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Effect of Electrochemical Dissolving in Laser Drilling Assisted with Jet Electrochemical Machining

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Laser Drilling assisted with jet electrochemical machining (LD-JECM) has been proved be a useful way for machining high quality holes without recast layer and spatter. In this paper, details of LD-JECM about theoretical analysis on electrochemical dissolving and experimental study on machined quality were performed using 321 stainless steel as workpiece material. Based on the analysis of different material removal mechanisms in pulse width and inter pulse of laser, the temperature field of laser drilling and electric field of jet electrochemical machining were simulated separately. The simulation results show that there is an electric field gradient in the processing area and electrochemical dissolving at the edge of entrance is the strongest, which is proved by the blind-hole experimental results that have removed the spatter around the entrance and expanded the diameter of hole. Additionally, the through-hole experimental results show that recast layer adhered to the sidewall have been completely removed and the exit of the hole is very clean without any spatters. On the surface of sidewall, there are not grain boundary corrosions and only a few of micro pitting. Furthermore, the applied electrochemical voltage and inter electrode gap both affect the taper. It has been observed that within an optimized process parameters window i.e. electrochemical voltage 120-200V and inter electrode gap 1.5-2.5mm, high quality surfaces and high forming accuracy are obtained with less defects. Overall, this work has shown that LD-JECM has a high potential for micro-hole precision machining on difficult-to-machine materials.

Keywords: Laser drilling; Jet electrochemical machining; Electrochemical dissolving; Recast layer; Taper

1. INTRODUCTION

With the development of modern micro-manufacturing and new materials, the demand for fabrication of micrometer scale features with high dimensional accuracy and good surface quality has focused research on expanding manufacturing capabilities of state of the art processes. One solution is hybridization of unconventional machining technologies such as laser beam machining and electrochemical machining (ECM) [1-2]. Laser drilling is a well-established non-traditional machining process which can be used for production of high aspect ratio holes in variety of materials at high speed. However, in laser drilling, the material is removed through the process of melting and vaporization, as well as melting and resolidification with the resolidified droplets at the sidewall. Laser drilling suffers from thermal defects such as heat affected zone, spatter and recast layer. Jet electrochemical machining (JECM) is a micro-hole processing technology where an electrolyte is expelled through a nozzle (cathode) and impinged on a workpiece (anode) causing localized anodic dissolution [3]. JECM does not require expensive tooling and it has clear advantages such as being independent of workpiece hardness and a non-contact process with high surface finish. However, in JECM, there is a stray corrosion which leads reduce the effectiveness of machining.

In recent years, laser machining process and ECM process have been hybridized or combined to obtain better assurance and quality. Wang et al. have proposed a novel laser and electrochemical machining based on the internal total reflection of laser through the inner hole of the tube electrode with Teflon layer. The novel machining method has been successfully processed on aluminum alloy and stainless steel, which can decrease the side gap by 23.6%, reduce the taper angle by 60.8%, and improve materials removal rate by 118.8% [4-5]. K.K. Saxena et al. have developed a tool-based hybrid laser-electrochemical micromachining process by means of a hybrid tool where the tool acts both as an ECM anode and a multimode reflective waveguide for laser. They carried the hybrid micromachining process on Inconel IN718 alloy by using laser at wavelength of 532nm and pulse width of 10ns, and found that the effect of laser induced oxidation is useful to control stray dissolution problem to improve machined accuracy [6-7]. Z.Y. Zhang et al. have established a machining system of nanosecond pulse laser assisted electrochemical machining system, where a conductive glass tube made of ITO was used as the anode [8]. With the system, laser thermal-mechanical effects on electrochemical etching were studied. The results show that laser thermal-mechanical effects change the balance potential of the metal and promote the electrochemical reaction. Y.H. Long et al. carried a laser-induced electrochemical machining with excimer laser, where the workpiece is under the static salt solution [9-10]. It was found that excimer laser induced electrochemical machining is not suitable for metals but for silicon. Z.Y. Zhang et al. carried laser electrochemical machining on aluminum alloy with a 1064nm SGR-10 laser and $NaNO_3$ electrolyte, the results show that laser shock pressure can damage the oxide layer and enhance the localization of electrochemical reaction [11]. A. Malik et al. develop a hybrid laser-assisted jet electrochemical machining for micro drilling of Inconel-718 with Nd:YAG (DPSS-diode pumped solid state) and $NaNO_3$ electrolyte jet [12-13]. With the assistant of laser, the temperature in the machining zone is increased that in turn changes the localized effects, where the localized effects increase current density and improve the machining accuracy.

The above-mentioned research works focused on laser-assisted electrochemical machining. In addition, there were other research works that used electrochemical reactions to improve the surface quality of laser machining. W.Q. Duan et al. have proposed to use electrochemical corrosion as a post processing method to remove the recast layer of gas assisted laser drilling, and they found that the recast layer on the hole wall could easily by removed, were laser drilling was assisted with non-oxidative gas

[14]. X.S Liu et al. used pulse electrochemical machining (PECM) to remove the recast layer of laser drilled micro-holes in Nickel based super alloy. The results show that a hydrogen pressure wave is generated during PECM and the hydrogen pressure wave was help to improve the current efficiency by stirring in the electrolyte of the machining gap [15]. A.X. Sun et al. have presented laser machining and electrochemical machining (LM-ECM) for machining metal micro-holes, where laser machining was first step with etching materials rapidly and electrochemical machining was second step to remove recast layer totally [16]. The result showed that material surface of LM-ECM is cleaner than single laser machining. S.Alistair et al. have combined laser pre-treatment and electrochemical jet machining to fabricate microstructure on mild steel [17]. J.Liu et al. have combined laser interference lithography and electrochemical etching to fabricate ordered pore arrays in silicon, and it was proved that the combined process is help to get highly homogeneous formation of micrometer-deep pores with periodicity as low as 300 nm [18]. In previous work of our team, a new method of laser drilling assisted with jet electrochemical machining has been developed and a two-dimension mathematical model was proposed to describe the shape of the machined hole [19-20]. The results showed that materials are removed mainly by laser, and the jet electrochemical machining is helpful to reduce the recast and spatter. However, the effects of electrochemical dissolving need to be further researched to obtain better machined quality.

In this paper, based on the previous work, the effects of electrochemical dissolving of jet electrolyte during LD-JECM are investigated through two-dimensional simulations and comparative experiments. The voltage and inter electrode gap are optimized to reduce taper of hole and improve the quality of machined surface.

2. LD-JECM PROCESS SCHEME

Fig.1 shows the process scheme of LD-JECM and Fig.2 shows a physical picture of the realized proof-of-concept of LD-JECM. In this process configuration, there are two different sources of energy: one is the energy of photons from focused laser beam and the other is the energy of ions from electrochemical dissolving. The two energies are applied simultaneously in the same machining zone with acting along the same machining axis. As shown in Fig. 2, a hybrid machining head is designed to hybridizing a focused laser beam and a jet electrolyte. Figure 3 shows a physical picture of successful result of the hybrid machining head. As shown in Fig.3, the jet electrolyte is aligned coaxially with the focused laser beam and creates a noncontact tool-electrode, where the focused laser beam is a red laser with continuous wave for indication. In the course of LD-JECM, a microsecond pulsed Nd:YAG laser at second harmonic wavelength and a DC power supply are employed. During the pulse width of laser, materials of workpiece are quickly removed by thermal action generated by pulsed laser. Then in inter-pulse, the defects of laser drilling such as recast layer and spatter are reduced by anode dissolution of jet electrolyte.

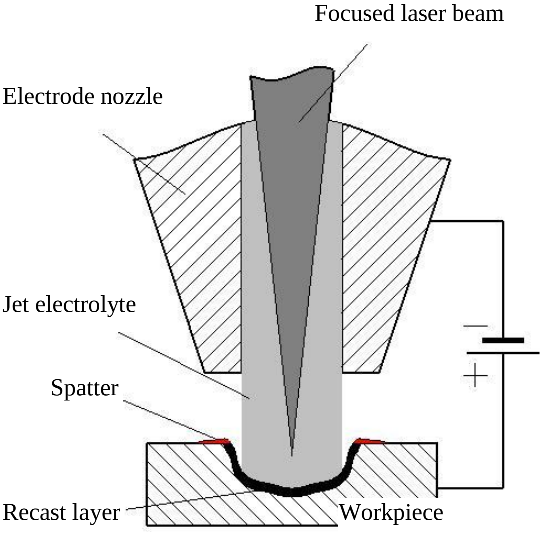


Figure 1. Process scheme of LD-JECM

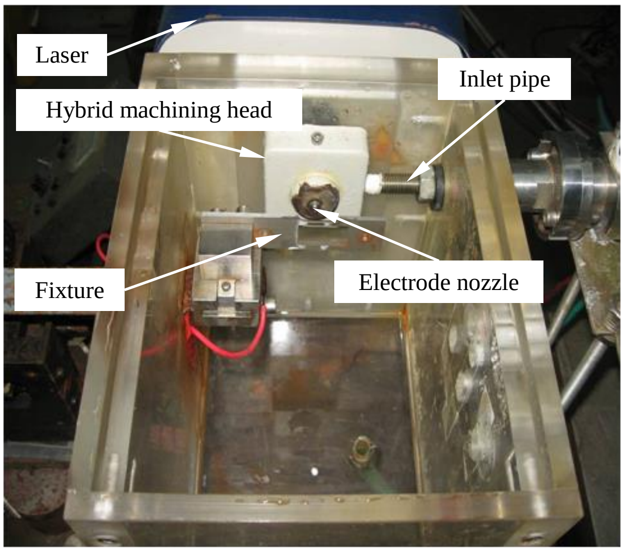


Figure 2. Physical picture of LD-JECM

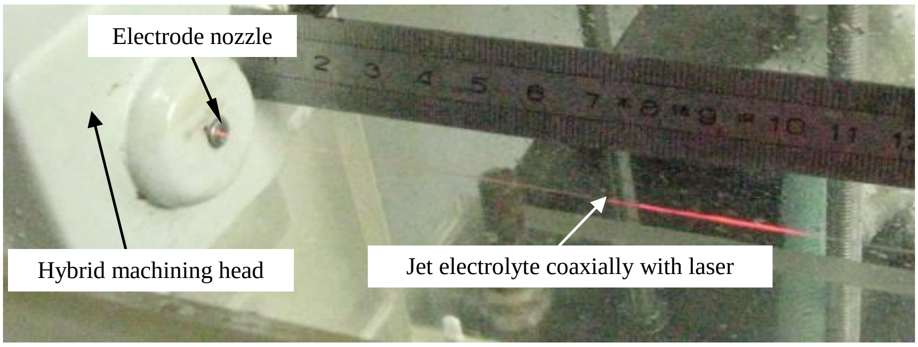


Figure 3. Physical picture of jet electrolyte coaxially with laser

3. SIMULATION RESULTS OF LD-JECM

According to the theoretical model for LD-JECM of previous work [19], there are two processing states in LD-JECM. One processing state is laser drilling coaxially with jet electrolyte in pulse width, the other processing state is just jet electrochemical machining during inter-pulse of laser. The temperature field of laser drilling coaxially with jet electrolyte and electric field of jet electrochemical machining were simulated separately. The processing parameters are given in Table 1. The workpiece used is 321 stainless steel with the thickness of 0.5mm. The conductivity of the $NaNO_3$ electrolyte is $12.2(\Omega\cdot\mathrm{m})^{-1}$. The volume electrochemical equivalent of 321 stainless is $2.1\times10^{-9}\mathrm{m}^3/\mathrm{A}\cdot\mathrm{min}$.

Table 1. Processing parameters of LD-JECM

LD-JECM Processing Parameters	Value
Wavelength (nm)	532
Per pulse energy of laser (mJ)	0~300
Pulse length of laser (ms)	0.2
Frequency of laser (Hz)	5
Voltage of DC power (V)	100~300
Diameter of nozzle (mm)	0.4
Concentration of $NaNO_3$ jet electrolyte	18%
Pressure of $NaNO_3$ jet electrolyte (MPa)	1.5

Fig.4 shows the temperature field on the workpiece surface by laser drilling coaxially with jet electrolyte with green laser pulse energy of 200mJ in the first pulse. It can be seen from Fig.4 that the surface temperature of the workpiece has reached more than 10,000 degrees. Therefore, the elements with temperature being higher than melting point can be deemed to be removed. Fig.5 shows the 2-D simulation result of section boundary of LD-JECM at the end of pulse width. The left elements of the machined zone have formed a new boundary as the initial condition for electric field of jet electrochemical machining.

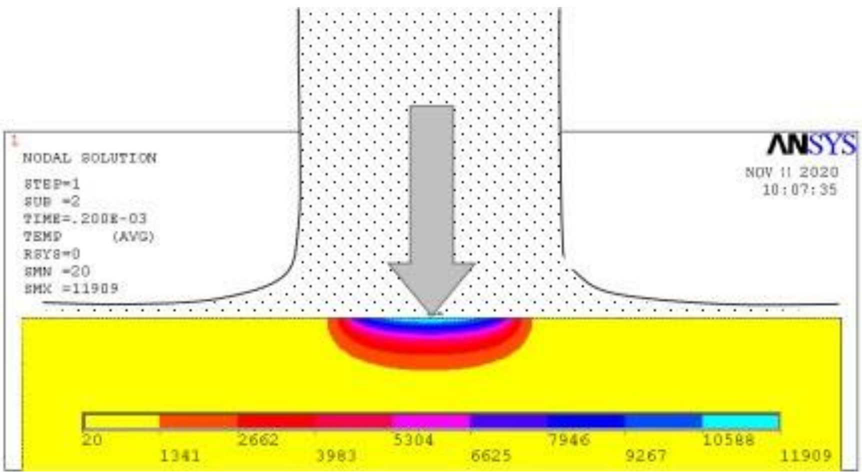


Figure 4. Temperature field distribution of LD-JECM at pulse width

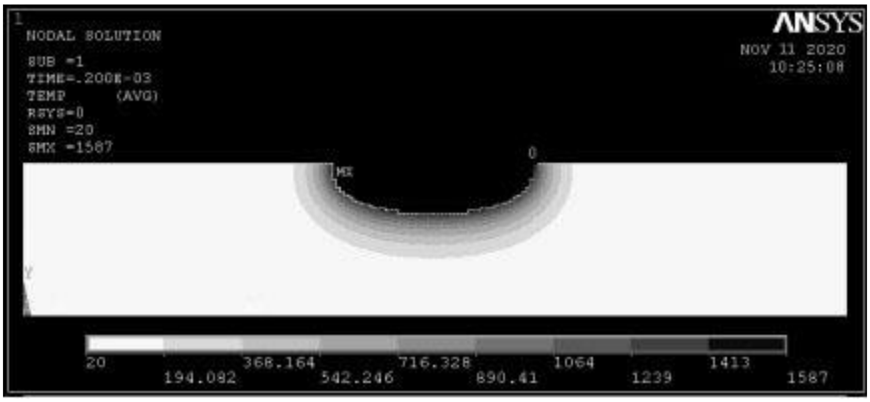


Figure 5. The 2-D simulation result of section boundary of LD-JECM at the end of pulse width

In inter pulse width, jet electrochemical machining is the main role to remove materials. Fig.6 shows the electric field distribution and current density distribution along the radius of hole. The applied electrochemical voltage is 280V. It is obvious that the current density is the maximum value at the entrance edge of the hole, up to 270A/cm^2. With the hole depth increases, the current density decreases and it on the sidewall is more than the bottom of hole. In the center area of the hole bottom, the current density is the minimum, only about 80A/cm^2.

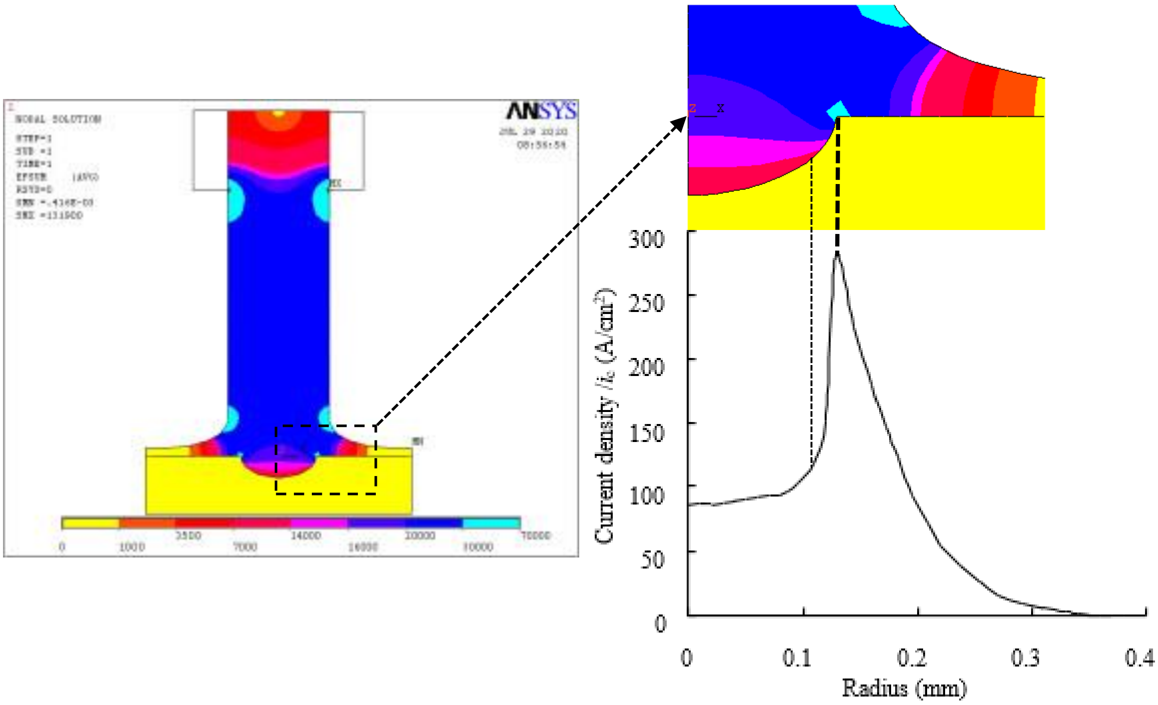


Figure 6. Electric field distribution and current density distribution in the inter pulse

The material removal rate of jet electrochemical machining is related to current density and current efficiency. Based on the experiments of jet electrochemical machining with $NaNO_3$ electrolyte, the characteristic curve of $\eta\omega$-i in LD-JECM with $NaNO_3$ jet electrolyte is shown in Fig.7. When the current density is less than 80A/cm^2, the value of $\eta\omega$ is much low. When the current density is more than

$80A/cm^2$, the increase of current efficiency gradually slows down, and shows a horizontal trend, which is a non-linear characteristic of $NaNO_3$ electrolyte. Therefore, the effect of electrochemical dissolving is helpful to reduce the spatter around the entrance of hole and remove the recast layer which adhere to the sidewall of hole.

Main chemical components of 321 stainless steel are iron, chromium and nickel. Formulas of electrochemical reaction of cathode and anode are as follow,

Anode: $\mathrm{Fe - 3e \rightarrow Fe^{3+}}$ and $\mathrm{Fe^{3+} + 3OH^- \rightarrow Fe(OH)_3 \downarrow}$

$\mathrm{Cr - 3e \rightarrow Cr^{3+}}$ and $\mathrm{Cr^{3+} + 3OH^- \rightarrow Cr(OH)_3 \downarrow}$

$\mathrm{Ni - 2e \rightarrow Ni^{2+}}$ and $\mathrm{Ni^{2+} + 2OH^- \rightarrow Ni(OH)_2 \downarrow}$

Cathode: $\mathrm{2H_2O + 2e \rightarrow 2OH^- + H_2 \uparrow}$

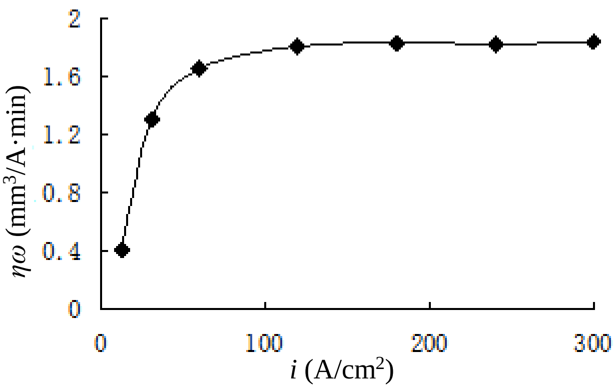


Figure 7. Characteristic curve of $\eta\omega$-i in LD-JECM with $NaNO_3$ jet electrolyte

4. EXPERIMENTAL RESULTS OF LD-JECM

4.1. Machined results for blind hole

Blind hole was machined by LD-JECM, which was compared with laser drilling coaxially with jet electrolyte. The energy per pulse is 200mJ, the applied electrochemical voltage is 280V and the machining time is 5s. SEM and 3-D profiler are used to detect the experimental results.

Fig.8 shows the SEM micrograph of blind hole machined with two different processes. As can be seen in Fig.8(a), around the entrance of blind hole machined by laser drilling coaxially with jet electrolyte, there are obvious circumferentially diffused spatter. On the sidewall of entrance, there are ‘white’ layers present, which are recast layers. In contrast, it is clearly evident from Fig. 8(b) that none spatter is present around the entrance and a few of recast layers are just adhere on the bottom of blind hole.

Three-dimensional topographies of the two blind holes are compared in Fig.9. It also proved that blind hole machined by LD-JECM can get smooth hole periphery. However, around the entrance surface, there is an obvious annular electrochemical overcut.

The above experimental results are consistent with the previous theoretical simulation results of LD-JECM. According to the current density distribution of simulation result, the current density at the entrance edge of the hole is the peak value, then the electrochemical anodic dissolutions around the entrance edge are higher than other areas. So the entrance of hole machined by LD-JECM is bigger than laser drilling coaxially with jet electrolyte. In LD-JECM, all spatters around the entrance have been removed assisted with jet electrochemical machining. Because of low current density at the bottom of hole, the electrochemical anodic dissolutions are weak. Therefore, there are some residual recast layers at the bottom of the hole machined by LD-JECM.

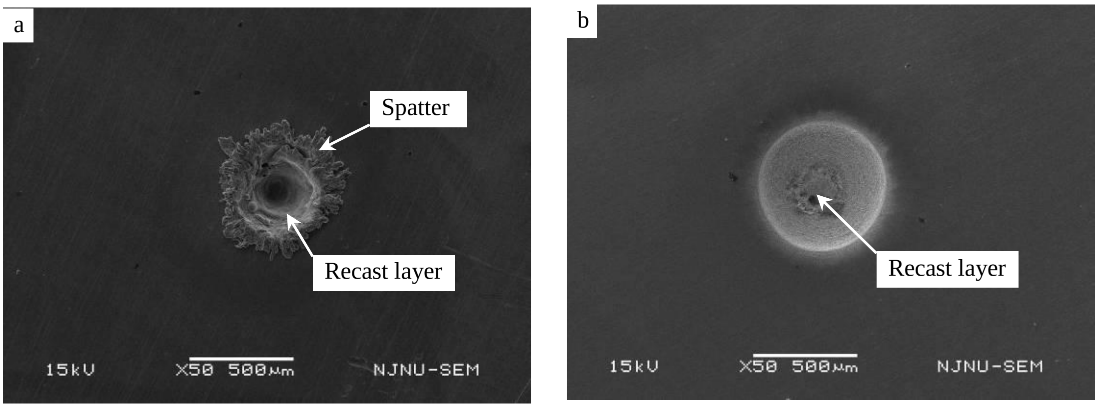


Figure 8. Micrograph of blind hole machined with different process (a) laser drilling coaxially with jet electrolyte; (b) LD-JECM

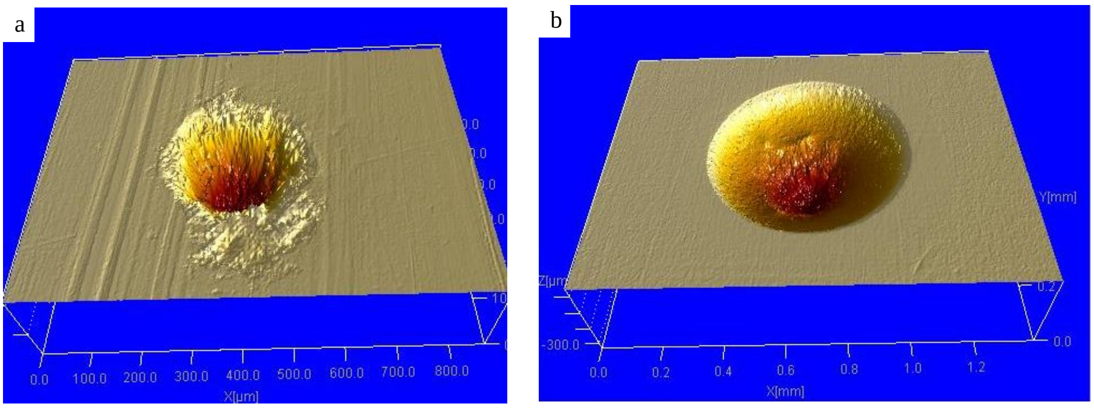


Figure 9. Three-dimensional topography of blind hole machined with different process (a) laser drilling coaxially with jet electrolyte; (b) LD-JECM

Similar results are compared in Table 2. Material removal principles are listed in the second column in the table. The primary effect and second effect are represented by the letter P and S separately. There are two combined type such as act together and act separately. The blind hole entrances are as results and listed in the last column.

LIECM and LECM both used static electrolyte. LIECM is a hybrid process of assembling excimer laser and static NaCl electrolyte. The blind hole machined by LIECM was compared with laser etching in air. It is shown that laser etching in air has a larger ablation zone and the cavity edge is not smooth, and there accumulates molten metal material round the cavity edge. The conclusion is that LIECM can overcomes great heat-affected zones, large sediments, thermal stress and impact damage in laser direct etching, however, excimer laser is not easy for machining metals in LIECM [9]. LECM is a combination of laser machining and electrochemical etching. Used the electrolyte is static NaNO3 solution and aluminum alloy sample in the solution. The blind hole machined by LECM was compared with nanosecond pulsed laser ablation in air. It is shown that the recast layer around the micro-hole is removed totally due to the electrochemical reaction and laser shock pressure. The conclusion is that faster material removal rate and better shape precision are achieved by LECM, and material removal process is localized to specified areas where the oxide layer is damaged by laser shock pressure [11].

Hybrid laser-ECM and Laser-STEM both used a shaped metal tube, which acts as an ECM tool and a reflective multimode waveguide for laser. Former tube is a 1.2mm outer diameter stainless steel tube with an inner concentric quartz glass hollow capillary. Latter tube is a 1mm outer diameter titanium tube with an inner Teflon tube.

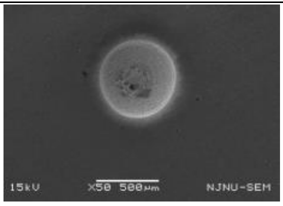
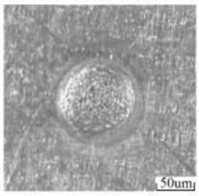
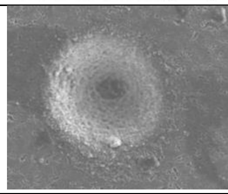
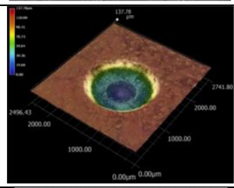
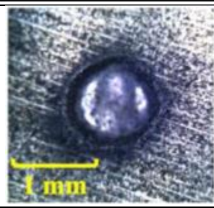
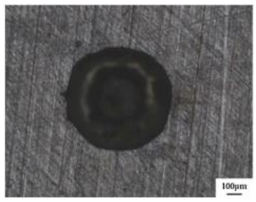
The blind hole machined by hybrid laser-ECM was compared with ECM without laser. In the ECM without laser, it is shown that there is a residual pin like structure is present in the center of the cavity due to low current density under the tubular region of the tool-electrode. On the contrary, hybrid laser-ECM can obtain deeper central part due to the local increase of reaction kinetics/electrolyte conductivity with high laser energy. The conclusion is that the machined surface of cavity is very well and hybrid laser-ECM can be useful for high aspect ratio machining of hard materials [6-7].

The influences of laser power on the performance of Laser-STEM were carried out [16]. When laser power is smaller than 10.3W, the central residual is always formed. As the laser power exceeds a threshold value, the central residual could be avoided due to the electrochemical dissolution rate also increases. The conclusion is that materials are mainly machined by ECM and the electrochemical machining rate could be enhanced by the synchronous laser irradiation on the machining area. The machining efficiency could be enhanced and the machining side gap could be decreased by 62.7% in Laser-STEM compared with that without laser assistance.

LM-ECM is only one that has separated laser machining and ECM in table 2. Firstly, millisecond pulsed laser is used to drilling with auxiliary gas; Secondly, ECM with a shaped metal tube is used to remove recast layer. Experimental results of LM-ECM were compared with single laser machining (SLM). It is shown that material surface of LM-ECM is cleaner than SLM and has none molten slag. Molten slag on metallic materials was basically carried away by electrolyte. Compared with single ECM, the efficiency and accuracy of LM-ECM are improved by 51.35% and 30.43% respectively [5].

Compared with these similar results, it is clearly that the surface and roundness of blind hole entrance machined by LD-JECM and hybrid laser-ECM both are better than other results.

Table 2. Comparison of blind-hole experimental results of similar processing methods

Processing method	Material removal principle	Laser parameters	ECM parameters	Workpiece material	Results
LD-JECM (this paper)	P: laser S: jet-ECM Act together	λ=532nm E_p=200mJ f=5Hz	U=280V Electrolyte: $NaNO_3$ IEG=2mm	321 stainless steel	
LIECM[9]	P: ECM S: laser Act together	λ=248nm E_p=100mJ f=5Hz	U=0.5V Electrolyte: NaCl	stainless steel	
LECM[11]	P: ECM S: laser Act together	λ=1064nm E_p=80mJ f=5Hz	U=5V Electrolyte: $NaNO_3$	aluminum alloy	
hybrid laser-ECM[6-7]	P: ECM S: laser Act together	λ=532nm P=30W	U=10V Electrolyte: $NaNO_3$ IEG=20μm	Inconel IN718	
Laser-STEM[16]	P: ECM S: laser Act together	λ=532nm P=19.6W	U=16V Electrolyte: NaCl IEG=0.5μm	aluminum alloy	
LM-ECM[5]	P: laser S: ECM Act separately	λ=1064nm pump current=120A f=7Hz	U=7V Electrolyte: $NaNO_3$ IEG=40μm	stainless steel	

4.2. Machined results for through hole

According to the experiments for blind hole machined by LD-JECM, the applied electrochemical voltage is too high and the annular electrochemical overcut increases the taper of hole. Thus, in the LD-JECM experiments for through hole, the used electrochemical voltage is 120V. The energy per pulse is also 200mJ. To machine a through hole with the laser in air, machining time is just 10s. LD-JECM needs 20s to get a through hole. The material removal rate of LD-JECM is lower than laser drilling in air.

The above blind hole experimental results have confirmed that LD-JECM can obtain better hole entrance without spatter and recast layer. For through hole, the quality of exit surface and section were further researched. Fig.10 compares the edge of exit surface machined by laser drilling in air and LD-JECM. It is shown that there are irregular spatters around the exit and traces of thermal burns on the exit surface surrounding the hole. In contrast, the exit of through hole machined by LD-JECM is very clean and has none resolidified molten layers.

Fig.11 compares the section of through hole machined by laser drilling in air and LD-JECM. From Fig.11(a), it is shown that white and thick recast layer is pronounced on the sidewall of holes with laser drilling in air and the thickness of recast layer is about 50μm. Fig.11(b) shows that the recast layers have been effectively removed in LD-JECM. It can be explained by the difference of working environment. Compared with laser drilling in air, added the anode electrochemical action is significantly to remove recast layer. In addition, it is beneficial to cool the ejected molten material and carry debris away by the high-speed jet electrolyte.

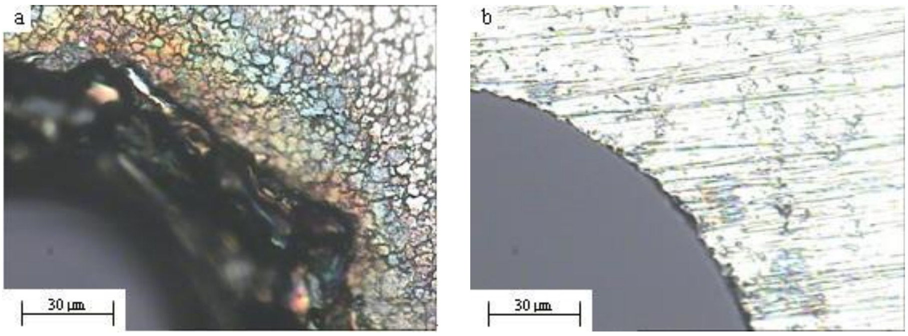


Figure 10. Partial figure of exit of through hole machined with different process (a) Laser drilling in air; (b) LD-JECM

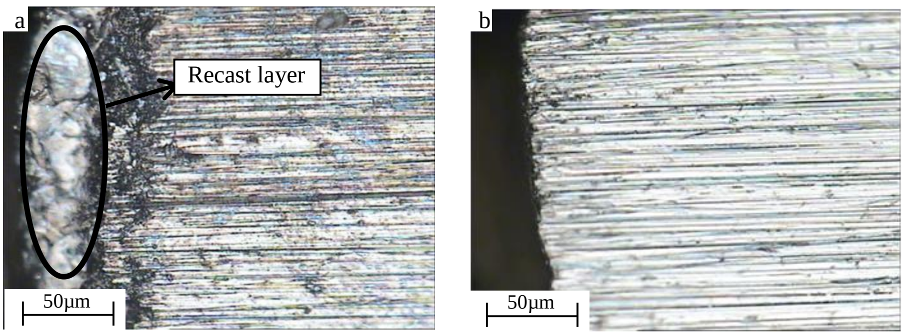


Figure 11. Partial figure of section of through hole machined with different process (a) Laser drilling in air; (b) LD-JECM

Fig.12 further shows the machined surface of sidewall of through hole machined by LD-JECM. It is shown that there are not grain boundary corrosions on the machined surface, and there are only a few of micro pitting. It further confirms that the quality of LD-JECM processed surface is determined by jet electrochemical dissolving.

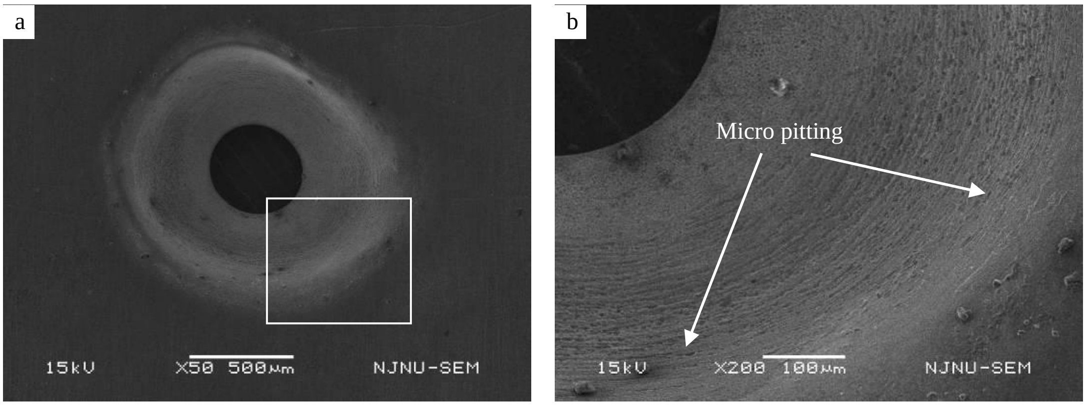


Figure 12. Machined surface of through hole machined by LD-JECM (a) Overall figure of entrance; (b) Partial figure of sidewall

Above the experimental results prove that LD-JECM can get better surface quality without spatter and recast layer. The roundness of entrance and exit of the holes machined by LD-JECM is also improved. In addition, the influence of electrochemical dissolution on taper was studied. The electrochemical voltage (U) varied from 120V to 280V, and the gap between electrodes(L) varied from 1mm to 3.5mm. The taper is defined as follows:

$$\text{Taper} = \frac{D_{\text{in}} - D_{\text{out}}}{T} \tag{1}$$

Where, D_{in} is the diameter of hole entrance, D_{out} is the diameter of hole exit, and T is the thickness of workpiece.

Fig.13 shows the relationship between applied voltage and taper with different inter electrode gap. Firstly, under the three different inter electrode gap, there are the same trend that taper is increased with the increase of applied voltage. The reason is that increase in voltage results in corresponding enhances the anodic dissolution of the work material, which leads to the diameter of hole entrance become larger. Secondly, with the increasing of inter electrode gap, the gradient of the curve of taper changing with voltage gradually becomes smaller. The most probable reason is that the excessive inter electrode gap weakens electrochemical anode dissolution. Therefore, the preferred range of electrochemical machining voltage is 120 to 200V in LD-JECM.

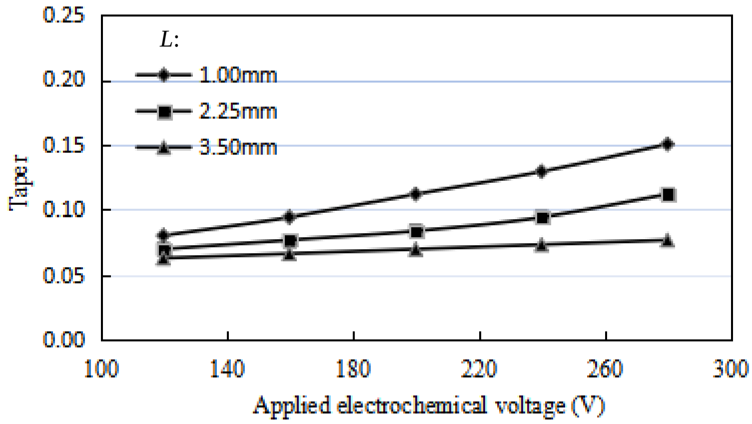


Figure 13. Effect of applied voltage on taper of hole machined by LD-JECM

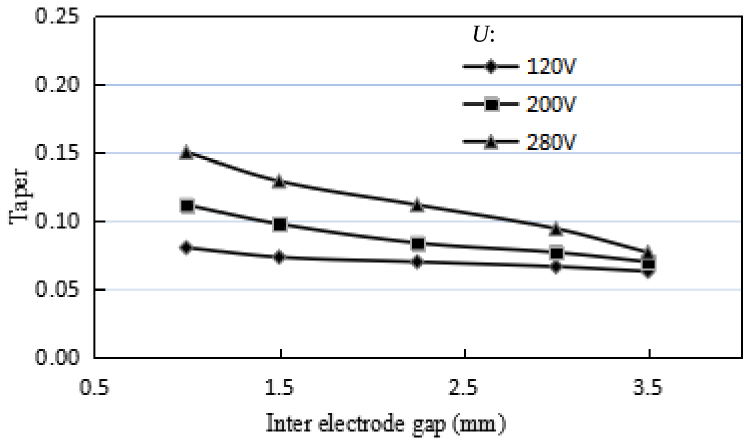


Figure 14. Effect of inter electrode gap on taper of hole machined by LD-JECM

Fig.14. shows the relationship between inter electrode gap and taper with different applied electrochemical voltage. As the inter electrode gap increases, the taper of the through hole machined by LD-JECM decreases. The reason is that the larger the machining gap, the weaker electrochemical effect on the machining area. In addition, with the increase of inter electrode gap, the decline of taper between the different applied voltage becomes smaller and smaller. This result shows that the machining gap is too large to control the forming accuracy of the through hole. Therefore, considering the quality of processed surface and the taper of through hole, the inter electrode gap prefer to be 1.5-2.5mm.

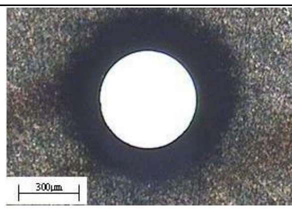
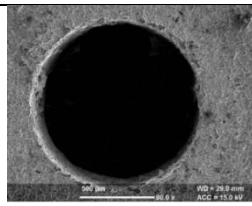
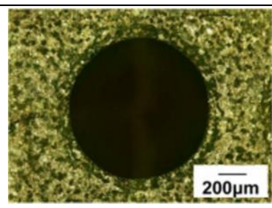
Similar through hole results were compared in Table 3. The entrances of through holes were listed in the last column. There are two material removal principles. First one is simultaneous action of laser drilling and electrochemical machining. Second one is followed by separate actions, first laser, then electrochemical machining.

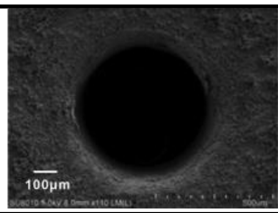
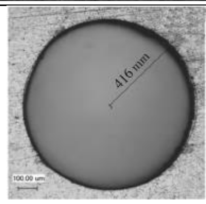
Be different with LD-JECM, LA-JECM and LECM-ITR both used the thermal effect of laser to strengthen the localization and reduce stray corrosion. The through hole machined by LA-JECM were compared with JECM [12-13]. It is clear that there is no evidence of damage on the periphery of the machined hole. The reason of it is that laser beam helps in focusing the electrochemical action in the longitudinal direction. LA-JECM has increased 29.16% material removal rate (MRR) and decreased 36.83% taper angle. The supply voltage is the strongest correlation with the MRR and taper angle. LECM-ITR used a metal tube as electrode and there is a Teflon layer on the inner wall of metal tube to get internal total reflection of laser [4]. The electric current and thickness of the anodic oxide layer during LECM-ITR were compared with that without laser irradiation. The electric current of LECM-ITR was stable and larger than that without laser irradiation due to the enhanced diffusion rate induced by the temperature rise. Compared with single ECM, the thickness of the anodic oxide layer of LECM-ITR has been increased from 6.57μm to 27.57μm by using laser power 20W. LECM-ITR could decrease the side gap by 23.6%, reduce the taper angle by 60.8% and improve MRR by 118.8%.

Laser-ECC and LM-PECM both have separated laser action and ECM action, where are characterized by removing recast layer offline. Laser-ECC used electrochemical corrosion to as a kind of post-processing technique to remove the residual recast layer on the hole wall [14]. Compared to the hole drilled before ECC, after ECC processing, the average thickness of recast layer is reduced from 58 μm to 19μm. LM-PECM used pulse electrochemical machining to remove recast layer of hole machined by laser drilling [15]. The workpiece material is nickel based superalloy. When the frequency of voltage is 1-3kHz and the duty cycle is 40-50%, the recast layers are completely removed by PECM.

Compared with these similar results, it is clearly that the roundness of through hole entrance machined by LD-JECM is better than other results. The taper of the hole machined by LD-JECM is comparable to laser-ECC and LM-PECM.

Table 3. Comparison of through-hole experimental results of similar processing methods

Processing method	Material removal principle	Laser parameters	ECM parameters	Workpiece material	Results
LD-JECM （This paper）	P: laser S: jet-ECM Act together	λ=532nm E_p=200mJ f=5Hz	U=120V Electrolyte: $NaNO_3$ IEG=2mm	321 stainless steel; thickness:0.5mm	
LA-JECM[12-13]	P: jet-ECM S: laser Act together	λ=532nm P=500mW	U=200V Electrolyte: $NaNO_3$ IEG=2mm	Inconel-718 thickness:5mm	
LECM-ITR[4]	P: ECM S: laser Act together	λ=532nm P=20W	U=12V Electrolyte: NaCl	aluminum alloy thickness:2mm	

laser-ECC[14]	P: laser S: ECC Act separately	λ=1064nm E_p=3.2J f=70Hz	U=10V Electrolyte: $NaNO_3$ IEG=1mm	Inconel-718 thickness:1.1mm	
LM-PECM[15]	P: laser S: ECM Act separately	λ=1064nm P_{max}=16kW f=70Hz	U=60V f=2kHz Electrolyte: $NaNO_3$	nicked based superalloy thickness:2mm	

5. CONCLUSIONS

(1) According to the machining principle of LD-JECM, a hybrid machining experimental system has been constructed to meet the technical requirements of combination of laser and jet electrolyte. The new method can manufacture holes without spatter and recast layer.

(2) Based on the analysis of different material removal mechanisms in pulse width and inter pulse of laser, the temperature field of laser drilling coaxially with jet electrolyte and electric field of jet electrochemical machining were simulated separately. Simulative results are consistent with experimental results. The electrochemical dissolving at the edge of entrance is the strongest, which removes the spatter around the entrance and expands the diameter of hole.

(3) Compared with laser drilling in air, recast layer adhered to the sidewall of through hole have been removed in LD-JECM and the exit of the hole is very clean without any resolidified substances. There are not grain corrosions on the machined surface, and there are only a few of micro pitting.

(4) Applied electrochemical voltage and inter electrode gap both are key parameters of the electrochemical dissolving for LD-JECM, which have significant effect on the taper of through hole. In order to obtain high forming accuracy with low taper, the range of electrochemical voltage prefer to be 120 to 200V and the range of inter electrode gap prefer to be 1.5 to 2.5mm.

(5) LD-JECM has great potential for micro-hole precision machining on difficult-to-machine materials.

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