effect on surface roughness, followed by depth of cut and feed rate.

The same thing was also obtained from the results of the Analysis of Variance (ANOVA) as shown in Table 7. Spindle speed is the machining parameter that has the most influence on the value of surface roughness with a contribution of 51.80% followed by the depth of cut and feed rate with contributions respectively 36.88% and 10.72%.

In Taguchi analysis, the signal-to-noise ratio is designed to select the highest level factor values to optimize surface quality features. The surface quality gets better when the surface roughness value gets smaller, it's just that the signal-to-noise ratio value is designed so that it always changes to a better quality characteristic when the value gets bigger.

The optimum level for each machining parameter is obtained by separating each parameter based on the signal-to-noise ratio at various levels. Parameters with the best levels are shown in Table 6 and Fig. 7 where the spindle speed is level 3 (1100 rpm), the feed rate is level 3 (85 mm/min), and depth of cut is level 1 (0.25 mm). Under these conditions, the resulting surface roughness value is by the prediction results of the Taguchi method which is 0.267 µm with a signal-to-noise ratio of 11.297. The surface roughness value predicted by the Taguchi method is better than the best surface roughness value obtained from direct measurements of 9 test specimens that 0.275 µm for machining conditions with a spindle speed of 1100 rpm, a feed rate of 70 mm/min and a cutting speed of 0.25 mm.

4 Conclusion

In this study, the optimum surface roughness parameters were predicted using the Taguchi method in combination with Analysis of Variance (ANOVA) to obtain the percentage contribution of each machining parameter to the surface roughness value. The combination of the Taguchi method with the experimental design was carried out to obtain optimum response characteristics. A total of 9 tests have been carried out referring to the Taguchi orthogonal array L9. The relationship between machining parameters (spindle speed, feed rate, and depth of cut) with surface roughness was evaluated at different levels using the Design of Experiment method. Taguchi analysis was carried out with a smaller better trial option. The results of the analysis show that the surface roughness is strongly influenced by the three machining parameters. Signal-to-noise ratio analysis shows that spindle speed is a very significant machining parameter affecting surface quality followed by depth of cut and feed rate. Therefore, the optimal combination of machining parameters to produce the best surface quality is at the condition of spindle speed of 1100 rpm (level 3), depth of cut of 0.25 mm (level 1) and feed rate of 85 mm/min (level 3). The results of the ANOVA also show the same conditions as those produced in the signal-to-noise ratio analysis. Furthermore, the ANOVA showed that the spindle speed machining parameters contributed 51.80%, depth of cut 36.88% and feed rate 10.72% to the surface roughness value.

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