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ORIGINAL ARTICLE

Development of machining technology for micropatterns with large surface area

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Abstract With increasing demand for micropatterns such as V-shaped microgrooves and the trend of large surface areas in developing technologies, precision machining technology for micropatterns with large surface areas is expected to play an increasingly important role in today's manufacturing technology. In large-surface micromachining, machining time is much longer than that in general pattern machining and it is not easy to achieve uniform machining accuracy in the entire machined areas because of various factors. Therefore, systematic machining processes and technical development for achieving precision in each process are essential prerequisites to reduce the errors. In this study, we focused on developing machining technologies, which include a machine vision system for precise tool setting, an on-machine measurement system for large-area measurement, and software for tool path generation and simulation, for the fabrication of large-surface micropatterns in an electroless nickel-plated workpiece with single-crystal diamond tools and a 32-in., 675×450-mm mold with tens of V-and pyramid-shaped micropatterns.

Keywords Ultra-precision machining · Micro pattern · Machining process · Large surface area

1 Introduction

The demand for precision and micromachining technologies that enable the production of mechanical components on a micrometer scale with mechanical features such as V-shaped microgrooves has rapidly increased with the advent of various micropatterns, as shown in Fig. 1, in the latest developing fields related to advanced technologies such as optics, displays, communications, electronics, and fuel cell applications. Micropatterning requires reliable and repeatable methods with accurate analysis tools. Many common methods still depend largely on semiconductor processing techniques, where silicon materials are photo-etched through chemical and dry processes, usually in large batches. Numerous researchers have investigated the feasibility of using other fabrication processes such as LIGA, laser cutting, ultrasonication, ion beam cutting, and microelectro discharge machining to manufacture commercially viable micropatterns [1–5]. However, the majority of these methods are slow and limited to a few silicon-based materials with essentially planar geometries. Moreover, applications of these technologies are inhibited by the low productivity, by the inability to manufacture in small batch sizes cost effectively and by size to be machined and surface roughness to be obtained [6, 7].

Micromechanical machining technology is based on conventional cutting and has advantages such as high productivity, low cost, and good finish. It is another fabrication method for

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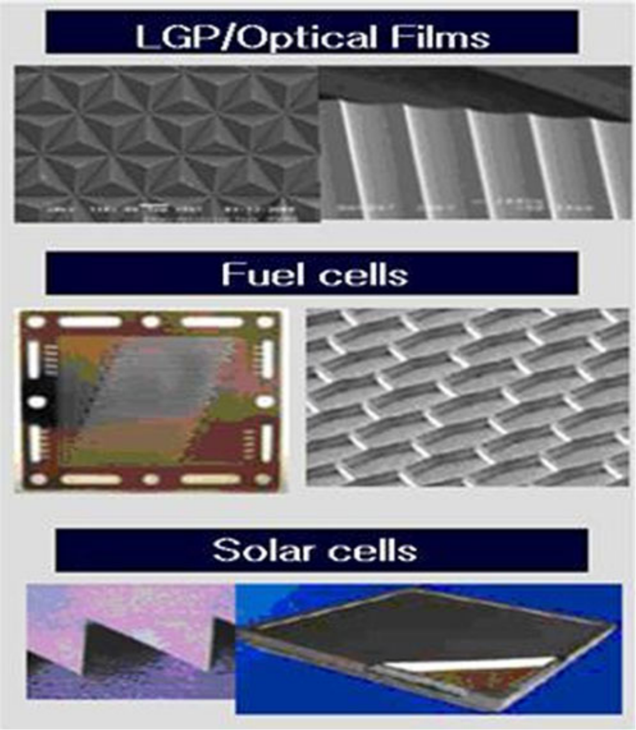


Fig. 1 Micropatterns in various products

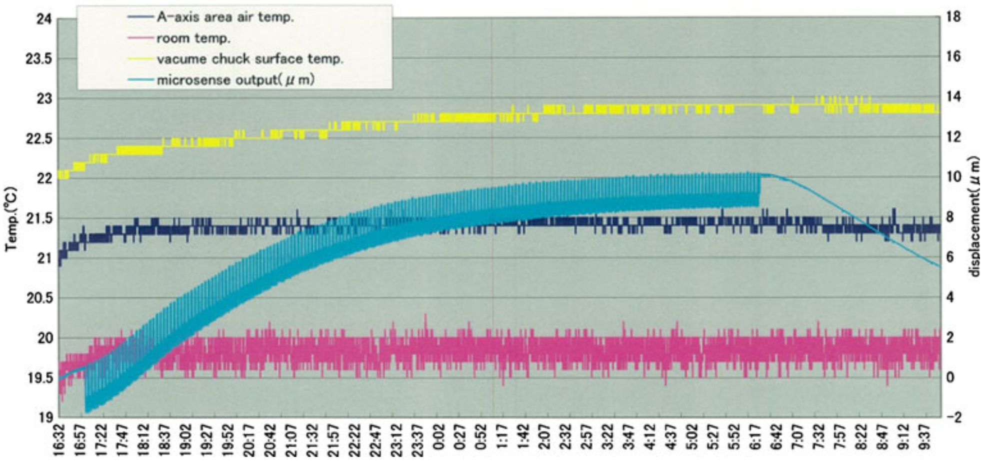
creating high-quality micropatterns on various materials with features ranging from a few inches to tens of inches across, as shown in Fig. 1. Therefore, recently, there has been strong interest in fabricating micropatterns through mechanical cutting processes, i.e., ultra-precision machining [8–10]. Through the 1970s, the technique was applied to a variety of optical components for its high precision, versatility, and lower overall manufacturing cost. More recent applications include the manufacture of optical parts such as liquid crystal display (LCD) panels with sophisticated forms and extremely high geometrical and surface quality [11]. The development of ultra-precision machining technology is contingent on the development of appropriate cutting tool technology, such as single-crystal diamond tools and machine elements, including air bearings, air slides, granite beds mounted on air dampers, and precise position-control technologies. The primary goal of ultra-precision machining is to achieve an optical surface with a surface roughness of a few nanometer root mean square by using a single-crystal diamond tool [12]. However, the use of such a tool greatly limits the materials that can be machined. The most popular metals subject to diamond machining, namely, copper and aluminum, can easily be ruined by abrasion and corrosion during cleaning and handling [13], and steel, which contains carbon, reacts with diamond tools. A very useful alternative is an electroless nickel-plated workpiece, which exhibits excellent hardness, corrosion resistance, wear resistance, etc. [14]. Such dies are commonly used to manufacture optical parts such as the light guide panels (LGPs) and optical films used in LCD panels because of the high degree of surface finish and dimensional accuracy necessary.

With this background, the fabrication of micropatterns through mechanical cutting processes [8–10] has recently attracted considerable interest. In particular, with the trend of technical development for micropatterns changing to those with large surface areas, machining techniques for large surface areas are required, since related products using micropatterns are getting larger. However, researches conducted thus far [15–17] have only focused on machining techniques for small surface areas of less than 10 in. or on those with fine micropattern machining for surface areas of 10~20 in. However, no researches have been conducted on large surface areas of over 30 in., which have generated strong interest in recent times. Moreover, the researches are based on macromachining concepts, but simple scaling cannot be used to model the phenomena of micromachining operations.

Basically, machining accuracy of designed shapes is determined by thermally induced errors, geometric errors, setup errors, and machining errors that are referred to be induced by cutting force or vibration. Among the error sources, thermal and geometric errors are known to be key contributors and thermal errors have been reported to be about 40~70% of total positioning errors of machine tools.

Generally, machine tools for microcutting have nanometer-scale position accuracy and control ability for compensation, and they are working in good environmental condition which is under constant temperature and humidity since the cutting process require high precision. Therefore, geometric errors developed in machine tools are relatively small as compared with macromachining. Machining errors induced by cutting forces are also very small and restrictive in micromachining since cutting forces are significantly small, below 1 N due to very small amount of cutting depths [18]. The major errors in micropattern machining are caused by thermal expansion and tool setup. Although the machine tool is working in a clean room, heat by spindle and drive units of machine tools such as motion guides and linear motors causes thermal displacement of the machine tools, and this makes effect on machining accuracy mainly. Figure 2 shows the thermal displacement in micropattern machining, and the thermal error, that is, *Z*-axis displacement of machine tool increases to 10 μm. However, the errors also can be minimized with enough warming up and compensating offset errors since thermal drift would turn into steady state after going through processes of heating and cooling as shown in Fig. 2. In other words, the minor error factors of macromachining such as tool setup and tool path generation are more significant issues in micropattern machining. Therefore, systematic machining processes and technical development for achieving precision in each process are essential prerequisites to reduce the errors, and this paper focuses on systematic machining processes and

Fig. 2 Thermal displacement of machine tool



reducing the error in each process for ensuring uniform form accuracy in large-surface-area machining. As a result, we developed machining technologies for the fabrication of micropatterns in an electroless nickel-plated workpiece with single-crystal diamond tools, and 32-in., 675×450-mm mold with tens of V-shaped micropatterns in this study.

2 Machining technologies for large surface area

In the case of pattern machining for large surface areas, machining time is much longer than that in general pattern machining and it is not easy to achieve uniform machining accuracy in the entire machined areas because of various factors such as tool wear and thermal deformation of machine tools. Figure 3 shows errors induced in actual pattern machining for large surface areas. *Z*-axis displacement caused by thermal expansion is one of most important errors caused by the movement of the machine tool, and this leads to a difference in cutting depths in the case of long distance cutting. In addition to this, many other error factors as shown in Fig. 3 must be considered for ensuring uniform form accuracy in large-surface-area machining.

Therefore, systematic machining processes and technical development for achieving precision in each process are essential prerequisites to reduce the errors shown in Fig. 3.

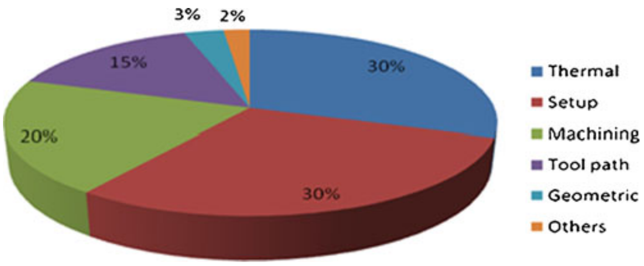


Fig. 3 Causes of errors in large-surface-area machining

These errors have hitherto been considered as minute errors and not of importance in general pattern machining work or in large-surface-area machining. Figure 4 shows machining processes and the requisite technologies that have been proposed in this paper to minimize error factors. These processes and technologies are considered as indispensable to mechanical-cutting-based pattern fabrication for large surface areas.

2.1 Improvement of tool-setting accuracy

In current pattern machining, it is difficult to expect precise setting accuracy and controllable setting errors because tool setting is executed on the basis of operators' experience and ability. Moreover, since the images for setting are magnified by using a powerful microscope with a very low depth of field, it is difficult to obtain an accurate focus position, thus resulting in difficulty in acquiring accurate geometrical information from magnified images; this in turn leads to operators achieving inconsistent setting accuracy. To solve these problems, a tool-setting system based on machine vision for guaranteeing consistent setting accuracy has been developed in this study. The machine vision system used for tool setting includes the following functions:

1. Image capturing
2. Focus positioning
3. Binarization with black–white mask
4. Edge detection
5. Distance measuring

2.1.1 Image capture and focus positioning

A Keyence microscope with a magnification range of 25 to 1,500 and a frame grabber, Matrox Vio, for capturing digital still frames from an analog video signal have been used for the proposed tool-setting system. The quality of the focus in

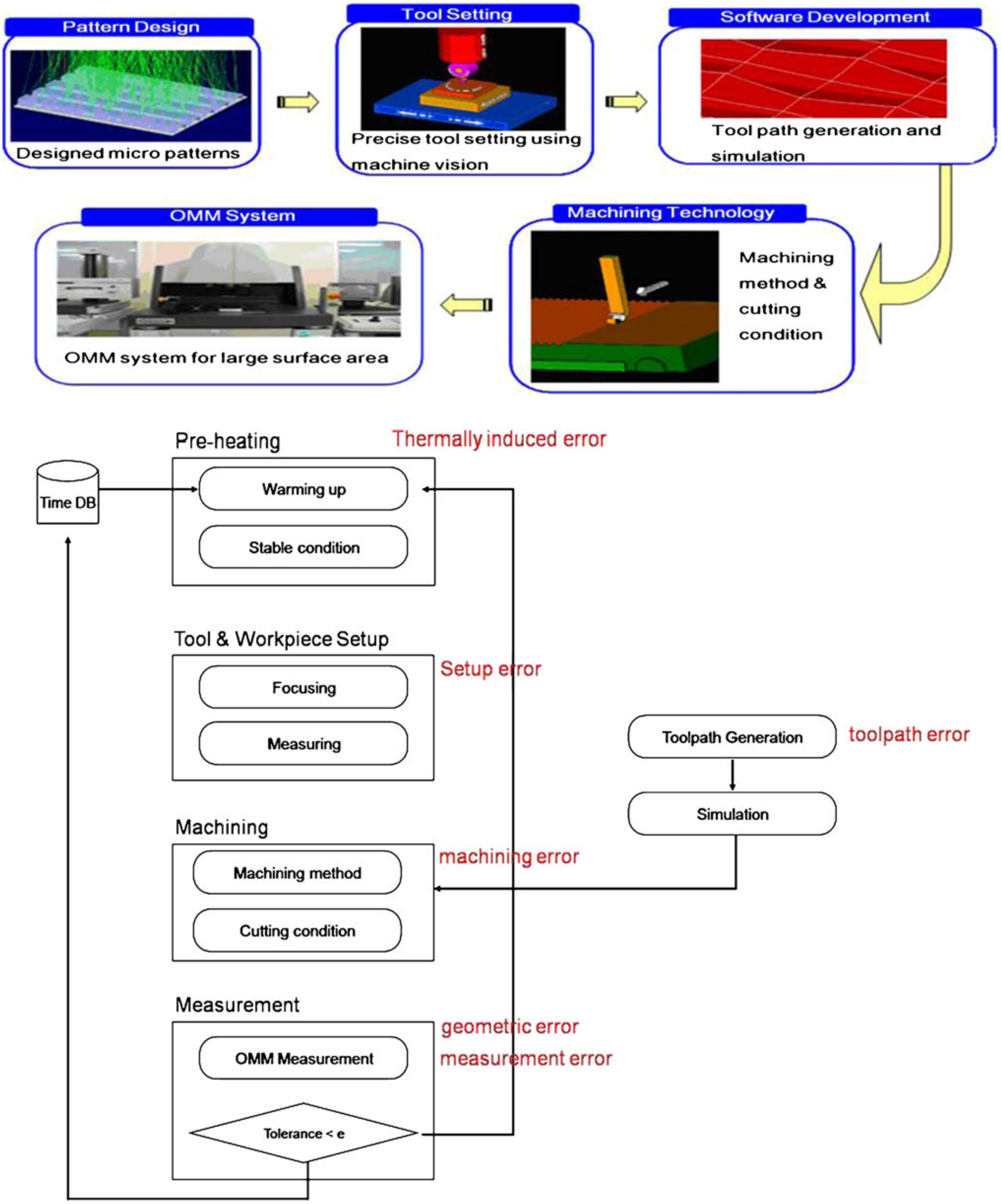


Fig. 4 Precision machining process and detailed technologies for large-surface-area machining

captured images should be evaluated to obtain precise geometric information. In this paper, the optimum focus position is determined by grabbing an image at an initial position, analyzing the focus quality of the grabbed image,

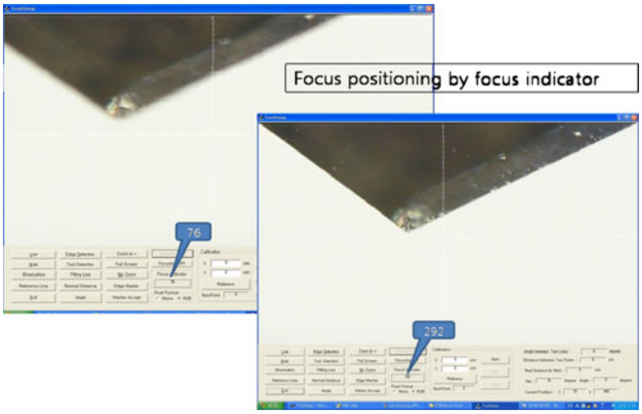


Fig. 5 Image capture and focus positioning

changing the position, and then grabbing and analyzing another image. The process repeats until the optimum focus position is found.

The focus quality of an image (shown as its focus indicator in Fig. 5) is measured by analyzing its edges. An image with good focus quality (a high focus indicator) has well-defined edges, that is, has a sharp difference in gray-levels between its object edges and its background. Through a focus indicator displayed with figures in the developed program shown in Fig. 5, the consistent and objective method for focus positioning using high-powered microscope with low depth of field is embodied and the deviation problem of focusing between operators is solved. Figure 5 shows the system that has been implemented for focus positioning, and the figure in the focus indicator box shows the quality of the captured image.

2.1.2 Binarization and edge detection

The machine vision system implemented in this study for precise tool setting is based on the edge detection principle. Edges are curves that delineate a boundary. These can be established from intensity transitions in an image. Well-defined edges come from sharp transitions in value, typically found in highly contrasted images. Conversely, weak edges come from gradual transitions in value, typically found in smooth images. For efficient edge detection, a binarizing operation that reduces an image to two grayscale values is performed in advance. Binary images are useful when trying to identify a tool, workpiece and background, and to detect edges in tool-setting system since they are not cluttered with shading information.

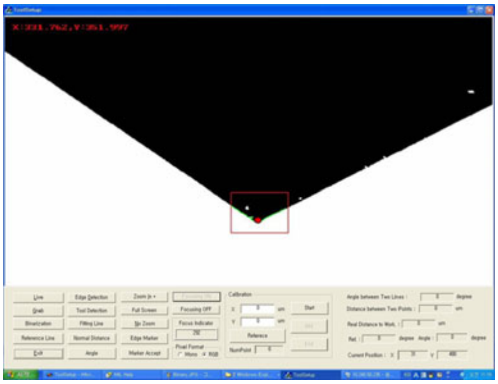


Fig. 6 Binarization and edge detection

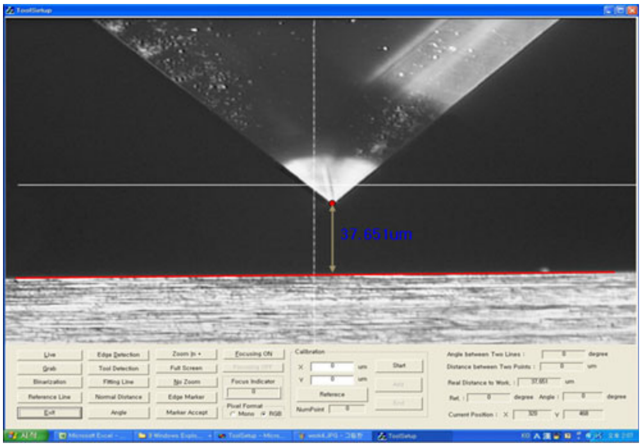


Fig. 7 Optical tool measuring system

Edges are extracted in three general steps. First, a filtering process provides an enhanced image of the edges based on the computation of the image's derivatives. The enhanced image of the object contours is achieved by calculating the gradient magnitude of each pixel in the image. The stronger the intensity transition, the greater the magnitude will be. The gradient magnitude is calculated at each pixel position from the image's first derivatives. It is defined as

$$\text{Gradient Magnitude} = \sqrt{I_x^2 + I_y^2}$$

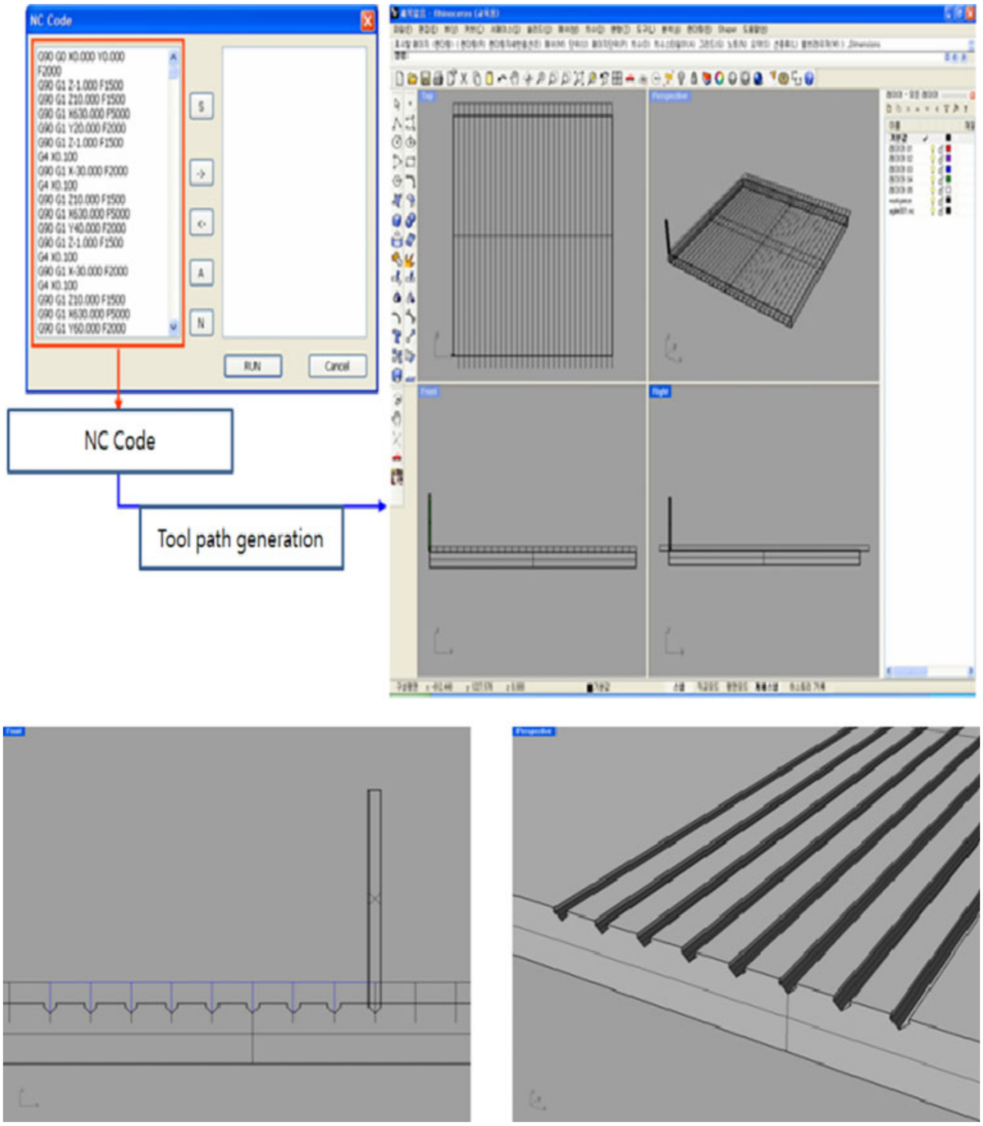
where I_x and I_y are, respectively, the X and Y derivative values. They define the components of the gradient vector as:

$$\text{Gradient Vector} = \begin{bmatrix} I_x \\ I_y \end{bmatrix}$$

Second, detection and thresholding operations determine, from the image enhancement, all pertinent edge elements, or edgels, and accurately calculates their positions. An edgel is

Table 1 Evaluation of optical tool measuring system

	Number 1	Number 2	Number 3
Target depth	4.17	4.52	4.89
Measured depth	4.40	4.68	4.98
Setting Error	0.23	0.16	0.09



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G90 G0 X0.000 Y0.000
F2000
G90 G1 Z-1.000 F1500
G90 G1 Z10.000 F1500
G90 G1 X630.000 F5000
G90 G1 Y20.000 F2000
G90 G1 Z-1.000 F1500
G4 X0.100
G90 G1 X-30.000 F2000
G4 X0.100
G90 G1 Z10.000 F1500
G90 G1 X630.000 F5000
G90 G1 Y40.000 F2000
G90 G1 Z-1.000 F1500
G4 X0.100
G90 G1 X-30.000 F2000
G4 X0.100
G90 G1 Z10.000 F1500
G90 G1 X630.000 F5000
G90 G1 Y60.000 F2000
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Fig. 8 Tool path generation and simulation software

located at the maximum value of the gradient magnitude over adjacent pixels, in the direction defined by the gradient vector. The gradient direction is the direction of the steepest ascent at an edgel in the image, while the gradient magnitude is the steepness of that ascent. Contours are extracted from strong and sharp intensity transitions. Third, neighboring edgels are connected to build the edge chains, and features are calculated for each edge. Figure 6 shows the detected edges and a tool end point obtained by using the proposed steps.

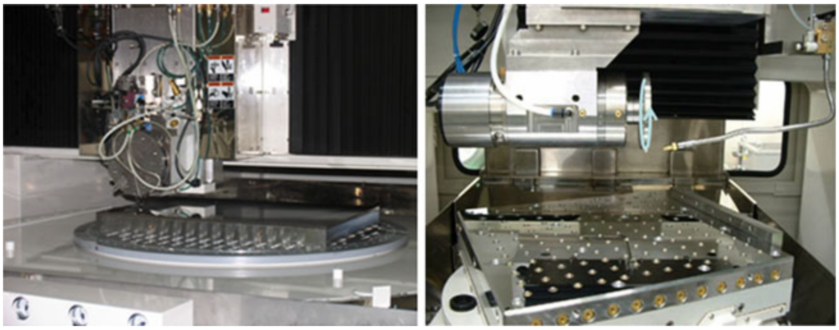


Fig. 9 Shaping vs. fly cutting

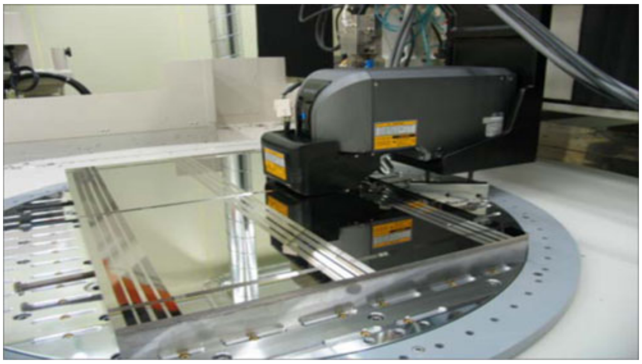


Fig. 10 OMM system

2.1.3 Distance measurement and performance evaluation for implemented system

Geometric distances between detected edges can be retrieved in the real world through the process of conversion from pixel units. An example of distance measurement between a tool and a workpiece is shown in Fig. 7. To verify the implemented tool-setting system, machining tests with arbitrary target depths were performed, and the measured results were examined. Table 1 shows measured results after V-shaped pattern machining with three arbitrary target depths. The average tool-setting error is 0.16 μm, a highly improved value as compared to the setting error of 0.5 μm generated because of the operator's experience.

2.2 Tool path generation and machining simulation

In the mechanical machining process, reliable tool path generation is required to get desirable machined shapes since the machine tool drives a cutter according to a prescribed cutter path which represents the trajectory of the reference point of the cutter. Incorrectly computed paths may cause undesirable results of gouging or leaving too much material on the workpiece. Undesirable problems can be avoided by reliable tool path generation. For generating such cutter paths, computer programs called computer-aided manufacturing (CAM) systems are generally utilized in conventional macromachining. However, in the case of pattern machining, operators calculate the cutter paths since there are no CAM systems that support micropatterns. Consequently, unwanted patterns or tool breakage occur frequently, resulting in a considerable increase in machining time and cost in the case of pattern machining for large surface areas.

Another important component for obtaining desirable patterns is a geometric simulation program for detecting potential problems prior to actual machining. A machining operation is geometrically equivalent to a Boolean subtraction of the swept volume of the moving cutter from a solid model representing the shape of the stock. On the basis of this concept, various machining simulation programs have been developed and used in practice, but these commercial programs are not available to micropattern machining. Therefore, in this paper, software that can be applied to micropattern machining has been developed, thus minimizing errors that can occur in actual machining since tool paths are generated and the machining process is simulated before actual machining. The developed program is shown in Fig. 8; it was implemented with visual C++ in Rhino3d 3.0 as a plug-in and with the use of Boolean operation and collision detection algorithms for path generation and simulation.

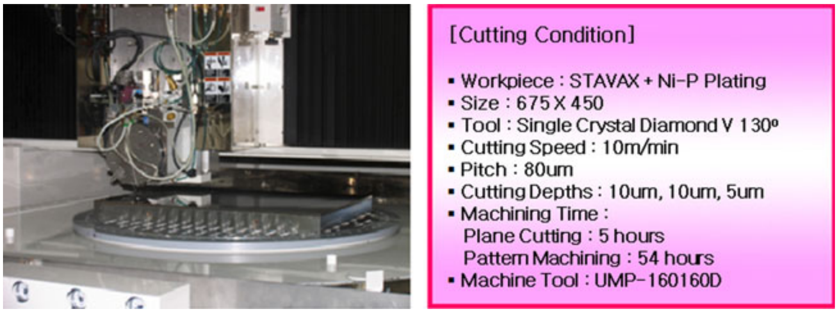
2.3 Machining method and condition

The cutting conditions and method required for stable machining must be selected carefully before actual machining, in order to prevent tool wear or breakage during machining; this is because several days are required for large-surface-area machining. In addition, the preheating of machine tools must be ensured to prevent thermal deflection, which is an important factor in ultra-precision machining. *Z*-axis displacement was measured during the movement of machine tools, and it was identified that stable machining that does not lead to greater thermal expansion if machining is carried out after 7 h.

Table 2 Specification of UMP-160160D

Main specifications		UMP-160160D
Table	Working surface (mm)	1,550×1,550
	C1 axis equipped (mm)	φ800
Travel	*X* (mm)	1,600
	Y (mm)	1,600
	Z (mm)	150
Maximum feed rate		*X*, 15,000 mm/min; *Y*, 9,000 mm/min; *Z*, 3,000 mm/min
Programming resolution		*X*, *Y*, *Z*: 0.001 μm; *A*, *C*: 0.00001°

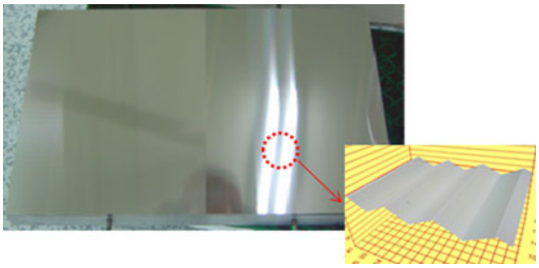
Fig. 11 Machining results. (**a**) Machine tool; (**b**) machining condition; (**c**) machining results



[Cutting Condition]

- Workpiece : STAVAX + Ni-P Plating
- Size : 675 X 450
- Tool : Single Crystal Diamond V 130º
- Cutting Speed : 10m/min
- Pitch : 80um
- Cutting Depths : 10um, 10um, 5um
- Machining Time :
  Plane Cutting : 5 hours
  Pattern Machining : 54 hours
- Machine Tool : UMP-160160D

(a) Machine tool (b) Machining condition



(c) Machining results

The pattern machining methods with shaping and fly cutting as shown in Fig. 9 were tested for machining performance evaluation, and a more precise machining accuracy was obtained in shaping, because of the elimination of vibration and run-out errors as the tool rotates in case of fly cutting. Micropattern machining was also carried out in sample cores with various cutting depths and speeds to in order to determine the optimum cutting conditions.

2.4 Construction of OMM system

A measurement system that has a 10-nm resolution is required for precisely measuring micropatterns after machining. However, no systems are available for measuring large surface areas despite the fact that some microscopes with such a resolution are in use commercially. To fix this, we separated the head part from a Keyence 3D violet laser scanning microscope with ×18,000 magnification and a 0.001-μm resolution and attached the separated optical part to a machine tool by a jig that was designed and tested through various vibration analyses. Figure 10 shows the on-machine measurement (OMM) system.

3 Experiments and results

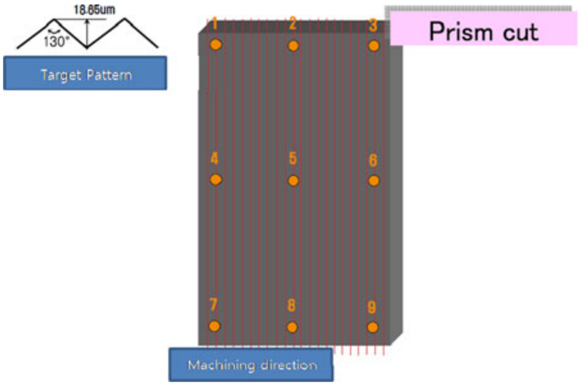
In this study, a 32-in., 675×450-mm mold with tens of V- and pyramid-shaped micropatterns was manufactured by the proposed technologies. A Toshiba UMP-160160D ultra-precision machine that has been developed with a positioning resolution of 1 nm for the purpose of high-precision machining via single-crystal diamond tools was used in the experiments. Table 2 lists the detailed specifications of the machine tool. The workpiece was a stainless steel substrate (Starvax) with a 100-μm-thick coat of nickel. Single-crystal diamond tools with a tool angle of 130°, rake angle of 0°, and {110} rake face crystal orientation were used.

Tool setting, path generation, and simulation were carried out by the proposed technologies when the machine tool was in a stable state without *Z*-axis displacement, and the V- and pyramid-shaped patterns were machined by the shaping method and under cutting conditions obtained by sample tests as mentioned above. Figure 11 shows the machining results. The right half of the workpiece shows prism (V-shaped) patterns and the left half shows pyramid-shaped patterns that were obtained by crossed prism patterns. To measure the machining accuracy of the entire machined surface, the nine points shown in Fig. 12 were measured using the implemented OMM system, and the difference between the designed values and the measured results was determined. From the results, it was concluded that form accuracy below average 0.2 μm can be guaranteed. A standard deviation of three sigma or more of the measured results is judged by the six sigma technique. Usually, the required form accuracy of micropatterns in optical instruments is roughly 0.5 μm, but for micropatterns with large surface areas, it is possible to obtain precision that is twice this value by the application of the proposed technologies.

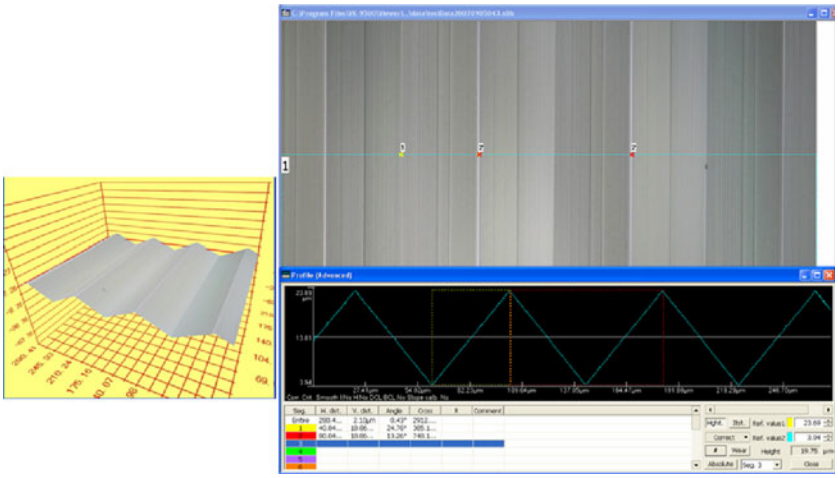
4 Conclusions

In this paper, machining technologies for large-surface-area microcutting have been proposed. These technologies

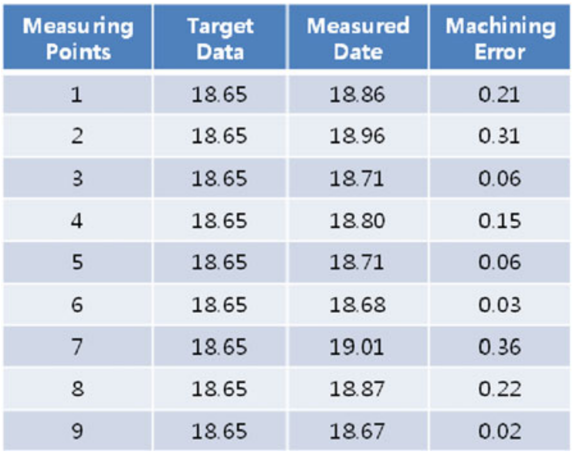
Fig. 12 Measured data. (**a**) Target pattern and measuring points; (**b**) measuring result; (**c**) measured data



(a) Target pattern and measuring points



(b) Measuring result



Measuring Points	Target Data	Measured Date	Machining Error
1	18.65	18.86	0.21
2	18.65	18.96	0.31
3	18.65	18.71	0.06
4	18.65	18.80	0.15
5	18.65	18.71	0.06
6	18.65	18.68	0.03
7	18.65	19.01	0.36
8	18.65	18.87	0.22
9	18.65	18.67	0.02

(c) Measured data

include a machine vision system for precise tool setting, OMM system for large-surface-area measurement, and software for tool path generation and simulation. In addition, shaping cut technique with experimentally determined optimum cutting conditions was applied for achieving uniform machining accuracy in fully machined areas of over 30 in. Finally, a 32-in., 675×450-mm mold with tens of V- and pyramid-shaped micropatterns was manufactured by using the proposed technologies, and it was experimentally verified that the application of the proposed technologies yields more precise micropatterns than those obtained by the conventional V-grooving method.

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