行政院國家科學委員會補助專題研究計畫成果報告

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計畫編號：NSC89－2212－E－032－008
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計畫主持人：王銀添

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中華民國 90 年 10 月 31 日

行政院國家科學委員會專題研究計畫成果報告

機械手臂輔助曲面工件研磨與拋光

Robot-assisted Grinding and Polishing of Specimens with Free-form Surfaces

計畫編號：NSC 89-2212-E-032-008

執行期限：89 年 8 月 1 日至 90 年 7 月 31 日

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摘要

本研究的目的是發展一套機械手臂輔助曲面工件研磨與拋光系統。相對於傳統直角座標工具機，串接式機械手臂具有較高的自由度與較大的工作空間，搭配適當的曲面路徑控制器與力量控制器，可執行具自由曲面模具的研磨與拋光作業。執行期間，我們將規劃曲面研磨路徑，推導研磨力模式，以及發展機械手臂 PC-based 運動與力量控制器。也將使用田口品質管制法，分析不同磨拋路徑、研磨接觸力、與進給速率對研磨後工件表面粗糙度的影響。整合的系統將在具自由曲面模具上測試，以評估所研發之系統的實用性。

關鍵詞：機械手臂輔助磨拋系統、曲面研磨與拋光、碎形路徑

1. Abstract

In this research, we will develop a robot-assisted grinding and polishing system for specimens with free-form surfaces. Comparing to the machine tools with mutually perpendicular coordinates, the serial manipulator has more degrees of freedom and larger workspace. Equipped with curved-path motion and contact force controllers, this kind of robot can used to grind and polish mold and die with curved-surfaces. We will plan and generate curved grinding paths, derive a grinding force model, and develop a PC-based motion and force controller for the manipulator. In this research, we will also utilize the Taguchi methods of quality control to analyze the effects of machining parameters on surface roughness of ground specimens. The parameters include several different groups of grinding and polishing paths, grinding contact forces, and the federate of the machining tools. The integrated system will be tested on the specimens with free-form surfaces to evaluate the practical usage of the developed system.

Keywords: Robot-assisted finishing system, curved-surface grinding, fractal path

2. Introduction

Finishing processes of die-cast manufacturing include grinding, honing, lapping, polishing lapping, and polishing. These processes are time-consuming and monotonous operations that strongly rely on skilled human-workers. To automate these processes and achieve desired surface roughness, it is important to control the grinding path and contact force, as well as to choose suitable feed-rate and tool diameter. Among them, to generate a suitable tool-path and to control the contact force are two major challenge issues. For example, to polish free-form surfaces of an object requires a delicate machine to follow complicated polishing paths. In this case, a polishing system based on a robot manipulator is more effective than that on a NC machining center in order to follow the curved free-form surfaces. Different robot grinding path on the specimen will affect the surface roughness. On the other hand, during finishing operations, the tool comes into physical contact with the workpiece and causes contact forces between them. It is difficult to control these contact forces that depend on the cutting depth, feed rate, grinding-wheel speed and material properties.

Many researchers have proposed automated systems for grinding of dies, deburring of castings, and removing of weld beans etc [5-8]. Usually, a grinding tool is mounted on a NC machining center or a robot manipulator and a multi-dimensional force sensor is included in the system to improve finishing accuracy. It is troublesome to handle the multi-dimensional motion and force control system in run-time processes, besides the passive-type force sensors are expensive in price and sensitive to a noise.

We propose an automated finishing system for polishing free-form surfaces of dies specimens. Two types of tool path, zigzag and fractal, are used in this research for comparison. To simplify the force-control action, only the contact force normal to the polishing surface is concerned and a software-type torque observer is used to replace the role of a hardware sensor. We decide four important grinding conditions, namely, path pattern, grinding contact pressure, tool diameter, and feed rate. In order to determine the best combination of the four grinding conditions, Taguchi's method for experimental design is utilized.

3. Results and Discussion

We use B-spline function to describe the surface of a specimen,

$$Q(u,v)=\sum_{i=1}^{n+1}\sum_{j=1}^{m+1}B_{i,j}N_{i,k}(u)M_{j,l}(v)$$

Where $B_{i,j}$ is a position matrix; $N_{i,k}(u)$ and $M_{j,l}(v)$ are two basis functions in u and v axes respectively. Typical curved surfaces of a specimen are shown in Figure 1. We can formulate different types of tool path for the robot to perform a task on this workpiece. Two types of tool path, zigzag and fractal, are used in this research for comparison. A zigzag is a path with repeated switching of directions. Figure 2 depicts the top-view of a specimen ground by zigzag tool path. On the other hand, a fractal tool path is generated based on the Hilbert "⊓" pattern. A L-system method [4] using logical symbols is adopted here to generate the Hilbert "⊓" pattern. Definitions of the logical symbols are stated as following:

- F: *Drawing a fixed-length line from current position to new position*
- -: T*urning an angle of 90º in CCW direction*
- +: *Turning an angle of 90º in clockwise direction*
- L: +F-F-F+
- R: -F+F+F-

Generation rules of the Hilbert curve are: (a) substituting "+RF-LFL-FR+" into L, "-LF+RFR+FL-" into R when the order increases by one, (b) repeating the processes in every increment of order, and (c) the zero-order starting from the L-operation.

Figure 1 depicts a 3rd-order fractal tool path based on the generation rules, while the top-view of the ground specimens by fractal tool path are shown in Figure 2-4. We found that the fractal path has an advantage of consistency in direction [4].

We develop a PID position controller for the motion of each axis of the xy-table. The control block diagram is shown in Figure 5 and the transfer function is given by

$$\frac{P(s)}{P^*(s)} = \frac{K_t K_d s^2 + K_t K_p s + K_t K_i}{Js^3 + (B+K_t K_d)s^2 + K_t K_p s + K_t K_i}$$

Where $P^*(s)$ and $P(s)$ represent the position command and output, respectively; J is the inertia and B is the coefficient of viscous friction; K_t is the drive torque constant; K_p, K_i, K_d are gains of the PID controller. For the xy-table, point-to-point motion is programmed by using a trapezoid velocity profile as shown in Figure 6.

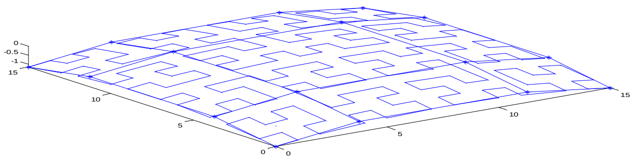

Figure 1 Third-order fractal tool path

In this experiment, we have four grinding factors with several levels shown as follows,

Tool Diameter	3mm, 4mm
Path Pattern	zigzag(200μm), 5th-order fractal, 4th-order Fractal
Feedrate	12.5mm/s, 25mm/s, 37.5mm/s
Grinding Pressure	0.556N, 1.111N, 1.667N

Note that, only the scale of tool diameter is divided into two levels, scale of all the other factors are divided into three levels. Results for the various factors are also shown in the last two columns of Table 1. According to the method in reference [3], contribution of each factor is calculated, and the results are shown in Table 2. From this table, we know that among the four factor which may affect surface roughness, their contribution in descending order are path pattern, grinding contact pressure, tool diameter, and feed rate. The signal-to-noise ratio for each of the grinding factors can be determined from Table 1. The results show that the best combination of the grinding factors is $A_1B_1C_1D_3$, which includes 4-mm tool diameter, 5th-order fractal path, 12.5mm/s federate, and 1.667N grinding pressure.

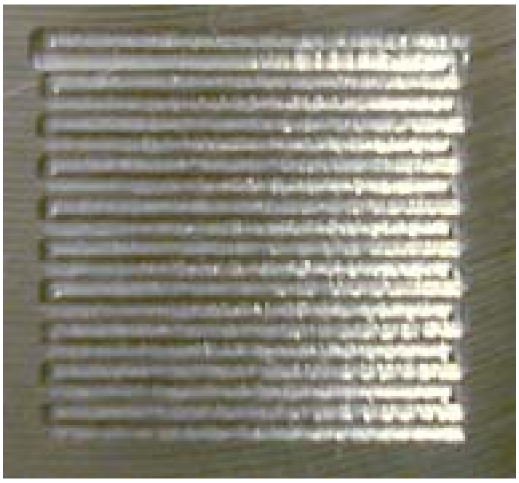

Figure 2 Ground zigzag tool path

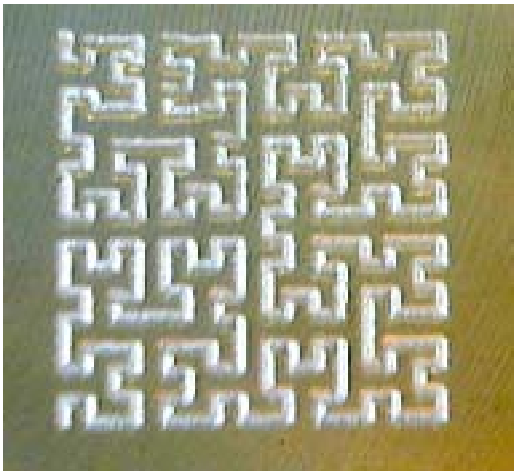

Figure 3 Ground 3rd-order fractal path

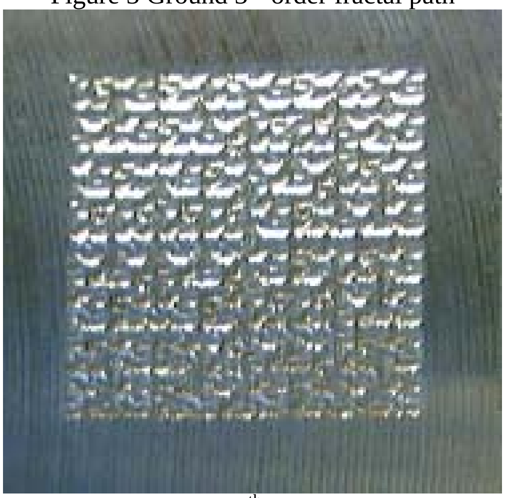

Figure 4 Ground 4th-order fractal path

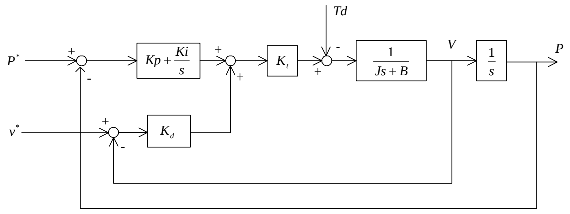

Figure 5 PID position control

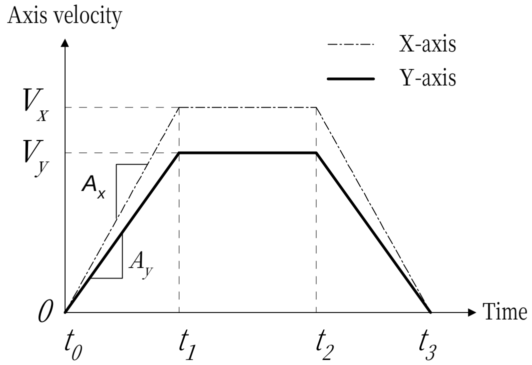

Figure 6 Trapezoid velocity profile

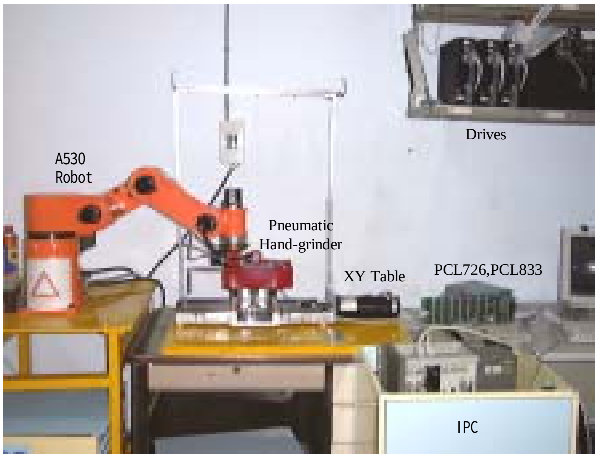

Figure 7 Automated Surface Finishing System

Table 1 Experiment design and results

	tool diameter (mm)	path pattern	feed-rate (mm/sec)	grinding pressure (N)	Surface roughness Ra(μm)	SN Ratio η_i
1	4	5th-order fractal	12.5	0.556	5.000	6.021
2	4	5th-order fractal	25	1.111	3.500	9.119
3	4	5th-order fractal	37.5	1.667	3.750	8.519
4	4	4th-order fractal	12.5	0.556	8.250	1.671
5	4	4th-order fractal	25	1.111	6.000	4.437
6	4	4th-order fractal	37.5	1.667	6.000	4.437
7	4	zigzag	12.5	1.111	4.250	7.432
8	4	zigzag	25	1.667	5.250	5.597
9	4	zigzag	37.5	0.556	6.750	3.414
10	3	5th-order fractal	12.5	1.667	4.500	6.936
11	3	5th-order fractal	25	0.556	6.250	4.082
12	3	5th-order fractal	37.5	1.111	5.000	6.021
13	3	4th-order fractal	12.5	1.111	7.500	2.499
14	3	4th-order fractal	25	1.667	6.750	3.414
15	3	4th-order fractal	37.5	0.556	10.500	-0.424
16	3	zigzag	12.5	1.667	6.750	3.414
17	3	zigzag	25	0.556	9.250	0.677
18	3	zigzag	37.5	1.111	6.500	3.742

Table 2 Contribution of various factors

Factors	Degree of freedom (DF)	Sum of squares (SS)	Variance (V)	Pure sum of squares (TS)	Percent contribution (%)
Tool diameter	1	22.862	22.862	22.862	20.2%
Path pattern	2	52.549	26.275	52.549	46.5%
Federate	2	0.453	0.227	0.453	0.4%
Grinding pressure	2	33.487	16.744	33.487	29.6%
Error		3.656			3.3%
sum	7	113.008			100.0%

4. Self Evaluation of this research

This paper presents the development of a robot-assisted surface finishing system with an active torque controller. The system utilizes a dexterous manipulator to attain the desired position and orientation of finishing processes in three-dimensional space. A torque observer is attached to the tool frame of the robot manipulator, and a pneumatic hand-grinder is serially mounted on the observer. The function of the active torque controller in the system includes observing the contact torque, applying a desired contact pressure in the normal direction of the workpiece surface, and adjusting the contact angle between the hand-grinder and the surface of the workpiece. In this research, we construct the prototype of a robot-assisted finishing system. The experimental results show that the developed torque observer and controller system functions well under a variety of grinding conditions. Taguchi's method is used to determine the effects of the following factors: tool diameter, path pattern, federate, and grinding contact pressure. Tendencies of these factors are found. From the experimental results, we know that among the four factors that may affect surface roughness, their contributions in descending order are path pattern, grinding contact pressure, tool diameter, and feed rate.

The content and the experimental results of this research agree with the expectation in the original planning of the proposal. Some of the achievements will be written in technical papers for publication.

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