Automation of Polishing Work by an Industrial Robot*
(System of Polishing Robot)

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This study deals with the automation of polishing work by use of an industrial robot with 6 degrees of freedom. Since polishing work, which takes much time, requires experience, patience and skill, it is manually performed by skilled workers. This study aims at rationalizing such difficult polishing work by introducing a robot and CAD technology. The arm of the robot can be equipped with two kinds of polishing tools, i.e., a rotational tool or an ultrasonic vibrational one, to cope with various cofigurations of the workpiece surface. In addition, the system allows collision-free polishing paths derived from the CAD system to be expressed in the robot coordinate system by use of a touch sensor. The system is found to be effective for obtaining a smooth workpiece surface, based on several experimental results.

Key Words: Robot, Polishing Tool, CAD, Collision-Free Polishing Path, Coordinate Transformation

1. Introduction

Polishing work, a kind of finishing work carried out after machining, is necessary to obtain good surface roughness as well as form accuracy. The automation of machining operations in manufacturing processes has been actively pursued; however, the automation of polishing work lags behind in terms of special characteristics such as uncertain polishing method corresponding to the surface roughness and difficulties in recognizing workpiece surface conditions. In particular, the shape of metal moulds requiring polishing is generally complicated due to the detailed requirements of designers. Thus, polishing work for such complicated workpieces has been manually conducted, depending on the skills and experience of workers. In recent years, the ratio of finishing time to the entire process time has increased with the increasing demand for high surface quality. Therefore, the automation of polishing work, the key component in realizing total factory automation, is becoming more and more important to meet the demands of both high-efficiency and low-cost production in the high-diversity low-quantity method of production.

Polishing work must comply with the requirements of surface roughness without deteriorating the form accuracy, particularly at the edges and corners of workpieces. Thus, attention must be paid to the development of automated polishing mechanisms and machines, with consideration of types and functions of polishing tools[1].

Most polishing tools are pressed against the workpiece surface at a constant pressure by use of air, and are controlled on one axis. However, in order to polish a curved surface uniformly, it is necessary to control the axis of the polishing tool in the direction normal to the surface or at a certain angle from the normal direction. For this purpose, industrial robots are used to arbitrarily position tools in the correct attitude in space. The teaching-playback method allows the robot to take the correct position and attitude against the workpiece surface ; however, it is limited to workpieces with relatively simple surfaces

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due to the difficulty of manual teaching. On the other hand, polishing tools equipped with force sensors or magnetic sensors have been developed that can learn the surface by themselves, in order to eliminate such difficulties of teaching[(2)-(4)]. However, even such systems cannot cope with complicated surfaces.

This study deals with an automated polishing system consisting of an industrial robot having 6 degrees of freedom and polishing tools such as a rotational tool driven by air and an ultrasonic vibrational tool, based on a Computer Aided Design/ Computer Aided Manufacturing (CAD/CAM) software system, Personal Computer Aided Production System (P-CAPS), employing a solid model[(5)]. The system structure, polishing tools and their performance, the transformation of the collision-free polishing path into robot control commands and experimental results are discussed in this report.

2. Polishing Robot System

As shown in Fig. 1, the robot having 6 degrees of freedom is controlled by a controller linked to an Engineering Workstation (EWS) or a Personal Computer (PC) with an RS 232 C communication line. To expand the work area of the robot, whose arm is 790 mm in length, it is hung upside down from the frame. The positioning accuracy of the robot is 0.05 mm, and the load capacity is about 20 N. The polishing tool is mounted at the tip of the arm.

The workpiece geometry is defined by P-CAPS in EWS or PC. The collision-free polishing path is generated by P-CAPS employing a solid model. The polishing tool path described in the workpiece coordinate system must be transformed into the robot coordinate system. Therefore, a touch sensor on the robot arm is used to obtain the location information about the workpiece on the table. Without the sensor, it takes a great deal of time to set up the workpiece.

The robot control commands generated by combining the polishing path data with the sensor information are transferred to the robot controller from the computer through the RS-232 C. Then, the tool mounted on the robot arm begins polishing.

3. Polishing Tool

Two kinds of polishing tools, a rotational tool and an ultrasonic vibrational one, are provided in order to cope with a variety of workpiece shapes.

3.1 Rotational tool

The rotational tool, consisting of an air motor spindle, a linear guide and an air cylinder, is shown in Fig. 2. The tool, whose length is 200 mm, is designed to be pressed against the workpiece surface in the tool axis direction at a certain contact force, which can be adjusted by changing the air pressure.

A grinding wheel and a rubber pad are mounted at the tip of the tool. After the workpiece surface is roughly ground with sandpaper attached to the rubber pad, it is polished, with change in the abrasive grain size of diamond paste according to the surface roughness. The rotational tool can polish workpieces with not only flat surfaces but also various curved surfaces.

The parameters affecting polishing in the case of the rotational tool are feed speed, rotational speed of the tool, contact force, the angle between the tool axis and the direction normal to the surface, abrasive hardness, and grain size. The selection of parameters is important to obtain uniform, well-finished surfaces in a short working time. Experiments were carried out to determine the appropriate parameters, using the workpiece material S 55 C. With regard to the robot movement, the polishing points forming the path were set 1 mm apart. Since there is a time lag in the robot, the robot's motion is slightly intermittent.

From experimental results concerning the rotational speed and the surface roughness under several different contact forces, the most appropriate rotational speed was found to be about 6 000 rpm. The optimal angle between the tool axis and the vector normal to the surface was found to be 2 degrees. The feed speed of 59 mm/min was selected and the pressure for the air cylinder was set at 1.2 atm.

Figure 3 shows the relationship between the grain size of the sandpaper and the reduction in surface roughness under the working conditions mentioned above in the case of polishing of a workpiece with a

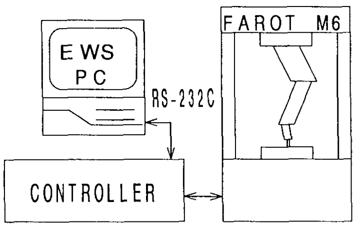

Fig. 1 System of polishing robot

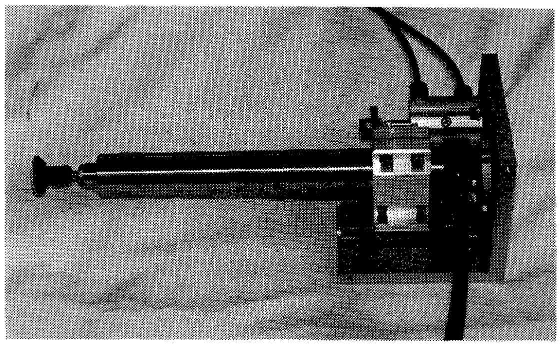

Fig. 2 Rotational polishing tool

flat surface.

In the final polishing, diamond paste attached to felt was used instead of sandpaper. The relationship between the surface roughness and the grain size is shown in Fig. 4. In this case, the rotational speed of 3 000 rpm was used. From the figure, it is found that the surface roughness is reduced with increasing grain size.

3. 2 Ultrasonic vibrational tool

The tip of the ultrasonic vibrational tool, as shown in Fig. 5, is pressed against the workpiece surface and polishes the surface in the complex vibrational mode in the longitudinal and perpendicular directions of the tool. There are many kinds of tips, such as ceramic, wood and so on. For surfaces with relatively large cutter marks, it is desirable to use harder tips to reduce the surface roughness in a shorter time. The ultrasonic vibrational tool can be appropriately used to polish the side walls or bottoms of deep grooves. The frequency of ultrasonic vibration is 30 KHz, and the vibrational magnitude is 15 μm.

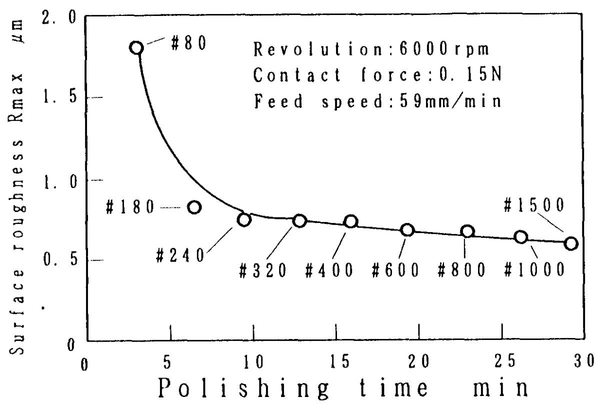

Fig. 3 Relationship between the surface roughness and the grain size of sandpaper

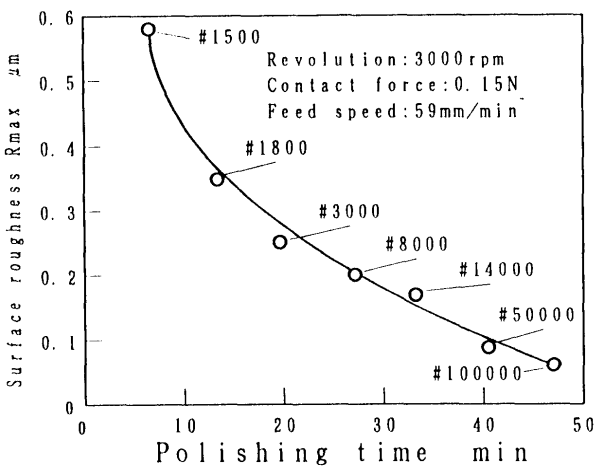

Fig. 4 Relationship between the surface roughness and the grain size of diamond paste

Figure 6 is a photo taken during the experiment of polishing a groove with the tool with a ceramic tip whose width and thickness were 6 mm and 1 mm, respectively. The workpiece used was plain carbon steel, S 55 C, and was machined by use of a ball-end mill of 3 mm in diameter with the pick feed of 1 mm.

The experimental results of polishing the side walls and bottom of the groove in the manner mentioned above are shown in Fig. 7 and Fig. 8, respectively. The tool is used in the complex vibrational mode, and is fed at a rate of 43 mm/min in 0.5 mm increments. From the figures, it is seen that the surface roughness is reduced to about 10 μm. The

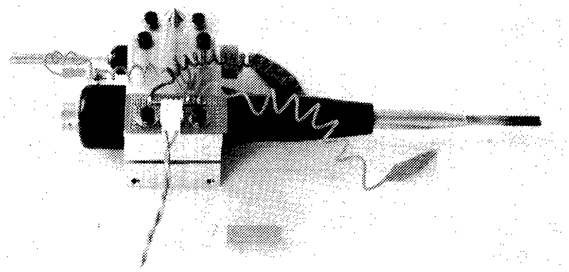

Fig. 5 Ultrasonic vibrational tool with touch sensor

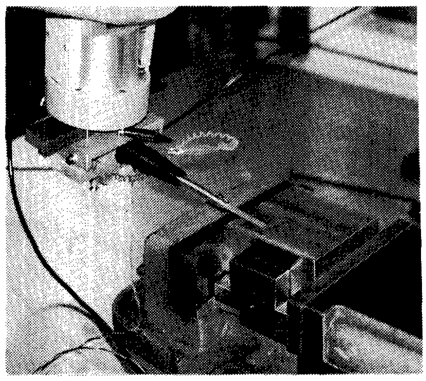

Fig. 6 Photo taken during polishing with the ultrasonic vibrational tool

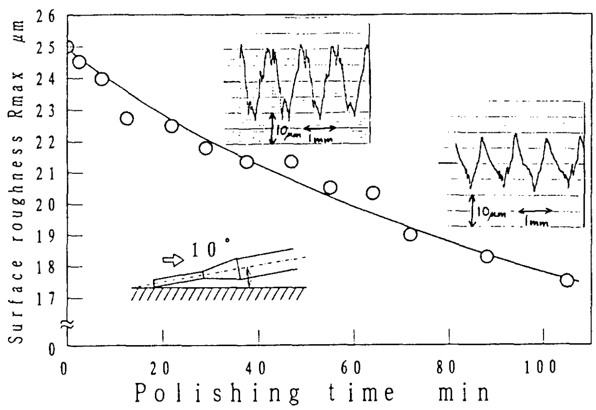

Fig. 7 Surface roughness during groove side wall polishing with the ultrasonic vibrational tool

surface roughness obtained with the ultrasonic vibrational tool and the polishing efficiency are not as good as those obtained with the rotational one. To investigate the surface roughness attainable by the tool, a polishing experiment using a wooden tip with diamond paste was carried out. As a result, the surface roughness of R_{max} 0.34 μm was obtained.

4. Generation of Robot Control Data and Coordinate Transformation

4.1 CAD data and polishing tool attitude

Figure 9 shows the flow chart of robot control command generation from CAD data. With P-CAPS employing a solid model, the required workpiece geometry can be defined by means of the input function of primitives such as cone, cylinder, sphere, Bezier free-form surface, rotating body, etc., together with the editing functions of scaling, rotation and translation, and the functions of arithmetic operation between primitives. The generated workpiece geometry data are stored in the memory as Constructive Solid Geometry (CSG) and Boundary representation (B-rep) expressions.

The CAD/CAM system can calculate the normal vector and feed vector at each point on the workpiece surface from CSG data. Then, the coordinates of the tool center and the tool axis vector are calculated to keep the tool in the appointed position and attitude, taking account of collision. The method of collision avoidance will be discusses in the following report.

4.2 Handling of 6th robot axis

The polishing path generated in the workpiece coordinate system is translated into actual robot control data by the coordinate transformation explained in the following paragraph. With use of the rotational polishing tool, 5 degrees of freedom are enough to determine the position and attitude of the tool due to the tool axis rotation as the 6th axis. The robot is designed to work as a robot with 6 degrees of freedom, and may rotate unnecessarily in order to maintain its posture with regard to the 6th axis. When the 6th axis arm travels beyond its range, the robot stops, which results in a narrow working area for the robot. Thus, the program fixes the 6th axis, and ensures a wide working area for the robot arm, taking account of the limit of the 6th axis, when the polishing path data expressed in terms of the tool axis vector are transformed into the tool posture, expressed as angles with respect to each coordinate axis.

4.3 Coordinate transformation and robot command data

The workpiece, defined and machined on the basis of P-CAPS, can be placed arbitrarily on the table. The polishing path is generated in the workpiece coordinate system, and has nothing to do with the robot coordinate system. In order to match the two coordinate systems, a cone-shaped touch sensor of 10 mm in diameter and 30 mm in length is mounted on the robot arm, which enables the computer to determine the location information of the workpiece by reading the coordinate of two points on the side face (we assume that the z-axis of the workpiece is set parallel to that of the robot, as shown in Fig. 10). When the sensor with a certain voltage makes contact with the workpiece, the voltage drops to zero. As a result, obtaining the signal from an A/D converter, the computer can recognize the contact position with the accuracy of 0.05 mm.

By use of the location information of the workpiece, the tool center position and the tool axis vector in the workpiece coordinate system can be transformed into those of the robot coordinate system to

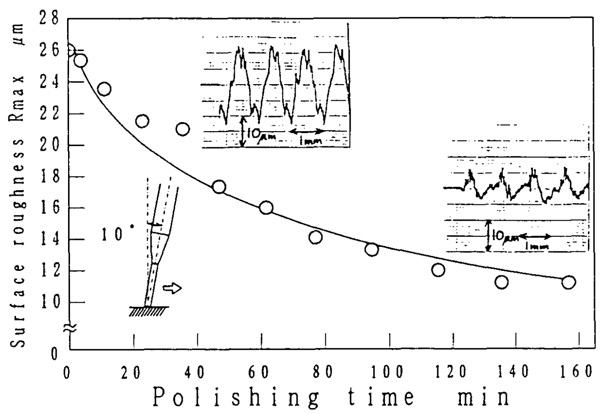

Fig. 8 Surface roughness during groove bottom polishing with the ultrasonic vibrational tool

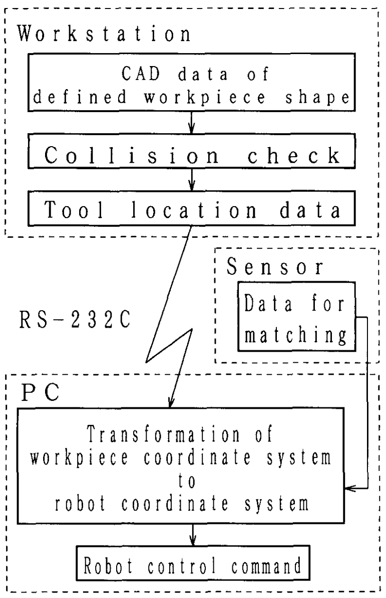

Fig. 9 Data flow from CAD to robot control commands

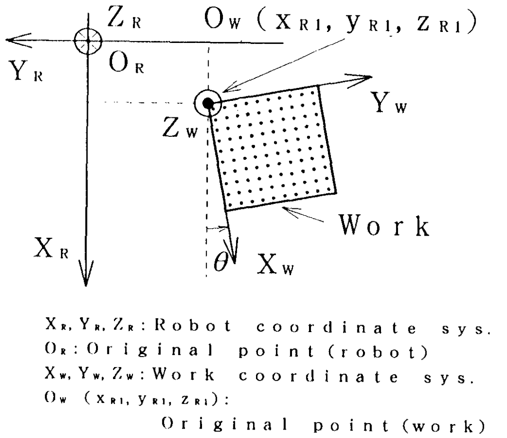

Fig. 10 Transformation of work coordinate system to robot coordinate system

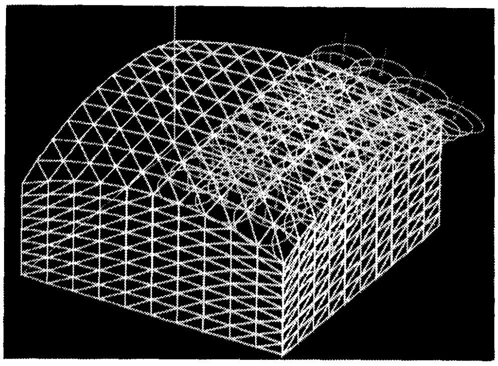

Fig. 11 Defined workpiece shape with curved surface and polishing tool path

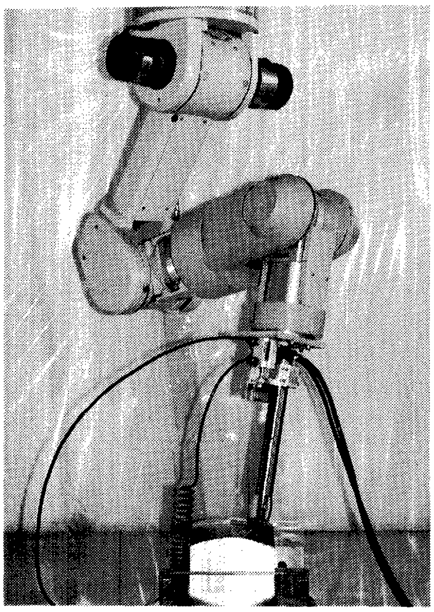

Fig. 12 Photo taken during polishing of workpiece with curved surface

generate the commands necessary to control the robot arm. The sensor system also makes it possible to cope with changes in polishing path due to the change in

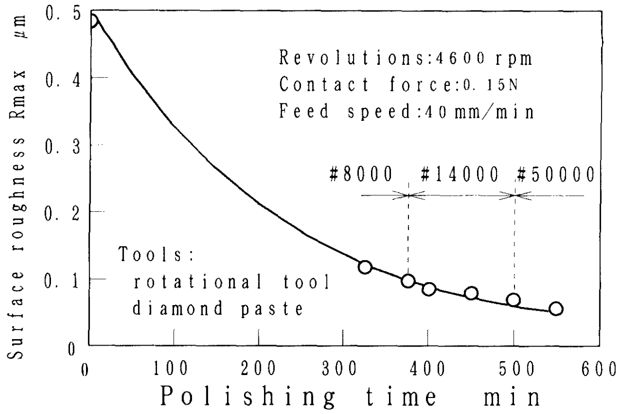

Fig. 13 Variation in the surface roughness for the curved surface

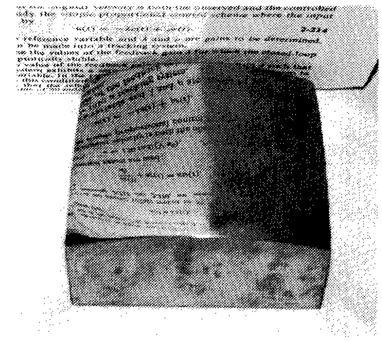

Fig. 14 Polished workpiece surface

tool length, as well as the determination of workpiece position.

5. Experiments of Curved Surface Polishing

A workpiece having a convex curved surface, defined by P-CAPS, was machined and ground by a 5-axis machining center in advance. Figure 11 shows the workpiece shape and polishing tool path. The material of the workpiece was plain carbon steel, S 55 C, and the area to be polished was 100 mm × 100 mm. The surface roughness before polishing was R_{max} 0.5 μm.

The rotational polishing tool was used. The machined surface was polished with diamond paste of grain size from # 1 500 to # 50 000 (because of the low initial surface roughness of R_{max} 0.5 μm) under the conditions of the tool rotation 4600 rpm, contact force 0.15 N and feed rate 40 mm/min. A photo taken during the actual polishing operation is shown in Fig. 12.

Figure 13 shows the gradual reduction in surface roughness with changing grain size of diamond paste. The polished workpiece surface is shown on the left side of Fig. 14 ; on the right side of the same figure is the machined surface. The surface roughness of R_{max} 0.05 μm was achieved in about 9 hours.

6. Conclusions

We have developed an automated polishing system using an industrial robot controlled off-line by CAD/CAM data without teaching. It is found that the system has the potential to realize flexible automated polishing of various workpieces with curved surfaces. The study can be summarized as follows.

(1) Two kinds of polishing tools are provided. One is an air-driven rotational tool capable of polishing relatively wide surfaces with higher efficiency. The other is an ultrasonic vibrational tool suitable for polishing sides and bottoms of grooves.

(2) The automatic coordinate transformation function between the workpiece coordinate system and the robot coordinate system allows direct control of the robot by CAD data and ease in setup of workpieces through the location information of workpieces obtained by a touch sensor.

(3) A workpiece with a curved surface, machined in advance by a 5-axis control machining center, was polished. As a result, the system was found to be capable of producing a smooth finished surface of 0.05 μm R_{max} efficiently and accurately.

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