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Hybrid Micromachining of Glass Using ECDM and Micro Grinding

Xuan Doan Cao[1], Bo Hyun Kim[2,#], and Chong Nam Chu[1]

1 School of Mechanical and Aerospace Engineering, Seoul National University, Gwanak 599 Gwanak-ro, Gwanak-gu, Seoul, Korea, 151-742
2 Department of Mechanical Engineering, Soongsil University, 511 Sangdo-dong, Dongjak-gu, Seoul, Korea, 156-743
Corresponding Author / E-mail: bhkim@ssu.ac.kr, TEL: +82-2-820-0653, FAX: +82-2-887-7259

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Micro electrochemical discharge machining (ECDM) is a well-known machining process that achieves 3D micro structures in glass-type material. However, a rough surface is the main disadvantage of this process. In the present work, a hybrid process of ECDM and micro grinding using polycrystalline diamond (PCD)tools is investigated. Micro structures in glass workpieces were machined by ECDM and then ground by PCD tools to improve the surface quality. Micro grinding by PCD tools is used to overcome the rough surfaces that are generated by sparks in ECDM. The characteristics of micro grinding, such as the surface roughness of the tool, depth of cut, and feedrate, using PCD tools for ECDM structures were investigated. It is experimentally shown that the grinding process under PCD tools reduces the surface roughness of ECDM structures from a few tens of a μm to 0.05 μm R_a, and the total machining time of the hybrid process is less than a third compared to that under a conventional grinding process.

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1. Introduction

Micromachining has become an important technology for fabricating micro structures. For micromachining of metals, electrochemical machining (ECM) and electrical discharge machining (EDM) have been developed for several decades.[1] These methods can machine micro structures on various materials.[2-4] However, a drawback is that only conductive materials can be machined by these methods whereas structures made of non-conductive materials are widely preferred in MEMS devices, micro analysis, systems and micro fluidic devices. Thus, the micromachining of non-conductive materials, especially glass, has been intensively investigated. Laser beam machining is used to machine a wide range of materials including non-conductive materials, but the main disadvantages are low energy efficiency and a converging-diverging shape of beams.[5] Chemical etching technologies are limited by a slow etch rate; only structures with low aspect ratios can be fabricated. Moreover, the formation of pinholes in masks is an unavoidable problem.[6] Powder blasting is also applied for machining glass.[7] Nevertheless, it has its own limitations such as low surface quality, low aspect ratios, and inflexibility in fabricating complicated structures.

Electrochemical discharge machining (ECDM) is an efficient process for machining glass.[8] By controlling tool paths, various 3D structures have been machined by ECDM in glass.[9] In ECDM, the machined surfaces are covered with many craters that are created by the resolidification of glass. Generally, the surface roughness is a few tens of a micrometer.[10] Moreover, the rims and edges of ECDM structures are rounded due to the thermal effect of sparks. To overcome the drawbacks of ECDM, in the present work, the grinding of ECDM structures using polycrystalline diamond (PCD) tools is undertaken. PCD, which consists of micro-sized diamond grits sintered together with cobalt under high temperature and pressure, is well known as a material for hard cutting tools. Kuljanic et al. used a PCD tool to machine titanium alloy compressor blades and Morehead et al. investigated the machinability of ultra-grained copper using PCD tools.[11,12] PCD is also popularly used in machining brittle materials.[13,14] Suzuki et al. used a micro PCD milling tool shaped by wire electrical discharge machining (WEDM) to machine aspherical ceramic molds with a surface roughness, R_z, of 15 nm.[15] Morgan et al. machined micro grooves and micro pockets in glass using PCD tools that were shaped by EDM.[16] High accuracy and surface qualitywere obtained. However, the material removal rate was quite smallbecause the axial depth of cut of each layer was only 100 nm for ductile regime grinding.

The present work details a hybrid machining process that can combine the advantage of ECDM, viz., a high removal rate, and the advantage of grinding using PCD tools, namely, a high surface quality. The concept of this hybrid process is shown in Fig. 1. Micro structures were first machined

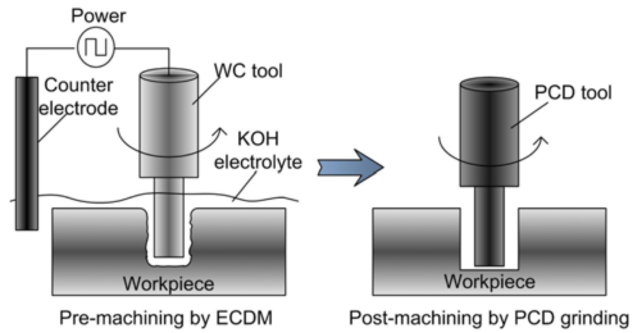

Fig. 1 Concept of the hybrid machining process

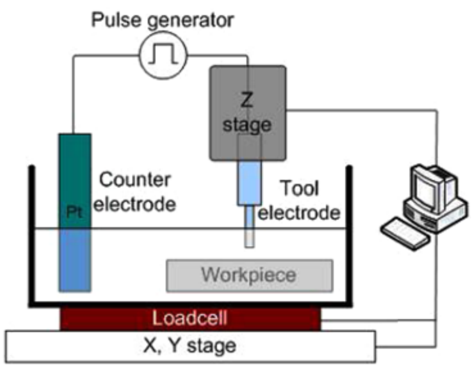

Fig. 2 Experimental system for the hybrid process of micro ECDM and PCD grinding

in soda lime glass workpieces by ECDM. This pre-machining step is used to machine a structure with a high material removal rate. Subsequently, the ECDM structure is ground by a micro PCD tool in a post-machining step that can enable a high surface quality. Consequently, the hybrid process can reduce the total machining time while maintaining the surface quality obtained by PCD grinding.The grinding conditions were investigated to reduce the machining time and improve the surface quality.

2. Experimental Details

The experimental equipment for ECDM and PCD grinding is shown in Fig. 2. The X-Y-Z stages were controlled to a resolution of 0.1 μm by using step motors and linear scale encoders. The rotational speed was set to 5000 rpm for all experiments in PCD grinding. A glass workpiece, a counter electrode, and a tool electrode were immerged in the electrolyte during the ECDM process. The workpiece was a soda lime glass plate with a thickness of 150 μm. At the anode, to prevent the oxidation of the electrode, an electrochemically stable material, platinum (Pt) was used for the counter electrode. During the ECDM process, pulse voltagesare applied between the cathode and the anode, which are immersed in a KOH electrolyte. The machining conditions of the ECDM process include a tool with a diameter of 40 μm, KOH of 30 %wt, pulse voltage of 23 V, pulse on/off-time of 1 ms/1ms, rotational speed of 300 rpm, and feedrate of 3 μm/s.[10] Then, the tungsten carbide (WC) tool is replaced by a PCD tool for the grinding process. PCD shafts are cut from a PCD blank (IPOL-series, ILJIN Diamond Inc.), which has a PCD layer with a thickness of 1 mm bonded on a substrate ofWC by WEDM and then machined to micro tools.[17] The

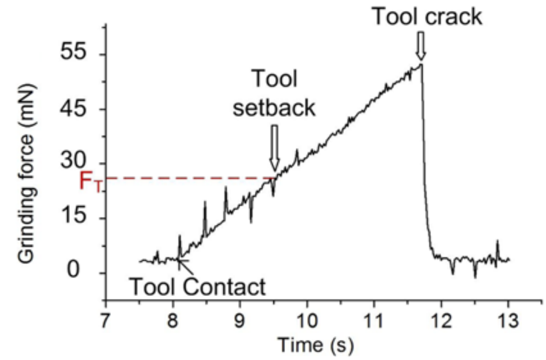

Fig. 3 Setback point and crack point of the micro PCD tool

volumetric ratio of diamond in PCD is 90% and the average diamond grit size is 10 μm. To avoid misalignment due to the re-clamping of workpieces, the ECDM process and the PCD grinding process were performed in the same worktable. Only the WC tool used in ECDM was replaced by a PCD tool for grinding. Because the mandrels that held the tools were mounted onto a V-shaped bearing mechanism, they were easily exchanged without rotational run-out.[1] Under the working tank, two sensitive load-cells were installed to monitor the grinding forces, as shown in Fig. 2. The observation of the grinding forces prevents breakage of the tool. As shown in Fig. 3, a PCD tool of diameter 60 μm and length 200 μm is not broken if the tangential grinding force, F_t, is smaller than around 50 mN. To protect the tool, the threshold force, F_T, was set to 25 mN. If F_t was greater than F_T, the tool fed backwards by 1 μm at a feedrate of 0.5 μm/s. The backward tool feed is called a setback.And then the tool fed forwards again. Consequently, the prevention of tool breakage was ensured. Moreover, the limitation on the grinding force guaranteed the ductile mode of grinding. Previous studies showed that cracks may be avoided if the grinding force, which corresponds to the material removal rate, is smaller than a critical value.[18,19] An investigation of the critical conditions for the brittle-ductile transition of brittle materials, which is not included in this work, can be examined inother report.[20] In Fig. 4, ECDM grooves ground by PCD tools without controlling F_t (Fig. 4b) and with controlling F_t (Fig. 4c) are compared with each other. The other grinding conditions were a PCD tool of 70 μm diameter and 100 μm length, feedrate of 0.75 μm/s, radial depth of cut of 10 μm, length of groove of 200 μm, and F_T of 25 mN. Groove 1 was machined under the brittle mode. Because of the lack of force control in grinding groove 1, the grinding force, F_t, was higher than the critical value and brittle-mode grinding occurred. On the contrary, in grinding groove 2, F_t could not be higher than F_T, which was smaller than the critical force; therefore, groove 2 was machined under the ductile mode. This result shows when the grinding force, F_t, is smaller than the threshold value of 25 mN, the protection of the PCD tool is ensured and cracks in the workpiece are prevented.

3. Results and Discussion

3.1 Machining PCD and the effect of the PCD tool roughness on ground surfaces

Since PCD is one of the hardest materials, EDM is the most effective method for machining it. PCD shafts were machined to micro

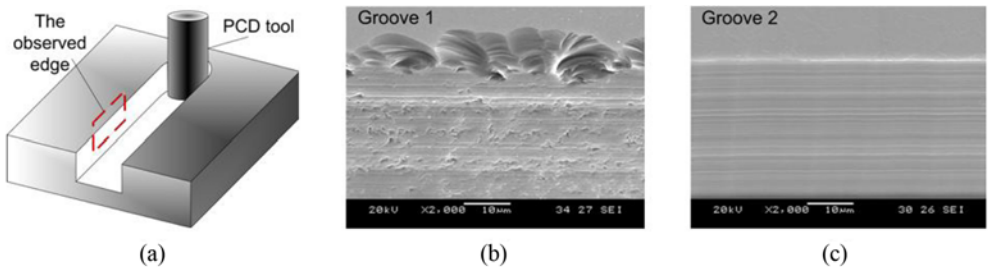

Fig. 4 (a) The observed edge of the ECDM groove machined (b) without controlling the grinding force and (c) with controlling the grinding force

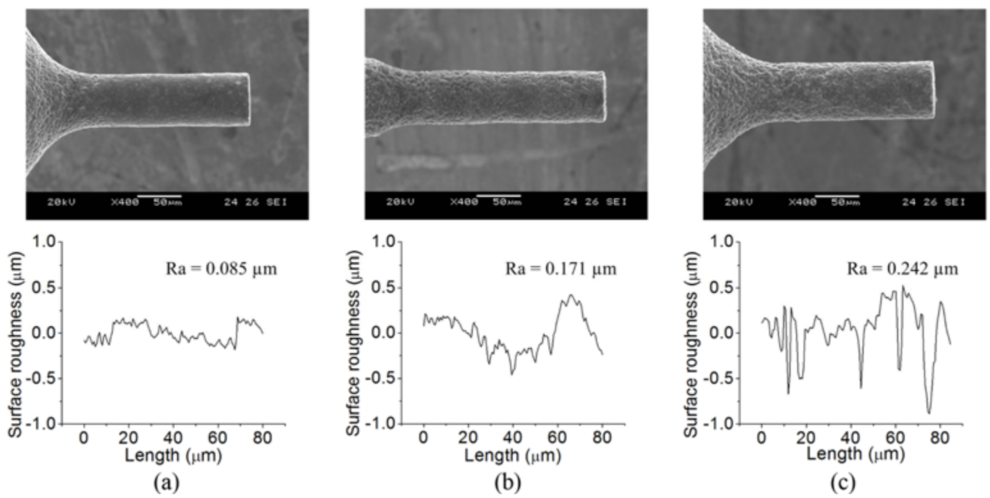

Fig. 5 Micro tools machined by WEDG under capacitances of (a) 400 pF, (b) 5000 pF and (c) 10000 pF

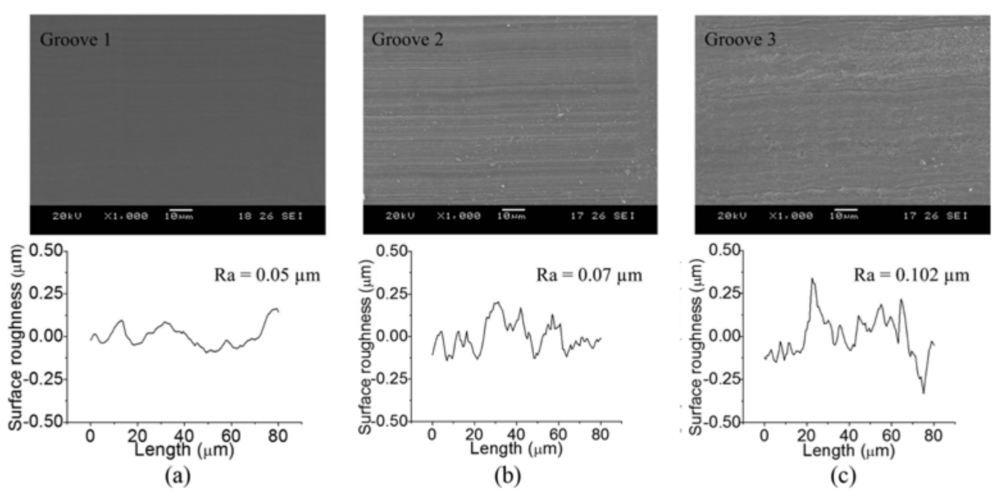

Fig. 6 Groove surfaces ground by the tools of (a) 0.085 μm R_a, (b) 0.171 μm R_a and (c) 0.242 μm R_a

tools with a diameter of 60 μm in two steps, a rough-cut step and a finish-cut step by wire electrical discharge grinding (WEDG).[1,3] The applied voltage was 100 V in both steps.A capacitance of 100 nF in the EDM circuit was used in the rough-cut step and it was varied in the finish-cut step to investigate the effect on the surface roughness of the tool and ground structures. In Fig. 5, tools machined with capacitances of 400 pF, 5000 pF, and 10000 pF in the finish-cut step are shown respectively. The surface roughness of the tool rises as the capacitance increases. As the capacitance increases, sparks are more intensive and larger craters are generated on the surface of the tool. The smallest surface roughness of the three, 0.085 μm, was obtained by using a capacitance of 400 pF.

These tools were used to grind ECD Med grooves to test the effect of tool roughness on the ground structures. The grooves were machined in soda lime glass with a depth of 50 μm. The machining conditions for grinding three grooves were a radial depth of cut of 5 μm and feedrate of 0.75 μm/s. Fig. 6 shows the ground surfaces of the grooves. The respective values of the surface roughness, R_a, were 0.05 μm, 0.07 μm, and 0.102 μm. In the grinding process, the surface quality is significantly dependent on the tool surface. The tool used in grinding groove 1 has a smaller surface roughness; hence, the surface quality of groove 1 is better than that of either groove 2 or groove 3.

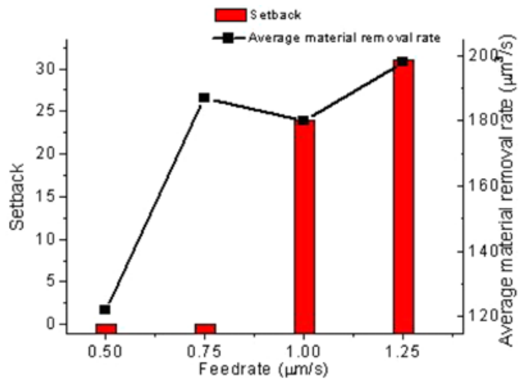

Fig. 7 The number of setbacks and the average material removal rate according to the feedrate

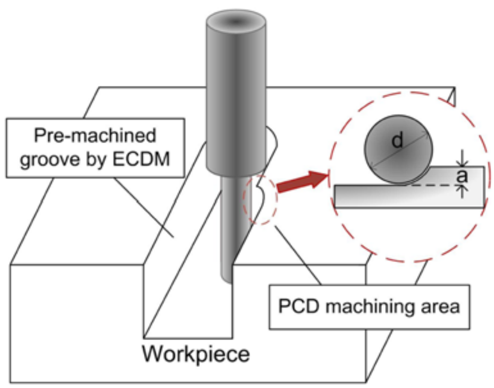

Fig. 8 The radial depth of cut in micro PCD grinding of glass (d: tool diameter, a: radial depth of cut)

3.2 Effect of the feedrate

In conventional grinding of glass, the grinding process should be performed under a slow feedrate and small radial depth of cut to obtain a crack-free surface. Thus, the material removal rate (MRR) for high-quality structures is small. In this part of the study, the machining feedrate was studied to increase the MRR. The feedrate was varied from 0.5 μm/s to 1.25 μm/s. ECDM grooves with a depth of 50 μm, and length of 200 μm were ground by a PCD tool with a diameter of 60 μm that was shaped by WEDG with a capacitance of 400 pF. The other machining conditions involve an F_T of 25 mN and radial depth of cut of 5 μm. Fig. 7 shows the effect of the feedrate on the average MRR (defined by the total material removal volume divided by the total machining time) and the number of setbacks. When the feedrate is higher than 0.75 μm/s, the number of setbacks increases rapidly with the feedrate, while the average material removal rate does not vary considerably. Basically, grinding forces are composed of chip formation forces and friction forces. The tangential grinding force, F_t, can be expressed as a function of the workpiece feed (feedrate), the rotational speed of tool and the radial depth of cut.[21,22] It was shown that F_t is proportional to the feedrate; therefore, F_t increases through the increase in the feedrate. At feedrates of 0.5 μm/s and 0.75 μm/s, F_t is still smaller than F_T; hence, setbacks do not occur. At feedrates higher than 0.75 μm/s, setbacks occur occasionally because F_t exceeds F_T. The higher is the feedrate, the greater is the occurrence of setbacks. Setbacks should be avoided because they cause a varying force to be applied to the

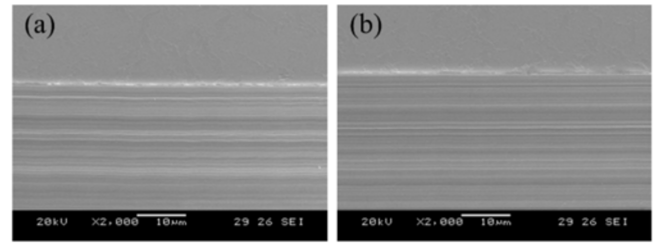

Fig. 9 Micro grooves machined under the ductile mode with a depth of cut of (a) 7.5 μm and (b) 10 μm and a feedrate of 0.75 μm/s

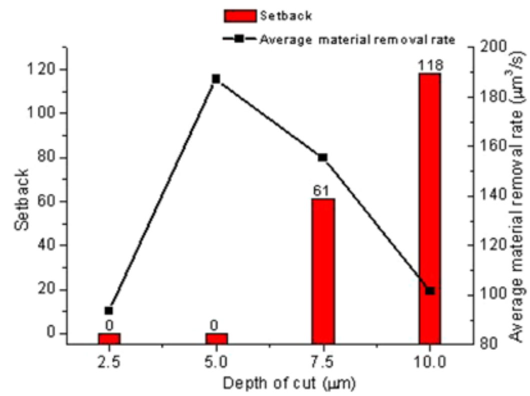

Fig. 10 Number of setbacks and the average material removal rate according to the radial depth of cut

tool, which is harmful to the tool and causes an unstable grinding process. Accordingly, a feedrate of 0.75 μm/s was used in subsequent experiments.

3.3 Effect of theradial depth of cut

In conventional grinding, the radial depth of cut (‘a’ in Fig. 8), together with the feedrate, is the factor that mainly affects the MRR. In the grinding of glass, if the radial depth of cut is too great, the removal rate is greater than the critical rate at which ductile mode grinding cannot materialize, and high-quality surfaces cannot be obtained. In this controlled-force grinding process, F_t is constrained to be smaller than F_T to ensure that ductile-mode grinding occurs even at a great radial depth of cut, as shown in Fig. 9. However, the machining time increases through the increase in the radial depth of cut. Experiments were conducted in this part of the study to investigate the effect of the radial depth of cut on the average MRR and the number of setbacks by which the MRR is improved. ECDM grooves with a length of 200 μm were ground by a PCD tool at a feedrate of 0.75 μm/s in the post-machining step. The grinding process was carried out with four different radial depths of cut: 2.5 μm, 5 μm, 7 μm and 10 μm. The average MRR and the number of setbacks according to the radial depth of cut were recorded and are shown in Fig. 10. The number of setbacks in the figure indicates that the grinding force is smaller than F_T if the radial depth of cut does not exceed 5 μm. It is higher than F_T and setbacks happen more frequently in the latter two cases because the grinding force increases through the increase in the radial depth of cut.[19] With a radial depth of cut of 5 μm, the great MRR was achieved. Accordingly, theradial depth of cut was set to 5 μm in the post-machining step.

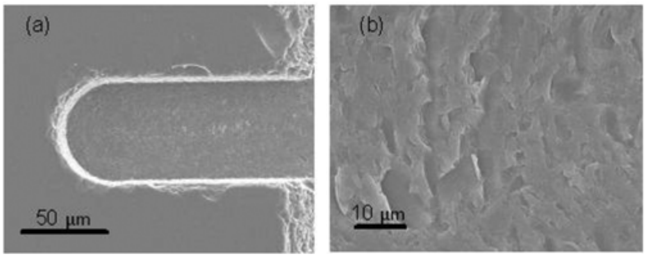

Fig. 11 (a) Micro groove machined only by micro grinding and (b) brittle fracture in the groove bottom

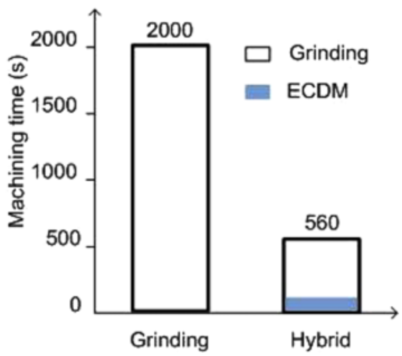

Fig. 12 Machining time for conventional grinding and the hybrid process

3.4 Machining efficiency

To evaluate the efficiencies of the hybrid process of ECDM and PCD grinding, grooves of 150 μm length and 50 μm depth were machined by two processes, the hybrid process and the micro grinding process by a PCD tool. The machining conditions of the conventional grinding process were an axial depth of cut of 5 μm, feedrate of 0.75 μm/s, and rotational speed of 5000 rpm. Accordingly, the process took 200 seconds to machine one layer. Ten layers were ground by a layer-by-layer process. Consequently, the total machining time was 2000 seconds. Although a slow feedrate and a small axial depth of cut were applied, the crack was not prevented as show in Fig. 11. In the hybrid process, an ECDM groove of 50 μm depth was machined; then, PCD grinding was performed to obtain the fine surface quality. This process took only 100 s for ECDM and 60 s to exchange and reposition the PCD tool. It took 400 s to grind two sides of ECDM groove by PCD tool. Fig. 12 shows the machining time comparison of conventional grinding and the hybrid process. The machining time in the hybrid process was considerably lower compared to that under the grinding. Moreover, the better surface quality was also achieved by the hybrid process.

3.5 Machining examples

Fig. 13(a) shows a groove in a soda lime glass workpiece machined by ECDM under the conditions mentioned in Section 2. The groove was machined by a layer-by-layer process; each layer was 25 μm. Fig. 13(b) shows the groove after the post-machining step under PCD grinding. Similarly, Fig. 13(c) shows a micro column machined by ECDM and Fig. 13(d) shows the micro column after the post-machining step. Sharp edges were obtained and the surface roughness was considerably reduced after the PCD grinding process. These examples show that this hybrid micromachining process can be applicable in the fabrication of complicated structures with high quality in glass material.

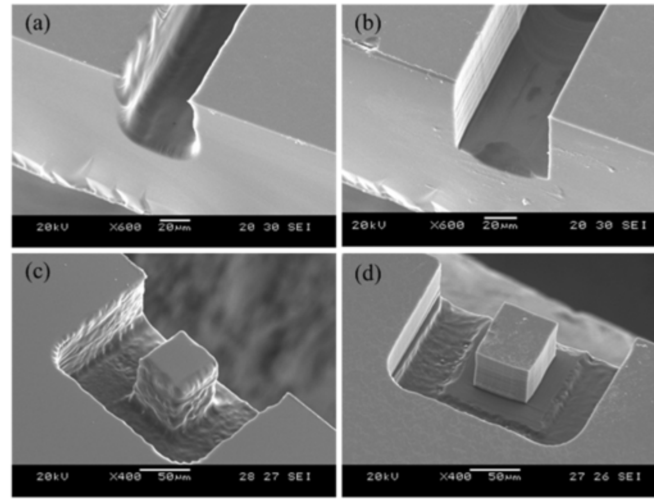

Fig. 13 Micro structures machined by (a,c) ECDM and (b,d) then ground by a PCD tool

4. Conclusions

The investigation presented in this paper has demonstrated the characteristics that affect the quality and efficiency of the machining of micro structures in glass by a hybrid process of ECDM and micro grinding using PCD tools. The results show that 3D micro structures with high surface quality in glass can be machined efficiently by combining ECDM and PCD grinding. The total machining time for micro grooves of 50 μm depth under the hybrid process was less than 30% of that under the conventional grinding process, while abetter ground surface quality was achieved.

The use of a load-cell system to monitor the grinding force prevents breakage of the micro tool and guarantees ductile-mode grinding of the glass material. The suitable machining conditions for the post-machining step, viz., a feedrate of 0.75 μm/s and radial depth of cut of 5 μm, ensure that the machining time is short. A surface roughness, R_a, of 0.05 μm can be achieved by grinding using PCD tools of 10 μm grit size machined by WEDG under the conditions of a capacitance of 400 pF and voltage of 100 V. In addition, sharp rims and edges can be obtained after grinding by PCD tools. Some examples show the feasibility of this hybrid process for machining crack-free and good surface structures in glass material.

ACKNOWLEDGEMENT

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