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Experimental Cutting Performance Evaluation of LGP using Vibration Assisted High Speed Shaping

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도광판의 고속 진동절삭 특성에 관한 연구

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Abstract PMMA (Polymethyle-methacrylate) optical components have recently been increasingly used as one of the important part of the high precision equipments. This research presents comparatively the surface preparation of light incident plane, LIP (Light Incident Plane) of LGP (Light Guide Panel) by end milling, high speed shaping, and vibration assisted high speed shaping. From several experiments, the results show that the surface quality was improved in high speed shaping and the vibration assisted HSS show not only decreasing waviness and breakage also raising the straightness property. For applying high speed shaping and vibration assisted HSS, an additional tool post was developed and experimentally used.

요 약 폴리메틸메타클릴레이트(PMMA)는 광 관련 부품제조에 있어 중요한 재료로 많이 사용되고 있다. 특히 TV,모니터, 휴대폰 등에 쓰이고 있는 디스플레이의 도광판(Light Guide Panel)에 적용되고 있어 현재까지는 매우 큰 상업적인 수요가 있다. PMMA 도광판의 가공은 일반적으로 고속밀링에 의해 이루어지는데 부품에 대한 높은 정밀도 요구특성에도 불구하고 가공표면의 굴곡, 균열 등에 대한 불량이 적지 않게 발생하고 있다. 이러한 문제점을 해결하기 위하여 PMMA 진동을 부가하는 고속선삭의 적용이 시도되었으며 절삭공구에 진동을 부가하기 위한 장치와 최적 조건이 조사되었다. 도광판용 PMMA의 진동절삭은 일반적인 밀링가공법에 비해 절삭력의 현저한 감소, 열변형영역의 축소 등을 유도하였다. 가공면에 있어서는 가공방법이 엔드 밀링에서 단인공구를 사용하는 선삭으로 변경되었음에도 불구하고 진동절삭법에 의해 가공표면의 균일성이 크게 향상되어 가공면의 표준편차 1.0~6.0 ㎛, 평균거칠기 0.3 ㎛가 달성되었다.

Key Words : High Speed Shaping, Vibration Cutting, PMMA, Light Guide Panel

1. Introduction

PMMA (Polymethyl-methacrylate) sheet is one of the important components of LGP (Light Guide Panel). One edge side of a PMMA sheet is used to refract incident light. As light falls on LIP(Light Incident Plane), the optical properties and the qualities of LIP surface are very important.

End milling is widely used to generate a comparatively plain surface and to cut out four sides of a PMMA sheet for fitting it in the frame in which a gate that is generated during the production of the

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PMMA sheet is also removed. HSS (High Speed Shaping) is applied to remove the waviness and edge breakage of LIP caused by high speed milling operation [1]. There are other efficient cutting processes that use CO2 lasers [2-4] or a Single Crystal Diamond (SCD) tool [5] for getting the ultra fine surfaces.

For the application of PMMA in LGP, the HAZ will drop the light transmission inside the PMMA and the ultra finish surface will reduce the scattering of the light at LIP. Investigation shows that the application of HSS though waviness and edge breakage are removed but still have problem with the straightness of LIP. The impact at the beginning of HSS, which causes vibration at the tool plate, and the high depth of cut, which causes deviation of PMMA sheet during machining and high friction between the cutting tool and the workpiece, are responsible for the problem with the straightness of LIP. To overcome this problem, a tool post has been developed for application of vibration assisted HSS by combining the HSS and ultrasonic vibration cutting. The designed tool post was analyzed and experimentally optimized. Table 1 shows the parameters for vibration assisted HSS.

Chandra Nath and M Rahman [6] applied UVC (Ultrasonic Vibration Cutting) for machining Inconel 718 and have shown the performances such as tool wear, required cutting force, and machining cost reduction. Theoretical research [7,8], simulation [9], and experimental results [10-12] for the vibration cutting method mentioned that the lower cutting force is due to a considerable reduction of the workpiece-tool frictions and the pulse cutting characteristic of the tool. In UVC, the cutting tool vibrates as very high frequency using a high speed actuator like PZT.

In this study, the surface generated from machining of LIP by end milling, HSS, and vibrations assisted HSS are analyzed by applying different cutting parameters that are related with the surface quality.

2. Vibration cutting theory

The cutting parameters which is related to the vibration assisted HSS are the cutting stroke/amplitude of the cutting tool, applied frequency to the cutting tool, and the feedrate of the workpiece (PMMA sheet). Those parameters are related with each other and have effect on the surface quality of the cut materials.

From the vibration theorem, the displacement and velocity of an oscillating point are expressed as follows.

$$x = asin(\omega t) \quad \cdots (1)$$

$$\dot{x} = aw\cos(wt) \quad \cdots (2)$$

From the above equations, it is clear that the cutting speed, amplitude, and applied frequency are organically related to each other.

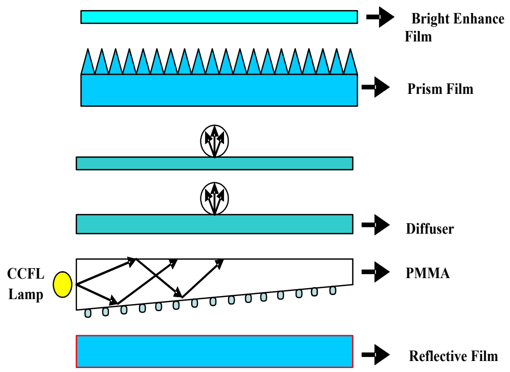
During cutting, if the applied cutting speed exceeds the speed , the cutting will transform from conventional HSS into vibration assisted HSS. From previous research work [13,14], an optimized parameters for vibration assisted HSS were found depending on different types of experiment.

3. Experiments

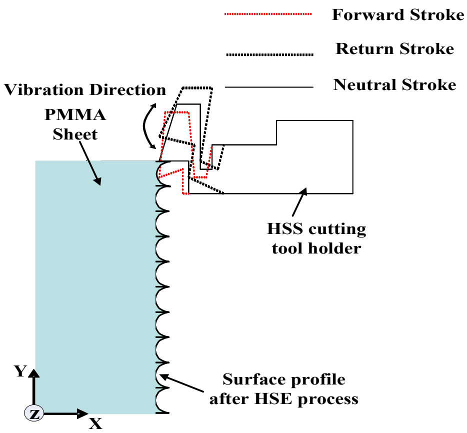
3.1 Properties for stress-strain

To get a better LIP, its machining process is also very important. The higher thickness edge surface is the LIP of PMMA sheet. Fig. 1 shows the function of PMMA. The light from the CCFL (Cold Cathode Fluorescent Lamp) falls on the LIP and it scatters the light inside the PMMA sheet. The light from the reflective film pass through the upper surface of PMMA.

The present machining process for the LIP of a PMMA sheet is composed of both end milling and HSS. The purpose of the HSE process is to size the raw PMMA materials -following the injection molding process- to the BLU frame, where in the tool holder of the HSE rotates at a very high speed of over 30,000 RPM. As the PMMA sheet is fed at a rather slow rate in comparison with the rotational speed, very fine diamond particles on the HSE tool holder can achieve a very small amount of Material Removal Rate (MRR) per tooth, which consequently result in a periodically waved profile similar to the serrations on the surface of the LIP. For better optical characteristics, the HSS process removes the spatial waviness in the direction of feeding and shapes very fine grooves on the LIP surface at a very high feedrate of up to 1.2 meters per second and at a very small depth-of-cut. Even though the HSS process improves the optical characteristics, the instant impact and large cutting forces due to the high feedrate cause breakage and/or lack of straightness.



[Fig. 1] Structure of Back Light Unit in LCD screen

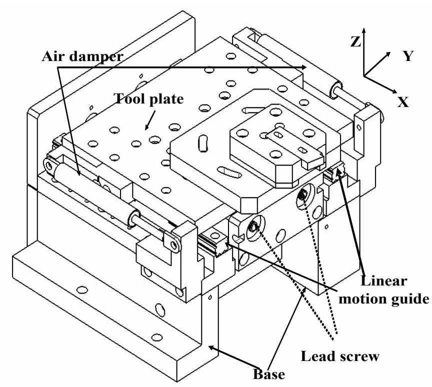


[Fig. 2] Schematic of vibration assisted HSS

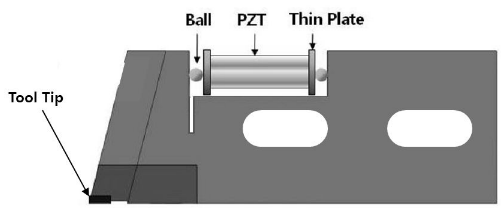
[Table 1] Optimized parameters for vibration assisted HSS

Applied volt (V)	10	20	30
Simulation Frequency(kHz)	13.98	13.98	13.98
Experimental Frequency(kHz)	13.4	13.4	13.4
Error in Frequency (%)	4.18	4.18	4.18
Amplitude (X-direction)	±0.4	±0.53	±0.9
Amplitude (Y-direction)	±1.34	±2.0	±2.75
Amplitude (Z-direction)	±0.6	±0.85	±1.75
Cutting Speed (mm/s)	122	168	230

Fig. 2 shows a schematic of vibration-assisted HSS for overcoming the limits of conventional HSS process. Through a micro actuator like PZT, the cutting tool vibrates at a frequency that escapes the natural frequencies of the machine structure. When the cutting tool vibrates, the PMMA sheet is fed in the forward direction and the material is removed repeatedly through sequenti al cutting. Thus, there is a relative motion between the workpiece and the cutting tool. The applied frequency of the cutting tool is very important with regard to vibrational cutting as it defines the maximum cutting speed that can be applied.



(a)



(b)

[Fig. 3] Schematic of tool post and vibrated tool
(a) Structure of tool post
(b) Vibration assisted tool mechanism

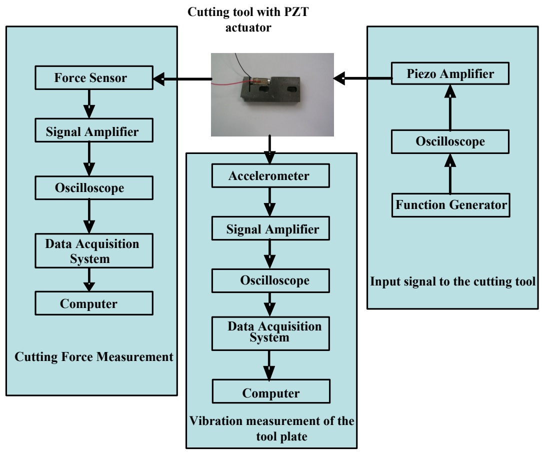
Fig. 3 shows the structure of a tool post and vibration assisted tool for HSS. The tool post is composed of a base, tool plate, motor, timing belt, linear motion guide, and air dampers. The tool post is driven by a servo motor and two parallel lead-screws with a resolution of 1 um for adjusting the depth-of-cut of the diamond cutting tool in the x direction. To reduce the vibration that is caused by the impact force at the beginning of HSS, two air dampers are used with a reaction force of 30 N at the full-stroke compressed position.

Three cutting methods were applied for shaping LIP and the performance parameters were investigated to find out the best cutting method. Experimental conditions are shown in Table 2 where the cutting parameters for vibration cutting assisted HSS are taken from [Table 1]. End milling, high speed shaping, and vibration assisted high speed shaping are applied sequentially. High speed shaping or vibration assisted high speed shaping is applied after the end milling process.

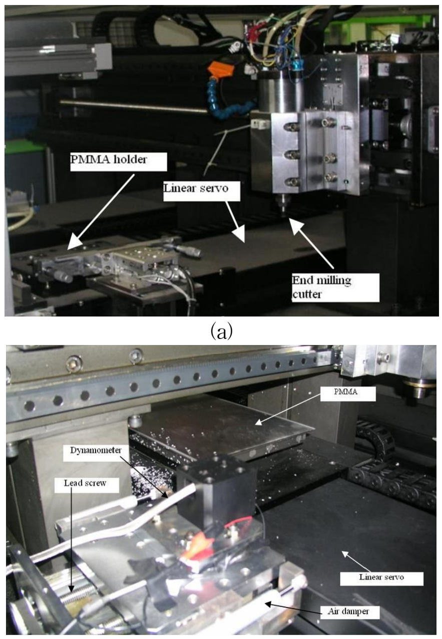
[Table 2] Experimental conditions for LIP machining

End Milling	Spindle speed: 27,000 rpm. Feed rate: 2000 mm/min, Cutter diameter: 25 mm. No. of tooth on cutter: 2 Feed per tooth= 37 μm/rev
HSS	Tool material: SCD Workpiece: PMMA. W/P Size (mm) : L335 × W205 Depth of cut: 10 μm. Cutting speed: 100, 150 and 200mm/s. No. of Cycles: 4
Vibration assisted HSS	Applied Frequency: 13.4 kHz Applied Voltage: 10, 20, and 30 V Depth of cut: 10 μm; Feed 1: 100mm/s for 10 v. Feed 2: 150mm/s for 20v. Feed 3: 200mm/s for 30v. No. of cycle: 4

To reduce the deflection of the PMMA sheet small depth of cut (10 μm) is applied for several cycles to get the ultimate finished surface. During machining of LIP, the cutting force was measured and the procedure is described in [Fig. 4].



[Fig. 4] Diagram for measuring the cutting force and toll plate vibration during machining by HSS and vibration assisted HSS.



(b)

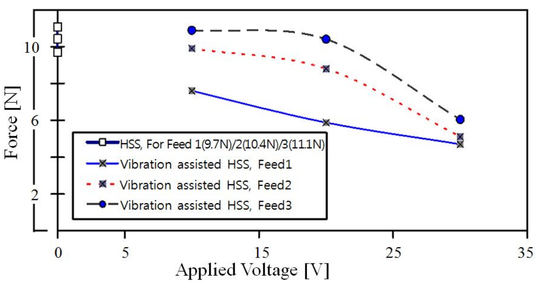
[Fig. 5] Experimental setup for end milling, HSS and vibration assisted HSS
(a) Experimental setup for end milling
(b) Experimental setup for the HSS and vibration assisted HSS

Fig. 5 shows the experimental setup for end milling (a), HSS, and vibration assisted HSS (b). In high speed shaping process, the PMMA sheet is chucked by vacuum and moved perpendicularly (Y-Direction) to the cutting tool.

4. Results

4.1 Cutting force

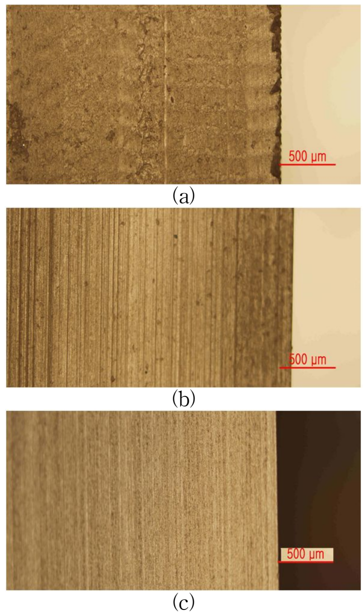
The cutting force in vibration assisted HSS is decreased which is due to less friction of the tool-workpiece and intermittent cutting. For the above mentioned cutting condition, the cutting forces are shown in [Fig. 6]. The cutting force reduced with the increase in applied voltage. According to the vibration cutting theory, higher cutting stroke makes lower cutting force. The cutting forces for vibration assisted HSS conditions are lower than the cutting force for conventional HSS. Kistler-9117A force sensor was used to measure the cutting force. The cutting force also increased with growing feedrate for all cases. For the same feedrate, the cutting forces for conventional HSS are always higher than those of the vibration cutting assisted HSS. This reduction in cutting force will assist to generate a better surface.



[Fig. 6] Cutting force for HSS and vibration assisted HSS

4.2 Surface appearance

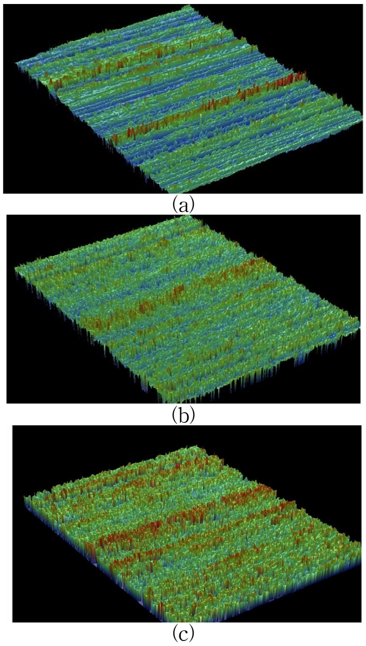
For comparison of surface appearance, a microscope was used and Fig. 7 (a) shows the waviness and breakage of the PMMA surface after end milling. Fig. 7 (b) shows the surface after high speed shaping where the waviness and breakage has been removed but surface is not so smooth. Fig. 7 (c) shows the surface after vibration assisted HSS with 30 applying voltage and 200 mm/s feedrate where parallel grooves was generated without waviness and breakage. It is apparently that the surface has higher quality than the surface from HSS.



[Fig. 7] Surface appearance of LIP machined by end milling, HSS and Vibration assisted HSS
(a) End milling (b) HSS (c) Vibration assisted HSS

4.3 Surface roughness

The parallel groove by the cutting tool with adding fine particles on its cutting edge is intentionally created for scattering the light at LIP. So the surface roughness is not so improved. In order to investigate the surface roughness, 2D and 3D surface roughness measurement was carried out. For measuring surface roughness, Veeco NT9100 Optical 3D surface profiler was used and 3D interactive display is shown in [Fig. 8]. Surface roughness were investigated and the comparative results are given in Table 3. The results show that average roughness value R_a increment is negligible in spite of using cutting tool with particles on its cutting edge. The outstanding change in R_t is due to the peak and valley created by the cutting tool which is absent in end milling. The value of R_t is lower at 10, 30 V of applying voltage in vibration assisted high speed shaping than HSS. It is expected that the extensive amount of friction between the tool and workpiece may pulls out some additional materials from the groove and the phenomena is reduced in vibration assisted HSS by its pulsating cutting. In vibration assisted cutting with 30 applying voltage, the minimum surface roughness was generated which is due to the high amplitude.



[Fig. 8] 3D interactive display of LIP machined by end milling, HSS and vibration assisted HSS (a) End milling (b) HSS (c) Vibration assisted HSS

[Table 3] Statistics comparison of surface roughness for end milling and High speed shaping

Cutting method \ Roughness		R_a(μm)	R_q(μm)	R_z(μm)	R_t(μm)
End milling		0.296	0.377	3.38	3.73
High speed shaping		0.309	0.387	3.88	4.49
Vibration assisted HSS	10V	0.316	0.399	3.40	4.10
	20V	0.330	0.415	3.91	5.40
	30V	0.302	0.381	3.36	4.11

4.4 Surface flatness

For measuring the surface flatness, a coordinate measurement was conducted with Dukin-MHB-1000C CM machine and the measuring statistics are shown in Table 4. The maximum deviations was shown in end milling and the minimum deviation was found in vibration cutting method. Surface flatness property for HSS is higher than that for the end milling but not to reach the value of vibration assisted shaping.

[Table 4] Comparison of standard deviations

Cutting Method		Standard Deviations(μm)
End milling		Min=14 Max=27.12
High speed shaping		Min=2.7 Max=13.7
Vibration assisted HSS	10 V	Min=1.7 Max=7.1
	20 V	Min=1.5 Max=4.6
	30 V	Min=1.0 Max=6

5. Conclusions

From several machining experiments for end milling and high speed shaping with/without vibration assistance, the following conclusions can be drawn based on the experimental results:

1) It is an evident that the waviness, breakage has been removed in high speed shaping and the surface flatness quality is increased.
2) Surface quality has been raised up with higher acceleration of tool in vibration assisted high speed shaping. Especially standard deviations for vibration assisted high speed shaping are remarkably improved from 14.0 ~ 27.1 ㎛ into 1.0 ~ 6.0 ㎛.
3) Though the surface roughness remains almost constant compared to end milling despite applying high speed shaping, that of vibration

assisted shaping result from regular movement of vibrated tool.

4) Depending on the experimental results, the application of vibration assisted high speed shaping should be referred for shaping PMMA surface where HAZ is a concern with the breakage and waviness.

The variations of surface quality depending on machining conditions such as cutting direction, amplitude and frequency in tool vibration, and tool movement will be researched. The optical evaluation of machined PMMA is also a point to be considered.

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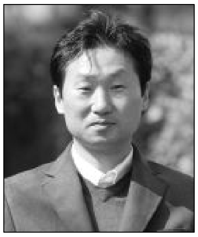

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