User-friendly Automatic Polishing Robot System and Its Integrated Operating Program

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ABSTRACT

Polishing a die that has free-form surfaces is a time-consuming and tedious job, and requires a considerable amount of high-precision skill. In order to reduce the polishing time and cope with the shortage of skilled workers, an automatic polishing robot system was developed. The polishing robot system is composed of two subsystems, a three-axis machining center and a two-axis polishing head. The machining center is controlled by a FANUC controller, and the polishing head by DSP controller. The system has five degrees of freedom and is able to keep the polishing tool normal to the die surface during operation. To easily operate the developed polishing robot system, this study developed an integrated operating program in the Windows environment. The program consists of five modules: a polishing data generation module, a code separation module, a polishing module, a graphic simulator module, and a teaching module. Also, the automatic teaching system was developed to easily obtain teaching data and it consists of a three dimensional joystick and a proximity sensor. Also, to evaluate the performance of the integrated operating program and the polishing robot system, polishing experiments of a die of shadow mask were carried out.

Key Words : Automatic polishing robot system, Machining center, Polishing head, Integrated operating program, Automatic teaching system

1. Introduction

In the process of die manufacturing, some polishing work must be performed to remove the tool marks and to improve the smoothness and flatness of die surfaces. However, the polishing process still depends on the experience of an expert while the cutting process has been automated due to the progress made in CNC and CAD/CAM. Also, even though an expert polishes a die, it takes a lot of time to obtain the required degree of smoothness. This represents a major problem because the polishing process consumes 30 - 40 % of the total die-manufacturing time[1-3]. Moreover, workers tend to avoid the polishing workplace because of the excessive exposure to dust and noise[1-4]. Therefore, to improve productivity and to solve the potential shortage of skilled workers, several studies on the automation of the polishing process have been conducted[1-8]. Some researchers developed a five-axis articulated polishing robot. The robot, however, has some defects in its stiffness

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and position accuracy[6,7].

In this study a polishing robot system was developed to automate the polishing process and to cope with the shortage of skilled workers. The developed polishing robot system consists of a linear motion part with three degrees of freedom and a rotative motion part with two degrees of freedom. The latter part is the polishing head and is attached to the linear motion part of a commercial machining center. To make the operation of the polishing robot system easier, this study developed an integrated operating program in the Windows environment. The program consists of five modules: a polishing module, a graphic simulator module, a polishing data generation module, a code separation module, and a teaching module. In the process of die polishing, a worker often wants to obtain the polishing data of a specific area from the whole die[9]. To easily obtain the polishing data of a specific area, this study developed an automatic teaching system.

In order to evaluate the polishing performance of the polishing robot system and the stability of the integrated operating program, the polishing experiments on a shadow mask die were conducted.

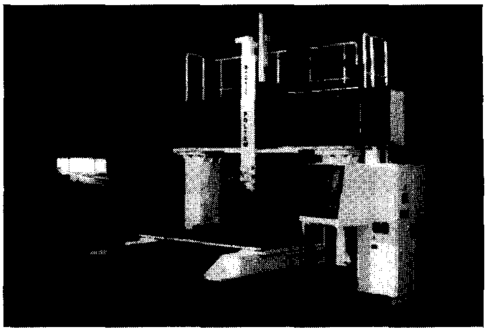


Fig. 1 Polishing robot system

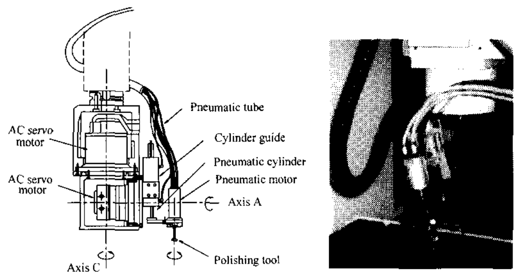


Fig. 2 Two-axis polishing head

2. Automatic Polishing Robot System

2.1 Five-axis Polishing Robot System

The polishing robot system, named the POLYEM (polishing expert machine), was developed to automate the polishing process. The photograph of the POLYEM is shown in Fig. 1. Also, the structure and photograph of the two-axis polishing head is shown in Fig. 2. The specifications for the POLYEM are listed in Table 1.

The POLYEM is composed of a three-axis machining center and a two-axis polishing head attached to the machining center as shown in Figs. 1 and 2. The machining center is controlled by the FANUC controller, and the polishing head by a DSP controller. By developing the DSP controller, the commercialization cost was reduced and the flexibility in developing the system was achieved[10]. The DSP controller is composed of the DSK (DSP Starter Kit) which includes a TMS320C31 for real-time signal processing as well as the peripheral circuits with DIO (Digital Input and Output), DAC (Digital to Analog Converter), ADC (Analog to Digital Converter), and counters. The architecture of the double controller system for the POLYEM is shown in Fig. 3.

Table 1 Specifications of the POLYEM

POLYEM	Specification
Stroke of axis X	1800 mm
Stroke of axis Y	1400 mm
Stroke of axis Z	800 mm
Rotation of axis A	±95°
Rotation of axis C	±180°
Working space	1800 mm × 1400 mm
Carrying capacity	5000 Kg
Control unit	FANUC 18M / DSP
Teaching system	Joystick / MPG

A host computer uses the CAM software to generate the polishing trajectory data on the polishing system. Since the polishing robot system is composed of two subsystems, the host computer must transmit the generated polishing data to the FANUC controller and the DSP controller through a serial port.

The polishing tool is controlled by the DSP controller to maintain it normal to the die surface. The pneumatic

Table 2 Characteristics of the POLYEM and other polishing systems

	POLYEM	Five-axis polishing system	Six-axis polishing system
Structure	Three-axis machining center + two-axis polishing head	Three-axis gantry type + two-axis pneumatic tool system	Three-axis articulated robot + three-axis tool system
Degree of freedom	5	5 (Axis A is handled manually)	6
Working space (mm^2)	1800 × 1400	1550 × 1000	1200 × 800
Carrying capacity (kg)	5000	8000	5000
Stiffness	Good	Good	Bad
Cost	Cheap	Expensive	Expensive
Control unit	FANUC 18M / DSP	NC controller	SEL controller
Teaching system	MPG / joystick	Joystick	Without
Teaching mode	Manual mode / auto mode	Manual mode	Without

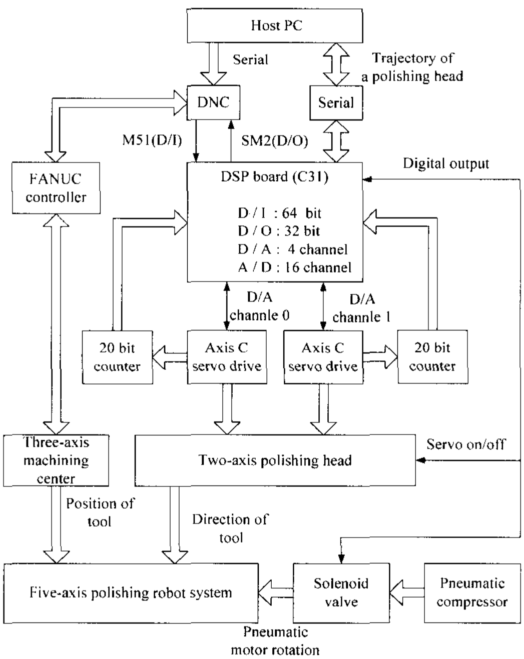


Fig. 3 Architecture of the double controller system for the POLYEM

cylinder presses the polishing tool against the die surface with a constant force. At the same time, the polishing tool is rotated by the pneumatic motor and performs the polishing work. These processes are synchronized with the machining center. In order to synchronize the start points of each polishing trajectory for the machining center and the polishing head, the M51 and the SM2 terminals of the machining center are connected to the DIO ports of the DSP controller[11]. A flow chart for the operation of the polishing robot system is shown in Fig. 4.

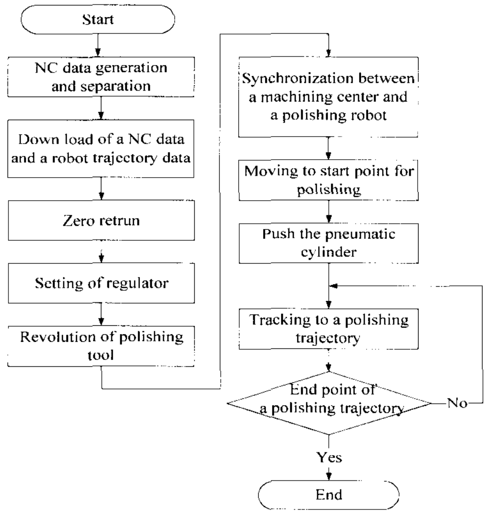


Fig. 4 Flow chart for operation of the polishing robot system

The developed polishing robot system is able to reduce the number of steps in the polishing process and improve the surface roughness and waviness. The system has several advantages: reduced time for setting up polishing work, decreased labor costs, effective operation, continuous polishing work without an operator, improved machine accuracy, and the ability to polish a free curved surface die. Table 2 shows the differences between the POLYEM and other polishing systems manufactured by some companies.

2.2 Automatic Teaching System

The polishing robot system's polishing data is generated from both the CAD data and the teaching data.

If the CAD data for a die is known, the desired five-axis polishing data is generated from the CAD data by using PolyCAM, a dedicated CAM software package for the polishing system[12,13]. In the die polishing process, workers often want to obtain not only the polishing data for the whole die but also the polishing data for a specific area[9]. In order to obtain the polishing data for a specific area, the polishing robot system was designed so that workers could use a teaching device such as a MPG (Manual Pulse Generator) or a joystick. However, the teaching process is time-consuming because the workers must determine whether the selected point is exact or not with the naked eyes.

Therefore, an automatic teaching system was developed to easily obtain teaching data. The teaching system consists of a three dimensional joystick and a proximity sensor as shown in Fig. 5. The joystick is used to drive the polishing robot system simultaneously to an arbitrary point and the proximity sensor is used to precisely obtain the teaching points.

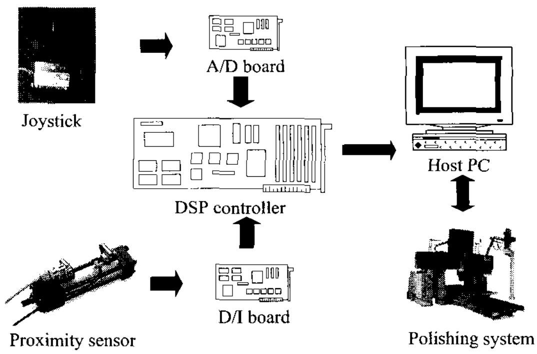


Fig. 5 Configuration of teaching system

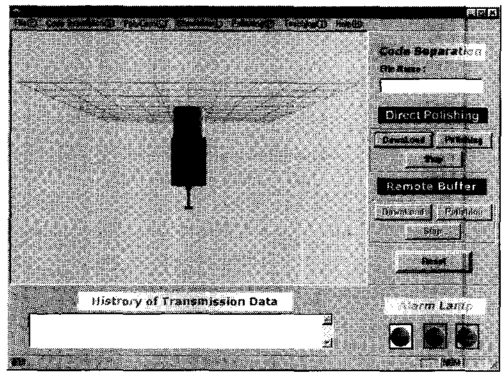


Fig. 6 Screen configuration of the integrated operating program

3. User-friendly Integrated Operating Program

Since it is inconvenient for a user to operate two subsystems such as a polishing head and a machining center, an integrated operating program was developed in the Windows environment to provide easy control of the system. The integrated operating program was composed in Visual C++ 5.0. Also, MFC (Microsoft Foundation Class) and CG (Component Gallery) were used to make the program structure simple.

3.1 Integrated Operating Program

The screen configuration of the integrated operating program is shown in Fig. 6. The screen is composed of a pulldown menu bar, a graphic simulator, a code separation part, a polishing part, a list box and an alarm lamp. The pulldown menu is placed on the top of the screen. The pulldown menu has many functions such as file open, generation of five-axis NC code, code separation, simulation, teaching, and polishing work, and other tasks.

PolyCAM was developed to generate the desired five-axis polishing data[12,13]. It supports various methods of constructing surfaces such as point data interpolation, skinning, sweeping, and blending. Its geometric processing routines cover various functions such as surface/surface intersection, curve/surface intersection, curve projection, surface and face trimming, polyhedral surface model conversion, and so on. The point data interpolation functions are used to construct a surface from the teaching data of the polishing robot system. In addition, PolyCAM has an exchange function for CAD data that supports IGES, DXF, and ZES formats.

3.2 Code Separation and Polishing Module

Since the polishing robot system is composed of two subsystems, the host computer must transmit the generated polishing data to the FANUC controller of the machining center and the DSP controller of the polishing head. Thus, the three-axis trajectory data for the machining center and the two-axis trajectory data for the polishing head are separated from the generated five-axis polishing data by the code separation as shown in Fig.

7.

If the size of the separated polishing data is big, the data cannot be transmitted at once to the machining center due to the limited memory size. To solve this problem, the integrated program offers two modes to transmit the polishing data and to drive the polishing robot system. One is a direct polishing mode and the other is a remote buffer mode. When the size of the polishing data is small, the direct polishing mode is used. When the size of the polishing data is big, the remote buffer mode is used. The polishing work function is on the right side of the screen and consists of a pulldown menu as shown in Fig. 6.

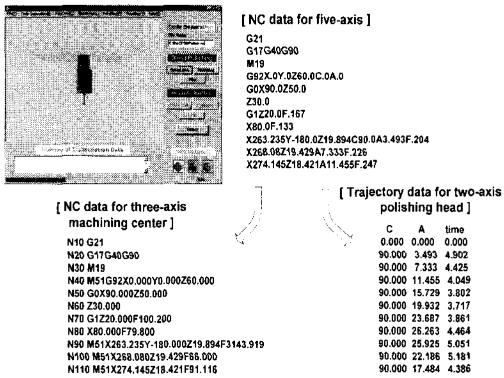


Fig. 7 Code separation

3.3 Graphic Simulator Module

Users of this system may want to verify whether the two subsystems will satisfactorily follow the separated trajectory data before actually operating the polishing robot. For this purpose, the graphic simulator provides the functions to draw the tool paths and animate the movement of the polishing robot.

Forward kinematics of the polishing robot system is obtained by Denavit-Hartenberg (D-H) representation [14,15]. Once the D-H coordinate system has been established for each link, a homogeneous transformation matrix is easily calculated by relating the ith coordinate frame to the (i-1)th coordinate frame. A base coordinate (x_0, y_0, z_0) is established at the origin of the machining center and every other coordinate frame is established as shown in Fig. 8.

The position vector $\vec{P}$ of the polishing tool is obtained by[15]

$$\vec{P}=\begin{bmatrix}P_x\\P_y\\P_z\end{bmatrix}=\begin{bmatrix}l_x+l_1C_4C_5+l_2S_4+l_3C_4S_5\\l_y-l_1S_4C_5+l_2C_4-l_3S_4S_5\\l_z-l_1S_5+l_3C_5\end{bmatrix}\quad(1)$$

where $C_i=\cos\theta_i$, $S_i=\sin\theta_i$.

The approach vector $\vec{a}$ of the polishing tool is obtained by

$$\vec{a}=(C_4S_5,\ -S_4S_5,\ C_5)^T\quad(2)$$

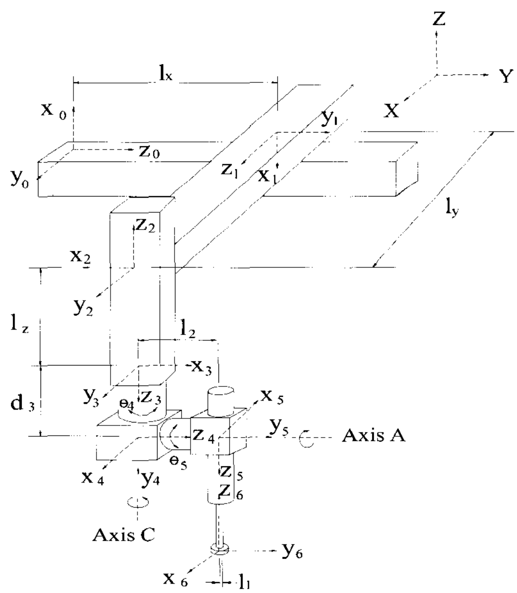


Fig. 8 Kinematic modeling of the polishing robot system

In order to control the position and the orientation of the polishing tool, it is important to solve the inverse kinematics solution. The position and the orientation of the polishing tool is given as the homogeneous transformation matrix ${}^0A_6$ and its joint and link parameters. The corresponding joint position (l_x, l_y, l_z, θ_4, θ_5) of the polishing robot system is found as

$$\begin{bmatrix}l_x\\l_y\\l_z\end{bmatrix}=\begin{bmatrix}P_x-l_1C_4C_5-l_2S_4-l_3C_4S_5\\P_y+l_1S_4C_5-l_2C_4+l_3S_4S_5\\P_z+l_1S_5-l_3C_5\end{bmatrix}\quad(3)$$

$$\theta_4 = atan2\ (-a_2\ ,\ a_1) \quad (4)$$
$$\theta_5 = atan2\ (a_1 / C_4\ ,\ a_3)$$

where, $atan2\ (\ x,\ y\ ) = \tan^{-1}(\ x/y\ )$

Fig. 9 shows the animation screen. In particular, the simulator provides a kinematic simulation function which draws the trajectory of the actual tool by simulating the linear interpolation function of the robot controller. Many trajectory problems were found and solved through this function while the system was being developed.

3.4 Teaching Module

Although the CAD data for a die is not known, the data is obtained from the shape of the die by using the teaching system. To use the teaching system, a worker must select the teaching mode on the pulldown menu. After selecting the mode, a teaching box appears as shown in Fig. 10. The teaching program offers two method to obtain the teaching data. One is shape teaching and the other is edge teaching as shown in Fig. 11. If the 'start' button is selected, the teaching data is obtained automatically by the system. The teaching data is displayed on the right side of the teaching box as shown in Fig. 10. Fig. 12 shows the teaching data resulting from the die of a shadow mask. Fig. 12(a) shows the selected teaching data. Fig. 12(b) shows the polishing surface using the NC code with five axes generated from the selected teaching data.

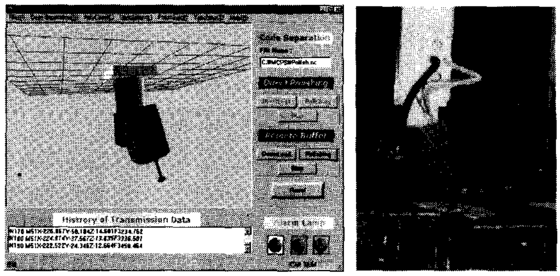


Fig. 9 Graphic simulator

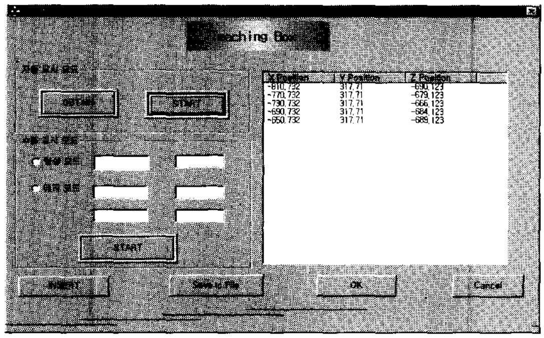


Fig. 10 Teaching box

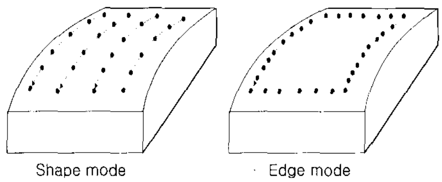
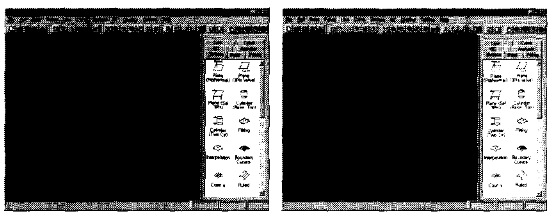


Fig. 11 Shape teaching and edge teaching



(a) Teaching points (b) Polishing surface

Fig. 12 Teaching data and PolyCAM generating surface

4. Experiment

4.1 Polishing Conditions

Since polishing work is performed to remove the tool marks and to improve the smoothness and flatness of die surfaces, it is important to select a proper polishing tool. In this study, the polishing tool composed of a ball joint from Nagasei company and the polishing sheet were developed[16]. The polishing sheets are an embossed type which puts an abrasive grain in the flexible fiber.

In the polishing process of the die, the contact force of the polishing robot, which is caused by removing the tool marks and rotating the polishing tools, always changes. In the previous study, the sliding mode control algorithm with velocity compensation was designed to reduce chattering in the sliding mode control and to provide a robust trajectory tracking performance in the operation of the polishing robot system[16]. The proposed algorithm is stored in ROM (Read Only Memory) of the DSP board as shown in Fig. 3.

Polishing is most efficient when the velocity of the polishing tool is 1200 rpm, a number 100 polishing sheet is used, and the polishing force is set at 40 N. However, when the velocity of the polishing tool is 1200 rpm, a number 800 polishing sheet is used, and the polishing force is set at 20 N, the surface is burned black[16]. This is due to the heat is generated by the friction between the polishing tool and the surface of the die. Therefore, the magnitude of polishing force must be restricted to 20 N at 800 mesh and 1200 rpm to prevent the tool from burning the surface of the die.

4.2 Polishing of the Die of Shadow Mask

In order to evaluate the polishing performance of the polishing robot system and the stability of the integrated operating program, polishing experiments were performed on a die of a shadow mask.

The material of the die is STD, and its size is 570 mm × 340 mm as shown in Fig. 13. The desired polishing trajectory patterns for the die of a shadow mask are generated by PolyCAM.

The polishing conditions are listed in Table 3. The polishing force is set at 10 N to prevent the tool from burning the die surface. The control results along the lissajous pattern are shown in Fig. 14. In Fig. 14(a) and (b), the maximum error of axis A and axis C are 0.07 degree and 0.15 degree, respectively. It is possible to absorb these small errors because the structure of the polishing tool has some flexibility and the tool is always in contact with the polishing surface due to the constant polishing force.

The surface of the polished die is shown in Fig. 15. The roughness of the surface is measured to evaluate the polishing performance of the developed polishing robot system. The maximum profile valley depth (R_{max}) is 0.3 μm and the center line mean roughness (R_a) is 0.02 μm. Generally, the required value of R_{max} is 0.2 - 0.5 μm[17,18]. Therefore, the results of the polishing experiment show that the polished surface is as smooth as a mirror and that the developed polishing robot system provides a reliable polishing performance.

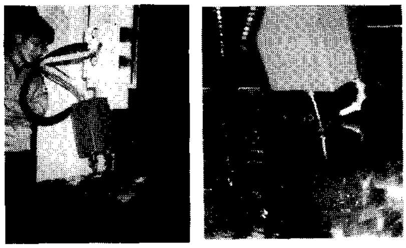
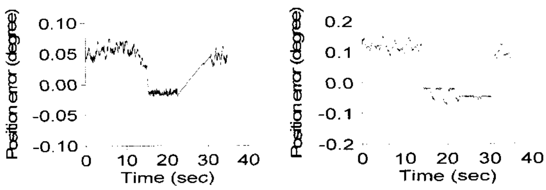


Fig. 13 Polishing of a shadow mask die

Table 3 Polishing conditions

Polishing sheet	800 mesh
Polishing force	10 N
Velocity of polishing tool	1200 rpm



(a) Axis A (b) Axis C

Fig. 14 Control results along lissajous pattern

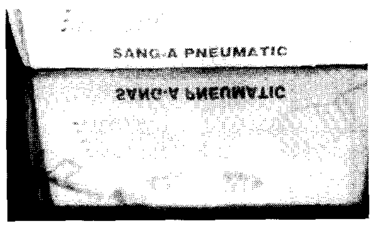


Fig. 15 Polished surface of a shadow mask die

5. Conclusion

This study developed a five-axis polishing robot system to reduce the polishing time and to cope with the shortage of skilled workers. The developed polishing robot system is composed of a polishing head, a machining center, a teaching system, and an integrated operating program. The developed polishing robot system is more economical than other conventional systems because a new polishing head is attached to a commercial machining center. In order to operate the developed polishing robot system easily, the integrated operating program is structured in the Windows environment. The program consists of a polishing module, a graphic simulator module, a polishing data generation module, and a teaching module. The teaching system was added to obtain the polishing data of a specific area from the whole die automatically. Also, in order to evaluate the polishing performance of the polishing robot system and the stability of the integrated operating program, polishing experiments were performed on a die of a shadow mask. The R_{max} and R_a of the polished surface were 0.3 μm and 0.02 μm, respectively. The polishing experiment showed that the surface was as smooth as a mirror. It may be concluded that the developed polishing robot system provides a reliable polishing performance.

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