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# The Effect of Depth of Cut and Spindle Speed on Cutting Parallelism Results on Aluminum 6061 CNC TU-3A Retrofit Machine

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**ABSTRACT**

Machining process is an important part of manufacturing to form and finish high-precision components. Milling is a commonly used technique, and the advancement of CNC technology has enabled precise and consistent production. This study evaluated the effect of spindle speed and depth of cut on the surface parallelism (µm) of aluminum 6061 using a TU-3A retrofit CNC milling machine. A quantitative experimental method with factorial design of experiments (DOE) was applied, testing spindle speeds of 600 RPM, 800 RPM, and 1000 RPM and depths of cut of 1.0 mm, 1.5 mm, and 2.0 mm, while maintaining constant feed rates of 48 mm/min, 64 mm/min, and 80 mm/min. The results showed that spindle speed had no significant impact on surface parallelism (µm) (P-value = 0.924), although higher speeds showed a trend of better results. In contrast, depth of cut significantly affects parallelism (µm) (P-value = 0.000), with greater depth improving surface quality (µm). In addition, the interaction between spindle speed and depth of cut is also significant (P-value = 0.002), indicating that the combination of higher spindle speed with lower depth of cut produces better results. These findings suggest optimal machining parameters to improve surface parallelism (µm) in aluminum milling operations.

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Keywords: CNC, depth of cut, parallelism, retrofit, spindle speed

## 1. Introduction

In the manufacturing industry, machining processes play an important role in shaping and finishing components with high precision. One of the most commonly used machining methods is the milling process. In this process, various machining parameters, such as depth of cut and spindle speed, have a significant impact on the final result, including the parallelism of the work surface.

The development of technology in the industrial sector is currently experiencing rapid acceleration, especially in the use of computer systems in the field of machining. Consumer demand for component quality that is precise, consistent, quickly completed, and in large quantities can be more easily met with CNC machines compared to conventional machines [1].

In production activities using CNC milling machines, the quality of the resulting surface will affect the selling value of the product [2]. In metalworking using machining processes, surface quality is determined by the roughness and smoothness of the surface of the resulting product. The latest machining method improvements aim to improve the quality of the processed surface. Smooth surface quality is not only related to product tolerance and aesthetics, but can also extend the life of the machine, especially for contact surfaces that rub against each other [3].

According to Asep and Arya (2014), the CNC Headman machine is a CNC milling machine that can be operated manually or automatically using GSK program control. The purpose of their study was to determine the effect of spindle rotation speed and feed depth on the level and parallelism of the aluminum 6061 surface using the CNC Headman milling machine [4].

Malang State Polytechnic has a CNC laboratory equipped with six TU-3A series CNC machines. This machine has three axes and is controlled by a computer, allowing operation according to the design made by the programmer.

The purpose of this study is to analyze the effect of cutting depth and spindle speed on CNC TU-3A Cutting Parallelism using DOE. Modifications made to the TU-3A

CNC machine include a 4-Channel 24 V Relay Module, Wired Numeric Keyboard, DC Speed Drive, 1200W DC Booster, 24 V 40 A DC Power Supply, Mach 3 Board, TB6600, and Nema 23 70 mm Stepper Motor. Based on this background, this study is entitled "The Effect of Cutting Depth and Spindle Rotation Speed on Parallelism in the TU-3A Retrofit CNC Machine".

## 2. Methodology of Research

This research uses a quantitative type with experimental methods and conducts literature reviews from various other sources. This study, using a retrofit CNC milling TU-3A CNC retrofit machine and 6061 aluminum, aims to determine the surface alignment of objects. In this study, the DOE factorial method was used to analyze the effect of depth of cut and spindle rotation on workpiece surface parallelism. The factorial method is used to evaluate all possible combinations between the tested factors. In this experiment, there are two main factors, which are the variation of spindle rotation at 600 RPM and 1000 RPM and the depth of cut at 1.0 mm, 1.5 mm and 2.0 mm. The feed rate was kept constant at 48 mm/min and 80 mm/min for each experimental combination.

*2.1 Experimental Setup*

*2.1.1 Materials*

Specimens: The material used for the specimens in this study is 6061 aluminum [5]. Each specimen has dimensions of 80 mm in length, 35 mm in width, and 15 mm in thickness. A total of nine specimens were prepared for the experiment.

*2.1.2 Machine*

CNC Machine: The machining was performed using a TU-3A CNC retrofit machine. This machine is equipped with GSK program control, allowing for both manual and automated operation.

*2.2 Variables*

This study aims to evaluate the effect of machining variables on the surface quality of machining results. The variables tested consist of independent and dependent variables as follows:

*2.2.1 Independent Variables:*

- Spindle Speed:
  Variable Level: The spindle speed is set at three different levels: (600 RPM, 800 RPM and 1000 RPM). Spindle speed affects cutting speed and surface quality. This variation is designed to assess the effect of spindle rotation speed on surface parallelism.
- Depth of Cut:
  Variable Level: The depth of cut is tested at three different levels: (1 mm, 1.5 mm and 2.0 mm). Depth of cut refers to how deep the cutting tool removes material in one pass. This variation is used to evaluate how changes in depth of cut affect the quality of surface parallelism.
- Feed Rate:
  Variable Level: The feed rate was set at three different levels: (48 mm/min, 64 mm/min and 80 mm/min).Feed rate is the speed at which the cutting tool moves through the material. This variation was maintained to see the effect of feed rate on surface quality.

*2.2.2 Dependent Variable:*

Surface Parallelism:The primary variable measured in this experiment was the surface parallelism of the machined specimen. Surface parallelism refers to the alignment of the machined surface, measured in micrometers (µm). The purpose of this measurement was to assess how the independent variables affect the surface quality of the final product.

*2.3 Experimental Design:*

This experimental design used a factorial approach to evaluate the effects and interactions between spindle speed, depth of cut, and feed rate on surface parallelism. Each combination of independent variable levels was tested to determine their effect on the dependent variable, as well as to identify optimal machining parameters.Procedure

*2.3.1 Specimen Preparation*

- Nine 6061 aluminum specimens were cut to the specified dimensions (50 x 50 x 30 mm).
- Each specimen was labeled and recorded to ensure accurate tracking throughout the experiment.

*2.3.2 Machining Process*

- The specimens were machined on the TU-3A CNC retrofit machine.
- The spindle speed, depth of cut, and feed rate were set according to the experimental design for each specimen.
- The machining was performed in a controlled environment to ensure consistency.

*2.3.3 Measurement of Surface Parallelism*

- After machining, the surface parallelism of each specimen was measured using a dial indicator.
- The dial indicator was carefully placed on the machined surface, and measurements were

taken at multiple points to determine the overall parallelism.

- The parallelism values were recorded for each specimen.

- Place the dial indicator on a known accurate measuring block or reference surface to check and adjust the initial reading. If there is any deviation, adjust the tool according to the manufacturer's instructions.

## 3 Result and Discussion

This research aimed to study the effect of depth of cut and spindle rotation on workpiece surface alignment. The tests were carried out using experimental methods, and the data were processed using statistical software with the DOE Factorial method. Table 1. shows the results of the parallelism test data obtained are as follows:

The graph shown in Figure 1. shows how spindle speed and depth of cut impact the surface parallelism value of a milling workpiece. This graph shows the effect of each combination of the two parameters on surface parallelism. The graph also combines various combinations of the two parameters. The surface parallelism value varies depending on the spindle speed and depth of cut used, as shown in the graph. Based on the graph, it is recommended to use a larger depth of cut with a high spindle speed for optimal surface parallelism. However, technical and practical limitations such as machine load and tool life should be considered [6].

**Table 1.** Parallelism Test Results

| Spindel Speed (RPM) | Depth of Cut (mm) | Parallelism(µm) |
|---|---|---|
| 600 | 1,0 | 0,12 |
| 600 | 1,0 | 0,10 |
| 600 | 1,5 | 0,14 |
| 600 | 1,5 | 0,19 |
| 600 | 2 | 0,15 |
| 600 | 2 | 0,16 |
| 800 | 1,0 | 0,09 |
| 800 | 1,0 | 0,10 |
| 800 | 1,5 | 0,20 |
| 800 | 1,5 | 0,19 |
| 800 | 2 | 0,12 |
| 800 | 2 | 0,14 |
| 1000 | 1,0 | 0,04 |
| 1000 | 1,0 | 0,03 |
| 1000 | 1,5 | 0,20 |
| 1000 | 1,5 | 0,17 |
| 1000 | 2 | 0,19 |
| 1000 | 2 | 0,21 |

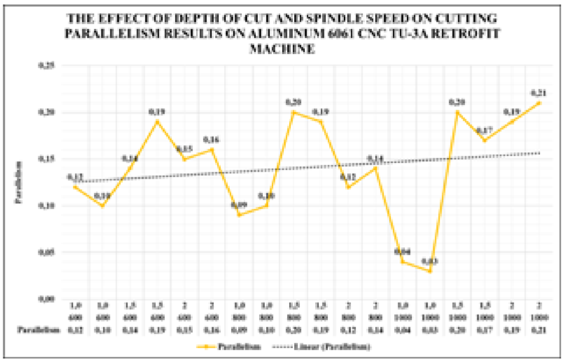


**Figure 1.** Parallels Result Chart

With a spindle speed of 600 RPM, the parallelism value tends to increase with depth of cut from 1.0 mm to 1.5 mm, with the highest value being 0.19, indicating that the surface becomes less parallel with greater depth of cut. However, at a spindle speed of 800 RPM, a similar trend was found, with a depth of cut of 2 mm obtaining the highest parallelism value 0.20 µm.

The results showed that for depths of cut of 1.0 mm and 1.5 mm, higher spindle speeds (1000 RPM) generally resulted in better parallelism values; however, for depths of cut of 2 mm, the parallelism values remained high, indicating a less parallel surface. Therefore, to achieve a more parallel surface, it is imperative to understand how the spindle speed and depth of cut interact to set the machining parameters to achieve the desired goal [7]. This will help reduce vibration and improve cutting stability, which translates to better surface quality. In machining theory, higher spindle speeds typically contribute to smoother cuts and more consistent material removal [8]. This is because high-speed cutting reduces the distance between the cutting bands, resulting in a smoother surface [9]. At smaller depths of cut (1.0 mm and 1.5 mm), increasing spindle speeds allows the tool to cut material more effectively and reduces surface roughness.

### *3.1 ANOVA Analysis Results*

Data analysis of experimental results was carried out using statistical software with the Factorial DOE method. The significant level used was 5% or α = 0.05.

**Table 2**. ANOVA Results

Analysis of Variance

| Source | DF | Adj SS | Adj MS | F-Value | P-Value |
|---|---|---|---|---|---|
| Model | 8 | 0,047078 | 0,005885 | 21,19 | 0,000 |
| Linear | 4 | 0,034856 | 0,008714 | 31,37 | 0,000 |
| Spindel Speed (RPM) | 2 | 0,000044 | 0,000022 | 0,08 | 0,924 |
| Depth of Cut (mm) | 2 | 0,034811 | 0,017406 | 62,66 | 0,000 |
| 2-Way Interactions | 4 | 0,012222 | 0,003056 | 11,00 | 0,002 |
| Spindel Speed (RPM)*Depth of Cut (mm) | 4 | 0,012222 | 0,003056 | 11,00 | 0,002 |
| Error | 9 | 0,002500 | 0,000278 | | |
| Total | 17 | 0,049578 | | | |

With a P-value of 0.000, which is much smaller than the α = 0.05 value, the ANOVA analysis results show that the depth of cut has a highly significant effect on the workpiece surface parallelism, as shown in Table 2. This shows that variations in depth of cut greatly affect the surface finish of the workpiece. The required cutting force increases with the depth of cut, which may cause greater elastic and plastic deformation of the workpiece surface [10]. As a result, surface unevenness may occur as a result of these larger deformations. Therefore, it is very important to control the cutting depth parameter when cutting the workpiece.

With a P-value of 0.924, which is greater than the α = 0.05 value, spindle speed does not affect the surface parallelism of the workpiece. This indicates that the surface parallelism is not affected within the tested spindle speed range from 600 RPM to 1000 RPM. This may be due to the variability of the experimental data which is not very sensitive to changes in spindle speed or because the tested spindle speed range has not reached the point where a significant effect can be observed. As a result, although there is some indication of an effect, the effect is not statistically significant [11].

With a P-value of 0.002 which is less than α = 0.05, the interaction between spindle speed and depth of cut shows a significant effect on surface parallelism. This indicates that the relationship between these two parameters plays a significant role in contributing to variations in workpiece surface alignment. The effects of spindle rotation and depth of cut are strong enough to significantly affect each other within the range of tests performed [12]. In other words, rather than affecting surface parallelism separately, a particular combination of spindle speed and depth of cut can produce a greater impact. Therefore, to achieve ideal surface results, it is important to consider how these two parameters interact in the machining process.

**Table 3**. Model Summary ANOVA

**Model Summary**

| S | R-sq | R-sq(adj) | R-sq(pred) |
|---|---|---|---|
| 0,0166667 | 94,96% | 90,48% | 79,83% |

It can be concluded that the regression model used is excellent for explaining and predicting variations in workpiece surface parallelism based on spindle speed and depth of cut, as shown in **Table 3**, which shows the relationship between the ANOVA data and the model summary. The ANOVA results support this conclusion by showing that the effect of depth of cut is substantial, and the interaction between spindle speed and depth of cut is also significant.

The high R-squared value of 94.96% and the predicted R-squared value of 79.83% show that the model can explain almost all of the variation in the data. Both values indicate that the model also has good predictive ability. Although spindle speed has no significant effect individually, its role in interaction with depth of cut is still important and should be considered during the machining process to achieve the best results [13].

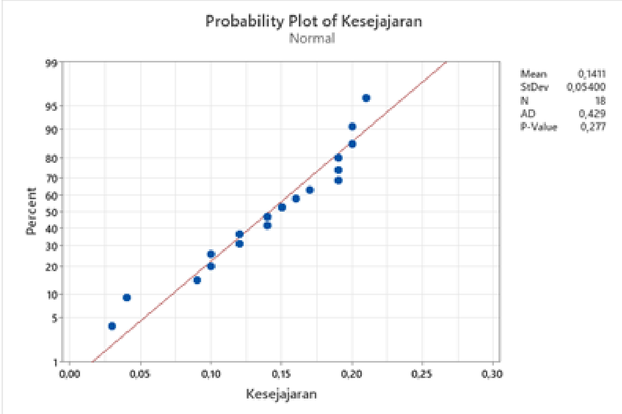


**Figure 2.** Data Normality Test Chart for parallelism

As shown in plot **Figure 2.** the distribution of residuals from the ANOVA analysis, which assesses the effect of spindle speed and depth of cut on the surface parallelism of milling workpieces, is shown. In this plot, the points close to the diagonal red line indicate that the residuals are normally distributed, which is one of the important assumptions of ANOVA. The assumption of normality being met indicates that the ANOVA results can be considered valid, and shows that the model used is suitable for explaining the effect of these variables on the workpiece surface parallelism [14].

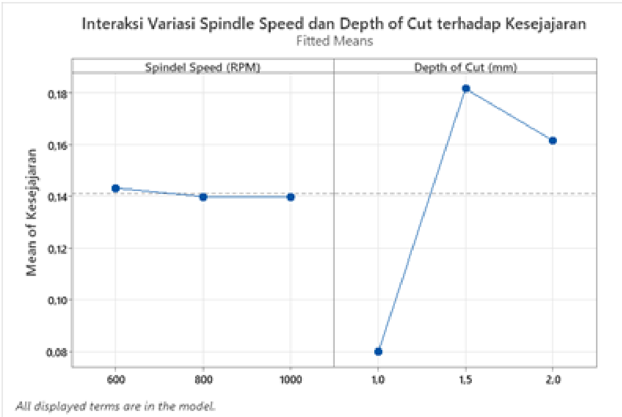


**Figure 3.** Interaction Chart

**Figure 3.** shows the interaction graph of spindle speed and depth of cut on the surface parallelism of the milling workpiece. This graph shows the significant effect of the two process variables on the surface quality of the workpiece. The graph shows that depth of cut has the most significant effect [15]. At a depth of cut of 1.0 mm, the average workpiece surface parallelism is the lowest, which is about 0.08 µm, indicating that lower depths of cut tend to produce misaligned surfaces. However, when the depth of cut rises to 1.5 mm, the average parallelism increases significantly to about 0.18 µm, which indicates that increasing the depth of cut can improve the surface parallelism significantly [16].

In contrast, the surface parallelism is also affected by the spindle speed, but the impact is not as strong as the depth of cut. With a spindle speed of 600 RPM, the average parallelism is about 0.14 µm. This value increases slightly when the spindle speed rises to 800 RPM, but then drops dramatically to about 0.12 µm at 1000 RPM. This shows that higher spindle speeds can only achieve ideal surface alignment, and further increases can only degrade surface quality.

## 4 Conclusion

The conclusions from the research related to the effect of depth of cut and spindle rotation on parallelism on the TU-3A CNC retrofit machine include the following:

1. From the results of the analysis, it can be concluded that spindle speed does not show a significant effect on the parallelism of the workpiece surface with a P-value of 0.924 more than the α = 0.05 value. These results indicate that within the range of spindle speeds tested (600 RPM, 800 RPM and 1000 RPM), there is no significant effect on surface parallelism. The data shows that higher spindle speeds (1000 RPM) tend to produce better alignment values with lower alignment values resulting.
2. From the analysis, it can be concluded that the depth of cut has a significant effect on the workpiece surface parallelism. The very low P-value (0.000) is less than α = 0.05, indicating that the change in depth of cut substantially affects the final surface parallelism result after the milling machining process. Based on the result data a greater depth of cut tends to increase the surface parallelism value, showing a higher deviation.
3. From the analysis, it can be concluded that the interaction between spindle speed and depth of cut also has a significant effect on surface parallelism with a P-value of 0.002 smaller than the value of α = 0.05. These results indicate that the combination of spindle speed and depth of cut has a significant effect on surface parallelism, where higher spindle speed and lower depth of cut tend to produce a more parallel surface.
4. Based on the research results, the setting of the cutting depth should be the main focus to improve the quality of surface parallelism. The spindle speed setting can be adjusted based on production needs without sacrificing surface quality.

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