The Effect of Machining Parameters to the Surface Roughness in Low Speed Machining Micro-milling Inconel 718

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Abstract. In recent years, the rapid technology development in industry sector, especially in aviation industry has been increasing. So that we need more capabilities in the micro-scale manufacturing process, especially micro-milling process which can produce good surface roughness and high complexity parts. In this study, the effect of machining parameters to the surface roughness investigated by using Inconel 718 material with cutting tool diameter 1 mm, carbide material with coating TiAlN. The machining process was performed in low speed machining category. There are three variations of spindle speed (3,000, 7,000, 10,000 RPM) and also feed rate (0.5, 1, 2 mm/s) with constant depth of cut 10 µm. The relationship between machining parameters and surface roughness was obtained. The higher the feed rate, the higher the surface roughness produced. On the other hand, the higher the spindle speed the smaller the surface roughness. It also found that the machining process with low spindle speed, below 10,000 RPM, successfully carried out on hard-to-cut material, Inconel 718, that will be increasing the flexibility of machining parameters.

1. Introduction

Development of manufacturing process is necessary because of the rapid technology development, especially aviation industry. For example, the development of aircraft engine to achieve higher efficiency. Hard materials like Inconel 718 has been used as a material of aircraft engine parts including blades, disc, etc. Besides aircraft engines, Inconel 718 also used for rocket parts, gas turbine, and also molding because it has good strength, corrosion resistance, and also good creep resistance at high temperatures. Inconel 718 consist of nickel, chromium, iron and etc that makes the material strong. However Inconel 718 has poor machinability because of its difficult-to-cut materials, so it needs more investigation for this material especially in manufacturing process. Optimization of electrochemical micro-machining has been done on Inconel 718 [1]. Drilling on Inconel 718 by using electrochemical machining has also been done. But, there is still difficulty on micro-machining Inconel 718 [2].

Aviation part’s, like aircraft engine, gas turbine’s blade, and also molding have a high complexity in shape to achieve optimal performance of the part’s and also require high accuracy geometry. To fulfil these requirements, micro-milling process employed. Micro-milling is a part of micro-manufacturing process that has an ability of producing 2D and 3D parts with high complexity shape. It’s also offers good surface quality and high accuracy after machining so it can deny finishing stage process like grinding and polishing. Removing this finishing stage process requires machining that results good surface quality, like surface roughness, and good geometry accuracy. So that to achieve these requirements, optimal machining process must be observed. Not only the rigidity of the machine
tool, choosing optimal machining parameters significantly impact the surface quality, especially the surface roughness. Machining parameters consist of cutting tool, feed rate, spindle speed, depth of cut, etc. The effect of tool wear through machining process also must be considered since it can affect the cutting process when the cutting tool contact with workpiece material. Tool wear rate also will affect the cost of production of the product. Kiswanto et al (2015) investigated the effect of cutting parameters, like spindle speed, feed rate, and machining time, to the surface roughness. It was found that feed rate and machining time gave an impact significantly to the surface roughness. The lower feed rate would produce smoother surface [3].

The effect of machining parameters to surface quality in micro-milling Inconel 718 has been investigated in the past years. Kuram et al (2019) investigated the effect of overhang length of cutting tool and also feed per tooth to the cutting force during machining process. It was found that, overhang length affect cutting force and also produced chatter vibration. The longer of overhang length the higher of cutting force it be. The increasing of feed per tooth also increased cutting force because the enlargement of chip cross sectional area to be cut [4]. Sredanovic et al (2017) also investigated the machinability of Inconel 718. It was found that, Inconel 718 can be machined by using long neck flat micro end mills with diameter 0,6 mm. The best machining parameters combination obtained with feed per tooth 0,012 mm, cutting speed 40m/min, and depth of cut 0,02 mm. These parameter combination gave best output, especially in surface roughness. It was also found that the increasing of feed per tooth would increase surface roughness [5]. Kuram et al (2015) also investigated the effect of spindle speed, feed rate, and depth of cut. It was found that spindle speed and feed rate were a significant factor to surface roughness and also tool wear [6]. Lu et al (2018) optimized machining parameters with high material removal rate (MRR) to achieve machining efficiency [7].

Unfortunately, the recent research only covered spindle speed above 10.000 RPM and not yet covered below 10.000 RPM. In machining process, machining can be done with low spindle speed range because of the low budget specification of the machine tool, where the spindle speed only offers up to 10.000 RPM for machining process. Therefore, this research investigates the ability of machining Inconel 718 below 10.000 RPM and also the effect of machining parameters to the surface roughness. The relationship of machining parameters to the surface roughness with three variation of spindle speed and feed rate, and also constant depth of cut will be observed.

2. Experimental Setup

A miniaturized 5-axis micro-milling machine was used in this experiment for machining process. The machine tool movement was moved by motor stepper that has resolution 1 micron. The 3-Axis is linear axis that do linear movement and the 2-axis is rotational axis that do rotational movement. These motor stepper controlled with three units DS102 Suruga Seiki. An electric motor spindle
Nakanishi HES 810 also used in this experiments as a motor that provide spindle speed with maximum rotation 80,000 RPM. The picture of machine tool can be seen in Figure 1.

A carbide cutting tool DIXI 7242 with diameter 1 mm and 2 flutes with TiAlN coating was used in this experiments. Then, Inconel 718 with dimension 10 mm x 10 mm x 4.8 mm with hardness 66 HRC was selected as a workpiece materials. Before machining process, cleaning of workpiece material and cutting tool was done by using ultrasonic cleaners to remove dust and dirt. Then, facing process was employed in this experiment to get common flat surfaces as machining surface reference on the workpiece experiments. Each of machining parameters was machined in every channels which can be seen in Figure 2. Every machining parameters has been done by using new cutting tool to diminish tool wear effect in every machining parameters. The new tool condition can be seen in Figure 3.

In this experiments, the variation of machining parameters can be seen in Table 1. The low spindle speed selection below 10,000 RPM to achieve the aim of this research. Dry cutting without cutting fluid performed in this machining process. Then, overhang length of cutting tool was 15 mm to prevent high cutting force and chatter vibration during machining process. This experiments performed slot milling process. The surface roughness of every channels measured by using SURFCOM 2900 SD3 with cut off 0.8 mm, evaluation length 2.4 mm, and measure speed 0.3 mm/s.

![A condition of new cutting tool DIXI 7242 captured with dino-lite.](image-url)
Table 1. Machining parameters of this experiments.

| Parameter | Spindle Speed (RPM) | Cutting Speed (m/min) | Feed Rate (mm/s) | Feed per tooth (mm/tooth) |
|-----------|---------------------|-----------------------|------------------|--------------------------|
| 1         | 3000                | 9.43                  | 0.5              | 0,0050                   |
| 2         | 7000                | 22.00                 | 0.5              | 0,0021                   |
| 3         | 10000               | 31.43                 | 0.5              | 0,0015                   |
| 4         | 3000                | 9.43                  | 1                | 0,0100                   |
| 5         | 7000                | 22.00                 | 1                | 0,0043                   |
| 6         | 10000               | 31.43                 | 1                | 0,0030                   |
| 7         | 3000                | 9.43                  | 2                | 0,0200                   |
| 8         | 7000                | 22.00                 | 2                | 0,0086                   |
| 9         | 10000               | 31.43                 | 2                | 0,0060                   |

3. Results and Discussion

Every channel that has been machined measured by using SURFCOM 2900SD3 to get the surface roughness (R_a). The result of surface roughness every machining parameters can be seen in Table 2.

Surface quality, like surface roughness and burr, influenced by machining parameters. Based on Figure 4, we can see the effect of feed rate on surface roughness. If the value of feed rate was increasing, the surface roughness in the channel was also increasing. Machining parameters with spindle speed 3.000 RPM and feed rate 2 mm/s produced highest surface roughness with value 0.4163 µm. Otherwise, machining parameters with spindle speed 10.000 RPM and feed rate 0.5 mm/s produced lowest surface roughness with value 0.0673 µm. So that low spindle speed with high feed rate will produce high surface roughness and vice versa.

Table 2. Results of surface roughness of each machining parameters.

| Parameter | Spindle Speed (RPM) | Cutting Speed (m/min) | Feed Rate (mm/s) | Feed per tooth (mm/tooth) | Surface Roughness (µm) |
|-----------|---------------------|-----------------------|------------------|--------------------------|------------------------|
| 1         | 3000                | 9.43                  | 0.5              | 0,0050                   | 0,1253                 |
| 2         | 7000                | 22.00                 | 0.5              | 0,0021                   | 0,0678                 |
| 3         | 10000               | 31.43                 | 0.5              | 0,0015                   | 0,0673                 |
| 4         | 3000                | 9.43                  | 1                | 0,0100                   | 0,2974                 |
| 5         | 7000                | 22.00                 | 1                | 0,0043                   | 0,0874                 |
| 6         | 10000               | 31.43                 | 1                | 0,0030                   | 0,0935                 |
| 7         | 3000                | 9.43                  | 2                | 0,0200                   | 0,4163                 |
| 8         | 7000                | 22.00                 | 2                | 0,0086                   | 0,0932                 |
| 9         | 10000               | 31.43                 | 2                | 0,0060                   | 0,1011                 |
Figure 4. The influences of feed rate into surface roughness.

Feed rate refers to the velocity of workpiece relative to the cutting tool. The higher value of feed rate, the faster machining process will be. Short machining process will cost into tool wear that can affect surface quality. Feed rate has a linear relationship with feed per tooth. The value of feed per tooth in this experiments can be seen in Table 1. Feed per tooth is the magnitude of material that will be cut by every tooth of the cutting tool. If feed per tooth was increasing, the cutting load in the machining process was also increasing because of the enlargement of the cross sectional area of chip. This will affect the tool wear that will disturb cutting process and then gave bad impact to the surface roughness. The increasing of feed per tooth will lead into the escalation of tool wear rate. At spindle speed 3,000 RPM, we can see clearly that the increasing of feed rate from 0.5 mm/s to 2 mm/s produce high surface roughness. After that, the effect of increasing of spindle speed on surface roughness can be seen in Figure 5.

Figure 5. The influences of spindle speed into surface roughness.

Based on Figure 5, if the rotation of spindle speed is increasing, the surface roughness is decreasing. This occurred at the same feed rate with the increasing of spindle speed rotation. It can be seen in Table 1, the feed per tooth will be decreasing with the increasing of spindle speed. So the cutting load of the every tooth in the cutting tool will be decreasing. Spindle speed also refers into cutting speed. The increasing of cutting speed will reduce cutting force. But, high cutting speed will lead to high friction resulting in an increase in temperature of the cutting tool. This will lead to the increasing of tool wear that will affect surface roughness. However, this would have significant impact if we done high cutting speed machining with longer machining time.
Figure 6. The surface condition that has been machined with parameter 1.

The appearances of built up edge (BUE) during machining process was found in this experiment. Based on Figure 6, parameter 1, there was a chip attached to the surface after the machining process was carried out. This chip on the surface of the channel will affect the surface roughness measurement. The stylus will detect the chip and then increase the surface roughness of the channel. The appearances of built up edge must be avoided since it can affect the surface quality and cutting process.

4. Conclusion
This research observed and evaluated the effect of machining parameters into surface roughness. So this can be concluded that:

- Low surface roughness achieved by using machining parameters combination with spindle speed 10,000 RPM and feed rate 0.5 mm/s.
- High feed rate will produce higher surface roughness. It occurs because of the increasing of cutting load in machining process.
- High spindle speed will produce lower surface roughness. It occurs because of the increasing of spindle speed that lead into the decreasing of cutting load where the cutting force will be decreasing also.
- Machining process with low spindle speed, below 10,000 RPM, successfully carried out on hard-to-cut material, Inconel 718. This will increase the flexibility of the selection of machining parameters, especially spindle speed. Where the surface roughness can be produced below 0.5 µm.

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