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An Experimental Study on the Improvement of Microscopic Machinability of Glass using the Discharging Peak Control Techniques in the Electrochemical Discharge Machining Technologies

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Abstract: Electrochemical discharge machining is a very recent technique for non-conducting materials such as ceramics and glasses. ECDM is conducted in the NaOH solution and the cathode electrode is separated from the solution by H_2 gas bubble. Then the discharge is appeared and the non-conductive material is removed by spark and some chemical reactions. In the ECDM technology, the H_2 bubble control is the most important factor to stabilize the discharging condition. In this paper, we proposed the discharge peak monitoring/ discharging duty feedback algorithms for the discharge stabilization and the feasibility of this algorithm is verified by various pattern machining in the constant preload conditions for the cathode electrode.

Key words: ECDM (electrochemical discharge machining), glass machining, MEMS, micro-channel

Introduction

The use of the electrochemical discharge phenomenon to machine materials is a very recent technique in the field of non-conventional machining. When the machined material is electrically conducting, the process is usually termed 'electrochemical arc machining' (ECAM), whereas for non-conducting work material is termed 'electrochemical discharge machining' (ECDM) [3].

The phenomenon of small electric discharge at the anode tip was first observed by Taylor [1] during the electrolysis of molten NaCl at high current density: he termed the phenomenon 'anode effect'. Electric discharge at the electrode has been observed to occur during electrochemical machining and under some conditions, becomes the limiting factor for the process. The idea of using such electrode discharge for machining non-conductive material is implemented by Kurafuji and Suda [2]. But the machining efficiency of the ECDM is very low and it also has a limit to the maximum machinable depth. Basak and Gosh [3,4] proposed the mathematical model of critical voltage and current for the initiation of discharge between the electrodes and electrolyte in case of the electrochemical discharge at the tip of electrode and verified them experimentally. Sorkhel [5] investigated the improvement of machinability in the machining the hard material such as ceramics by ECDM technology.

The glass, due to its transparency and its chemical resistance, is often used in MEMS technology in combination with silicon wafers that have integrated mechanics and electronics (encapsulated accelerometers, pressure devices, fluid systems, etc). ECDM is an alternative solution to the laser machining, the etching with HF or normal drilling and milling with special tools. For example, ECDM can offer good surface quality than laser machining and small structures can be obtained more esily than by etching with HF. Langen *et al.* [6] applied the ECDM technology to the 3D high aspect ratio structuring of glass, using the voice coil actuator for vertical micro-positioning.

Generally, the workpiece and electrodes are dipped under the electrolyte in ECDM procedures and the process involves a complex combination of the electrochemical reaction and electrodischarge action. The electrochemical action helps in the generation of the positively charged ionic hydrogen (H_2) bubbles. The electrical discharge action takes place between the tool and the workpiece due to the breakdown of the insulating layer of the gas bubbles as the DC power supply voltage is applied between the tool (cathode) and the anode, resulting in material removal due to melting, vapourisation of the workpiece material and mechanical erosion [4]. But Lang en *et al.* [6] shows that the chemical reaction coincides with the electrodischarge action and the chemical machining is more important than electrodischarge machining, especially in the region of micro machining.

Not only the concentration of the electrolyte and its temperature, but also the dipping depth of the workpiece and electrode is very important factor for machinability in the ECDM. During the ECDM procedure for glass material, the concentration of the glass compound (Na_2SiO_3) in the electrolyte is gradually increase and the chemical activity of the electrolyte for the glass material is deteriorated. And, the tool generates not only the hydrogen bubble but also the water vapor by the regional heating of the electrolyte around the tool and they are condensed around the tool tip. Then the water dew

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drops on the discharging region periodically and dilutes the concentration of the electrolyte that it is almost impossible to make an uniform discharging phenomena in the ECDM with dipping the tool and workpiece into the electrolyte. Furthermore, the discharging phenomena arise between the tool and hydrogen bubble that it is very important to maintain the amount and depth of the hydrogen bubble uniformly. But the bubbles climb up to the tool because of the surface tension of the bubbles and large amount of the electrolyte in the bath always fills up the evaporated moisture that it is very difficult to maintain the uniform dipping depth and of the tool in the hydrogen bubble. Therefore, it is relatively easy to apply the ECDM technology to the single point drilling, but there are a lot of difficulties to apply the technology into the structural machining.

In this paper, in order to overcome the difficulties of the ECDM technology for the uniform discharging condition, the experimental apparatus is built-up to maintain the uniform film thickness and concentration of the electrolyte. And the PWM controlled feedback algorithm for the discharging current with monitoring the voltage signals of the discharging peak is composed that the algorithm automatically decrease the duty ratio of the discharging current when the peak voltage is too high and increase when the peak voltage is low. The experimental results show that the proposed system gives uniform discharging condition that the shapes of the machined hole, channels and surfaces by ECDM are quite nice, under the constant preload condition for the tool without any feedback motion control in vertical direction.

The principles of ECDM

ECDM for ceramic material

The ECDM technology is used mainly for the machining of the hard material such as ceramics, but because of the bad machinability, the investigations for this technology is usually intended to increase the material removal rate (MRR). According to Sorkhel [5], ECDM process is influenced by various process parameters such as the applied voltage; the inter-electrode gap, the temperature, concentration and type of electrolyte; the shape, size and material of the electrodes; and the nature of the power supply, etc. But in the machining the ceramic materials, there is no chemical reactions between workpiece and electrolyte, but only the chemical reactions as follows;

- anode:
  $M \rightarrow M^+ + e^-$ (dissolution of metal ions)
  $4(OH)^- \rightarrow 2H_2O + O_2\uparrow + 4e^-$
- cathode:
  $2H_2O + 2e^- \rightarrow 2(OH)^- + H_2\uparrow$

Generally the tool is cathode that if any electrically non-conducting material is placed in the closed vincinity of the electrical discharge, material erosion takes place. This is due to the transmission of a fraction of the spark energy to the workpiece, which raises the temperature of the spot quickly to a very high value, sufficient for melting of the work material at that spot. Apart of the molten portion of the workpiece is removed from the region due to the mechanical shock resulting from sudden phase change and the electrical shock due to the discharge [4]. Therefore, we can deduce that the material removal mechanism for ECDM in ceramic material is the regional melting and the electrical shock due to the discharge.

ECDM for glass material

When the voltage is applied in the machining glass material with ECDM technology, H_2 bubbles are generated at the cathode and O_2 at the anode. The two electrodes are separated from the solution by a gas film and sparks are generated through the bubbles around the cathode. The removal of glass takes place at the cathode, where discharges appear. The erosion of the glass is not only thermal, due to the spark generation, but also chemical due to the chemical attack of the glass by the alkali solution [6].

The alkali attack is function of the pH and the temperature of the solution. The rate of alkali attack is multiplied by a factor two with an pH increase of one unit or a temperature increase of 10°C according to Mc Lellan *et al.* [7].

The etching mechanism results in a smooth surface when the dissolution of the silicate is complete, otherwise a rough surface is produced. The presence of ions like Ca^{2+}, Mg^+ and Na^+ in the composition increases also the rate of alkali attack, due to their high mobility.

The etching reaction of the glass is:

$$2NaOH + SiO_2 \rightarrow Na_2SiO_3 + H_2O$$

Therefore, in order to machining the glass material in a micro-scale, the discharging voltage should be reduced to the critical voltage of 25 V~30 V that Gosh [4] and Langen [6] have proposed, to minimize the machining effect by the discharging spark and make the etching process by NaOH reaction into the major machining mechanism.

But the general ECDM procedures are performed in the electrolyte bath and stirring the electrolyte is not easy that the concentration of Na_2SiO_3 is gradually increase around the tool (cathode) and therefore the machinability is decrease. The water vapor is generated with the hydrogen (H_2) bubbles, condensed around the tool tip and then drops on the discharging region periodically. It leads to the sudden drop of electrolyte concentration that the discharging (or bubble generation) is temporary stopped. Therefore, in order to get an uniform machinability using the ECDM technology, the electrolyte should be supplied continuously in a constant rate, remove the used electrolytes in a same manner and especially, the thickness of the electrolyte film should be maintained constantly. Also, when the discharging voltage is lowered to the critical value, the regional heating by the tool discharge and therefore the vapor generation can be minimized that the vapor concentration phenomena at the tool tip can be eliminated.

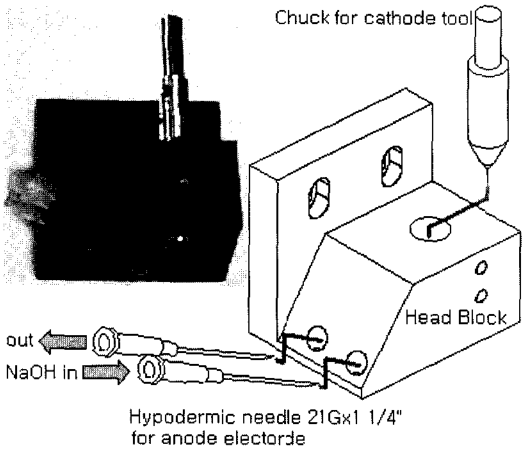

Fig. 1. Schematics of the head block and electrodes.

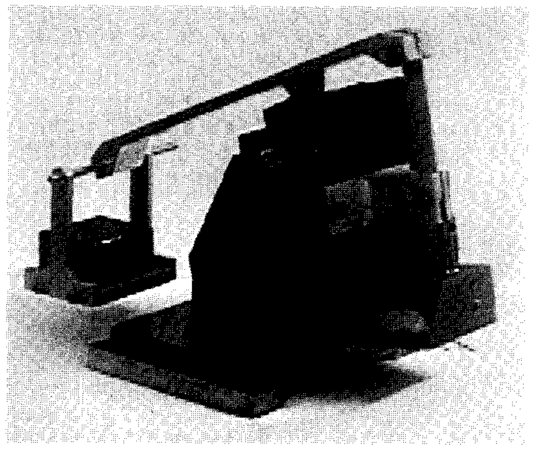

Fig. 2. The knife edged lever mechanism for constant pressure preload.

Experimental set-up

The head block for ECDM electrode and the driving mechanism

In order to maintain the uniform thickness of electrolyte film on the glass workpiece to stabilize the rate of bubble generation at the ECDM electrodes and to maintain the constant distance between the tool (cathode) and anode, the head block for electrodes is composed as shown in Fig. 1.

The head block is made of M/C nylon and the miniature type drill chuck for tool (cathode) electrode is attached vertically to the head block. The two hypodermic needles are used for anode. The two needles are assembled to the head block with an angle that the one for electrolyte feed and the other for drain. The two peristaltic pumps pumping and draining the electrolytes via silicon tube lines. The distance between the tool and needles are 5 mm each and the feeding rate of the electrolyte is 0.4 cc/min.

The head block is attached to the linear motion table, which is guided by the cross roller bearings for vertical movement. In order to investigate the effect of the stabilization of discharge peak to the machinability of glass material, the lever mechanism, which is supported by the knife type edge, is attached to the table for vertical direction as shown in Fig. 2 and the ECDM is performed with the tool press the workpiece in a constant pressure.

The bath is made of M/C nylon, which fix the workpiece and store the used electrolyte, and moved by the X-Y table system, which is driven by the stepping motors as shown in Fig. 6. The total system has no vertical motion control system except for the passive preload mechanism, but it is possible to move at any pattern in horizontal direction. Therefore, if it is not possible to generate and control the uniform discharging pattern, it is not possible also to generate the uniform machined shapes that it is possible to verify the feasibility of the discharge monitoring and PWM feedback system, which is proposed in this paper.

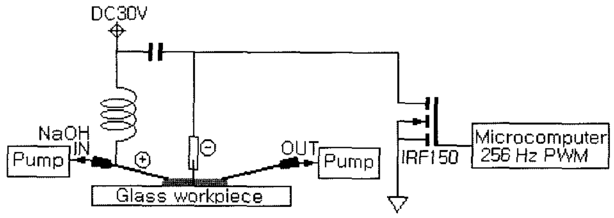

Fig. 3. The circuit diagram for the ECDM.

Electrical discharge generating/monitoring and feedback system

In order to generate the electrochemical discharge in the NaOH solution, the LC type discharging circuit, whose duty ratio of the power supplying time is controlled by the field effect transistor (FET), is composed as shown in Fig. 3.

In the LC type discharging system, the supply voltage is the critical value of 30 V to initiate the electrochemical discharge, the inductance is 4 mH, the capacitance is 156.7 (F and 15W% NaOH solution is used for the electrolyte. The LC type circuit for discharge generation is governed by the FET and its duty ratio is modulated by the microprocessor. When the FET is in OFF state, the discharge is halted and in ON state, the discharge is initiated. The continuous discharge may generates the excessive hydrogen bubbles and they climb up to the tool that discharge sparks are spread not only to the direction of workpiece but also to the directions of excessive bubbles that it is not possible to get an uniform machinability [4]. Therefore, in order to stabilize the discharging spark, DC power is supplied and blocked with a constant period to maintain the same amount of hydrogen bubble and the low frequency PWM control is efficient for this purpose that 256 Hz PWM control using the PIC16C74B microcomputer system is adopted in this paper.

In order to monitor the discharging intensity, the circuit for detecting the voltage variation of discharging peak is adopted as shown in Fig. 4. The voltage pickup location for discharging

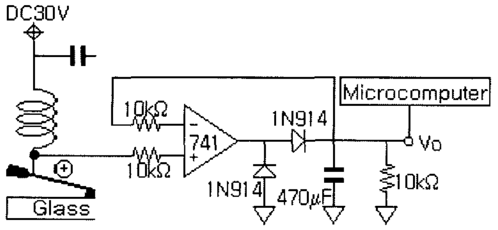

Fig. 4. Peak detector circuit for monitoring the voltage variations of the electrical discharge.

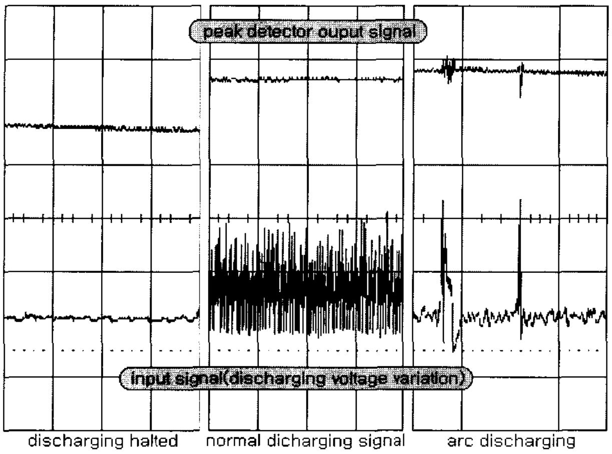

Fig. 5. Voltage variations for the discharging conditions.

peak monitoring is the needle for anode, which supplies the electrolyte.

The monitored results for the discharging voltage and its peak variations are shown in Fig. 5. The discharging is halted by the excessive NaOH solution of leak of hydrogen bubbles and the output voltage signal from the peak detection circuit is diminished. In order to re-initiate the discharge, the duty ratio of the PWM algorithm should be increased. On the contrary, the excessive hydrogen bubbles increase the erosion of electrodes and reduces the material removal rates. The experimental observation shows that the reduction of the duty ratio of the PWM algorithm makes the normal discharging conditions. Therefore, the algorithms for the duty ration modulation, based on the object value of the discharge peak voltage using the PIC16C74B is adopted.

The total system for the ECDM is shown in Fig. 6. The X-Y table, which is driven by the stepping motors, moves the workpiece, but the tool gives the constant pressure only to the workpiece in vertical direction.

Electrochemical discharge machining

ECDM drilling

In order to estimate the machining characteristics of ECDM procedure, the ECDM drilling is performed on the slide glass of 0.1 mm thickness. The ϕ0.25 mm brass wire for wire EDM is used for the drilling electrode and the electrode is rotated for 800 rpm. The workpiece and the electrode is dipped to 1 mm in the 15 W% NaOH solution and the feedback control for LC discharge is not activated during the ECDM drilling procedure. Fig. 7 shows the two different machined results.

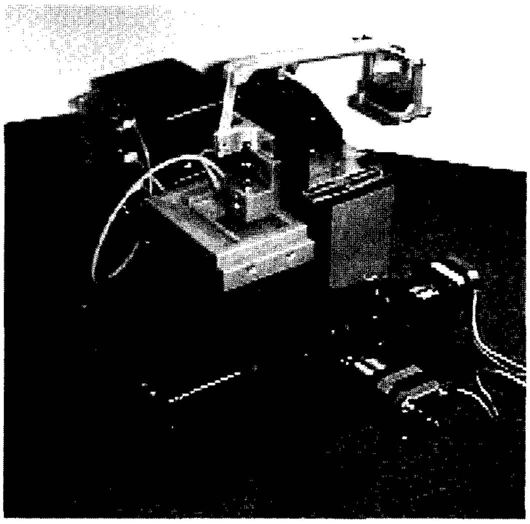

Fig. 6. Experimental set-up for ECDM patterning.

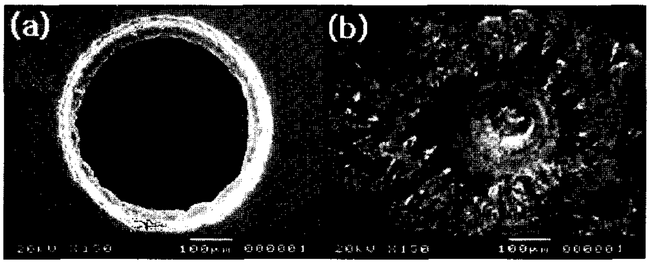

Fig. 7. The two different machined results for the same condition.

Without the discharging peak voltage monitoring and feedback control algorithms, the lack of hydrogen bubbles induce the regional ark discharging and the discharged sparks spread explosively that the machined surface is very rough and has cloudy shapes as shoun in Fig. 7 (b). But, if proper amounts of the hydrogen bubbles are maintained, it is possible to drilling to the glass material with using the ECDM technology as shown in Fig. 7 (a).

ECDM pattern machining

The various patterns of line are machined using a discharging peak voltage variation monitoring and PWM feedback algorithm. The X-Y table, which is driven by the stepping motors of 10 μm/pulse resolution and supported by linear guide systems, moves the workpiece and the feed rate is 10 μm/2 sec in each direction. The Fig. 8(a) and its magnified shapes of (b) are the case of 50 grams preload. In this case, the contact force between the tool and glass material is not enough during the ECDM procedure that the scallop appears to the machining direction. Increase the preload to 200 grams and the increase of the contact force improve the quality of the machined surface as shown in Fig. 8 (c) and (d).

Figure 9 shows the machined results for the 2-dimensional

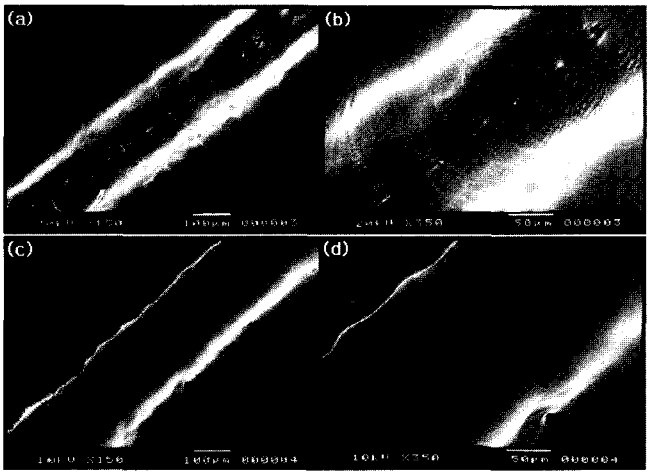

Fig. 8. The micro-channel machined on a glass.

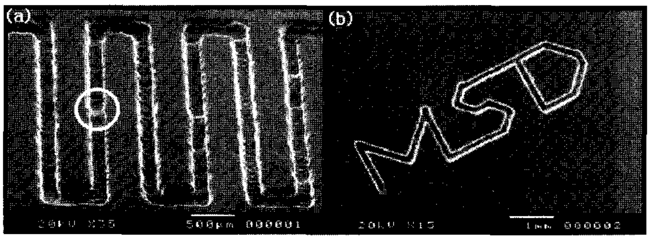

Fig. 9. The patterns machined on the glass.

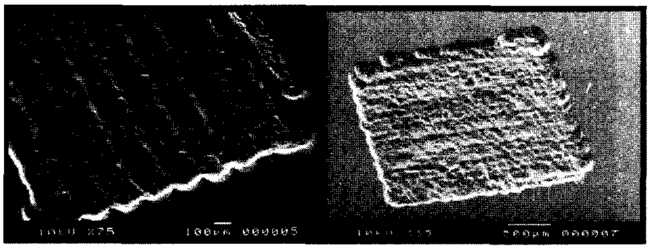

Fig. 10. ECDM milling for glass material.

micro-channel patterns. In the circle of the Fig. 9 (a), the discharging is interrupted for a moment during the ECDM procedures that the machining is not sufficient. The few more insufficiently machined places are found in the channel, but almost all the channel is machined very nice, even without the vertical motion control. Sudden extinction of the hydrogen bubble or, excessive/lack of the NaOH solution results the insufficient machining and it is possible to catch up the situation by the discharging peak voltage monitoring technology. At present, the algorithms of stop or slow down the feed rate, when the sudden discharging halt phenomena happens, are under investigation.

Figure 10 shows the machined result for 2-dimensional milling with ECDM technology. The machining is performed for the 2000 $\mu m \times 2000$ μm region by feeding speed of 10 μm/pulse-2sec and 100 mm span. The machined surfaces are relatively rough because of the various reasons. But this machining is performed only with the preloaded conditions for vertical direction that if the active position control algorithm is adopted in vertical direction, it is possible to improve the surface roughness and the shape completeness.

Conclusion

The usage of the glass material is gradually increased in the field of MEMS because of its chemical and biological stability. The ECDM technology is compatible for glass machining that it can be a solution for machining the various shapes on glass. But the discharging phenomena in ECDM is governed by the hydrogen bubbles, which is generated around the tool electrode, that it is very difficult to manage the stable discharging conditions. In this paper, in order to get the stable discharging conditions, the discharging peak voltage is monitored and the duty ratio of the discharging power is modulated by PWM. In order to verify the feasibility of the proposed discharging stabilizer system, various 2-dimensional machining are performed with constant preload condition, without any vertical motion control. The machined results shows that the machining conditions can be uniformed with the proposed system.

Future works

The proposed system can give the stabilized discharging conditions in ECDM procedures that if the active motion control system for the vertical direction is adapted in this system, the improvement of the machining characteristics is expected. At present, active tool electrode positioning system, with an eddy current type displacement transducer and a voice coil actuator, is developed and investigation for the improvement of machining characteristics is under going. It is expected to machining the 3-dimentional structures and micro channel for fluidics by ECDM technology with using the active controlled system for vertical direction.

Acknowledgments

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Appendix

The properties of the glass are as follows;

Coe. of thermal expansion: (20-300°C) × $10^{6(K-1)}$ = 8.69
Transformation temperature : 525~530°C
Density: 2.47 gram/cm^3
Chemical composition:

SiO_2	72.8~73.0%
Na_2O	14.6~14.8%
K_2O	0.7~0.8%
CaO	5.8~6.0%
MgO	3.9~4.1%
Al_2O_3	1.3~1.4%
Fe_2O_3	0.045~0.047%