Tool Wear Rate and Accuracy of Patterns in Micro Prismatic End-milling

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마이크로 프리즘 패턴의 엔드밀링에서 공구 마모와 정밀도

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ABSTRACT

Micro prism pattern is applying in order to get increase of luminance, control the light, and so forth especially in optics and display industry. Most patterns are fabricated by lithography, planning, and EDM, but they have limitations on the productivity or the unit cost of produce. However, ultra precision mold is one of the processes able to replace it, and assure high productivity required by industries. In this investigation, micro prismatic end-milling is suggested in order to fabricate the pattern effectively. Micro prism pattern having 100μm of pitch and height was machined on STD-11. After machining, the flank and boundary wear on micro end mill were measured and analyzed, as well as burr formation and dimensional accuracy of fabricated pattern were evaluated. Thus the optimal cutting conditions were derived.

Key Words : Micro Prismatic End-Milling(마이크로 프리즘 엔드밀링), Prism Pattern(프리즘 패턴), Tool Wear (공구마모), Pattern Accuracy(패턴 정밀도), Boundary Wear(경계마모)

1. Introduction

Micro patterning on a surface is promising machining technology in micro scale so it has been widely applied to various industries.[1,2]

In optical industry, demand for display devices with high picture quality and light weight has significantly increased. Back light unit (BLU) of LCD and LED has an important role in homogenizing light, weight and cost. In particular, optical sheets having micro prism patterns, as a component of BLU, are the most crucial factor to advance in luminance by control directions of angular light. Therefore, development of prismatic patterns on the sheets is needed to enhance brightness.[3]

In the past decades, many studies have focused on prism patterns in the micro scale fabricated by means of lithography, laser machining, ultrasonic machining, and EDM. However, these conventional processes have drawbacks to mass production due to

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less productivity and limited machinable materials. To overcome these negative attributes, high precision mold has attracted the attention.[4,5]

Therefore, this study aims to derive optimal cutting conditions using micro prismatic end-milling when manufacturing prism patterns. In order to suggest the effective conditions, flank and boundary wear of tool are measured and evaluated by employing Taguchi $L_9(3^2)$ orthogonal array table with analysis of variance (ANOVA). In addition, burr formation and dimensional accuracy were analyzed to find association among tool wear, burr and accuracy.

2. Micro Prismatic End-Milling

In case of traditional micro end-milling, a machined surface is perpendicular to end mill. On the other hand, with regards to micro prismatic end-milling using in this experiment, the specimen is placed on end-milling at a certain angle less than 90°. This suggested method makes possible to remove triangular cross section with flat end mill.

The advantages of this process are expected to be relatively short machining time, various range of machinable materials, and low unit cost. However, it has disadvantages in terms of deformation of tool and machining error because the tool receives cutting force only one side. Thus, it is necessary to evaluate the effect of machining parameters on tool and patterns in order to reduce defects of product and increase the dimensional accuracy.

3. Experiments

3.1 Experimental Setup and Conditions

Micro prism patterns on a STD-11 are fabricated by various feed rates and spindle speeds. During production, the flank and boundary wear of tool are analyzed and then burr on peak and valley as well as dimensional accuracy of patterns are evaluated for determining the optical cutting conditions. According to the all the results, it could be anticipated to gain relationship among tool wear, burr and accuracy.

A micro end-milling system used in this research consists of jig, spindle and integrated multi-process CNC machine (Hyper-15, Hybrid Precision) shown in Fig. 1. A magnified photo represents a micro flat end mill and a workpiece tilted at an angle of 45°. The specification of tool (4G Mills, YG1) is listed in Table 1 and specimens are STD-11.

For evaluating the effect of machining parameters, a Taguchi $L_9(3^2)$ orthogonal array table was adopted as listed in Table 2. The other selected parameters which are depth of cut, about 5μm, and a dry cutting condition are fixed in all the experiments. The size of pitch, height, angle and length are 100μm, 100μm, 90° and 5mm respectively as illustrated in Fig. 2.

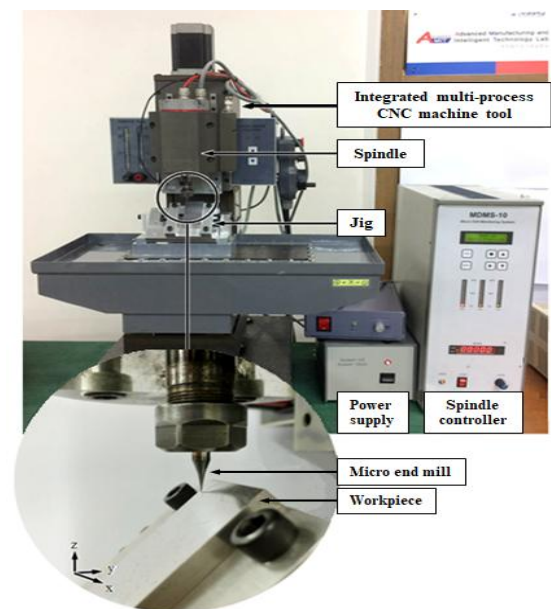**Fig. 1 Micro prismatic end-milling system**

Table 1 Specification of end mill

Items	Specification
Tool diameter (μm)	300
Length of cut (μm)	600
Helix angle (°)	30
Shank diameter (mm)	4
Flute	2 flutes
End mill type	Flat
Tool material	Micro grain carbide

Table 2 Taguchi $L_9(3^2)$ orthogonal array table

No.	Spindle speed (rpm)	Feed rate (mm/min)
1	15,000	20
2	15,000	30
3	15,000	40
4	17,500	20
5	17,500	30
6	17,500	40
7	20,000	20
8	20,000	30
9	20,000	40

3.2 Measurement Methods

As mentioned previously, flank and boundary wear are evaluated in the whole research. With regard to the flank wear, two various points are measured since a cutting process is conducted at the end and peripheral cutting edge. Therefore, wear at the end cutting edge is defined as width of flank wear and wear at the peripheral cutting edge is defined as depth of flank wear. Fig. 3 shows width and depth of flank wear. In machining progress, radius at the corner increases due to wear. Thus, these difference is defined as boundary wear shown in Fig. 4.

After manufacturing patterns, burr formation on peak and valley was measured and taken by video microscope system (SV-35, Sometech).

In addition, dimensional accuracy of produced patterns should be analyzed with 3D surface profiler(New View System, Zygo Corp.).
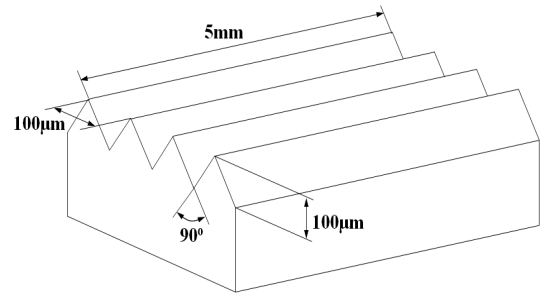
Fig. 2 Dimensions of micro prism pattern
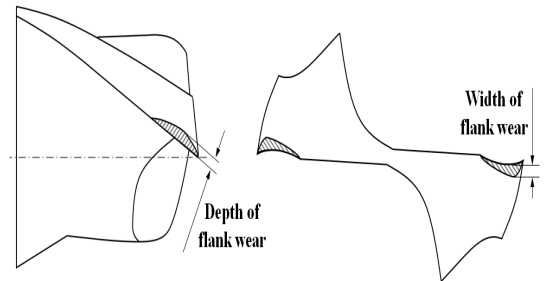
Fig. 3 Definition of flank wear
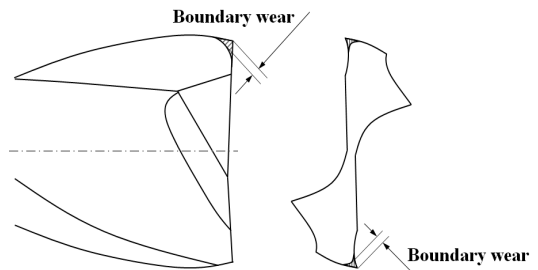
Fig. 4 Definition of boundary wear

4. Experimental Results

4.1 Evaluation of Tool Wear of End Mill

In this section, the effect of cutting parameters on flank and boundary wear was observed.

Based on Taguchi $L_9(3^2)$ orthogonal array table, experimental no.7 brought out the minimum width of flank wear, about 11.77μm, at 20,000rpm and 20mm/min while the smallest wear was measured in

no.3 at 15,000rpm and 40mm/min. Fig. 5 shows 600 times magnified end cutting edge.

Fig. 6 shows depth of flank wear and it observed same trends as width wear. In no. 3, the largest value, about 27.03μm, was observed while, the minimum wear was about 9.19μm in no.7.

Fig. 7 represents boundary wear was magnified 600 times. The largest wear occurred in no.3 experiment, about 8.06μm, whereas the smallest wear was about 5.24μm in no.7 experiment.

As it can be seen that the largest wear condition was conducted when spindle speed and feed rate were 15,000rpm and 40mm/min respectively. When feed rate and spindle speed were 20,000rpm and 20mm/min respectively, flank and boundary wear had the minimum values. Accordingly, it is noted tool wear was affected the amount of removed material per tooth and higher fractional force.

Based on above experimental results, the effect of machining parameters on tool wear was analyzed by a signal to noise (S/N) ratio and ANOVA. In this study, the-smaller-the-better characteristic was used since tool wear desired smaller value to reduce the unit cost of production and increase life expectancy The S/N ratio, η, could be defined as follows.[6,7]

$$\eta = -10\log\left(\frac{1}{n}\sum_{i=1}^{n}y_i^2\right) \tag{1}$$

Where, n is the number of experiments and y_i is measured experimental data.

Fig. 8 shows the effect of cutting parameters on tool wear and Table 4 represents ANOVA table for considered parameters. As can be seen at Fig. 8, the S/N ratio increased gradually along the selected levels of spindle speed whereas it is feed rated and S/N ratio was inversely proportional.

Based on theory of Taguchi's method, the highest values in Fig. 8 were desirable values for the optimal condition. Thus, it is expected to enhance
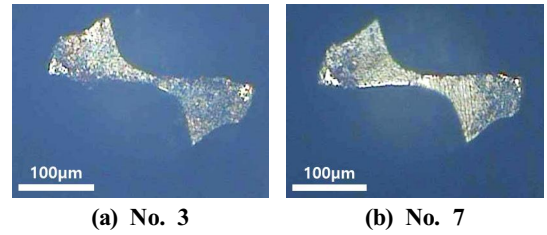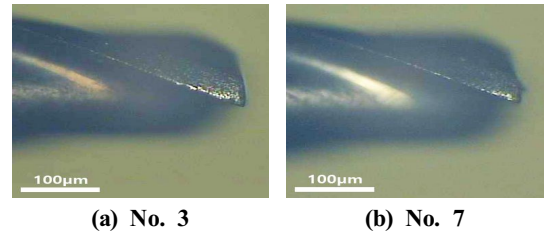

(a) No. 3   **(b) No. 7**

Fig. 5 Width of flank wear (x600)

(a) No. 3   **(b) No. 7**

Fig. 6 Depth of flank wear (x600)
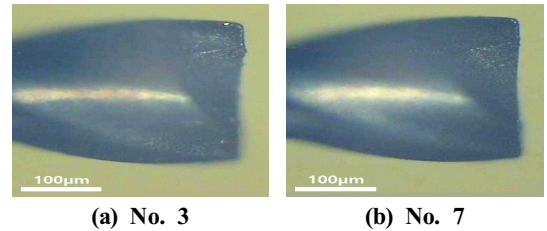

(a) No. 3   **(b) No. 7**

Fig. 7 Boundary wear (x600)

tool life expectancy and reduce purchase price at 20,000rpm and 20mm/min. In addition, ANOVA table shows that feed rate was statistically significant in 94.5% of confidence level.

4.2 Evaluation of Burr and Accuracy

The effects of two variances of spindle speeds and feed rates on burr on peak and valley and dimensional accuracy for patterns were evaluated.

Length of burr at each specimen was 1200 times magnified as shown in Fig. 9. As the results, the maximum value on peak was observed in no.3 at 15,000rpm and 40mm/min while no.9 at 20,000rpm and 40mm/min had minimum value. Therefore, low
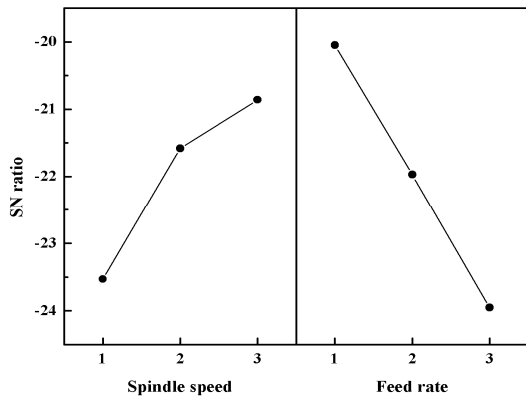
Fig. 8 Effect of machining parameters on tool wear

Table 3 ANOVA on wear of micro end mill

Source	DF	SS	MS	F	P
A	2	11.5092	5.7546	11.53	0.022
B	2	22.7896	11.3948	22.83	0.006
Error	4	1.9964	0.4991		
Total	8	36.2952			

$(R^2=94.5\%)$

(a) No. 3　　　**(b) No. 7**

Fig. 9 Peak and valley of machined pattern (x1200)

(a) Traditional system　　**(a) Suggested system**
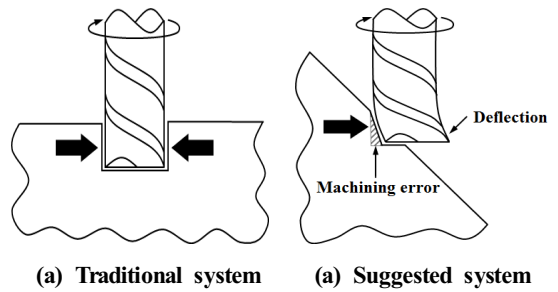
Fig. 10 Comparison cutting force
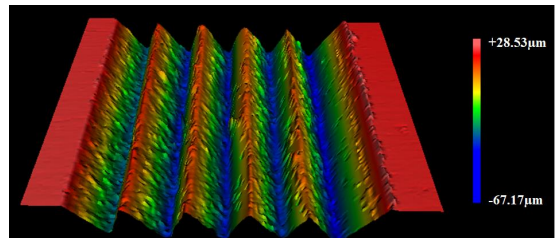
Fig. 11 3D model of experimental no.3

Fig. 12 3D model of experimental no.7

spindle speed generated more burr rather than high speed spindle at fast feed rate. It is clear that cutting speed and material removal ratio per tooth is important to minimize burr. Although, burr on valley has same trend as peak, it was less formed than a value on peak. It was considered that deflection at bottom of tool occurred at high spindle speed. As shown in Fig. 10, cutting force acts only one direction in a suggested system whereas two opposite force was applied in a traditional system. Therefore, unbalanced force resulted in larger deflection of tool.

Even though it seems that the effect of spindle speed on burr formation is more significant than feed rate, it could assume that life time of tool and length of burr are a linear positive association.

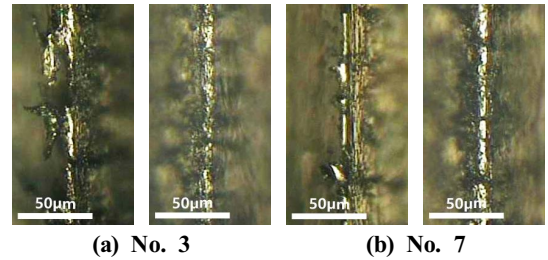In terms of accuracy, pattern height was measured as shown in Fig. 11 and Fig. 12.
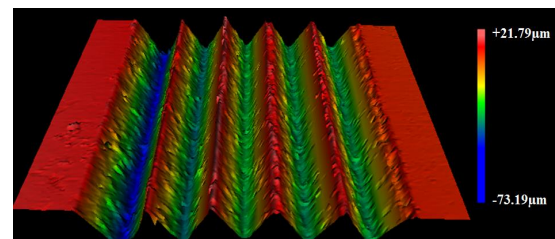
According to the results, the highest value was 82.88μm in experimental no.3 corresponding to maximum value of tool wear while the lowest

height was 79.03μm in experimental no.7 which have minimum value of tool wear. It was also caused by deflection at the bottom of the tool. Therefore, it is clear that the correlation between dimensional accuracy and tool wear took a reverse direction.

5. Conclusion

This paper aimed to find optimal parameters for micro prism patterns using micro prismatic end-milling in order to improve process efficiently. Thus, flank and boundary wear of tool, burr and dimensional accuracy of fabrication were analyzed in accordance with various spindle speeds and feed rates. After measurement, the relationship among them were evaluated to gain optimal conditions in ultra precision mold. As a results of experimentation, the following conclusions can be drawn :

1. Low spindle speed and high feed rate accelerated tool wear since high fractional force and the large amount of removal material per tooth.

2. Burr on peak and valley tend to be easily generated at low spindle speed and feed rate since higher cutting speed and material removal per tooth could minimize burr formation.

3. According to the result of pattern height, the trend of accuracy is opposite of tool wear since the deformation at the bottom of the tool were affected to its accuracy.

Acknowledgement

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