Real-time Gap Control for Micro-EDM: Application in a Microfactory

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Electrical discharge machining (EDM) is one of the most widespread nonconventional machining processes. Recently, a low-power micro-EDM process was introduced using a cylindrical electrode. Since its development, micro-EDM has been applied effectively to micromachining, and because the device setup for this process is simple, it is suitable for a microfactory that minimizes machines to fabricate small products economically in one system. In the EDM process, however, the electrode is also removed along with the workpiece. Therefore, the electrode shape and length vary as machining progresses. In this paper, a control method using a high speed real-time voltage measurement is proposed to regulate the rate and amount of material removed. The proposed method is based on the assumption that the volume of the workpiece removed in a single discharge pulses is nearly constant. The discharge pulses are monitored and controlled to regulate the amount of material removed. For this purpose, we developed an algorithm and apparatus for counting the number of discharge pulses. Electrode wear compensation using pulse number information was applied to EDM milling in a microfactory, in which a slight tilt of the workpiece may occur. The proposed control method improves the machining quality and efficiency by eliminating the inaccuracies caused by electrode wear and workpiece tilt.

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1. Introduction

The microfactory is a new concept of manufacturing suitable for the production of various small-dimension products. A microfactory represents a considerable saving in space and resources through the miniaturization of machine tools.[1] In this study, we applied electrical discharge machining (EDM) using a cylindrical electrode[2,3] to a microfactory for the following reasons: EDM is applicable to most conductive materials regardless of hardness because the process uses thermal energy induced by a plasma channel, tool breakage and deflection occur less often than with mechanical cutting processes because EDM is a noncontact machining process, and miniaturization of EDM systems has advanced dramatically.[4]

Severe tool wear is a characteristic of micro-EDM because the tool electrode is eroded along with the workpiece material during the machining process. This tool wear results in considerable geometrical errors, and accurate machining requires compensation methods. Several approaches are applied to solving this problem, including the uniform wear method,[5,6] tool wear compensation,[7,8] and in-process gap control.[9,10]

In a microfactory, however, another important issue must be considered in addition to the EDM tool wear problem. After the moving part of the planar motor has settled to the working position, the workpiece surface can be slightly and unpredictably tilted due to the irregular surface of planar motor plate. This tilt causes additional geometrical errors, especially in micro-EDM milling. The compensation method for machining along the prescribed tool paths can resolve the tool wear problem but is inappropriate for resolving this unpredictable problem of workpiece tilt. To solve both problems, an in-process gap control method for micro-EDM is required that is robust under the conditions of unpredictable tilting.

This study proposes a gap control method based on the pulse frequency. The pulse frequency of an RC type discharge circuit is calculated in real-time by differentiating the number of discharge pulses. The feedrate of the electrode is adjusted to the continuously changing gap condition using the pulse frequency to reduce the geometric machining errors caused by tool wear and workpiece tilt. This approach regulates the material removal volume on a machined surface with respect to the tool path. Section 3 discusses the implementation and experimental results for surface milling using this method.

2. EDM Module in a Microfactory

Figure 1 shows a drawing of the microfactory system developed in this study. The microfactory is composed of various modularized machining stations located along the transfer system based on planar motors. A carrier with a workpiece holder module travels on the planar motor stator plate in two dimensions. Therefore, the proposed microfactory is effective for micro batch production with less space, fewer resources, and reduced repetitive workpiece fixturing problems.

For this study, we developed an EDM module and its controller for integration into the microfactory. The testbed consisted of a planar motor, a precision feed drive, a vision monitoring system, control units, and a precise DC power supply. Figure 2(a) shows a carrier on

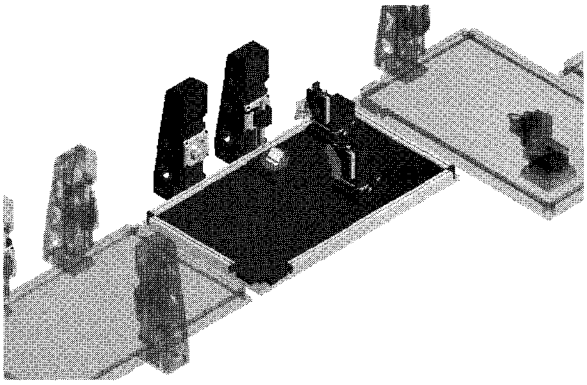
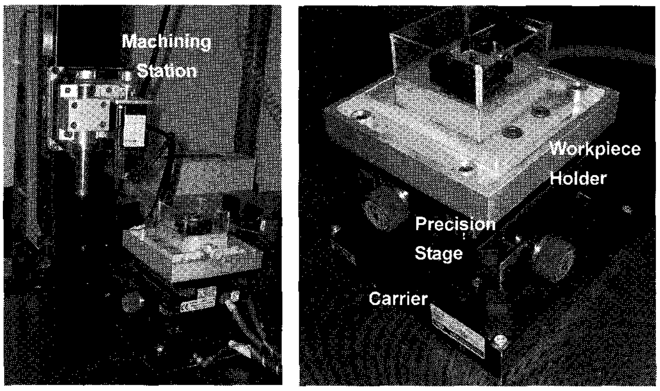


Fig. 1 A Drawing of the microfactory system



(a) EDM module (b) Microfactory carrier part

Fig. 2 Microfactory testbed for the micro-EDM process

the testbed approaching to the machining station. Because the surface planar motor that moves the carrier uses open loop control, the position error of the carrier is compensated by visual servo using a vision monitoring system.[11] However the position accuracy of the vision system is not sufficient for micromachining because the camera resolution corresponds to 500 μm on the stator plate. For that reason, a two-axis precision X–Y stage (VP-25XA, Newport) is included on the carrier part as shown in Fig. 2(b). During the machining process, the stages are used for tool path control while the carrier is locked in position in front of the micro-EDM station. After the machining process is complete, the carrier is unlocked and moved to the next stationary location according to the process plan.

A tilt error can be introduced to the combination of the carrier and precision X–Y stage after the motor is locked into position. This tilt error causes a geometric error in the microscale machining. Although the tilt angle of the workpiece surface may be very small, it results in major geometrical errors in micro-manufacturing due to the machining feature size. Furthermore, the direction and the degree of the tilt are difficult to measure, and thus to compensate for, during the machining process. The following section elaborates on the method applied to resolve this problem using in-process control.

3. EDM Process Control

3.1 Pulse Frequency Control Using Discharge Pulse Counting

We developed a system of pulse frequency control using real-time discharge pulse counting to improve the accuracy of EDM machining in a microfactory. Because we used an RC type discharge circuit, the electrical energy in every discharge is nearly constant, meaning that an almost uniform volume is removed under the conditions of constant energy.[12,13] We assumed that the pulse frequency is proportional to the material removal rate (MRR) of the process. Premature discharge generated from a less than fully charged capacitor inducing low energy rarely occurs because the time constant of the RC circuit is sufficiently small compared to the desired puls

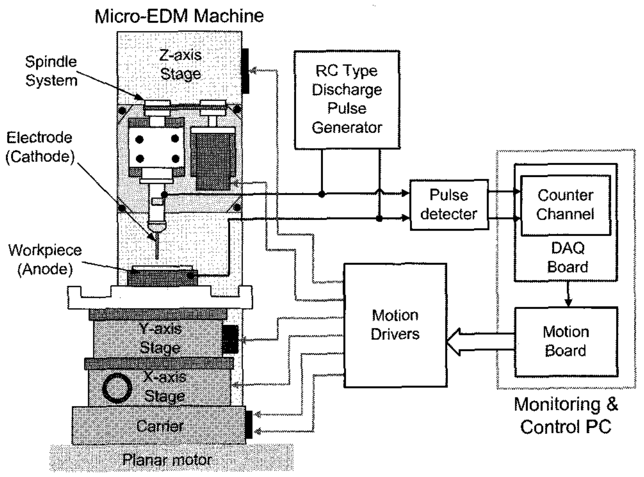


Fig. 3 Schematic setup of the EDM machine

frequency. Therefore, regulation of the pulse frequency can control the MRR. In our method, we regulate the pulse frequency by controlling the gap distance between the electrode and the workpiece. Since the pulse frequency increases as the gap distance decreases, gap distance control results in an effective pulse frequency regulation.

Figure 3 shows the schematic setup of our EDM machine. The gap voltage is sent to the voltage comparator via a voltage attenuator and then compared to the reference voltage. When the gap voltage is smaller than the reference voltage, the output signal of the comparator drops from +5 V to 0. The voltage-drop events are counted in real time in the counter channel of the data acquisition board (PXI-6259, National Instruments). The measured pulse frequency is used as the feedback signal of the PC-based machine controller with a motion control board (PXI-7344, National Instruments). The analog input channel is used to monitor electrical shorts.

Since the discharge frequency fluctuates with high-frequency components, the moving average of the pulse frequency is used. The moving average equation is defined as

$$\bar{N}_p(t) = \left(\sum_{i=0}^{n-1} \dot{N}_p(t-i)\right) \Big/ n \qquad (1)$$

where $\bar{N}_p$ and $\dot{N}_p$ are the moving average and measured pulse frequencies, respectively. We used 10 samples per second for averaging (n = 10).

3.2 EDM Milling Control

Pulse frequency control is used to compensate the tool wear in micro-EDM milling. Regulation of the pulse frequency by controlling the vertical motion of electrode tip results in constant MRR machining along the contour path if the workpiece moves in two dimensions at a constant feedrate. Therefore, this control can effectively compensate the tool wear in-process.

Figure 4 shows the block diagram of the control loop for the micro-EDM milling process. The electrode is controlled along the vertical Z-axis at a feedrate determined by the output of PD controller corresponding to the pulse frequency error. The feedrate of electrode in milling is shown in Eq. (2):

$$f_z = (K_P + K_D s)(\dot{N}_{pr} - \bar{N}_p) \qquad (2)$$

The X- and Y-axis stages move along a predetermined path. Although the pulse frequency is controlled to maintain the gap distance, the pulse frequency itself fluctuates because of time-varying gap conditions caused by debris formation and gas bubbles.[14,15] To maintain the material removal volume constant with respect to the machined contour, the feedrate of the X- and Y-axis stages must be adjusted as shown in Eq. (3),

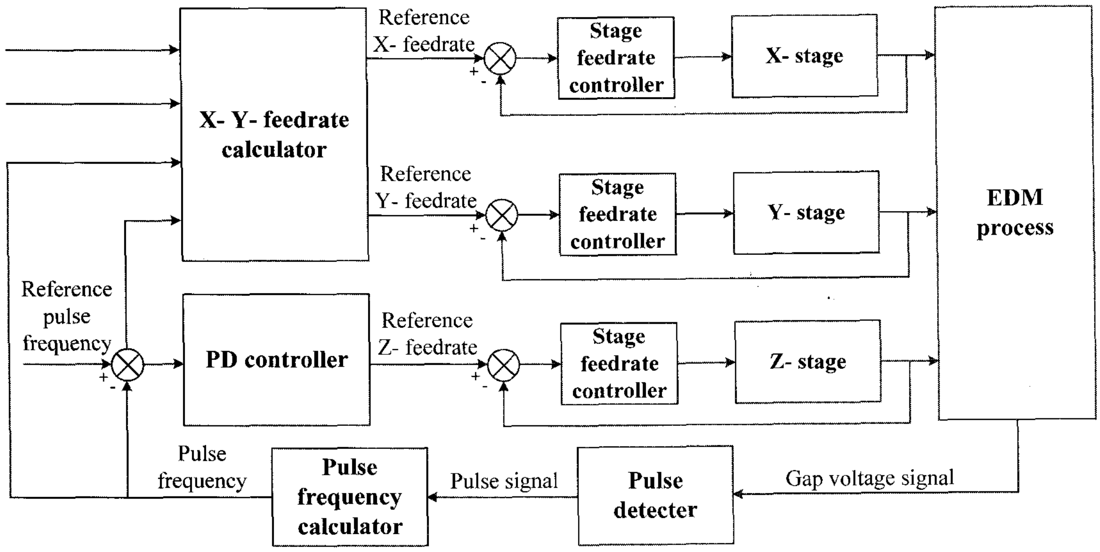


Fig. 4 Block diagram of the EDM milling control system

$$f_{x,y} = \left(\bar{N}_P / \dot{N}_{pr}\right) f_{init.x,y} \tag{3}$$

where $f_{x,y}$ and $f_{init.x,y}$ are the feedrate and initial feedrate of the X- and Y-axis stages, respectively. To test the effectiveness of the controller in reducing tool wear during milling, we used it to machine a groove 2.5 mm long, 300 μm wide, and 3.5 μm deep. Figure 5 shows the depth profiles of the groove produced by the proposed controller and a typical CNC controller. Both surfaces were generated by machining on a single unidirectional electrode path. As the figure

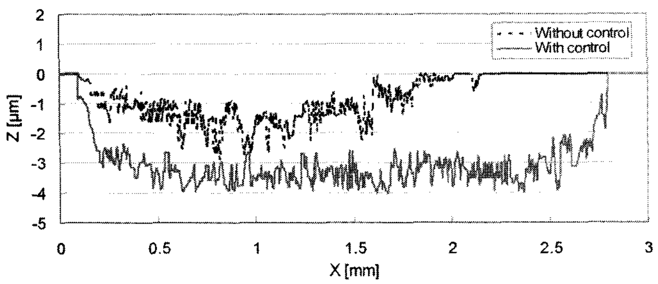


Fig. 5 Comparison of depth profiles using the proposed controller (solid line) and a typical CNC controller (dashed line)

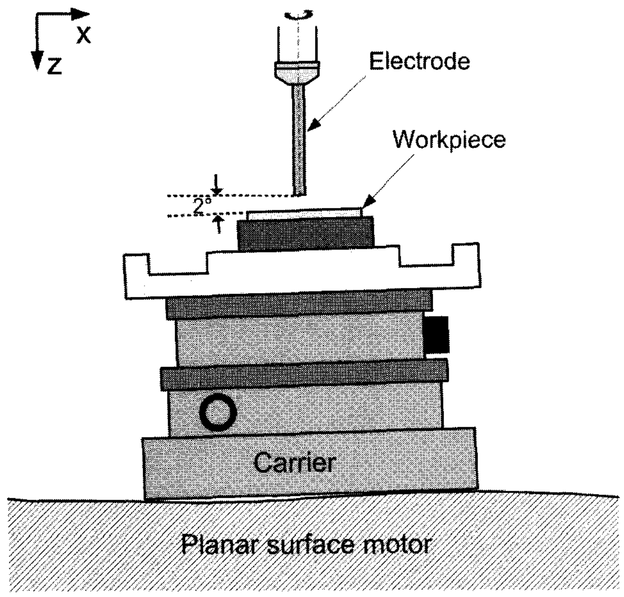


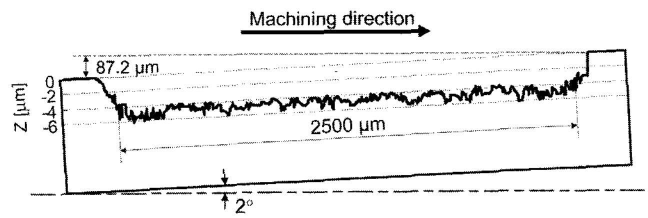
Fig. 6 Machining of the tilted workpiece

shows, when the standard CNC controller was used, only a shallow and inclined groove could be machined with limited travel. However, when the pulse frequency control was applied, a flat bottom profile was obtained without the influence of electrode wear.

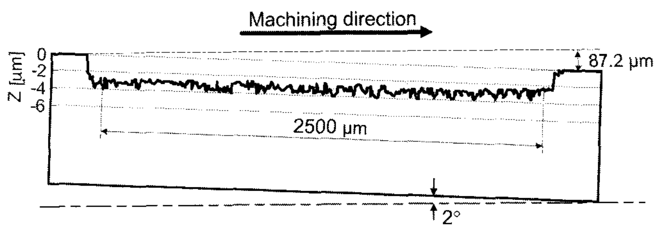
In the proposed microfactory testbed, the transfer system used a planar surface motor. Because the moving part (i.e., the carrier) of the planar motor is lifted on the stator by pneumatic pressure during the motion, the workpiece surface can be tilted after the carrier is locked into machining position.

Figure 6 shows the situation in which the carrier is locked on the tilted surface. For example, when the carrier stage is inclined with a 2° and 2.5 mm line is machined, the Z-directional height difference at each end of the groove is about 87.2 μm while the lateral (X- and Y-directional) error is only 1.5 μm.

Machining grooves is a typical process implemented in a microfactory for applications such as the creation of microchannels. However, when an inclination error exists, the regulation of the groove depth is a challenging problem because the inclination is difficult to measure. However, the pulse frequency control maintains the gap between the tool electrode and the machined surface. Therefore, it has the advantage of being able to machine an inclined surface when the machined depth needs to be maintained constant. As a result, the proposed pulse frequency control has been applied to creating a channel with uniform depth on an inclined surface.



(a) Along positive X-direction in Fig. 6



(b) Along negative X-direction in Fig. 6

Fig. 7 Profile of the machined groove by EDM milling on a tilted workpiece

Figure 7 shows the groove machining experiment results using a workpiece tilted 2° as shown in Fig. 6. The profile in Fig. 7(a) was machined following the positive X-direction in Fig. 6 while Fig. 7(b) shows the results for the opposite direction (negative X-direction). The graph demonstrates that the machined depth is maintained regardless of the inclination or tool wear. All machined profiles were measured by a white light scanning interferometry profiler (NanoScan, Nano System Co.).

4. Conclusions

In this report, we proposed a pulse frequency control approach to improve the machining accuracy of micro-EDM processes. The idea of pulse frequency control is to maintain a constant MRR by regulating the pulse generation from an RC-type EDM circuit through adjusting the gap distance between the tool electrode and the workpiece. We then applied the proposed control to regulate the pulse frequency of the EDM milling process.

The experimental results demonstrated that flat grooves could be machined without encountering the tool wear problem. The method was also applied to a microfactory test bed in which geometric errors were generated by work and tool transfer mechanisms. The experimental results of groove machining in the microfactory test bed showed that the controller performed well when the workpiece table was tilted 2°.

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