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Study on the Application of Electrode Control Aided Electrochemical Discharge Drilling Method in Transparent Brittle Materials

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Keywords： electrochemical discharge machining, transparent hard and brittle material, Polarity reverse machining, digital image processing.

ABSTRACT

The Electrochemical Discharge Machining is a kind of innovative machining method newly developed for processing the non-conductive brittle materials. To enhance the machining efficiency and optimize the drilling depth, normally the voltage or the electrolyte concentration increasing method is applied. However, excessively high voltage and electrolyte concentration are the main reasons causing the over-cutting, heat-affected area expansion and cavities as to degrade the quality. Therefore, the graphic and current monitoring approaches are used in the online-aided machining system during the research to achieve the parameter-based real-time feedback and adjustment effect. To support the glazing system, the cumulative extent of bubbles and the electrode features are observed to determine the appropriate timing for performing the polarity switching; further, the current values are also controlled to minimize the glass shattering effect when passing through the conveying hole. The polarity switching result indicated that this research can reduce 22.84% of front-side cavity overcut and 36.73% of through-hole overcut. In heat-affected area, 41.99% can be reduced for part of front-side heat-affected area; whereas, 24.4% can be reduced for the through-hole heat-affected area. Regarding the sapphire machining, the current-responsive inching control method was applied that the electrolyte at the electrolyte tip can be renewed as to minimize the influence resulting from electrolyte degradation while limiting the discharge of current. In view of this, the machining work can be performed under higher level of voltage without damaging the electrode. Furthermore, multiple pieces of electrodes are also used in this research for easier replacement as to stabilize the electrode material. Finally, during the composite control aided machining, we have achieved 184.06 μm maximum depth which represents 61.67% more of drilling depth when compared to the uncontrolled machining result.

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INTRODUCTION

Nowadays, the advanced non-conductive materials such as quartz glass and sapphire are provided with excellent tensile strength, higher abrasion resistance, higher hardness, transparency and high-temperature stability and they are widely applied by all kinds of technological industries. The glass products are popularly applied by the semiconductor, microfluidic devices, communication instruments, national defense- related high-accuracy measuring instruments, nuclear energy industry and nano industry. Although sapphire is used in fabricating the handsel tablet, wristwatch mirror and lens set, it would also be hard for the machining due to its material characteristics.

In modern industries, the following machining methods are normally used for processing the brittle materials: Electric discharge machining, electrochemical machining, laser processing, chemical etching, casting, grinding and ultrasonic processing. However, a certain extent of barrier still exists for these machining methods where the electric discharge machining method and electrochemical machining cannot be applied in processing the non-conductive materials; the laser processing method would cause glass cracking and the cutting face coarseness issues (Tu, 2010); the Chemical etching method would be too slow in machining speed (Huang, 2009); the ultrasonic processing and grinding methods would usually result in the surface breaking of the brittle materials (Lin, 2010); and the casting method is not suitable for fabricating micro-based structure and the dimensions are inaccurate as well. In view of this, the highly efficient electrochemical discharge machining (briefed as ECDM) method is an innovative method very suitable for processing the non-conductive brittle materials. Furthermore, the ECDM method is also suitable for carrying out faster micro-based processing for quartz glass and sapphire.

In spite of the aforesaid characteristics and advantages achieved by ECDM Method, however, the ECDM also has its own problems that should be dealt with. For example, the heat-affected area during the drilling, the hole-expansion issues at the inlet and outlet, the cracking at the outlet hole due to the presence of sudden high-current discharging, the lower working efficiency when cutting deeper during the micro-based processing, and the slower machining speed when compared to other working method. Due to these reasons, the machining industry in modern days is still reluctant to use the ECDM Method for dealing with the non-conductive brittle materials.

To resolve the aforesaid issues, many scholars proposed the tentative solutions through their researches. For example, the use of varied power parameters (Kim et al., 2006, Zheng et al., 2008), the application of different electrolytic solutions and electrolyte concentration (Yang et al., 2006, Bhuyan et al., 2014, Sabahi et al., 2018, Varghese et al., 2018), the change of properties and the shape of the processed electrode (Zheng, et al., 2007, Yang et al., 2011), the use of electrode rotation (Gautam et al, 1998, Wüthrich, et al., 2006) as the support, the use of air (stream) injection, and applying varied polarities on the processed electrodes (Wu et al. 2017, Chen et al, 2018) in the hope of enhancing the machining efficiency and the working quality. However, the online monitoring feedback system is rarely used in most of the aforesaid methods to improve the defect of lower repeatability as found in the ECDM method. Furthermore, the aforesaid methods tend to fix the machining electrode as negative or positive in which, the polarity switching approach is rarely used in the machining in order to bring out the results for discussion.

The purposes of this research are described as follow:

1. Enhancing the working quality and the machining efficiency by the ECDM method.
2. Creating the online visual and current monitoring feedback system.
3. Execute the study according to the result and data acquired from the experiment.

GLASS MACHING SYSTEM DESING

Glass is not only one of the materials that can be easily acquired and convenient for machining but is also the material frequently seen in our daily life. In most of the researches, quartz is frequently used as the material for the machining. As such, one of the key points of this research would be the optimization of the glazing result through the electrochemical discharge machining. In Fig. 1, the glass machining system is mainly divided into two sectors. The first is the camera image processing procedure (industrial camera) in order to determine the electrode machining status and if the polarity reverse kind of machining is being executed. The second sector is the current control procedure (DC Analyzer) where the feedback current signal is used to determine the electrochemical discharge status in order to set up the current limit.

Polarity Reverse Machining

Two kinds of electrode reverse positions are attempted in this research. During the first attempt, the anodic processing method is applied for conducting the polarity reverse when the conical electrode approaches the glass surface with the maximum diameter and then the cathodic processing is applied for attempting the polarity reverse again when the electrode is about to pierce through the glass surface (as per Fig. 2). Such supporting method is called as the longer reverse aided machining. The reversing position of the second attempt is similar to the first attempt where the first round of reverse time is the same as the first attempt, but the polarity reverse is attempted at the second reversing position when the electrode is piercing through the glass with maximum diameter (per Fig. 3). Such kind of aided machining is called as the shorter reverse aided machining.

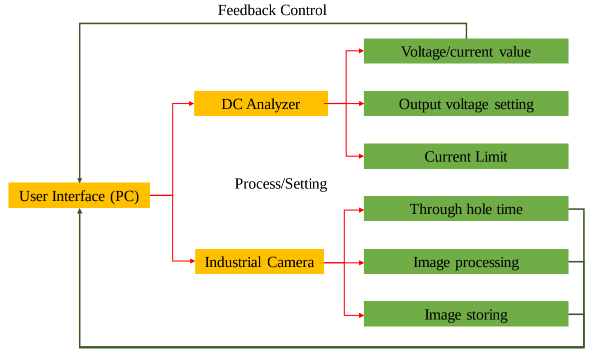

Fig. 1. Glass Machining System Flow Chart.

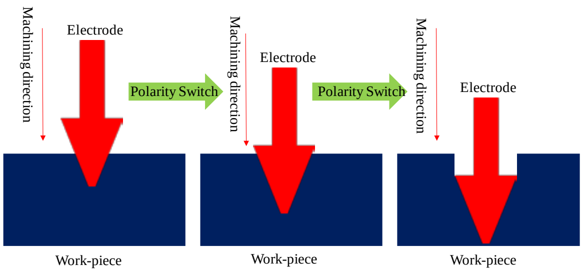

Fig. 2. Longer Reverse Polarity Position Switching Schematic.

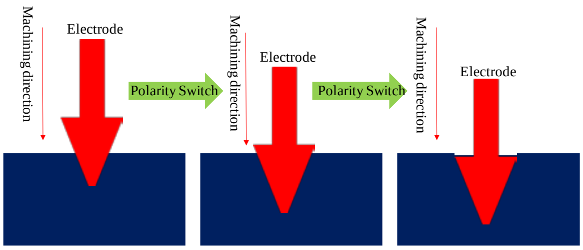

Fig. 3. Shorter Reverse Polarity Position Switching

Schematic.

Current monitoring and Control Method

Based on the varied setup parameters mentioned in Wüthrich et al., 2019, the current limit and the voltage limit would be different and such variation would happen to the stabilized discharge current in the discharge area. According to the voltage limit set for the conducted experiment, it is between 28 V and 30 V and the current limit is between 1.8 A and 2 A. When configuring the instrument required for the research, the current values are acquired for drafting the chart as shown in Fig. 4. After learning the figures from the statistical chart, we have the calculated current count as shown in the Fig. 5.

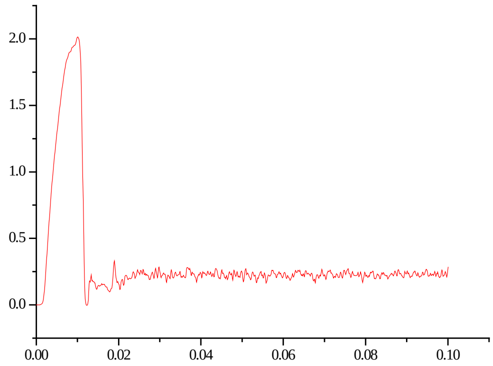

Fig. 4. In-process Current Response Chart (at 1.024 ms of sampling frequency).

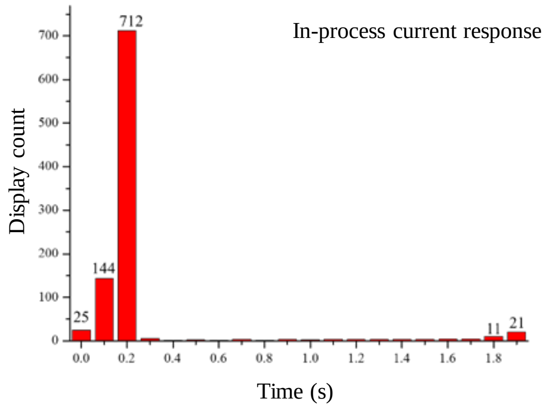

Fig. 5. In-process current response statistical chart.

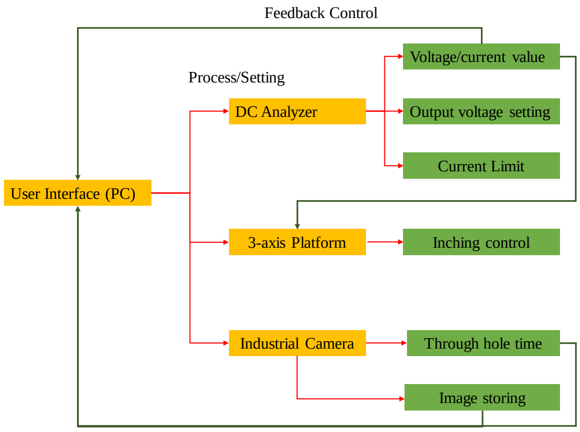

Fig. 6. Sapphire machining system flow chart.

SAPPHIRE MACHING SYSTEM DESING

When processing the sapphire with electrochemical discharge machining method, because the sapphire tends to exhibit much higher melting point and boiling point than the glass, extremely slow material removing speed would occur during the sapphire machining process. Therefore, the plasma temperature will be applied during the discharge process only in order to melt and remove these materials. For this reason, it would be impossible to use the positive pole as the electrode during the sapphire machining process.

PerFig. 6, the Sapphire Machining System comprises mainly two sectors. The first sector is the movement control procedure (control platform) in which, the inching distance is controlled with the current feedback in order to replenish the electrolyte remaining in the hole and to improve the electrolyte degradation problem. The second sector is the current control procedure (DC Analyzer). This sector uses the current feedback signal to determine the status of the electrochemical discharge machine in order to set up the current limit. In the meantime, the height of the inching control area is used to observe the current change and then feed the data back to PC.

The electrode changing experiment is conducted by changing the electrode when working until the certain time and then the experiment figures are used for comparison and discussion. It is because of the figures proposed by our previous research Ho et al., 2019 in claiming that the compositions forming the electrode surface will change after conducting the electrochemical discharge machining on the electrode (per Table 1 and Table 2). In result, the content of tungsten (W) in the electrode will reduce from 81.72% to 11.89%, with 8% of potasium (K) presented on the electrode surface in the meantime. The change of electrode properties may lead to a less discharge phenomenon or non-discharge phomenon in some areas. Therefore, this research expects that the same compositions will be maintained in the electrode during the machining process in order to increase the working rate and the working depth.

Table 1. Content of Elements in the Compositions of EDS Surface Sampling Area (used electrode)

El	AN	Series	Net	unn. C [wt.%]	norm. C [wt.%]	Atom. C [at.%]	Error [wt.%]
Si	14	K-series	0	0.00	0.00	0.01	0.0
K	19	K-series	102	1.65	4.46	8.00	0.2
Cr	24	K-series	145	6.07	16.40	22.13	0.6
Co	27	L-series	1650	18.15	49.03	58.38	3.6
W	74	M-series	723	11.14	30.10	11.49	0.7
			Total:	37.02	100.00	100.00	

Table 2. Content of Elements in the Compositions of EDS Surface Sampling Area (used electrode)

El	AN	Series	Net	unn. C [wt.%]	norm. C [wt.%]	Atom. C [at.%]	Error [wt.%]
Si	14	K-series	0	0.00	0.00	0.01	0.0
Cr	24	K-series	119	0.61	1.29	3.98	0.1
Co	27	K-series	345	2.56	5.42	14.74	0.2
W	74	L-series	1557	44.07	93.29	81.27	2.1
			Total:	47.24	100.00	100.00	

Inching Machining Method

Due to higher difficulty in performing the sapphire machining, the hole overcut amount will be smaller than that of glass. With the overcut improved, it would also be impossible to replenish and change the electrolyte in these holes. For this reason, the inching method is applied to heighten the electrode; thus, allowing the electrolyte outside the hole flow into the hole for carrying out the replenishing. The conventional inching control is performing the movement by moving the fixed interval. In this research configuration, the gravity feeding method is applied to perform the machining. When applying the gravity feeding, it would be impossible to confirm the exact heightening distance due to pre-stress reason and the moving distance will be reduced along with the depth after certain period of machining time. On account of this, it would be difficult to use conventional inching control method in the Gravity Feeding System.

The results of this research indicated that the current response shown below will occur when the electrode is ascending gradually during the electrochemical discharge machining process. Per Fig. 7, a higher current value emerges within a certain period of time as soon as the electrode leaves the workpiece surface. When the electrode keeps ascending, the current will reduce along with the shrinking of electrode surface area size in the electrolyte. This is because the total current value will be reduced along with the shrinking of the electrode surface area size when the current density remains unchanged.

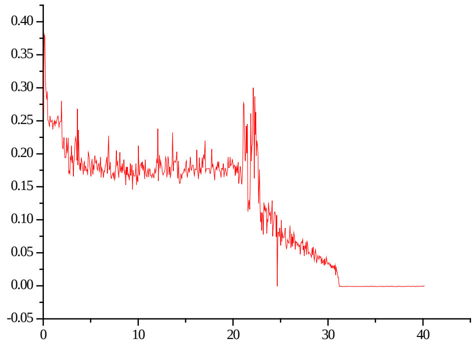

Fig. 7. Electrode ascending-related current response chart.

Based on the previous description, it is learned that the electrode will resume the machining speed due to the replenishment of the electrolyte after leaving the glass and then it will return to the original position to proceed with the machining task. Because most of the replenished electrolyte will be expelled from the hole by the electrode, the electrolyte tends to present very quick degradation speed because the electrolyte cannot be entirely replenished. Another reason is that the electrochemical discharge machining is a kind of unstable working method that has led to inconsistent electrolyte degrading speeds after completing each round of inching movement. As such, it will present varied effective machining time after each inching movement as to reduce the machining efficiency. For this reason, we hoped that the electrode will not return to its original position after the inching movement, but will be located at 10μm to 20 μm from the working position.

When applying in the Gravity Feeding System, the innovative inching control method will encounter ordinary inching control problems and the glass would be deformed when sustaining the force resulting from gravity feeding (per the Fig. 8). Therefore, this research assumes the inching ascending distance as a fixed height in order to maintain identical distance with the machining point when each inching movement reaches its highest point. In this way, the ascended electrode may lower down to 10 μm ~ 20 μm before the machining point to realize the innovative inching control.

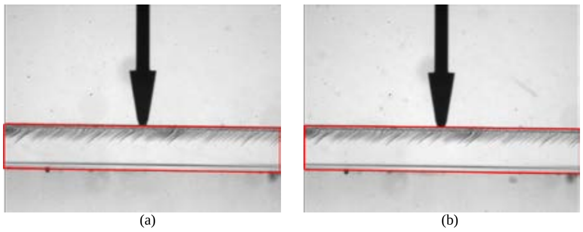

Fig. 8. Gravity feeding pre-stress related deformation: (a) with pre-stress; (b) without pre-stress.

RESULT AND DISCUSSION

Based on the applied machining system, the experiment will be conducted for a glass machining system and sapphire machining system and the result is analyzed and discussed. In the glass machining system, 50 V of voltage and 5M concentration of KOH electrolyte are used; whereas in sapphire system, 60 V of voltage and 5M concentration of KOH electrolyte are used.

Glass Machining Results

In this research, the following machining methods are applied for summarizing and discussing the glass machining result and they are aid-free, current control aided together with two types of polarity reverse composite current control aided methods. This section will discuss the inlet hole result, outlet hole result, machining time and electrode consumption, and experiment parameters are indicated in Table 3.

Table 3. Glass machining experiment parameter table.

Working voltage	50 V	Electrolyte soaking depth	0.8 mm
Type of electrolyte	KOH	Electrolyte concentration	5 M
Workpiece	Quartz glass	Electrode pre-stress depth	1.5 mm
Electrode rotation speed	300 rpm		

Inlet Hole Results for Glass Machining

The radius of the machining hole inlet and that of the thermal affected area for the aforesaid 4 kinds of machining methods are measured. The figures are collected for calculating the thermal area size and the hole overcut amount as shown in the following Table 4, Table 5, Table 6 and Table 7.

Table 4. Non-aided Machining Inlet Hole Experiment Result

Experiment Count	Hole Radius (μm)	Overcut Amount (μm)	Thermal affected radius (μm)	Thermal affected area size (mm^2)
1	291.5	91.5	436.0	0.330
2	341.0	141.0	493.0	0.398
3	315.0	115.0	486.5	0.432
Avg. value	315.8	115.8	471.8	0.387
Deviation	24.8	24.8	31.2	0.052

Table 5. Current Control-Aided Machining Inlet Hole Experiment Result

Experiment Count	Hole Radius (μm)	Overcut Amount (μm)	Thermal affected radius (μm)	Thermal affected area size (mm^2)
1	290.5	90.5	454.5	0.384
2	300.5	100.5	428.5	0.293
3	285.0	85.0	427.0	0.317
Avg. value	292.0	92.0	436.7	0.331
Deviation	7.9	7.9	15.5	0.047

Table 6. Longer Reverse Composite Current Control- Aided Machining Inlet Hole Experiment Results

Experiment Count	Hole Radius (μm)	Overcut Amount (μm)	Thermal affected radius (μm)	Thermal affected area size (mm^2)
1	308.5	108.5	422.0	0.260
2	279.0	79.0	366.5	0.177
3	312.0	112.0	430.5	0.276
Avg. value	266.5	66.5	323.5	0.106
Deviation	291.5	91.5	385.6	0.205

Table 7. Shorter Reverse Composite Current Control- Aided Machining Inlet Hole Experiment Results

Experiment Count	Hole Radius (μm)	Overcut Amount (μm)	Thermal affected radius (μm)	Thermal affected area size (mm^2)
1	282.5	82.5	447.5	0.378
2	280.0	80.0	436.0	0.351
3	328.5	128.5	429.5	0.240
Avg. value	281.5	81.5	401.0	0.256
Deviation	293.1	93.1	428.5	0.306

From the figures in Table 4, Table 5, Table 6 and Table 7, it is learned that the hole overcut results can be improved either with individual current control or composite-aided machining and that more frequent experiment repeatability can be achieved under current control. Based on the average overcut value, we have the average overcut amount comparison chart (per Fig. 9) which shows that the overcut amount with aided current control has reduced for 68.26% when compared to the non-aided standard.

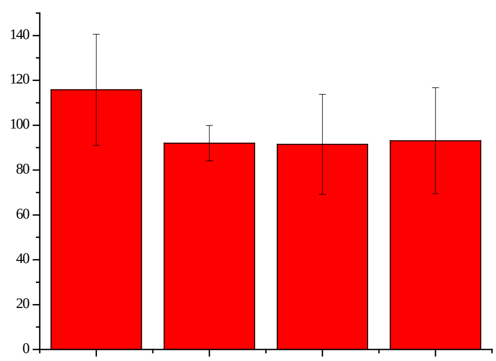

Fig. 9. Average overcut Number of Inlet Holes with different aiding methods.

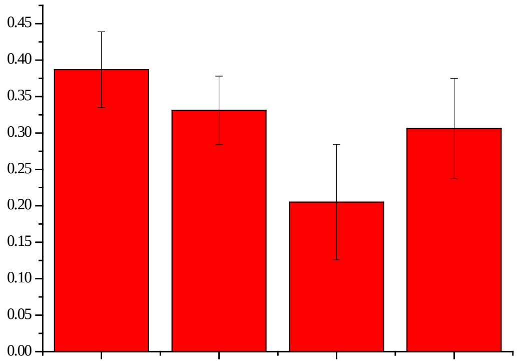

Fig. 10. Average Thermal Affected Area Size of Processed Inlet Holes with different aiding methods.

Based on the average radius value of the thermal affected area, we obtained the thermal affected average area size comparison chart (per Fig. 10). As indicated in Fig. 10, both composite machining methods can reduce the radius of the thermal affected area. Because the anodic processing is more unstable than the cathodic processing, it has presented higher standard difference for the longer-duration reverse and such problem can be improved by using the standard difference obtained from shorter-duration reverse aided method. As a result, the standard difference of shorter-duration reverse aided machining is 12.56% less than that of longer-duration composite aided machining result method.

The Optical Microscope is used to observe the hole inlet processed by different machining control methods and the results are compared (per Fig. 11). After applying the reverse machining, the thermal affected area at the hole has become more constant (with higher true roundness) and the breaking of the front-side hole is also improved in quantity and seriousness. Through the reverse control results, lighter thermal affected areas can be achieved; whereas, darker traces are observed in the thermal image in the area without using reverse control.

When measuring the overcut amount, the minimum fit roundness is obtained for the hole that is at the same height as the glass surface. Taking the maximum diameter of the Tool as the standard, the overcut amount is obtained by deducting the maximum tool diameter from minimum roundness diameter. When measuring the thermal affected area, same as the method used in the overcut amount, the fit roundness of the maximum affecting area is selected and the thermal affecting area size is acquired by deducting the area size of the overcut portion. In the event that it is impossible to select with fit roundness, the length measured from the circle center to the farthest damage area is used as the radius of the thermal affected area (per Fig. Fig. 11(a)).

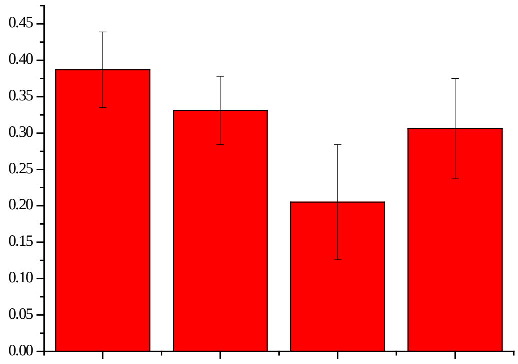

Fig. 11. Comparison between the hole inlets processed by different aided methods: (a) Air-free; (b) Current control aided; (c) Longer reverse composite aided; (d) Shorter reverse composite aided.

Outlet Hole Results for Glass Machining

The outlet is measured with the radius of the inlet hole processed by the aforesaid 4 kinds of machining methods and that of the thermal affected area. The figures are collected for calculating the thermal affected area size and the hole overcut number per Table 8, Table 9, Table 10 and Table 11.

Table 8. Un-aided Machining Outlet Hole Experiment Result

Experiment Count	**Hole Radius** (μm)	**Overcut Amount** (μm)	**Thermal affected radius** (μm)	**Thermal affected area size** (mm^2)
1	246.5	46.5	480.5	0.533
2	270.5	70.5	470.5	0.465
3	229.5	29.5	479.5	0.555
Avg. value	248.8	48.8	476.5	0.518
Deviation	20.6	20.6	5.2	0.047

Table 9. Current Control-Aided Machining Outlet Hole Experiment Results

Experiment Count	**Hole Radius** (μm)	**Overcut Amount** (μm)	**Thermal affected radius** (μm)	**Thermal affected area size** (mm^2)
1	273.5	73.5	457.5	0.423
2	263.5	63.5	484.5	0.518
3	274.5	74.5	408.5	0.286
Avg. value	270.3	70.3	449.8	0.409
Deviation	6.0	6.0	38.6	0.117

Table 10. Longer Reverse Composite Current Control- Aided Machining Outlet Hole Experiment Result

Experiment Count	**Hole Radius** (μm)	**Overcut Amount** (μm)	**Thermal affected radius** (μm)	**Thermal affected area size** (mm^2)
1	261.5	61.5	410	0.313
2	238.0	38.0	346	0.198

3	213.5	13.5	333	0.205
Avg. value	217.0	17.0	255.5	0.057
Deviation	232.5	32.5	336.1	0.193

Table 11. Shorter Reverse Composite Current Control- Aided Machining Outlet Hole Experiment Results

Experiment Count	**Hole Radius** (μm)	**Overcut Amount** (μm)	**Thermal affected radius** (μm)	**Thermal affected area size** (mm^2)
1	254.5	54.5	348.5	0.178
2	230.5	30.5	360.5	0.241
3	240.5	40.5	383.5	0.279
Avg. value	248.0	48.0	355.5	0.204
Deviation	243.4	43.4	361.9	0.226

Through the figures in Table 8, Table 9, Table 10 and Table 11, it is learned that the average size of the current control-aided machining is bigger than that of the aid-free method, but better repeated accuracy can be obtained from the current control aided machining. Likewise, the overcut number of reverse composite aided machining is less than that of aid-free method. In the aspect of experiment repeatability, the shorter reverse aided machining exhibited more superior experiment repeatability. With the overcut Avg. value, the average overcut comparison chart is obtained (per Fig. 12) in which, the standard difference of current control aided machining has reduced for 71.02% than that of the unaided machining.

Based on the average thermal affected area size, we obtained the thermal affected average area size comparison chart (per Fig. 13). As indicated in Fig. 3.5, both composite machining methods can reduce the thermal affected area size. Because the anodic processing is more unstable than the cathodic processing, it has presented higher standard difference for the longer-duration reverse and it can be significantly reduced with shorter-duration reverse aided method. By adding the standard difference, the area size of the longer-duration reverse method will be bigger than the area size of shorter-duration reverse where the standard difference of the shorter reverse composite aided machining will be reduced by 58.10% than that of the longer reverse composite0-aided machining.

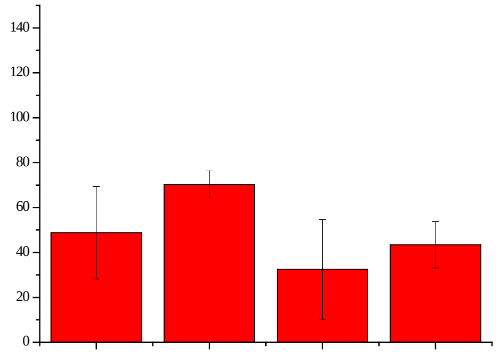

Fig. 12. Average overcut Number of Outlet Holes processed by different aided methods.

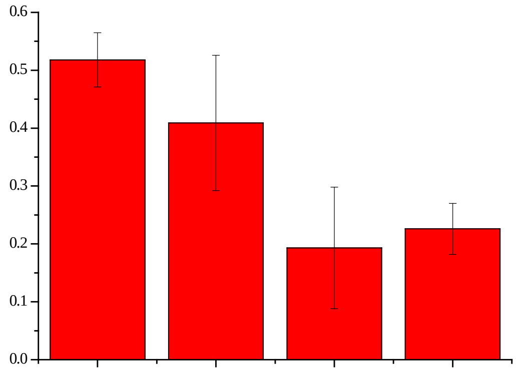

Fig. 13. Average overcut Number of Outlet Holes processed by different aided methods.

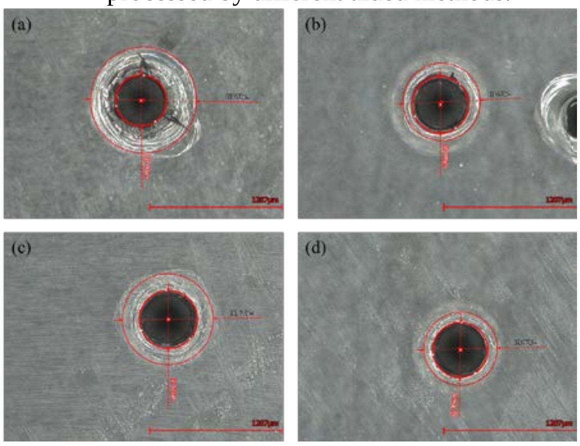

Fig. 14. Comparison between the hole outlets processed by different aided methods: (a) Air-free; (b) Current control-aided; (c) Longer reverse composite aided; (d) Shorter reverse composite aided.

The Optical Microscope is applied to observe the hole outlet processed by different machining control methods compared (per Fig. 14). The results indicated that extremely big cracking will be found under the aid-free processing method and there are also lots of minor breaking spots in the thermal affected area and the hole connecting end. However, the breaking phenomenon can be improved either with individual current control or composite method. The cracking traces at the outlet processed by reverse composite aided method are presenting a much better hole mass when compared to the individual current control method. This is because the electrode consumption has resulted in bigger electrode tip as to reduce the current density where the discharge damage is minimized in the long run.

Sapphire Machining Results

In this research, the results of the sapphire processing obtained from the following five kinds of machining methods are collected and discussed and they are air-free, changing electrode, inching control aided, innovative inching control aided, and changing electrode composite inching control aided. Listed below (Table 12) are the relevant experiment parameters.

Table 12. Sapphire Machining Experiment Parameter Table

Working voltage	60 V	Electrolyte soaking depth	0.8 mm
Type of electrolyte	KOH	Electrolyte concentration	5 M
Workpiece	Sapphire test piece	Electrode pre-stress depth	1.5 mm
Electrode rotation speed	300 rpm		

Machining Depth Results for Sapphire

By comparing the machining depth data obtained from the aforesaid 4 kinds of machining methods (per the Table 13 and Fig. 15), it is learned that the sapphire machining depth can be increased through changing the electrode and the inching control machining during the electrochemical discharge machining. Due to different portions to be improved by both aided methods, a higher maximum machining depth can be achieved by the composite machining in which, better effects can be achieved by the innovative inching than ordinary inching method. Because the innovative inching aided method tends to damage the electrode during the machining process, it cannot be applied in the composite machining process. However, the maximum machining depth from the composite machining method will be improved by 61.67% than that from the aid-free method.

By comparing the machining data indicated in the aforesaid list, we can find that the changing of electrodes can improve uneven discharge phenomenon due to varied electrode compositions. Likewise, the innovative inching machining method can slightly improve the degrading phenomenon due to being unable to changing the electrolyte. Because the electrode will not contact the workpiece during the innovative inching control machining processing, it would be easier for exchanging the electrolyte in the hole with that in the container. Therefore, it can effectively improve the situation being unable to execute the discharge due to the degradation of electrolyte.

Table 13. Machining depth for sapphire from different machining methods

Machining Method	Machining Depth (μm)
Aid Free	113.85
Changing Electrode	143.09
Inching Aided	143.42
Innovative Inching Aided	163.45
Changing Electrode Inching Control Aided	184.06

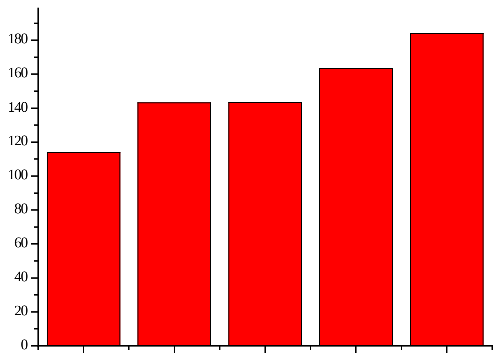

Fig. 15. Machining depth from different machining methods.

CONCLUSIONS

In this article, the processing issues related to the removal of non-conductive brittle materials are studied for the Electrochemical Discharge Machining (ECDM) Method. In the meantime, the supporting system is also developed for the glass and the sapphire in order to improve the quality of holes required for glass machining, such as overcut and thermal affected area, etc. Furthermore, the ECDM Method is also applied to improve the difficulty in processing the sapphire (machining depth being too shallow) in order that the ECDM may achieve the maximum depth for the sapphire

Described below are the results of this research:

1. Set up the electrochemical discharge machining experiment system structure possessing the online

feedback function.

2. The longer reverse composite aided machining and shorter reverse composite aided machining proposed in this research help reduce 21% and 19.6% of overcut at glass inlet hole respectively than ordinary machining method. In aspect of thermal affected area size at the glass inlet hole, they can also reduce 47.03% and 20.93% respectively than ordinary machining method.
3. The longer reverse composite aided machining and shorter reverse composite-aided machining proposed in this research help reduce 33.44% and 11.16% of overcut at glass outlet hole respectively than ordinary machining method. In the aspect of thermal affected area size at the glass inlet hole, they can reduce 62.74% and 56.37%, respectively, than ordinary machining method.
4. This research also discussed the machining time of the reverse-aided method and the results indicated that the working efficiency of anodic machining period is instable than that of the cathodic machining and it has led to longer machining time.
5. Based on the electrode consumption data obtained during the research process, it is learned that the current control tends to cause damage to the electrode tip. It is because the discharge phenomenon is concentrating on the tip end of electrode as to cause excessive consumption of such tip. In aspect of anodic machining, the overall consumption speed of the electrode is faster than that of cathodic machining.
6. This research proposed a kind of current feedback method in order to control the inching machining travel in the Gravity Feeding System, and it can increase the maximum depth for 43.57% than ordinary machining method.
7. The composite-aided machining method proposed in this research can achieve 184.06μm of the maximum depth for the sapphire machining and it is also 61.67% higher than that of the ordinary machining method.

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基於電極操控輔助電化學放電鑽孔加工法於透明硬脆材料之研究

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摘 要

電化學放電加工是一種針對非導電硬脆材料之非傳統加工法，為了提高加工效率和鑽孔的最大深度，通常使用增加電壓或電解液濃度的方式，然而過高的電壓與電解液濃度是造成過切、熱影響區擴大和孔洞品質降低的主要原因。本研究提出了一種線上輔助加工系統，此系統利用圖像和電流監測來實現參數化的即時反饋和調整，在輔助對玻璃加工的系統上，本論文觀察氣泡的堆積的程度和電極特徵以決定進行極性切換的時機，並且使用控制電流數值來降低通孔時的玻璃碎裂。根據極性切換結果，本研究可以降低 22.84%的正面孔洞過切與36.73%的通孔過切，在熱影響區的部份正面熱影響區降低了 41.99%，而通孔熱影響區降低了 24.4%。在加工藍寶石方面，本研究使用了根據電流響應的寸動控制法，使得電極尖端部分的電解液得以更新，降低電解液鈍化的影響，並且限制電流進行放電之控制，因而本研究可以在較高電壓下進行加工，而不使電極損毀；研究另外使用了多支電極加工中進行更換來確保電極材質穩定。最後在採複合控制輔助加工中，可得到最大深度 184.06 μm，對比未進行控制的加工結果提升了 61.67%的鑽孔深度。