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Efficient ultraprecision machining system by means of industrial robot

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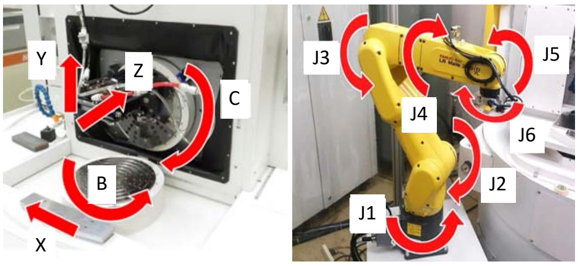
Abstract
Ultraprecision machining is applied to machining of optical parts such as aspherical lens core that requires surface roughness and form-accuracy in nanometer-order. To obtain highly precise optical parts, the whole machining procedure is usually conducted on the same ultraprecision machine tool. However, the feed rate is relatively slow and the machining depth is quite small, compared to the ordinary machine tools, although various ultraprecision machine tools have been developed to realize high positional accuracy and resolution. As optical parts become complex and the machining area becomes wide, the machining time and cost would be increased rapidly. Thus, the study aims at developing an ultraprecision machining system to improve the machining efficiency. In the proposed method, ultraprecision machining is conducted for the workpiece having a shape near the target shape, which is beforehand prepared by ordinary machine tools. Then, it is difficult to set the workpiece correctly on an ultraprecision machine tool due to the manual setting operation. Furthermore, in ultraprecision machining, the workpiece setting errors are extremely larger than the positional resolution of machine tools. Therefore, the workpiece position and attitude on the machine table should be known to create highly precise parts before ultraprecision machining. In this study, the workpiece is set on an ultraprecision machine tool by an industrial robot firstly so that the influence of human errors can be removed. Then, a contact type of on-machine measurement device is used to detect the workpiece position and attitude, and NC data is modified to compensate the estimated workpiece setting errors. From the experimental results, it is confirmed that the proposed system has the possibility of reducing machining time in ultraprecision machining to create highly precise parts with high efficiency.

Ultraprecision machining, Setting operation, Setting errors, Industrial robot, On-machine measurement

1. Introduction

Optical elements such as lenses used in photolithography need nanometric accuracy [1]. To satisfy the demand, the machining technology with high precision is extremely required. The authors have developed some machining methods to fabricate the microparts by means of diamond cutting tools [2]. To obtain highly precise optical parts, the whole machining procedure is usually conducted on the same ultraprecision machine tool. However, the relatively slow feed rate and small machining depth of ultraprecision machine tool are not allowed to improve the machining efficiency. Especially, the recent optical parts are changed to be complex and the machining area becomes wide, the increasing machining time leads to the rising cost.

It is difficult to improve the machining efficiency just by using one ultraprecision machine tool. Thus, this study aims at developing an efficient ultraprecision machining system by means of an industrial robot and an ordinary machining center to obtain the workpiece having a shape near the target shape quickly. However, the setting errors of the beforehand prepared workpiece mounted on the ultraprecision machine tool are inevitable when an industrial robot is used to automate a manual setting operation. To solve the problem, in this study, an on-machine measurement device is adapted to identify the actual position and attitude of workpiece on the ultraprecision machine tool and original NC data is modified to compensate the workpiece setting errors estimated to create highly precise parts.



(a) Ultraprecision machining (b) Industrial robot

Figure 1. Experimental setup in this study

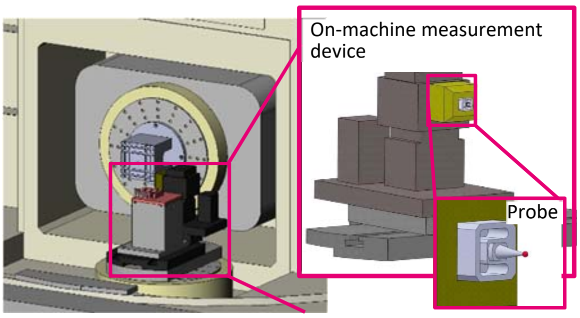


Figure 2. On-machine measurement device and its probe

2. Experimental equipment

Figure 1 illustrates a 5-axis control ultraprecision machining center ROBOnano α-0iB and an industrial robot LR Mate 200iD (FANUC corp.) used in the study. The robot is a 6-axis

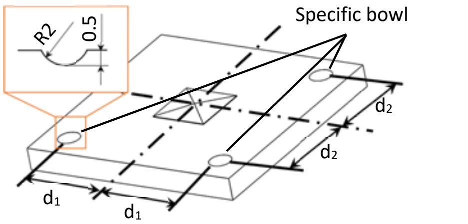


Figure 3. Specific bowls created to identify workpiece position

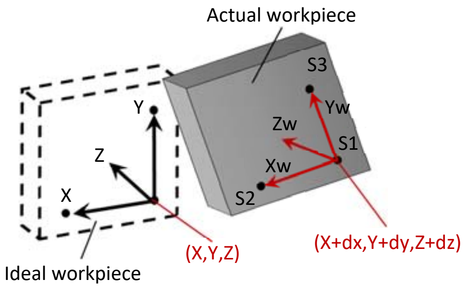


Figure 4. Workpiece setting errors

vertical articulated robot. The repeatability is 30 µm and the maximum allowable payload is 7 kg. The workpiece is beforehand machined by an ordinary 3-axis machining center which has 1 µm resolution of each axis.

In order to detect the workpiece position, a contact type on-machine measurement device is mounted on B table of the ultraprecision machining center as shown in Fig. 2. The device NANOCHECKER (FANUC corp.) has 1 nm resolution and is controlled by the same NC system. Then, the displacements of the probe which contacts the workpiece surface and machine coordinates are recorded together in a PC.

3. Setting errors compensation of workpiece

The workpiece beforehand prepared by an ordinary machine tool is firstly located on a vacuum type chuck fixed on C table by an industrial robot in this study. Then, the probe of on-machine measurement device follows the workpiece surface. The workpiece setting errors are identified based on the probe displacements. As a result, NC data is modified to compensate the workpiece setting errors.

In order to detect the workpiece position and attitude, some simple specific bowls are created in rough cutting on an ordinary machine tool and they are used as the references. For example, three bowls are created as shown in Fig.3. The bottom points of bowls are detected so that the origin of workpiece coordinate system is converted according to the actual workpiece position and attitude. The bowls are created using a ball endmill. The radius of the ball endmill should be much larger than the radius of probe.

Figure 4 shows an example of setting errors compensation. S1, S2, S3 is the bottom point of each bowl, respectively. S1 is treated as the origin, **S1S2** and **S1S3** are assumed as $\mathbf{X_w}$ and $\mathbf{Y_w}$ axes which accord with X and Y axes of workpiece coordinate system. In addition, the vector which is vertical with the plane S1S2S3 is defined as Z axis of workpiece coordinate system $\mathbf{Z_w}$. If there are no setting errors, the position of S1 is expressed as (X, Y, Z). However, in practice, it is expressed as (X+dx, Y+dy, Z+dz) and the unit vectors of the axes of real workpiece coordinate system is expressed by $\mathbf{e_x}$, $\mathbf{e_y}$, $\mathbf{e_z}$, respectively. In order to compensate the setting errors, x, y and z coordinates of the original NC data are modified as follows:

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} \rightarrow (\boldsymbol{e}_x \quad \boldsymbol{e}_y \quad \boldsymbol{e}_z) \begin{pmatrix} x-X \\ y-Y \\ z-Z \end{pmatrix} + \begin{pmatrix} X+dx \\ Y+dy \\ Z+dz \end{pmatrix}$$

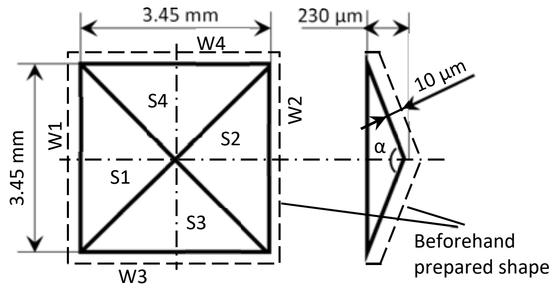


Figure 5. Target shape of machining experiment

Table 1. Machined results with confocal micro scope

		Actual size	Target size
Width	W1	3449.5 µm	3450 µm
	W2	3450.3 µm	
	W3	3451.4 µm	
	W4	3448.4 µm	
Angle α	S1&S2	164.86 deg.	164.81 deg.
	S3&S4	164.90 deg.	

4. Machining experiment and result

An experiment machining of a tiny pyramid shown in Fig.5 is conducted in order to verify the proposed method. This pyramid is located at the center of an aluminium plate. Firstly, the workpiece is set on the ordinary machining center to obtain the approximated target shape by using a square milling tool with R3.0. Then, a ball endmill with R2.0 is used to create three bowls and the workpiece is set on the ultraprecision machine tool. After the actual workpiece position and attitude are identified, the original NC program is modified as mentioned above. Finally, finishing cutting is conducted to obtain the target shape.

The machining results are summarized in Table 1. From the results, it is found that the widths of pyramid are correctly obtained and the angle between the two opposite slopes can be machined precisely. Therefore, it is confirmed that the workpiece setting errors can be compensated and the target shape can be obtained efficiently and precisely by the proposed method.

5. Conclusion

An efficient ultraprecision machining system by means of industrial robot is proposed in this study. The workpiece having a shape near the target shape, which is beforehand prepared by ordinary machine tools, is set on an ultraprecision machine tool by an industrial robot firstly. By on-machine measurement of bowls created on workpiece in advance, the workpiece position and attitude are identified with high accuracy. NC data is finally modified to compensate the estimated workpiece setting errors.

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