The Effects of Cutting Parameters to the Surface Roughness in Low Speed Machining of Micro-milling of Titanium Alloy Ti-6Al-4V

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Abstract. The demand for micro-scale products is increasing rapidly in various fields of industries such as electronics, bio-medical, optical industry, and so on. Titanium alloys especially Ti-6Al-4V is one of the commonly used in bio-medical industries because of its biocompatibility properties. However, poor surface quality in terms of surface roughness commonly occurs because of inappropriate cutting parameters to machine this hard to cut material. This study aims to investigate the influencing machining parameters to produce micro-products with a low level of surface roughness in Titanium Alloy (Ti-6Al-4V) material using a miniaturized micro-milling machine. Experiments carried out by micromilling process with variations in low rpm spindle speed and feed rate with a constant depth of cut using a carbide cutting tool of with a diameter of 1 mm. The machining results in the form of a 4 mm slot with a depth of 10 μm, which then measures its surface roughness. It was found that as the feed rate increases, the surface roughness also accordingly increases. On the other hand, the surface roughness decreases as the spindle speed increases.

1. Introduction

The increasing of demand of micro products in recent decades are getting higher attention for bio medical researches. Material upgrades are one of the optimizations of the product that can make it stronger and more efficient. The characteristics of the micro products are including functional sizes in the range of 1 to 100 μm, high levels of precision, generally less than 1 μm of tolerances, very small surface roughness with less than 0.5 μm of Ra , a complex shape and design, and uses heat resistance materials such as ceramics, titanium alloys etc [1].

Titanium alloys are commonly used for bio-medical micro-product for its bio-compatibility, corrosion resistance, and a lightweight yet strong material. Implants, and dental products such as crowns, dentures, etc. are using titanium alloys [2]. However, poor machinability of titanium alloys is the main problem of machining this hard to cut material. Thepsonthi et. al. [3] stated that rapid tool wear and severe burr formation is one of the difficulties for machining of titanium alloys. Micro-milling is one of the choices for 3D micro-manufacturing processes, especially for complex micro product that need high accuracy and high surface quality without further finishing process such as grinding and polishing. Despite of requiring a relatively longer, micro-milling has the ability to make products from various materials with complex shape.

To achieve the best surface quality, an optimal cutting parameter have to be obtained. In micromilling, selection the right : cutting tool , feed rate, spindle speed, and depth of cut is the most
important to do since the quality of the process totally rely on those parameters. There are several studies that present the challenges of selecting cutting parameters in the micro-milling process. Sharp cutting edge will cause chatter vibration at a relatively small depth of cut where the cutting depth of the micro-milling process is generally very small, less than 500 µm [4]. Bandapalli et al [5] already investigated the tool wear on various coated cutting tools for titanium alloy high speed micro-milling. It is found that uncoated carbide cutting tool performed better than any coated carbide tools in titanium alloy high speed micro-milling process. Wang et al [6] investigated the errors in micro-milling. It is found that increased surface roughness is directly proportional to the increase in tool diameter and spindle speed. In addition, certain range of spindle speed can cause vibration and affect surface roughness. To improve the quality of the workpiece surface roughness, the stiffness of the tool structure must be increased. This can be done by reducing the distance of the cutting tool with the collet.

However, from literature review, it is found that most researches in machining titanium alloy Ti-6Al-4V carried out high speed machining at the range of 10,000 rpm to 120,000 rpm [3][5][7][8]. The main reason is that high speed machining produces better surface quality with high material removal rate (MRR). On the other hand, low speed machining still has a potential of offering high quality machined surface with an appropriate low budget cutting tool and low budget milling machine that have an ability of producing spindle speed only up to 10,000 rpm. Bach et al [9] investigated the effect of cutting parameters to surface quality in a conventional titanium alloy Ti-6Al-4V low speed milling. It was stated that low speed milling offers high stability that would have ability to machine in a high depth of cut with high surface quality. Moreover, lower feed rate generally produced smoother surface [10]. Thus, this study aims to investigate the influence of the cutting parameters to the surface roughness of low speed Ti-6Al-4V micro-milling.

2. Experimental Setup

The Titanium alloy Ti-6Al-4V micro-milling experiment was conducted using a miniaturized 5-axis micro-milling machine as shown in Figure 1. The machine has three linear axes of XYZ and two rotational axes of A & C but only the linear axes are used in this experiment. The movement of the axes are powered by Suruga Seiki stepper motors with 1 µm of motion resolution for each axis which the speed, direction, and distance are controlled by DS102 motor controller from Suruga Seiki.

![Figure 1](image-url)
The workpiece material that is used was Ti-6Al-4Al with a hardness of 44 HRC with the dimension of 10 mm × 10 mm × 4.82 mm. DIXI 7242 uncoated carbide cutting tool that has 2 flutes as shown in Figure 2 and has a specification as shown in Table 1 was used in the experiment as the recommendation for titanium alloy cutting. The tool was clamped and rotated by an electric spindle Nakanishi HES 810-ST32 which the spindle speed is controlled and measured by Nakanishi E3000 spindle controller. The overhang length of the cutting tool is 10 mm to the spindle nose to prevent deformation and vibration from the cutting tool due to high cutting forces. Before the experiment, the workpiece and the cutting tool were first cleaned by using an ultrasonic cleaner for removing excessive dust that can cause build-up edges on the cutting tool. The cutting tool was then observed using a digital microscopes as shown in Figure 3 to verify the condition. A facing processes were also conducted to get common flat surface on the workpiece relative to the machine using a 3mm flat end mill.

![Figure 2](image)

**Figure 2.** DIXI 7242 end mill cutting tool.

| Type   | D1  | D   | L   | L1  | Number of flute | Material |
|--------|-----|-----|-----|-----|-----------------|----------|
| End Mill | 1 mm | 3 mm | 38 mm | 2 mm | 2               | Carbide  |

![Table 1](image)

**Table 1.** DIXI 7242 specification.

![Figure 3](image)

**Figure 3.** Condition of a new cutting tool.

In the experiments, slots with 4 mm length and 10 μm depth were produced by a slot-milling operation with the width equal to the cutting tool’s diameter which is shown in Figure 4. Zig toolpath was used in this experiment. The depth of cut for the slot-milling was constant at 10 μm. 9 different low speed cutting parameters were conducted for each slot as shown in Table 2. A new cutting tool is used for every slot with different cutting parameter to ensure the same cutting condition. Dry cutting was performed in this experiment. The output of the experiment is the surface roughness of each slot and all were measured using Surfcom 2900SD3. The measurement settings were 0.8 mm cut off, 2.4 mm evaluation length, and measure speed of 0.3 mm/s.
Figure 4. (a) Design of slot milling (b) Slot milling toolpath.

Table 2. Variable of low speed cutting parameter.

| Spindle Speed (rpm) | Feed Rate (mm/s) | Depth of Cut (µm) |
|---------------------|------------------|------------------|
| 3,000               | 0.4              |                 |
|                     | 0.8              |                 |
|                     | 1.6              |                 |
|                     | 0.4              |                 |
| 7,000               | 0.8              | 10              |
|                     | 1.6              |                 |
|                     | 0.4              |                 |
| 10,000              | 0.8              |                 |
|                     | 1.6              |                 |

3. Results and Discussion
The result of measured surface roughness from the various cutting parameters are shown in Table 3. The lowest surface roughness at 0.0972 µm was obtained by the lowest feed rate with the highest spindle speed. On the other hand, the highest surface roughness at 0.4496 µm was obtained by the highest feed rate with the lowest spindle speed. In order to give clearer visualization on the influence of cutting parameters on the machined surface roughness, the results of the experiment are shown in Figure 5 and Figure 6.

Table 3. Surface roughness of each cutting parameters.

| Parameter | Spindle Speed (rpm) | Feed Rate (mm/s) | Surface Roughness (µm) |
|-----------|---------------------|------------------|------------------------|
| 1         | 3,000               | 0.4              | 0.1522                 |
| 2         |                     | 0.8              | 0.2594                 |
| 3         |                     | 1.6              | 0.4496                 |
| 4         |                     | 0.4              | 0.1155                 |
| 5         | 7,000               | 0.8              | 0.1546                 |
| 6         |                     | 1.6              | 0.1647                 |
| 7         |                     | 0.4              | 0.0972                 |
| 8         | 10,000              | 0.8              | 0.1058                 |
| 9         |                     | 1.6              | 0.1446                 |
Figure 5. Influence of spindle speed to the surface roughness.

In Figure 5, it is seen that the surface roughness decreases as the spindle speed increases. The relationship shows that the increase of spindle speed causes the cutting forces to be decreased. This will lead to good tool life because of the low cutting load in the tool. Using a low feed rate with a higher spindle speed tend to produce lower surface roughness. Thus, using higher spindle speed with lower feed rate is recommended for saving cutting tools as well as producing a high surface quality.

Figure 6. Influence of feed rate to the surface roughness.

In Figure 6, it is clearly seen that with the same spindle speed, the lower the feed rate, the lower the surface roughness is. This relationship shows that machining process in low feed rates allows the cutting tool to remove more material than the high feed rate does. High feed rate must be followed by higher spindle speed so that the removal of the material can be done more perfectly. If high feed rates are not followed by setting higher spindle speeds, the cutting load of the tool will be too much that can lead to excessive heat, rapid tool wear or even tool breakage that can crucially affects the surface roughness. It is clearly seen that the surface roughness is increasing significantly on the cutting
parameter of the highest feed rate with the lowest spindle speed. Thus, the increase of feed rates must be followed by increasing spindle speed in order to lower the cutting load.

The difference of the surface view between the lowest and the highest surface roughness are shown in Figure 7 that are taken with digital microscope with 100× magnification. It is seen that the cutter marks on the lowest surface roughness of 0.0972 μm are thinner than on the highest surface roughness. It is shown that on the higher feed rate with low spindle speed tend to leave a thick mark on the surface that cause the surface roughness to rise because of the uncut material.

![Figure 7. Top view of the slot with (a) lowest and (b) highest surface roughness.](image)

From the result of published researches of Ti-6Al-4V high-speed micro-milling, the surface roughness between the low-speed and high-speed Ti-6Al-4V does not making significant difference. It means that low speed micro-milling can be done in terms of saving cost of cutting tools and lower budget of machines without sacrificing the surface quality. In practice, despite of designing a production plan with a lowest machining time as possible, the cost and budgets for a production is still being considered. Thus, low speed machining Ti-6Al-4V micro-milling can still be a good choice for producing micro products with high surface quality in terms of low cost and budgeting.

4. Conclusion
From the results to the discussion of this experiment, it can be concluded that:

- Higher spindle speed in low-speed Ti-6Al-4V micro-milling can produces lower surface roughness.
- High feed rates in low-speed machining of Ti-6Al-4V micro-milling must be followed by higher spindle speed in order to lower the cutting load that causes tool wear or even tool breakage that can increases the surface roughness significantly.
- Cutting parameter with high feed rates with low spindle speed tend to leave thicker cutter marks that will increase the surface roughness.
- The result between low-speed machining and high-speed machining of Ti-6Al-4V is not have significant differences.
- Low speed machining Ti-6Al-4V micro-milling can still be a good choice for producing micro products with high surface quality in terms of low cost and budgeting.

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