Influence of Size Effect on Cutting Edge Rounding and Surface Roughness in Micro-Milling of Ti-6Al-4V

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Abstract. The quality of cutting depends most on the cutting tool condition. Towards having a good quality finish, cutting tolerance becomes a major concern, especially when machining at micro-scale where highly precise cutting is desired. This research investigates the size-effect during the micro-milling of Ti-6Al-4V under dry condition where the observations were made on cutting edge rounding (CER) and workpiece surface roughness. The result showed that the lower the feed rate, the greater rounding on the cutting edges were observed. Similar trend in result was obtained when measuring the surface roughness. The best feed rate for both observations was at 60 mm/min, where this setting has brought the mechanism to shearing, as the ratio between undeformed chip thickness and cutting edge radius started at 1.

1. Introduction

Titanium alloy has been widely used in aerospace and biomedical industry due to its prominent properties such as high strength-to-weight ratio and excellent corrosion resistance [1]. The effect of tool failure for a micro-sized tool or workpiece could be worse compared to the conventional scale. A broken micro tool could cause damage to the workpiece, which is beyond repair and may turn to scrap [2]. This reason has encouraged researchers to search for the best parameters to extend the micro-tool life while getting the desired machining quality. In order to witness the tool condition, direct observation is carried out by examining the tool flank wear [3], cutting edge rounding [4-5] and also by detecting anomalies on the tool such as material adhesion or built-up edge [6]. An indirect indication about the tool could be expressed by the quality of cutting, which often relies on observation on the machined surface, e.g. through the measurement of surface roughness [7] or burr formation [8-9].

The indications about the tool condition as mentioned above depend much on the machining parameters such as cutting speed and feed rate settings [10-16] and other factors such as the use of cutting fluids and various cutting tool configuration. These parameters’ settings hold significant influence on the size-effect. In this condition, the undeformed chip thickness, \( t \), becomes smaller than cutting edge radius, \( r \), which could affect the material deformation during cutting [15]. Also, titanium alloy holds low thermal conductivity, most of the heat that produced during cutting get transferred to
the tool, hence deteriorating its condition and resulting in poor surface quality. This material could also become harder to cut when exposed to heat due to the effect of strain hardening [16].

2. Experimental Setup

2.1. Materials and Machine Tools
The material was titanium alloy Ti-6Al-4V α-β grade 5, which was prepared in a cubic shape of 27mm x 27mm x 17mm, see figure 1 a). The workpiece was milled once using conventional milling tools before the start of each test to ensure its surface was normal to the cutting axis. This operation could eliminate tool slanting, a situation where a tool penetrates the workpiece at a certain angle, thus producing an imbalance tool rotation which could result in premature failure.

All tests were performed using 3-axis Akira Seiki Performa SR3 XP CNC milling machine. As for the cutting parameters, this research employed the same spindle speed, \( S \) and depth of cut, \( d \) where the values were set at 3,000 rpm and 0.2 mm, respectively. The step-over value, \( s \) was set to be at 0.4 mm, which was 40% of the tool diameter. Three levels of feed, \( V_f \) was applied at 15, 40 and 60 mm/min which was equivalent to a value of feed per tooth, \( f \) of 0.00125, 0.00333 and 0.005 mm/t, respectively, where \( f \) can be determined by the following equation:

\[
\text{Feed per tooth, } f = \frac{V_f}{S \times \text{number of flutes}} \tag{1}
\]

As depicted in figure 1 b), the tool travelled surpassing the entire workpiece surface, making a total path to 45.

2.2. Experimental Method
A set of 9 four-flute HSS end mills from Miranda Tools were used, see figure 2. With a diameter of 1.0 mm, it holds a flute length of 4 mm and a shank diameter of 5 mm. Before cutting, all tools’ cutting edge were examined and measured to ensure that they were in good form, i.e. within a tolerance of 2 μm. All edges’ radii were taken for the purpose to determine the starting value of the ratio between feed per tooth, \( f \) and edge radius, \( r_{\text{initial}} \) as well as for comparison with edge radius after the process has been completed, \( r_{\text{final}} \), as illustrated in figure 3. The percentage of cutting edge increment is calculated based on the following equation:

\[
\% \text{ radius increment} = \frac{r_{\text{final}} - r_{\text{initial}}}{r_{\text{initial}}} \times 100 \tag{2}
\]
Figure 2. 1 mm-diameter high-speed steel end mill with an initial radius of 5 μm at one of its edges

Figure 3. Cutting edge radius measurement method

Cutting edge rounding after machining were determined and measured through images that pictured with a tabletop scanning electron microscope (SEM), model TM3000 from Hitachi. As for the surface roughness, the measurement was made using a surface roughness tester of Miyutoyo CS-3100. The arithmetic mean roughness, R_a was taken by scribing the tester’s probe for 4 mm at four different points across the milling path, as shown in figure 4. The arrangement of the cutting tools and their operating parameters is presented in table 1.

Figure 4. Surface roughness measurement points
Table 1. Parameters Setting

| Tool No. | Spindle speed, $S$ (rpm) | Depth of cut, $d$ (mm) | Feed, $V_f$ (mm/min) | Feed per tooth, $f$ (mm/tooth) |
|----------|-------------------------|-----------------------|----------------------|-------------------------------|
| 1,2,3    | 3,000                   | 15                    | 15                   | 0.00125                       |
| 4,5,6    | 3,000                   | 0.2                   | 40                   | 0.00333                       |
| 7,8,9    |                         | 60                    | 60                   | 0.005                         |

3. Results and Discussions

3.1. Cutting Edge Rounding

Figure 5 shows images of three sample tools showing their cutting edge condition after machining. It can be seen that for Tool 1, which had operated at a feed of 15 mm/min, produced greater rounding of cutting edges when compared to Tool 5 and 9, which fed at a rate of 40 and 60 mm/min, respectively. There is a less significant difference between geometry of Tool 5 and 9 even though the latter fed at a higher rate. Tool 9 had a consistent penetration on all cutting edge as all edges looked particularly similar in geometry; meanwhile, for Tool 5, two edges were observed duller compared to the others. This could be attributed by the fact that the tool had an imbalance cutting, which was possibly happened due to several reasons, among which were material adhesion on random edge and built-up-edge (BUE) formation. Also, the web line of Tool 9 is still visible when compared to Tool 5, as the latter tool could have experienced the aforementioned situation, thus causing excessive rubbing on one or two of the edges. In addition, the low thermal conductivity of titanium workpiece makes most of the heat that generated in the shear zones get transferred to the tool rapidly, where, within a dry condition and with uncoated HSS tool, the tool could deteriorate even faster.

![Figure 5. Cutting edge image of tool 1, 5 and 9 after machining](image-url)
It is noticed that direct observation on samples as above is significant with the measurement of final cutting edge radius as depicted in figure 6 and table 2. Tool 1-3 that run on lowest feed had resulted in the higher value of \( r_{\text{final}} \) with an average radius of between 32.5 to 40 \( \mu \text{m} \) while Tool 7-9 recorded the lowest at between 15 to 22.5 \( \mu \text{m} \). It is also pertinent to note that, the maximum edge radius of tool 4 and 6, which run at 40 mm/min, had recorded a similar reading with tool 1 and 3. Based on table 2, the percentage increment for all four cutting edges described a similar pattern where tool 1-3 produced high percentage at between 550 to 700\%. Tool 7-9 remained at the lowest side with percentage radius increment of between 200 to 350\%, and tool 4-6 were in the middle range at 350 to 550\%.

![Figure 6. Average cutting edge radius per tool after machining](image)

This situation could be explained by the size-effect phenomenon, which is presented by the ratio between \( f \) and \( r_{\text{initial}} \) as shown in table 2. The ratio for tool 1-3 as well as tool 4-6 was 0.25 and 0.67, respectively thus both lied in the ploughing region \( (t_c/r < 1) \). As for tool 7-9, the ratio was equal to 1, meaning that they were shearing the material. Ploughing exerts high cutting force because of the negative rake angle cutting mechanism while shearing encourages positive rake angle cutting that promotes smooth chip flow and much lower cutting force [15]. Probably, this is the reason why tool 1-3 with low feed rate had significant cutting edges rounding when compared to the other tools with higher feed rate settings.

**Table 2. Calculated results on cutting edge rounding**

| Tool No. | Feed, \( V_f \) (mm/min) | Feed per tooth, \( f \) (mm/tooth) | Avg New tool Radius, \( r_{\text{initial}} \) (\( \mu \text{m} \)) | Avg Worn tool Radius, \( r_{\text{final}} \) (\( \mu \text{m} \)) | Edge Radius Increment (%) | Ratio of Feed per tooth to radius, \( f / r_{\text{initial}} \) |
|----------|--------------------------|-------------------------------|---------------------------------|-----------------------------|--------------------------|--------------------------------|
| 1        | 15                       | 0.00125                       | 35                              | 600                         | 0.25                     | 0.25                           |
| 2        | 15                       | 0.00125                       | 35                              | 600                         | 0.25                     | 0.25                           |
| 3        | 15                       | 0.00125                       | 35                              | 600                         | 0.25                     | 0.25                           |
| 4        | 40                       | 0.00333                       | 32.5                            | 550                         | 0.67                     | 0.67                           |
| 5        | 40                       | 0.00333                       | 32.5                            | 550                         | 0.67                     | 0.67                           |
| 6        | 40                       | 0.00333                       | 32.5                            | 550                         | 0.67                     | 0.67                           |
| 7        | 60                       | 0.005                         | 15                              | 200                         | 1.00                     | 1.00                           |
| 8        | 60                       | 0.005                         | 15                              | 200                         | 1.00                     | 1.00                           |
| 9        | 60                       | 0.005                         | 15                              | 200                         | 1.00                     | 1.00                           |
3.2. Surface Roughness

The surface roughness, $R_a$ value could represent an indirect indication about the tool condition where high roughness value indicates ineffective cutting, possibly due to worn tools, i.e. poor cutting edge condition. As shown in figure 4, with regards to the tool entry point and cutting direction, the measurement points 1 and 2 are considered at early tool stage while point 3 and 4 are more towards the end. Table 3 and figure 7 present the surface roughness value at every measurement point for each tool. Tool 1-3 created higher average roughness value as compared to other tools. Also, the difference between moderate feed (tool 4-6) and high feed (tool 7-9) can be observed where tool 4-6 produced roughness of greater than 2 $\mu$m meanwhile tool 7-9 was always recorded a roughness of less than 2 $\mu$m. Towards the end of the workpiece, high roughness value could be attributed by the toolpath’s burr, which was reported to be higher as the tool gets worn [18].

Based on figure 7, some of the tools such as tool 1,3,8, and 9 started with a higher roughness value at point 1, before dropped at point 2 and increased beyond that. This situation is not uncommon as such, it is normal for a new tool to have a running-in period [19-22], i.e. an unstable starting condition before it begins to gain linear deterioration.

| Tool No. | Surface Roughness, $R_a$ (μm) |
|----------|--------------------------------|
|          | Point 1 | Point 2 | Point 3 | Point 4 | Average |
| 1        | 4.459   | 4.199   | 5.177   | 5.575   | 4.853   |
| 2        | 4.69    | 4.8     | 5.673   | 5.991   | 5.289   |
| 3        | 5.397   | 4.269   | 5.673   | 5.991   | 5.333   |
| 4        | 1.594   | 2.228   | 2.31    | 2.632   | 2.191   |
| 5        | 1.613   | 2.041   | 2.098   | 2.745   | 2.124   |
| 6        | 2.644   | 2.239   | 1.986   | 2.204   | 2.268   |
| 7        | 1.006   | 2.179   | 1.762   | 1.283   | 1.558   |
| 8        | 1.417   | 1.311   | 1.35    | 3.09    | 1.792   |
| 9        | 1.653   | 1.455   | 2.216   | 2.108   | 1.858   |

**Figure 7.** Surface roughness, $R_a$ trends for all tested tools
4. Conclusion
Selection of suitable feed rate is essential as this parameter caters the size-effect issue, which becoming the primary concern when machining at micro-scale. A feed rate or feed per tooth value that is much lower than the radius of cutting edge could result in ploughing mechanism, which deteriorates tool faster when compared to shearing. However, putting the micro-sized tool into too much shearing could be ineffective, since it is low in strength and may deflect, which could finally cause catastrophic tool breakage.

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