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Fabrication of Micro-Hole Array on Glass Material by Abrasive Jet Machining

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Abstract. Brittle materials such as glasses, silicon, and silicon carbide are normally categorized as difficult to machine materials for its high hardness and brittleness. However, they have attracted more and more attentions and been playing critical roles in many scientific/engineering applications for their advanced physic/optical/electronic properties. Micro-patterns such as micro-holes (array) of various sizes and shapes are frequently required to be generated on brittle materials. Many researchers have tried different approaches such as laser ablation, ultrasonic machining, and rotary ultrasonic machining to produce micro-holes in brittle materials. This research applied abrasive jet machining to fabricate micro-holes array on glass. Efforts have been made to investigate the effect of grit-size, stand-off distance, pressure on the material removal rate and the obtained holes accuracy. Micro-hole arrays of various shapes and with characteristic dimension ranging from 0.2 mm to 2 mm are successfully produced in glass plate of 0.4 mm thickness.

1. Introduction

As the demands for machining micro holes/patterns in brittle materials are steadily increasing, many attempts have been conducted by applying various machining techniques such as laser ablation, ultrasonic machining, rotary ultrasonic machining, chemical etching, focus ion beam and abrasive jet machining. Laser ablation is a very versatile technique and has the advantage of fast machining a wide range of materials[1-3]. However, the melt ejection, re-deposited debris, micro-cracks generated by the heat and thermal stress involved in the machining process frequently make the surface quality and holes accuracy unacceptable. Although short wavelength or pulse duration such as femtosecond laser can minimize the photo-thermal effect, it is, in many cases, just too expensive to be economically viable. Ultrasonic machining is considered to be a relatively effective way to generate micro-holes in brittle materials [4,5] but the cost for making the ultrasonic tools can be very expensive. In comparison to laser ablation and ultrasonic machining, abrasive jet machining is a much cheaper and effective way to produce micro holes/patterns in brittle materials[6-10]. Unlike conventional sand blasting which is mainly used for cleaning, abrasive jet machining is frequently used to cut complicated shapes in brittle materials. A summary of the pros and cons of frequently used micro hole-drilling processes are listed in Table 1.

This research applied abrasive jet machining to fabricate micro-holes array on glass. Efforts have been made to investigate the effect of grit-size, stand-off distance, pressure on the material removal rate and the obtained holes accuracy.

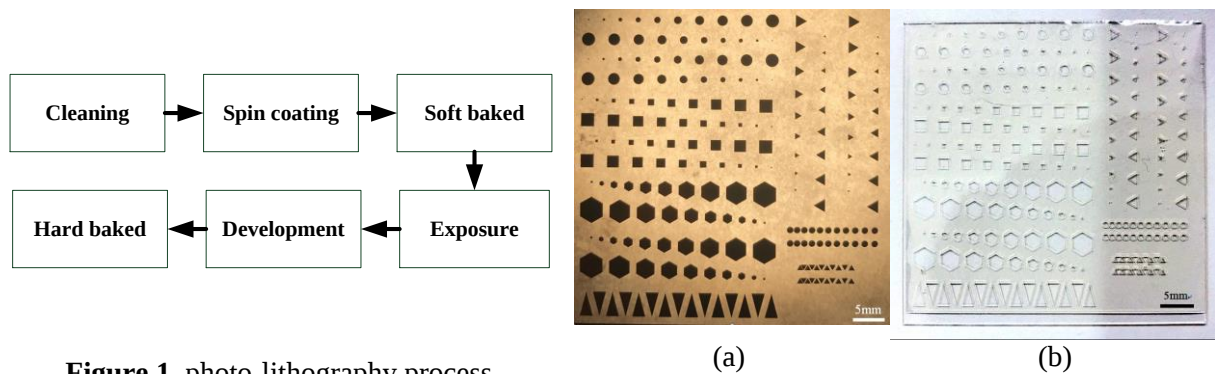


Table 1. Summary of the pros and cons of frequently used micro hole-drilling processes

	Wet Chemical Etching	Dry Etching	EDM	Laser drilling	Ultrasonic machining	AJM
Pros	1. Cheap 2. Almost no mechanical damage	1. Avoid dangerous acids and solvents 2. Use a small amount of chemicals 3. High resolution and cleanliness 4. Less undercuts 5. Easy to automate	1. Can machining hard materials to very tight tolerances. 2. Non-contact process 3. Surface finish is good 4. Small hole down to micrometers scale can be easily drilled	1. Non-contact 2. High aspect ratio possible. 3. Holes at shallow angles. 4. Drilling of difficult to process materials 5. High process speed good dimensional accuracy.	1. Produces very little heat 2. Various hole shape due to the vibrator motion of the tool 3. Relatively high MRR	1. Low cost 2. High productivity 3. Very suitable for machining brittle, and heat resistant materials. 4. Can effectively produce complex hole shapes
Cons	1. Undercut due to isotropic etching 2. Process control is critical (temperature sensitivity) 3. High chemical disposal costs 4. Environmental pollution	1. Some gases used are quite toxic and corrosive 2. Re-deposition of non-volatile compounds 3. Expensive equipment	1. Small material removal rate 2. Conductive materials only 3. Reproducing sharp corners on the work piece is difficult due to electrode wear. 4. Over cut	1. Expensive equipment. 2. HAZ (Heat affected zone) 3. Melt ejection and debris	1. High tool wear 2. Sub-surface damage (micro-cracks) 3. Difficult to machine deep holes 4. Limitations in productivity	1. Taper in the obtained holes 2. Dust collection 3. Abrasive particles are embedded in the working surface.

2. Experimental Setup

A photo-mask was fabricated based on the designed hole patterns and was used to transfer those patterns to the mask material via photo-lithography process (Figure 1) before abrasive jet machining could get started. Shown in Fig. 2(a) and Fig. 2(b) are the optical-mask used in this study and the glass substrate with patterned mask respectively. Corning glass wafer SGW3 (Alkaline Earth Boro-Aluminosilicate) with Young's modulus of 73.6 (GPa), density of 2.38 (g/cm³), Vickers hardness of 640 (kgf/mm²) [11] and thickness of 0.4 mm was used in this study as the workpiece material.

**Figure 1.** photo-lithography process**Figure 2.** (a) Optical Mask and (b) glass substrate with patterned mask (SU-8)

A negative photoresist SU-8 was selected as the mask material for its good adhesion properties, easy processing and reasonable erosion durability. Alumina powder with grain size of 31-26 μm (WA320) and 22-18 μm (WA400) was used as abrasive and the machining parameters were listed in Table 2. The machined specimens were examined by optical microscope and a laser confocal microscope for holes shapes, erosion depth and sidewall taper angle (Figure 3).

Table 2. Process parameters for abrasive jet machining

Nozzle diameter (mm)	8
Abrasive	Al ₂ O ₃ #320 (26-31 μm) and #400 (18-22 μm)
Air pressure (MPa)	0.05, 0.1, 0.15....0.5
Stand-off-distance (mm)	2.5, 5, 10, 15, 20, 25, 30, 35, 40, 50, 60, 70
Mask patterns	Round, Square, Triangle (30°, 60°, 75°, 90°, 120°) Spacing (mm): 0.2, 0.25, 0.3.... 0.5
Scanning passes	160, 200, 240
Machining duration (sec)	20, 40, 60, 80

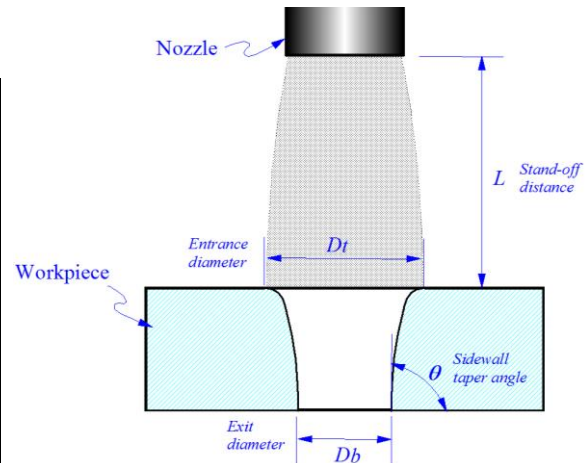


Figure 3. Schematic representation of the abrasive jet machining (without using mask)

3. Results and Discussions

Apart from hole shapes and sizes, the influences of machining parameters such as stand-off distance, air pressure, grit size, scanning speed/passes on the achieved material removal rate, sidewall taper angle and holes accuracy (as defined in Figure 4) were studied and the results were listed below.

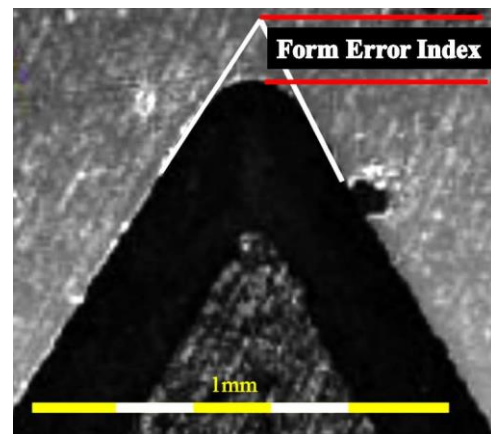
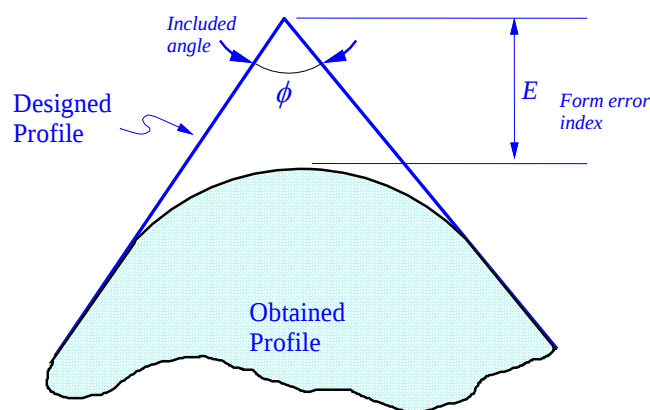


Figure 4. Form Error Index

3.1. Air Pressure

Shown in Figure 5 are the erosion depth under different air pressures. The stand-off distance and machining duration was 35 mm and 40 sec respectively. When pressure is under 0.2 MPa, the erosion depth increases slowly with increasing pressure. The increase rate reaches a stable value when pressure is between 0.2 to 0.35 MPa, and gradually declines when further increasing air pressure. Little change in erosion depth can be made when air pressure gets beyond 0.5 MPa. Air pressure is fixed at 0.5 MPa in most of the tests conducted in this study.

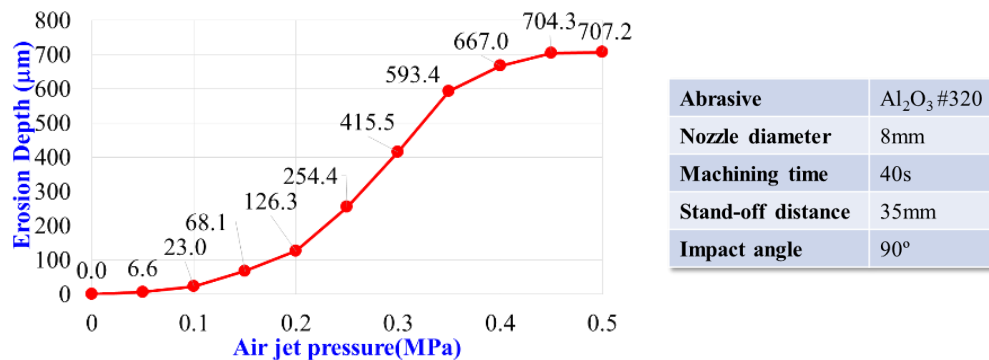


Figure 5 Air pressure vs. Penetration depth

3.2. Stand-off Distance

A series of abrasive jet machining tests with stand-off distance ranged from 2.5 mm to 30 mm were carried out without using mask just to investigate the influence of standoff distance on the obtained erosion depth and shape of the crater. The measured profiles of the machined craters were shown in Figure 6. The air pressure and machining duration was 0.4 MPa and 8 sec respectively. It is worth noting here that the profile of the generated craters gradually change from an “U” shape to a “V” shape as the erosion gets deeper. Thus, the sidewall taper angle gets smaller as the erosion depth gets higher. Owing to the divergent nature of abrasive jet, the entrance diameter increases with stand-off distance. Mask is a necessity in abrasive jet machining if effective control of dimension accuracy is required.

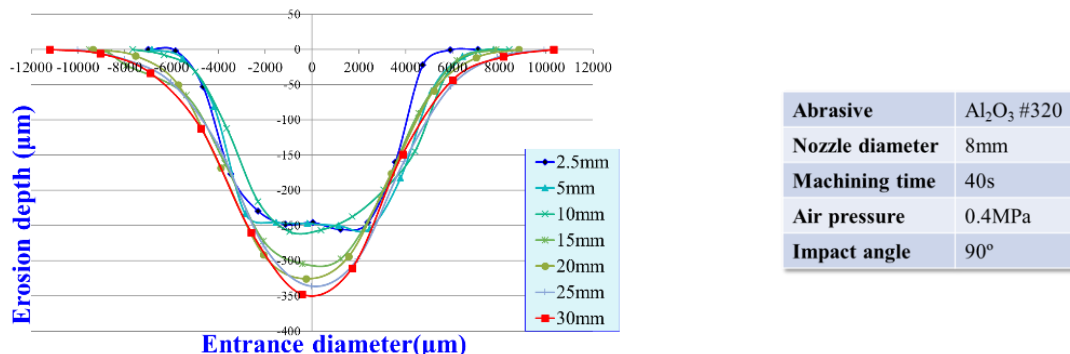


Figure 6 Erosion depth with different Stand-off distances

With air pressure and machining duration fixed at 0.4 MPa and 40 sec respectively, the material removal and erosion depth obtained by setting up various nozzle standoff distances are shown in Fig. 7.

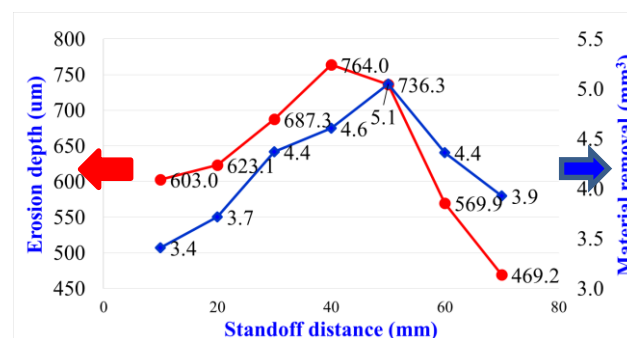
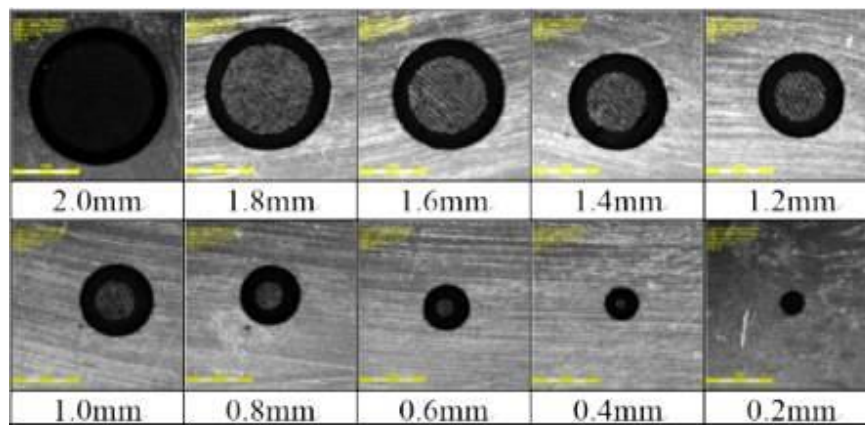


Figure 7 Material removal /Penetration depth vs. Stand-off distance

The erosion depth reaches its peak (764 μm) and 2nd highest (736 μm) when standoff distance equals to 40 mm and 50 mm respectively. The difference is less than 4%. The material removal reaches its peak (5.1 mm³) and 2nd highest (4.6 mm³) when standoff distance equals to 50 mm and 40 mm respectively. The difference is almost 10%. Standoff distance is then fixed at 50 mm in most of the tests conducted in this study.

3.3. Other Machining Parameters and Shape Effect.

Shown in Figure 8 are the optical micrographs of the obtained round holes with WA320 abrasive, 0.5 MPa, 50 mm stand-off distance and 160 passes at a scanning speed of 16.7 mm/sec. The measured sidewall taper angle of specimens machined with different scanning speeds are plotted against various designed hole sizes and shown in Figure 9. In comparison to small holes, big holes have deeper erosion depth and sidewall profile is more bias to a “V” shape than those obtained in small holes. Thus, small holes have higher sidewall taper angle than big holes, as shown clearly in this figure. Although scanning speed does not show too much influence on the sidewall taper angle at the hole with diameters ≥ 1.2 mm, it does have some effects on the smaller holes.



[Process parameter: WA320 abrasive, 0.5 MPa, 50 mm stand-off distance and 160 passes at a scanning speed of 16.7 mm/sec]

Figure 8. Optical micrographs of the obtained round holes.

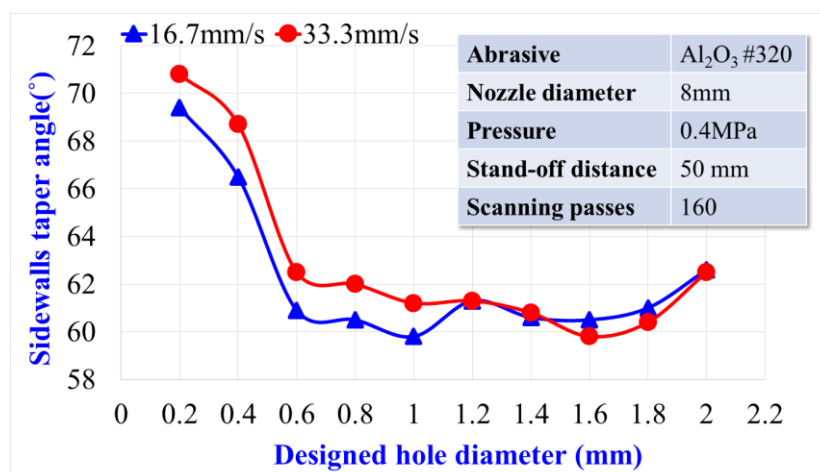


Figure 9. Sidewall taper angle vs. hole diameter at various scanning speeds

To study the influence of abrasive size and included angle on the achieved sidewall taper angle and form accuracy, triangular holes with various included angle are machined by WA320 and WA400 alumina abrasives and the result is shown in Figure 10.

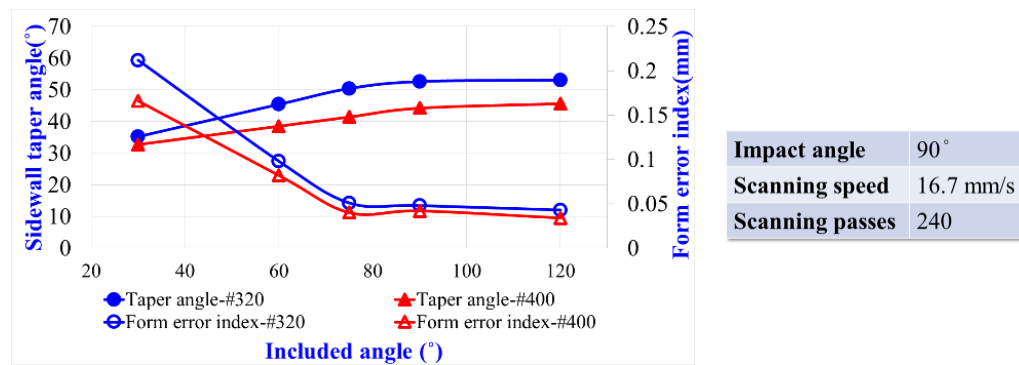


Figure 10. Influence of abrasive size and included angle on the achieved sidewall taper angle and form accuracy

It gets more and more difficult for abrasive particles to crush into the tip area when the included angle gets smaller. As a result, the form error index gets higher as the included angle gets smaller. Since finer abrasives have better chances to “cut” into the tip area, the smaller the abrasive gets the higher form accuracy (less form error) it can achieve.

In comparison to fine abrasive, coarse abrasive have deeper erosion depth and sidewall profile is more bias to a “V” shape than those generated by fine abrasive. Thus, fine abrasive generates higher sidewall taper angle than those generated by coarse abrasive, as shown clearly in this figure.

Since how narrow a spacing can be achieved in abrasive jet machining is an indicator for deciding how closely a holes array be arranged. Round (1 mm) and triangle (1 mm length) holes of various spacing were machined for 160 passes at 16.7 mm/sec scanning speed. The optical micrographs of the holes arrays and the measured spacing are shown in Fig. 11 and 12. The difference between designed and obtained spacing increases with increasing designed spacing. No matter it's a round hole or triangle holes array. However, if the differences (errors) are represented in error percentage $[(\text{designed}-\text{obtained})/\text{designed} * 100\%]$, as shown in Fig. 13, it is obvious that error percentage decreases with increasing designed spacing.

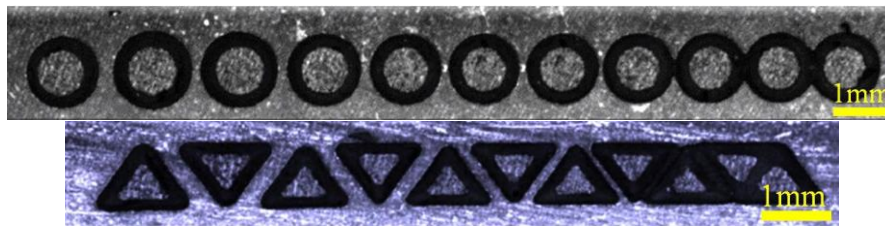
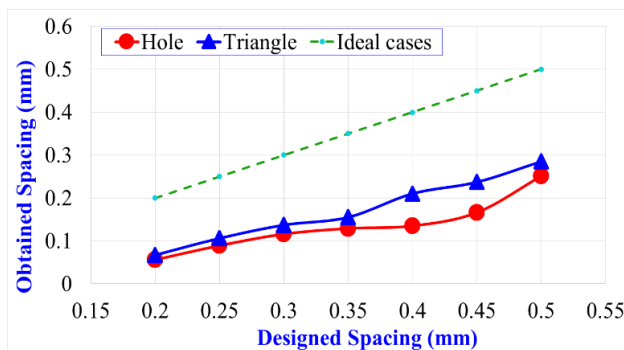


Figure 11. Optical micrographs of the obtained holes arrays



Abrasive	Al ₂ O ₃ #320
Nozzle diameter	8mm
Pressure	0.4MPa
Stand-off distance	50 mm
Scanning speed	160 passes @ 16.7 mm/s

Figure 12. The obtained hole spacing plotted against designed hole spacing

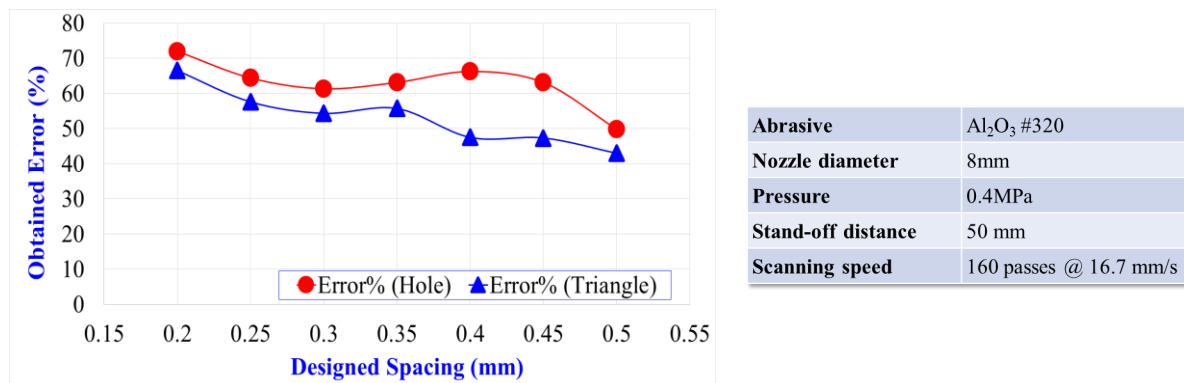


Figure 13. Error percentage decreases with increasing designed spacing

4. Conclusion

To conclude, when generating micro-holes on glass by abrasive jet, parameters such as grit-size, stand-off distance and pressure all have profound effects on the achievable material removal rate and the obtained holes accuracy. Since finer abrasives have better chances to “cut” into the tip area, the smaller the abrasive gets the higher form accuracy it can achieve. In comparison to fine abrasive, coarse abrasive have deeper erosion depth and sidewall profile is more bias to a “V” shape than those generated by fine abrasive. Thus, fine abrasive generates higher sidewall taper angle than those generated by coarse abrasive. Under the same machining conditions, big holes have deeper erosion depth than small hole and sidewall is more bias to form a “V” shape profile than those obtained in small holes. Thus, small holes have higher sidewall taper angle than big holes. As the included angle gets smaller, it’s getting more and more difficult for abrasive particles to crush into the tip area. As a result, the form error gets higher as the included angle gets smaller. Based on these results, a “hybrid process” that is applying coarse abrasive first for high material removal and followed by fine abrasive to improve form accuracy should be a very promising way to strike a balance between efficiency and accuracy.

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