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Characteristics of Grooving by Micro End Mills with Various Tool Shapes and Approach to Their Optimal Shape

by

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Abstract

Recently micro machining in many fields needs to be operated accurately and efficiently. The present paper deals with the fabrication of micro end mills with a diameter of 20 μm by precision grinding and their application to the micro grooving on duralumin in order to realize an accurate and efficient micro end milling. Micro end mills with various tool shapes are fabricated and their grooving tests are carried out. The characteristics of micro end mill in grooving test are clarified and the approach for its optimal tool shape is tested.

Keywords: Micro end mill, Micro grooving, Tool fabrication, Cutting force, Burr, Surface roughness, Tool life, Optimal tool shape

1. Introduction

In contemporary manufacturing, as the demand for product quality such as high precision and performance increases, the need of micro machining in many fields including electronic, information, medical devices etc. is also rising. There are some methods in micro machining, such as conventional cutting and grinding, electrodischarge machining, laser machining, LIGA process, etching and etc., which are developed in some researches[1)-6)]. Among them, cutting and grinding also has a remarkable existence as they could machine 2- and 3-dimensional shapes with a high precision and efficiency. Up to now, diamond still stands as the major material for micro cutting tool, whether researches[7)] relating to micro end mill made of carbide are not much. If it is possible for machining with high precision using carbide tool, machining of steel material becomes possible and also it is very remarkable from the point of machining cost.

In this paper, the characteristics of micro end mill in grooving test are clarified and the

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approach for its optimal tool shape is tested in order to realize an accurate and efficient micro end milling.

2. Experimental Method and Condition

In this research, after fabrication of micro end mill, the grooving test is conducted in order to investigate its machining characteristics. Experiment is conducted on vertical machining center (MSA40-0, Makino Seiki Co., Ltd.).

The structure of experiment devices used for micro end mill fabrication is shown in **Fig.1**. During the fabrication of micro end mill, grinding wheel is clamped on the main spindle. On the other hand, the tool blank of micro end mill (cemented carbide) is installed on the sub-spindle fixed on the rotary table. Firstly, dressing and truing for end and side faces of grinding wheel is conducted using rotary dresser fixed on machining center table. After finishing the dressing and truing processes, fabrication of micro end mill with a diameter of 20 μm is started. The material of micro end mill is ultra-fine grained cemented carbide having WC particle with a diameter of 90nm.

Basically, there are 4 types of tool shape tested in the experiment and they are shown in **Fig.2(a) – (d)**. To make it easier, each of them are named types a, b, c and d. Type a has 1 cutting edge, type b has 2 cutting edges with no flank at their side cutting edges and relief angle of 0˚ at the tool end surface, type c basically has the same shape with type b but it has a relief angle of 5˚ at the tool end surface and type d has 4 cutting edges. In the respect of comparison between types a, b and d, the influence of friction between tool side and groove wall surfaces and also the role of size of the chip pocket is evaluated. Moreover, regarding the comparison between types b and c, the effect of relief angle is evaluated. Further, the rake angle of types a, b and c is -37˚, whether type d has a

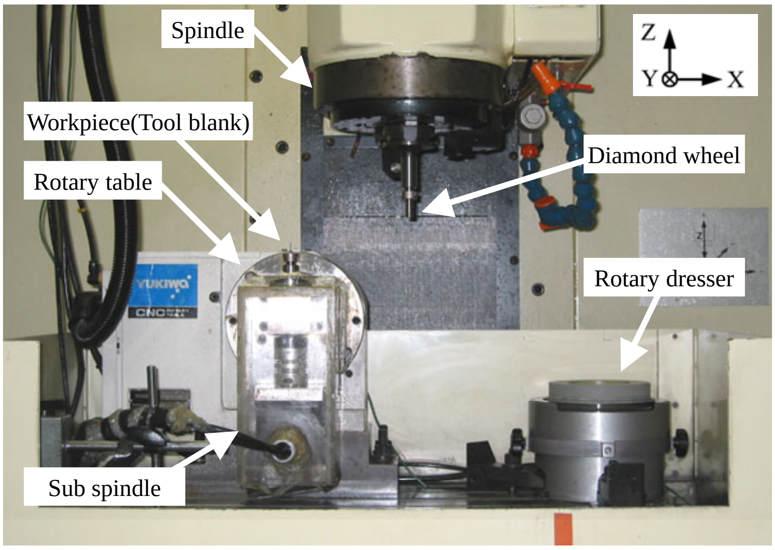
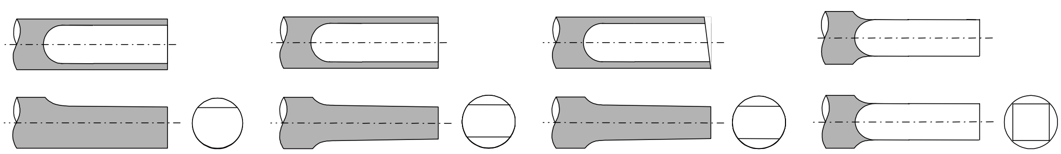
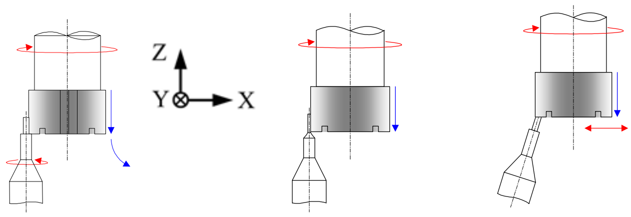


Fig.1 Experiment devices used for micro end mill fabrication.



(a) Type a (b) Type b (c) Type c (d) Type d

Fig.2 Tool shapes of micro end mills.

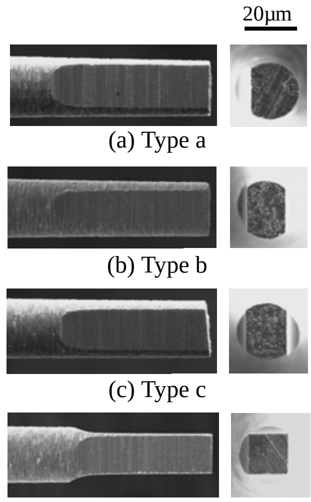


(a) Peripheral surface (b) Flute surface (c) End face

Fig.3 Procedures for fabrication of micro end mill.

Table 1 Experimental conditions for fabrication of micro end mills.

Grinding wheel	SD3000I100M
Workpiece (Tool Blank)	Ultra-fine grained cemented carbide End mill geometry to be desired Diameter : 20 µm
Grinding condition	
Rotational speed of spindle	4200 min^{-1}
Rotational speed of sub spindle	100 min^{-1} for peripheral surface
Feed speed	70 µm/min for peripheral surface 35 µm/min for flute surface 70 µm/min for end surface
Fluid	Water-based coolant
Truer & Dresser	GC3000



(a) Type a (b) Type b (c) Type c (d) Type d

Fig.4 Fabricated micro end mills.

rake angle of -45˚. In the case of types a, b and d, tool fabrication is conducted orderly from peripheral surface grinding (**Fig.3(a)**), then it is continued to flute surface grinding (**Fig.3(b)**). On the other hand, type c is fabricated firstly from end surface grinding (**Fig.3(c)**), peripheral surface grinding (**Fig.3(a)**), and flute surface grinding (**Fig.3(b)**). Experimental condition and fabricated micro end mill are shown in **Table 1** and **Fig.4** respectively.

During the grooving test, the fabricated micro end mill is clamped on the main spindle. On the other hand, the workpiece, which is duralumin (A2017), is clamped on the jig fixed on the machining center table. Further, in respect of the cutting force measurement, workpiece is fixed on the load cell clamped by the jig on the machining center table.

For the grooving test method, as it is shown in **Fig.5**, after giving a prescribed cutting depth,

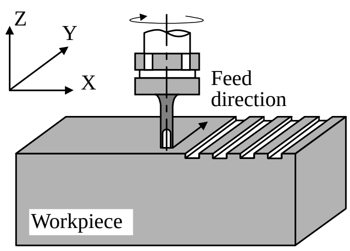


Fig.5 Method of grooving test.

Table 2 Experimental condition for grooving test.

Workpiece	Duralumin (A2017)			
Grooving condition				
Rotational speed	4200 min^{-1}			
Depth of cut	3 µm (1µm for measurement of cutting force only)			
Feed per tooth	Tool type	No. of cutting edge	Feed speed (mm/min)	Feed per tooth (µm/rev/tooth)
	a	1	2	0.476
	a	1	4	0.952
	b	2	4	0.476
	c	2	4	0.476
	d	4	8	0.476
	d	4	4	0.238
Fluid	Water-based coolant			

grooving of 10 mm length is conducted. In the case of measurement of a tool life, the grooving process is repeated until tool is broken. Normally, cutting depth is set to 3 μm, but during the measurement of cutting force, it is set to 1μm. The usual cutting depth is set to 3 μm, but in the case of measurement of cutting force, the cutting depth is set to 1 μm in order to suppress the changes of machining force as the result of chip pinching. Grooving condition is shown in **Table 2**.

3. Experimental Results

3.1 Cutting force

Figure 6 shows the average cutting force *Fy* in feed direction during grooving for each tool shape. In the case of the difference of feed rate per piece of cutting edge (named fz), for end mill with the same shape, as the feed rate is getting larger, the cutting volume is increasing, which causes *Fy* to be larger. In the case of the difference of the tool shape, type a which has a larger peripheral surface shows the largest cutting force, then it is followed by end mills types b and c having smaller peripheral surfaces compared to type a, and type d exhibits the smallest cutting force. Types a, b and c have a rake angle of side cutting edge of -37˚, and type d is -45˚. It is considered that although type d has a smaller rake angle compared with other, the friction between peripheral surface and workpiece is larger, which causes the above mentioned result. Furthermore, the influence of relief angle at the tool end surface on the change of *Fy*, especially in the comparison between type b, which has a 0˚ of relief angle, and type c, having relief angle of 5˚, is not significant.

Figure 7 shows the average cutting force *Fz* in *Z* axis direction during grooving for each tool shape. In the case of the difference of feed rate per piece of cutting edge, for the end mill having the same shape, as the feed rate is increasing, the cutting volume becomes larger and *Fz* is rising. On the other hand, in the case of the difference of tool shape, end mills types d, a and b, which are having a larger contact between the groove bottom and the tool end surfaces, show a larger cutting force compared with the type c which has a relief angle of 5˚.

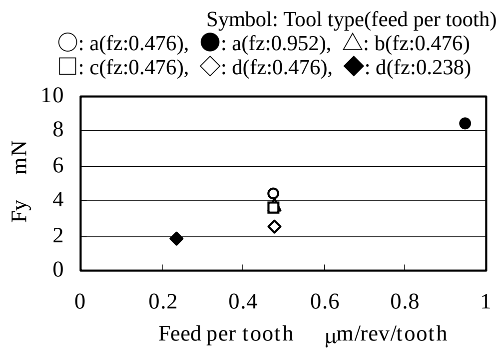


Fig.6 Cutting force *Fy*.

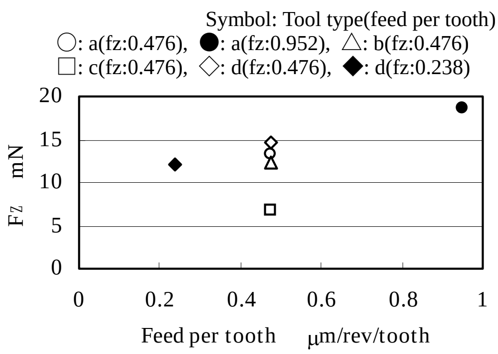
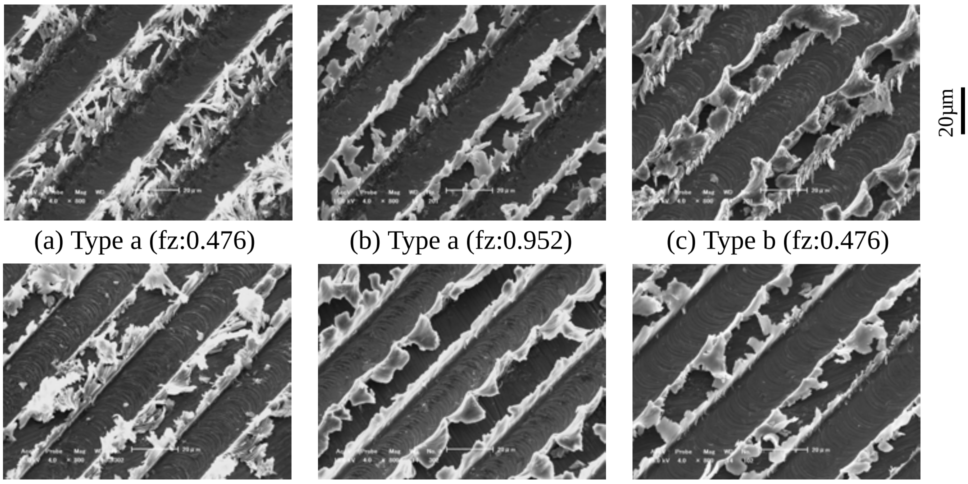


Fig.7 Cutting force *Fz*.

3.2 Burr

Figure 8 shows the pictures of the machined grooves. Moreover, for the purpose of numerical evaluation, burr height for each condition is shown in **Fig.9**. After measuring the length of parts corresponding to the burr height which is measured from the pictures taken in inclined direction, then it is converted to burr height in vertical direction. In the case of the difference of feed rate per piece of cutting edge, for the tool with the same shape, as the feed rate is increasing, the cutting



(a) Type a (fz:0.476) (b) Type a (fz:0.952) (c) Type b (fz:0.476)

(d) Type c (fz:0.476) (e) Type d (fz:0.476) (f) Type d (fz:0.238)

Fig.8 Machined micro grooves.

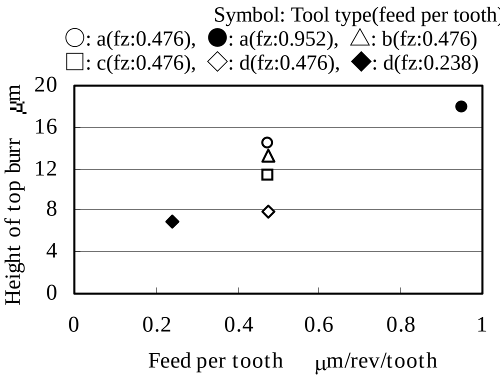


Fig.9 Height of top burr.

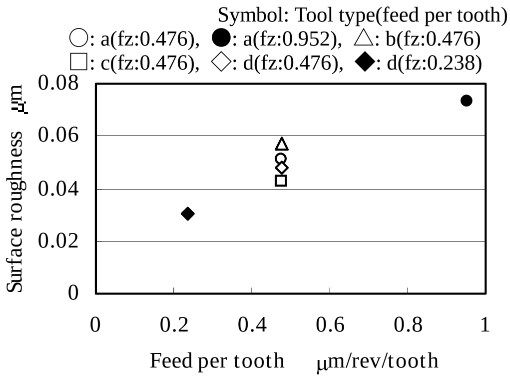


Fig.10 Surface roughness of groove bottom.

force, especially *Fy* which leads to top burr formation, is getting larger and as the result the burr is getting larger. Concerning the difference of tool shape, end mill type a, having the largest peripheral surface, brings the largest burr size. And it is followed by the end mill types b and c which have smaller peripheral surfaces compared with the type a. Type d gives the smallest burr size than other. This order is the same as that of the value of *Fy* as shown in **Fig.6**. It is considered that the rubbing at the peripheral surface, which is influencing a large cutting force, plays a significant role rather than the existence of rake and relief angles. As the result, it seems that the above order are obtained.

3.3 Surface roughness of the groove bottom surface

Figure 10 shows the surface roughness of the machined groove bottom surface. In the case of the difference of feed rate per piece of cutting edge, for the tool having the same shape, as the feed rate is increasing, the mark of feed pitch is getting larger and the machining force increases. These cause a larger tool bending, and as the result, formed chip becomes thicker and larger.

Regarding the difference of tool shape, although there is no significant distinction, when there is a relief angle of 0˚, the formed chip is pinched between the tool end and groove bottom surfaces, which causes a larger surface roughness. On the contrary, when there is a relief angle of 5˚, there is no chip pinched between the groove bottom and tool end surfaces, which leads to a smaller surface

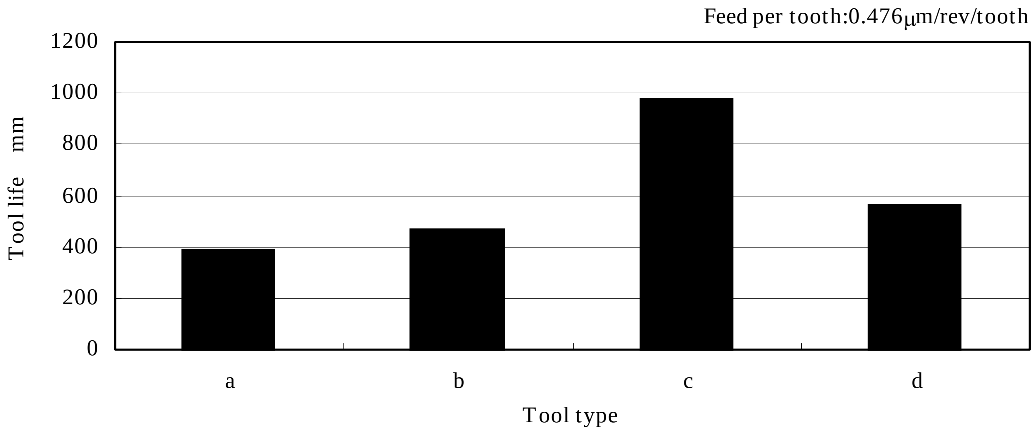


Fig.11 Tool life.

roughness.

3.4 Tool life

Figure 11 shows the tool life of fabricated end mills. Here, tool life is defined as the length of the groove which could be machined by end mill until its breakage. From the figure, it is shown that type c has the longest tool life. It is considered that the tool life could be improved by reducing the rubbing occurred at the tool end surface, decreasing the pinching of formed chip between the groove bottom and tool end surfaces, advancing the chip removal capability, etc.

4. Suggestion to the New Tool -Design and Experiment-

4.1 Suggestion to the optimal tool shape for micro grooving

From the results explained in chapter 3, there are some suggestions which could be drawn to get a better grooving capability.

- It is better to reduce the interference between the tool peripheral and groove wall surfaces.
- It is recommended to avoid any rubbing happened between the tool end and groove bottom surfaces.
- It is pointed out to give a large space between tool and workpiece to improve the capability of chip removal.

From the point of view of manufactured product, as the existence of burr on the machined groove is a very fatal factor that must be avoided, reducing the burr becomes very crucial. From the result, as end mill type d resulted in the smallest burr formation, hence the new tool shape, which is named as type e (**Fig.12**), is developed basically from type d. End mill type e has some characteristics as follow :

- No interference between tool peripheral and groove wall surfaces because the tool peripheral surfaces are removed.
- Reduce of rubbing between tool end and groove bottom surfaces as the result of eluding the 2 surfaces of type d.
- Better chip removal capability as 2 surfaces of type d is eluded.

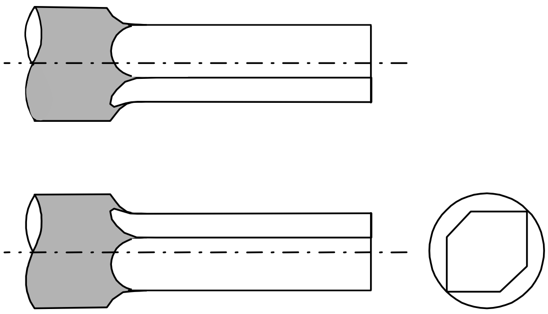


Fig.12 Proposed tool shape (Type e).

Table 3 Grooving condition of type e.

Workpiece	Duralumin (A2017)			
Milling condition				
Rotational speed	4200 min^{-1}			
Depth of cut	3 μm (1μm for measurement of cutting force only)			
Feed per tooth	Tool type	No. of cutting edge	Feed speed (mm/min)	Feed per tooth (μm/rev/tooth)
	e	2	4	0.476
Fluid	Water-based coolant			

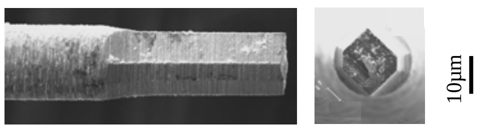


Fig.13 Fabricated micro end mill (type e).

4.2 Fabrication of new tool and its performance

4.2.1 Tool fabrication and grooving condition

Basically, the fabrication method and grooving condition are same as mentioned in chapter 2. The fabrication order for type e is similar with types a, b and d, it is started from peripheral surface grinding (**Fig.3(a)**) and continued to flute surface grinding (**Fig.3(b)**). Grinding and grooving conditions are shown in **Table 1** and **Table 3** respectively. **Figure 13** shows the fabricated end mill type e.

4.2.2 Machining performance

Figures 14 and **15** show the average cutting forces both in feed (Fy) and Z axis (Fz) directions. As there is no peripheral surface and also the chip removal capability is getting better, Fy becomes smaller. On the other hand, because type e has a relief angle of 0˚ as the same phenomenon as other tools with relief angle of 0˚, there is an interference between tool end and groove bottom surfaces causing a large Fz.

Figure 16 shows the machined grooves by end mill type e. Moreover, the burr height of the machined groove is described in **Fig.17**. As there is no peripheral surface, the interference with the groove wall surface could be reduced significantly resulting in a smaller burr height.

Figure 18 shows the surface roughness of groove bottom surface machined by end mill type e. It is clear that the surface roughness is smaller compared with other types. It is considered that although the interference between tool end and groove bottom surfaces still exists, the pinching of formed chip could be reduced significantly.

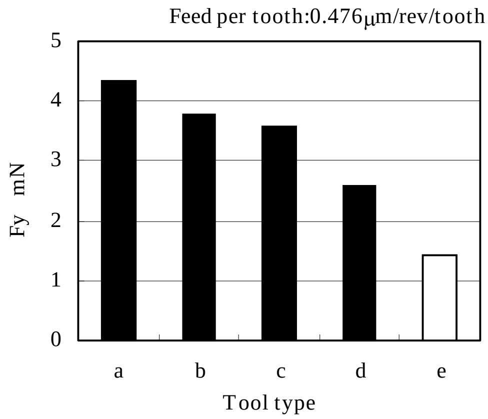


Fig.14 Comparison of cutting force *Fy* by using various tools.

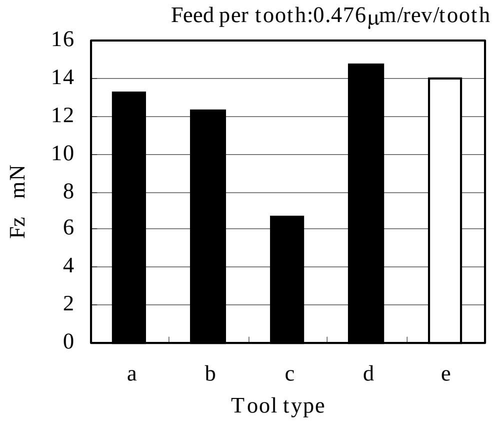


Fig.15 Comparison of cutting force *Fz* by using various tools.

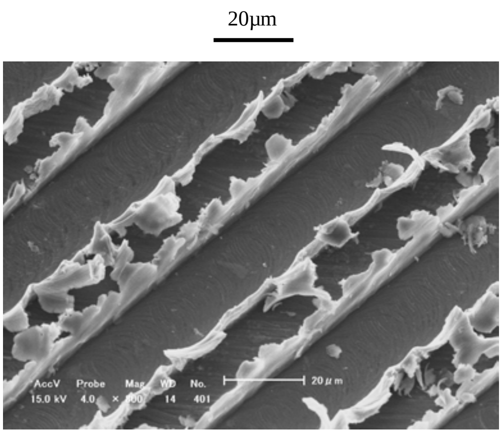


Fig.16 Micro grooves by using micro end mill type e.

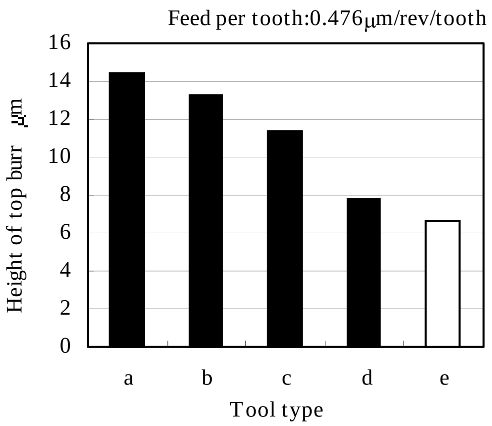


Fig.17 Comparison of burr height by using various tools.

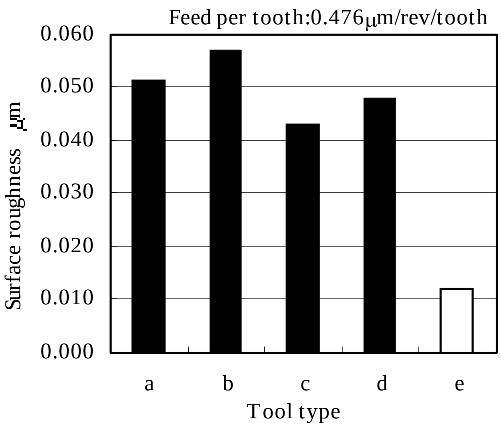


Fig.18 Comparison of surface roughness by using various tools.

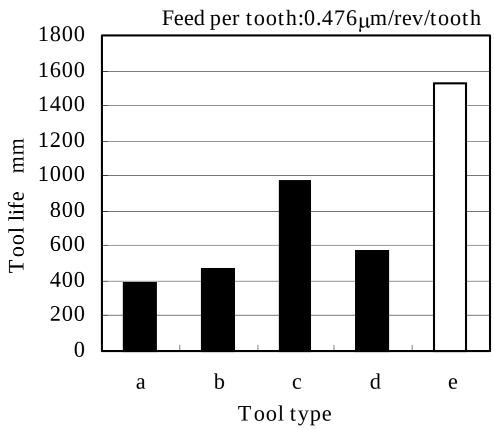


Fig.19 Comparison of tool life by using various tools.

Figure 19 shows the tool life of tool type e. End mill type e, which is designed especially to decrease the size of formed burr, could reach the longest tool life. It seems that the improvement in chip removal gives a contribution to a longer tool life.

5. Conclusion

In this paper, micro end mills with different tool shapes were designed and fabricated well and their characteristics of grooving are clarified. From the results, they could be summarized as follow :

- From the viewpoint of burr, it is better to decrease the interference between tool peripheral and groove wall surfaces.
- From the viewpoint of surface roughness and tool life, it is better to reduce the rubbing between tool end and groove bottom surfaces.
- From the viewpoint of surface roughness and tool life, it is better to increase the space between the tool and workpiece, which advances the chip removal capability.
- With the main objective of reducing the size of burr, end mill with the above proposed points is fabricated and its validity could be clarified through the performance evaluation.

Acknowledgements

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