Experimental Study on Machinability of Ti-6Al-4V in Micro End-Milling

Dae Hoon Kim, Pil-Ho Lee, and Sang Won Lee

Abstract—In this paper, the characteristics of micro end-milling of titanium alloy (Ti-6AI-4V), which is representative difficult-to-machine material, are experimentally investigated. The spindle speed and feed per tooth are considered as independent factors, and the resulting milling forces, burr formation, chip morphology and tool wear are studied through a series of micro end-milling experiments. In the cases of milling forces and burr formation, the feed per tooth is a dominant factor. It is found that the milling forces linearly increased with the increase of feed per tooth, and that the low feed per tooth generated more top burrs at the edges of milled slots. Meanwhile, low feed per tooth can generate long and connected chips and also cause larger tool wear at the cutting edge of micro end-mill.

Index Terms— Micro End-Milling, Titanium Alloy, Milling Force, Burr Formation, Chip Morphology, Tool Wear

I. INTRODUCTION

TITANIUM alloy has been an attractive material for aerospace and biomedical industries because of their superb mechanical property, high strength-to-weight ratio, corrosion resistance, and biocompatibility. However, titanium alloy is classified as a difficult-to-machine material due to strong affinity with tool materials and low thermal conductivity which can result in excessive tool wear [1, 2]. Due to these reasons, researches on mechanical machining of titanium alloys have been actively conducted.

Meanwhile, in recent years, there has been an increasing need to fabricate miniature parts and micro-scale features in a wide range of engineering materials. In this context, micro-milling is a key machining process which could be used to make complex three-dimensional micro-scale components with high aspect ratios. Micro-milling demonstrates distinguishing features compared to macro-scale milling in several ways. Micro tools with diameters in the range of sub-millimeter have relatively small stiffness, high risk of tool breakage, and high tool wear. Moreover, an edge radius of a micro tool becomes more significant in micro-milling process

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Dae Hoon Kim is with the Dept. of Mechanical Engineering, Graduate School, Sungkyunkwan Univ. 2066, Seobu-ro, Jangan-gu, Suwon-si, Gyeonggi, South Korea, 440-746 (e-mail: gosugns@skku.edu).

Pil-Ho Lee is with the Dept. of Mechanical Engineering, Graduate School, Sungkyunkwan Univ. 2066, Seobu-ro, Jangan-gu, Suwon-si, Gyeonggi, South Korea, 440-746 (e-mail: firobbong@skku.edu).

Sang Won Lee is with the School of Mechanical Engineering, Sungkyunkwan Univ. 2066, Seobu-ro, Jangan-gu, Suwon-si, Gyeonggi, South Korea, 440-746 (phone: 82-31-290-7467; fax: 82-31-299-4690; e-mail: sangwonl@skku.edu). since its magnitude is comparable to or smaller than the uncut chip thickness which is the thickness of the material to be removed. As a result, chips are not generated for every pass due to ploughing effect [3]. This ploughing effect could significantly increase cutting force, burr formation, surface roughness, and tool wear [4, 5, 6, 7].

The above-mentioned problems can be more significant in micro-scale machining of difficult-to-machine materials. However, a limited number of researches on micro-scale machining of difficult-to-machine materials have been studied. Aramcharoen and Mativenga conducted the micro-milling of hardened tool steel in order to investigate the size effect [8]. The results showed that the specific cutting force, surface finish, and burr formation were changed depending on the ratio of undeformed chip thickness to the cutting edge radius. In the case of titanium alloy, Schueler et al. studied the burr formation and surface generation characteristics in the micro end-milling of Ti-6Al-4V and Ti-6Al-7Nb with the micro end-mills having the diameter of 48 um [9]. The massive wavy-type burrs were formed at the low depth of cut, but the surface roughness did not differ according to feed rates solely. Ramesh et al. also investigated the burr formation and surface quality in the micro milling of Ti-6Al-4V [10]. Several types of burr were observed at different locations of the machined groove and the effect of machining parameters on burr size were analyzed. In addition, they reported that surface roughness increased with the increase in spindle speed, feed rate, and depth of cut. Thepsonthi and Özel conducted the multi-objective process optimization in order to obtain optimal process parameters in the micro end-milling of Ti-6Al-4V in terms of the burr formation and surface roughness [11]. They concluded that axial depth of cut is a major process parameter causing top burr formation and feed rate is a major process parameter affecting surface roughness.

This paper addresses comprehensive analysis on the micro-scale end-milling process of titanium alloy – Ti-6Al-4V by investigating the effects of machining parameters on milling forces, burr formation, chip morphology, and tool wear, respectively. The experimental results show that large feed per tooth (5 um/tooth) results in the increase in the resultant milling force and that large spindle speed (60,000 RPM) and feed per tooth (5 um/tooth) reduce the top-burr width. In addition, small feed per tooth (1 um/tooth) can generate long and connected chips while larger feed per tooth (3 and 5 um/tooth) can produce discontinuous chips. In the case of tool wear, small feed per tooth (1 um/tooth) can lead to large tool wear along the cutting edge of the micro endmill.

II. MICRO END-MILLING EXPERIMENTS

A. Experimental Setup

The micro end-milling experiments of Ti-6Al-4V were performed in the miniaturized machine tool system, which is shown in Fig. 1. The miniaturized machine tool consisted of three stepper motor driven linear translation stages (MX80S) for the precision positioning system and the high speed ultra-high precision brushless DC motor spindle (E-800Z) with the maximum spindle speed of 80,000 RPM in the horizontal configuration. In addition, the relative motion between a micro end-milling tool and a workpiece was controlled by the PMAC (CEM 104) motion controller. The 2-axis load cell was installed to stepper motor driven linear translation stages to capture the force signals during the micro end-milling process. The 2-axis load cell was connected with strain gage amplifier (DPM-911A) NI-DAQ (USB-6251) for process monitoring and data capturing. The overall size of the miniaturized milling machine tool system was 210 x 190 x 220 mm.

The tool used during the micro end-milling experiments was an ultra-fine tungsten carbide tool (JJ Tools). The micro endmill was a flat end-mill having two flutes having a diameter of 500 um. The workpiece material was representative titanium alloy, Ti-6Al-4V. The workpiece had the size $30 \times 30 \times 4.5$ mm, and was attached to the 2-axis load cell. The full-immersion milling was conducted with the axial depth of cut of 100 um, and ten slots of 30 mm in length (total length of cut: 300 mm) were machined. The experimental conditions are summarized in Table 1. In addition, burrs of machined slots, tool wear, and chip morphology were measured by using the optical microscope (OLYMPUS BX51M).



1) DC-slides 2) BLDC spindle 3) PMAC controller 4) Strain amplifier 5) DAQ board 6) 2-axis load cell 7) Workpiece 8) Micro-end mills Fig. 1. Experimental setup

TABLE I Experimental Conditions		
Workpiece	Ti-6Al-4V (Grade 5)	
Milling tool	Two flat carbide micro end-mill Tool diameter: 500 um	
Milling type	Full-immersion milling	
Cutting fluid	Dry cutting	
Axial depth of cut	100 um	
Length of cut	Ten micro-milled slots (30 mm) Total length: 300 mm	

B. Experimental Design

The micro end-milling experiments were designed based on Taguchi method with two factors and three levels. Two independent factors of spindle speed and feed per tooth were considered. Three levels of the spindle speed were selected as 30,000, 45,000, and 60,000 RPM and those in the case of feed per tooth were 1, 3, and 5 um/tooth. The results of experimental design, Taguchi orthogonal arrays (L9), are summarized in Table 2.

Run	Spindle speed (RPM)	Feed per tooth (um/tooth)
1	30,000	1
2	30,000	3
3	30,000	5
4	45,000	1
5	45,000	3
6	45,000	5
7	60,000	1
8	60,000	3
9	60,000	5

In order to investigate the machinability of Ti-6Al-4V in the micro end-milling process according to the changes in machining parameters, the milling forces, burr formation, chip morphology, and tool wear were observed and analyzed.

Fig. 2 shows a schematic diagram of the micro end-milling process. As can be seen in Fig. 2, the milling forces generated during the micro end-milling process were divided into two orthogonal components, normal (F_n) and feed (F_f) directional forces.



Fig. 2. Schematic of the milling process – milling forces (Fn: normal force, Ff: feed force) and burr formation (top-burr)

In case of a full-immersion milling, different types of burrs such as entrance, exit, top, and side burrs were generally formed according to relative position between tool and workpiece [12]. In this paper, the top burrs which were generated at the edges of the milled slot were considered for analysis, as can be seen in Fig. 2. In this case, the top-burr width was defined as the vertical length of the burr from the edge of the milled slot.

III. EXPERIMENTAL RESULTS AND DISCUSSIONS

A. Milling Forces

The peak-to-valley (P-to-V) forces at normal and feed directions for each tool revolution were obtained and averaged in the cases over 1,000 revolutions for each slot. Then, they were used to calculate the resultant milling force (in-plane force) by considering their vector sum. The average resultant milling forces in each experimental case are shown in Fig. 3. As can be seen in Fig. 3, the average resultant milling forces linearly increased with the increase of feed per tooth under the same spindle speed.

However, the differences were not significant according to the change in spindle speed ranging from 30,000 to 60,000 RPM. The main effect plots for the average resultant milling force in the case of spindle speed and feed per tooth are given in Fig. 4, and also indicated that the feed per tooth was the dominant factor affecting the resultant milling force.



Fig. 3. Average resultant milling forces



Fig. 4. Main effects plot for average resultant milling force

B. Burr Formation

Burrs are rough edges which are generated during mechanical machining process and a burr formation is one of common phenomena in end-milling process. The entrance burrs, exit burrs, top burrs, and side burrs are created at different edges of machined surface. However, burrs are very difficult to remove and negatively affect part quality.

In order to remove burrs, additional deburring process is generally needed, which requires high cost and complex assembly operation. The burr formation usually depends on workpiece material as well as cutting conditions, tool wear, and tool geometry. In particular, a radius of cutting edge can

ISBN: 978-988-19253-5-0 ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online) be highly related to burr formation. From this point of view, the burr formation in the case of a micro milling process can be more than that in the case of a conventional milling process since the radius of cutting edge of a tool can be similar to or smaller than feed per tooth during a micro milling process [13]. Similar researches on the interaction between the radius of cutting edge and feed per tooth have been reported by some researchers [8, 14].

The measured top-burr widths in the sides of both down and up milling of 10 milled slots were averaged, and their results are shown in Fig. 5 with the bars of standard deviation. In addition, the optical microscope images of top burrs of micro-milled slots according to the changes in the spindle speed and feed per tooth are given in Fig. 6.



Fig. 5. Average measured top-burr widths



Fig. 6. Optical microscopic images of top-burrs in micro-milled slots (scale bar = 100 um)

As can be seen in Fig. 5, the largest top-burr widths were observed at the lowest feed per tooth of 1 um/tooth for each spindle speed. In addition, the top-burr widths decreased when the feed per tooth increased in each case of spindle speed. Especially, the smallest top-burrs were observed at the high feed per tooth and low spindle speed – Run 3.

In the optical microscopic images of top-burrs given in Fig. 6, the largest and irregular top-burrs are observed at the low feed per tooth and low spindle speed – Run 1. In this case, ploughing effect could be dominant since the feed per tooth (1 um/tooth) could be comparable to the edge radius of the micro end-mill. As a result, workpiece material deformed plastically and became burrs. On the other hand, relatively small burrs were formed in the case of high feed per tooth of 5 um/tooth. When the feed per tooth increased, a dominant process

mechanism could be shearing, which resulted in less burrs.

The main effect plot for the average total top-burr width as the summation of up and down milling side burrs is given in Fig. 7. It can be found that the feed per tooth was more dominant factor than the spindle speed to influence on the burr formation in the micro end-milling process. The higher the feed per tooth, the smaller is the average top-burr width.



Fig. 7. Main effect plots for average total top-burr widths

C. Chip Morphology

In machining process, short and broken chips are usually desirable because they improve chip evacuation and handling, whereas unexpected long chips are entangled in the cutting edge and re-cutting of chips may cause tool wear. Moreover, the length of chips indicates the contact time between tool and chips, a long contact time may give rise to tool wear caused by abrasion and diffusion [15]. Therefore, it is of significance to investigate chip morphology during the micro end-milling of difficult-to-machine materials in order to improve its machining efficiency. Fig. 8 shows the optical microscopic images of representative chips collected during the micro end-milling process in the cases of varying feed per tooth and spindle speed.



Fig. 8. Optical microscopic images of chips under various machining conditions (scale bar = 200 um)

As can be seen in the first column of Fig. 8, long and connected chips were observed at the smallest feed per tooth of 1 um/tooth for each spindle speed. On the other hand, short

and broken chips were observed in the cases of higher feeds per tooth of 3 and 5 um/tooth, as can be seen in right two (2) columns of Fig. 8.

These long and connected chips may be due to the ploughing effect in the case of low feed per tooth of 1 um/tooth. This plough effect can cause intermittent chip generation, and the uncut volume of the workpiece could be added to the next chip formation during the micro end-milling process. As a result, long and connected chips could be generated.

D. Tool Wear

The qualitative analysis on tool wear was also conducted by taking the optical microscopic photos of the micro end-mills in each experimental case. They were taken after machining 10 slots (300 mm in length), and are given in Fig. 9. In particular, those in the cases of the feeds per tooth of 1 and 5 um/tooth with the spindle speed of 30,000 RPM. The photo of the unused micro end-mill is also given for comparison.



Fig. 9. Optical microscopic images of micro end-mills under the conditions of (a) unused, (b) 30,000 RPM, 1 um/tooth (run 1), and (c) 30,000 RPM, 5 um/tooth (run 3)

As can be seen in Fig. 9(b) representing the case of low feed per tooth -1 um/tooth, blunt cutting edge and large tool wear were observed. On the other hand, in the case of high feed per tooth, small wear was observed and relatively sharp cutting edge still remained, as can be seen in Fig. 9(c). Ploughing in the case of low feed per tooth could cause more wear at the cutting edge of the micro end-mill.

IV. CONCLUSION AND FUTURE WORKS

This paper experimentally studied the characteristics of micro end-milling process of titanium alloy (Ti-6Al-4V) in terms of milling forces, burr formation, chip morphology, and tool wear with varying machining parameters – spindle speed and feed per tooth, while other parameters were fixed.

In terms of milling forces, the average resultant milling forces linearly increased along with the increase of feed per tooth, and however, they did not show any clear trend according to the change of spindle speed. In the case of burr formation, it seemed that low feed per tooth (1 um/tooth) could cause irregular and large top burrs. In addition, it was observed that the effect of spindle speed on burr formation was not clear. Therefore, the feed per tooth was a critical factor to affect milling forces and burr formation in the micro end-milling of titanium alloy.

Regarding chip morphology, long and connected chips were observed at the lowest feed per tooth of 1 um/tooth. As feed per tooth increased, short and thick arc-shaped chips were generated. Regarding tool wear, blunt radius of the cutting edge and large tool wear were also observed at the lowest feed per tooth of 1 um/tooth.

These experimental results can be utilized as a basis for the further researches in order to have better understanding of micro end-milling process of difficult-to-machine material such as titanium alloy. In addition, optimal machining conditions to maximize the machinability of titanium alloy in the micro end-milling will be addressed in the future work.

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