Ultrasonic-assisted electrochemical drill-grinding of small holes with high-quality

Xiangming Zhu, Yong Liu, Jianhua Zhang, Kan Wang, Huanghai Kong

Abstract

Electrochemical drill-grinding (ECDG) is a compound machining technology, which combines Electrochemical machining (ECM) with mechanical drill-grinding process. On this basis, a new method of machining small holes which called ultrasonic-assisted electrochemical drill-grinding (UAECGD) is proposed. First, the principle of UAECGD is analyzed through analysis of UAECGD process and electrochemical passivation behavior of materials. Second, the simulation of electrochemical drill-grinding process was studied to illustrate the effect of ball-end electrode on reducing the hole taper and improving the machining accuracy. Afterwards, several groups of experiments are conducted to analyze the influence of electrical parameters, ultrasonic amplitude and matching degree between electrolysis and mechanical grinding on the machining quality of small holes. Finally, small holes with diameter of 1.1 ± 0.01 mm, surface roughness of 0.31 μm and taper of less than 0.6 degree were machined by UAECGD, which revealed UAECGD is a promising compound machining technology to fabricate small holes with high quality and high efficiency.

© 2020 THE AUTHORS. Published by Elsevier BV on behalf of Cairo University. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).
**Introduction**

Small holes are widely used in aerospace, automobile, ship and other industries, such as engine blades, combustion chambers, cooling rings, bottom plates and so on [1–4]. Generally speaking, holes with diameter of 0.3–3 mm are called small holes [5,6]. Because the diameter of small holes is relatively small, and the machining materials, such as titanium alloy [7], nickel-based superalloy [8] and stainless steel [9], are usually difficult to machine, therefore, it is hard to realize high machining precision and surface roughness by mechanical methods, in which machining tools also wear a lot [10]. In the field of non-traditional machining, laser machining and EDM will inevitably produce recast layer and micro-cracks on the machined surface, which is prone to stress concentration and do great harm to the structure [11–14]. Conventional ultrasonic-grinding machining can cause great wear and tear to abrasives, which is difficult to process materials with good plasticity and toughness. And Conventional ECM cannot meet the production needs of high machining accuracy and high stability [15,16].

In order to solve the defect of single machining method, many scholars combine different machining methods and put forward various compound machining methods. Among them, electrochemical grinding (ECG) is a compound machining method with many advantages, such as low induced stress, high machining efficiency, large depths of cut, and high machining precision [17–19]. During ECG process, with the feeding of machining tools, some of the substrates are dissolved, some of them are passivated and a thin and brittle passivation film is formed on the surface of the substrates are dissolved, some of them are passivated and a thin and brittle passivation film is formed on the surface of the substrates, which is from 0.5 mm/min to 2.4 mm/min, massive of electrochemical products are removed by grinding. On the tool electrode also wear a lot [10]. In the field of non-traditional machining, laser machining and EDM will inevitably produce recast layer and micro-cracks on the machined surface, which is prone to stress concentration and do great harm to the structure [11–14]. Conventional ultrasonic-grinding machining can cause great wear and tear to abrasives, which is difficult to process materials with good plasticity and toughness. And Conventional ECM cannot meet the production needs of high machining accuracy and high stability [15,16].

In order to solve the defect of single machining method, many scholars combine different machining methods and put forward various compound machining methods. Among them, electrochemical grinding (ECG) is a compound machining method with many advantages, such as low induced stress, high machining efficiency, large depths of cut, and high machining precision [17–19]. During ECG process, with the feeding of machining tools, some of the substrates are dissolved, some of them are passivated and a thin and brittle passivation film is formed on the surface of the substrate. The abrasive particles at the outer end of the tool contact the passivation film and some electrochemical product which adsorbed on the surface of passivation film, then scrape them off.

On the material removal principle of electrochemical drill-grinding, Ge et al. [20] consider that ECM dissolves the anode workpiece at high applied voltage which is 20 V and high feed rate which from 0.5 mm/min to 2.4 mm/min, massive of electrochemical products adsorbed on the surface of the substrate are scraped off by abrasive particles instead of the passive film formed. At the same time, due to the removal of the easily dissolved material, some insoluble components in the anode substrate materials are gradually exposed. All these insoluble components and electrochemical products are removed by grinding. On the tool electrode of ECG, Niu et al. [21] employed an abrasive tool with arrayed holes, and after finish machining with ECG, the surface roughness decreased dramatically, from 1.65μm to 0.648μm. On the abrasives wear in ECG technology, some scholars put forward that diamond is the common abrasive for grinding, compared with mechanical grinding, the tool loss of ECG with diamond is 4 to 15 times smaller [22]. On the practical application of ECG, Wang et al. [23] use it to improve MoP microparticles’ surface states to improve its catalytic activity.

The another advantage of ECG is that most of oxide/passivation layer on the workpiece is removed by grinding (5–10% of material removal), so harsh/harmful electrolytes are not needed to dissolve passivation layer [24]. However, ECG will produce lots of electrochemical products and insoluble materials, which will lead to the deterioration of the machining environment and may cause short-circuit phenomenon. In order to solve this problem, this paper proposed ultrasound-assisted electrochemical drill-grinding (UAECDG). It is a kind of compound machining method that uses electrochemical reaction to produce passivation film on the surface of material, and removes the passivation film through mechanical grinding and ultrasonic vibration to expose the machined substrate again, so that it can be machined under the alternating process of electrochemical machining, mechanical grinding and ultrasonic impact. In addition, in this paper, ultrasonic vibration is added to the spindle and it is transmitted to the machining tool to produce periodic vibration, then disturbs the electrolyte, so as to accelerate the renewal of electrolyte in the gap, then improve machining quality. The cavitation effect caused by ultrasound can produce lots of micro bubbles and then collapse between the machining gap, resulting in shock wave generation and accelerate erosion of materials [25,26], which is beneficial to improvement of machining efficiency. On the other hand, ultrasound can renew the electrolyte quickly to bring more stable machining environment [27].

**Materials and methods**

The flow chart of work methodology is shown as Fig. 1. Pre-hole machining is carried out on 304 stainless steel plate firstly, which uses cylindrical spiral electrodes for electrochemical drilling process, the real picture of cathode tool for preparing pre-hole is shown as Fig. 2a. In order to prepare the pre-hole, it is necessary to select reasonable machining parameters, which will significantly affect the hole diameter, hole roundness and hole wall surface roughness of the pre-hole, and will affect the machining allowance during the hole-enlarging process. If the machining allowance of the pre hole is too large, the mechanical grinding will be too strong, resulting in low machining efficiency and poor surface quality of the inner wall of the hole. If the pre hole machining allowance is too small, the mechanical grinding effect in UAECDG process will be weakened, which will not significantly improve the machining quality. Therefore, the parameters for preparing the pre-hole need to be selected reasonably, and the optimized parameters are shown in Table 1. After pre-hole with certain machining accuracy and surface quality is machined, the pre-hole is enlarged by means of ultrasonic-assisted electrochemical drill-grinding.

**UAECDG setup and process**

As shown in Fig. 3a, the small holes are machined by ultrasonic-assisted electrochemical drill-grinding set up. While the ball-end electrode rotates continuously, it is accompanied by downward feeding and periodic vibration. It can be seen that the ball-end electrode is equipped with diamond abrasive particles, which are added to the ball-end by electrodeposition as shown in Fig. 2b. The number of diamond abrasives is 1200#. The electrolyte is supplied by side spraying combined with pre-filling in the electrolyte tank.

In UAECDG process as shown in Fig. 3b, a ball-end electrode with diamond abrasive particles is used as tool cathode which rotating at a high speed and ultrasonic vibrating along the axis direction. The ball-end has a larger diameter than the pre-machined hole. Due to the passivation of metals in passive electrolyte, a kind of soft passive oxide film is formed and adhering to the material surface with the electrochemical anodic dissolution of metal materials. With the feed of ball-end electrode, this passive oxide film which negative to electrochemical reaction is soon removed by the diamond abrasives so that the fresh metal materials can be exposed for the consecutive electrochemical reaction. Therefore, the process of material removal includes both mechanical grinding and electrochemical reaction.

Fig. 3c is the schematic diagram of UAECDG. Before the process of UAECDG, a pre-machined hole with a diameter of \( D_0 \) has been fabricated by ECM. In UAEDCG, the material is electrochemically and mechanically removed by the tool’s ball-end with a diameter of \( d \) which is larger than the pre-machined hole diameter \( D_0 \). As
shown in Fig. 3c, the process of UAECDG includes the phases of ECM, ECG, and the secondary electrolysis. Because of too large machining gap during the phases of ECM and secondary electrolysis, the mechanical grinding is not able to remove the passive oxide film effectively which is negative to the electrochemical reaction, so that only a small number of material removal occurs during
the phases of ECM and secondary electrolysis. And the material is mainly removed during the phase of ECG. In addition, the ultrasonic vibration of tool electrode in UAECDG is conducive to update of electrolyte and removing of tiny bubbles and other electrolysis products so that the flow field can be more uniform. Therefore, in order to achieve high machining accuracy, many important factors in UAECDG process, such as the electrochemical behavior of materials, the influence of electrical parameters, ultrasonic amplitude and matching degree between electrolysis and mechanical grinding on the machining quality of small holes should be discussed in the following experiments.

### Electrochemical behavior of 304 stainless steel

304 stainless steel has a passive behavior in passive electrolytes such as NaNO₃ solution [28]. In passivation of metal material, a kind of passive oxide film is formed and adhering to material surface, the passivation film on stainless steel surface are mainly chromium and iron oxides / hydroxides [29]. This passive oxide film which in turn affects electrochemical reaction is a link between the electrochemical reaction and mechanical grinding in UAECDG. It has been found that the surface can be well protected from general corrosion by the passive oxide film which formed in passive solution [30]. To select a proper passive electrolyte and obtain a stable passivation during the process, it is essential to research 304 stainless steel's passivation phenomenon in different electrolyte environments. 304 stainless steel's polarization curves in different concentration electrolyte are investigated by potentiodynamic method as shown in Fig. 4.

As shown in Fig. 4, the passivation performance of 304 stainless steel in 10–20 wt% NaNO₃ solution is quite different. 304 stainless steel in 10 wt% NaNO₃ solution has no obvious passivation interval, and the passivation performance is weak; the passivation potential range in 15 wt% NaNO₃ solution is from 0.58 V to 0.76 V; in 20 wt% NaNO₃ solution, the passivation potential range is from –0.15 V to

| Item               | Value  |
|--------------------|--------|
| Peak voltage       | 7 V    |
| Feed rate          | 0.4 μm/s |
| Electrolyte        | 10 wt% NaNO₃ |
| Rotation speed     | 6000rpm |
| Pulse period       | 10 μs  |
| Duty cycle         | 0.25   |
| Ultrasound amplitude | 5 μm   |

Table 1: Parameters for preparing pre-hole.

---

![Experimental setup](image1)

**Fig. 3.** Sketch of UAECDG process.

![Sketch of machining area](image2)

![Cross-sectional views of UAECDG process](image3)
tion effect of 304 stainless steel in 10-20 wt% NaNO₃ solution is
UAECDG process and reducing stray corrosion In short, the passiva-
and more insulating. It is beneficial to mechanical grinding in
it indicates formed passive oxide film’s microstructure is denser
in passivation state, that is, the passivation reaction is more stable,
density, and among three of them, it has the lowest current density
stainless steel in 20 wt% NaNO₃ solution has quite stable current
0.7 V, the passivation range is wider, also, as Fig. 4 shows, 304
in 10% NaNO₃ solution with different concentrations.

![Polarization curves in NaNO₃ solution with different concentrations.](image)

Simulations of ECDG process

In UAECDG process, ECDG process is the majority, and electro-
chemical machining accounts for the vast majority of material
removal in ECDG, so it is necessary to study the electric field of this
method. In this paper, the electrochemical module of COMSOL
Multiphysics is used to simulate hole-enlarging process. Hole-
enlarging process of 304 stainless steel plate is studied with the
condition of primary current distribution.

Two-dimensional geometric model of gap’s electric field in
ECDG process was established by extracting the contours of pre-
hole and ball-end electrode, as shown in Fig. 5. Among them, the
thickness of workpiece is 500 μm, the diameter of tool electrode
is 1000 μm, the boundary B₁ · B₂ · B₃ · B₄ and B₅ are electrolyte
boundaries, the boundary B₆ and B₇ are workpiece boundaries,
and the boundary B₈ is tool electrode boundary.

For the primary current distribution in this simulation, it is only
 applicable to explain the loss caused by the solution resistance, but
ignores the loss caused by the electrode dynamics and concentration-dependent effect. It assumes that the charge trans-
fer in the electrolyte obeys Ohm’s law. Here, we make two
hypotheses: first, the electrolyte is electrically neutral, which
counteracts the contribution of current to current density; second,
the composition change of electrolyte is insignificant (i.e., uniform
distribution), which counteracts the contribution of diffusion to
current density, allowing us to consider ion strength as a constant.
In other words, there is no activated over-potential. It can be seen
that the distribution of primary current depends only on the geo-
metrical structure of positive and negative electrodes.

In electrochemical machining, the anode and cathode are good
conductors of metal. Therefore, it forms an equal potential surface
on the surface of the cathode and the anode. The potential of the
anode and cathode meet the Dirichlet Boundary Conditions:

\[ \varphi |_{\partial B_6} = \varphi |_{\partial B_7} = \Phi(t) \] (1)

\[ \varphi |_{\partial B_8} = 0 \] (2)

For the electrolyte boundary B₁ · B₂ · B₃ · B₄ and B₅, the
equipotential line in the electrolyte region is approximately verti-
cal to its surface, i.e., the potential derivative along its normal
direction on the electrolyte boundary is approximately 0, which
meets the Norman Boundary Conditions:

\[ \frac{\partial \varphi}{\partial n} |_{B_1} = \frac{\partial \varphi}{\partial n} |_{B_2} = \frac{\partial \varphi}{\partial n} |_{B_3} = \frac{\partial \varphi}{\partial n} |_{B_4} = \frac{\partial \varphi}{\partial n} |_{B_5} = 0 \] (3)

Combining Eq. (1), Eq. (2) and Eq. (3), boundary conditions of
gap electric field in ECDG process can be obtained:

\[
\begin{cases}
\varphi |_{\partial B_6} = \varphi |_{\partial B_7} = \Phi(t) \\
\varphi |_{\partial B_8} = 0 \\
\frac{\partial \varphi}{\partial n} |_{B_1} = \frac{\partial \varphi}{\partial n} |_{B_2} = \frac{\partial \varphi}{\partial n} |_{B_3} = \frac{\partial \varphi}{\partial n} |_{B_4} = \frac{\partial \varphi}{\partial n} |_{B_5} = 0
\end{cases}
\] (4)

The simulation parameters of ECDG process are shown in
Table 2. The simulation results for ECDG process are shown in
Fig. 6.

As shown in Fig. 6(a, b), the current concentrates in the area
where the ball-end is very close to the workpiece, while there is
almost no current in other areas, which indicates that the localization
of ECDG adopted in this paper is very good. As shown in
Fig. 6(d), it can be seen that the taper of final hole is much smaller
after hole-enlarging by UAECDG, compared with the pre-hole. This
is because compared with the cylindrical spiral electrode, the dis-
advantageous electrified area of the ball-end electrode has a larger
machining gap with the anode workpiece, which greatly reduces the
secondary electrolysis effect of the anode workpiece, which can
also be seen in Fig. 6(a, b, c). It is verified that the current den-
sity drops sharply in the machining area with machining gap more
than 50 μm, which reduces the secondary electrochemical corro-
sion and decreases the hole taper. It indicates that UAECDG can
effectively improve the machining quality of the small hole.

![Two-dimensional geometric model of gap electric field in ECDG process.](image)

| Item               | Value          |
|--------------------|----------------|
| Applied voltage    | 3.3 V          |
| Feed rate          | 4 μm/s         |
| Conductivity       | 11.65S/m       |
| Machining time      | 2805           |
| Initial machining gap | 20 μm         |
Results and discussion

Pre-holes were machined by ECM for preparing for further hole enlargement. Pulse power supply was employed in pre-hole machining process, and the tool is a spiral electrode with a diameter of 0.8 mm. Several pre-holes with good repetition accuracy were successfully machined on 304 stainless steel plate with 0.5 mm thickness. In order to meet the requirement of inner wall surface roughness less than 0.4 μm. Therefore, further UAECDG enlargement of pre-holes is a necessary process.

To measure diameter of small holes and observe contour of small holes, Nikon SMZ1270 optical microscope was used; to observe Micro-morphology of inner surface of the small hole, FEI Nova Nano-SEM 450 was employed; to measure surface roughness of hole wall, Wyko NT9300 white light interferometer was used.

Discussion on electric machining parameters

Electrical machining parameters are the controlling factors in UAECDG process. As we know, the material removed by electrochemical machining accounts for about 90% of the combined electrochemical grinding machining. In this paper, the role of ultrasonic vibration is to make the removal and renewal of electrolyte more effectively. In the UAECDG process, electrochemical machining is still the main etching way, so, the selection of electrochemical machining parameters is very important.

To explore the influence of machining voltage and duty cycle in UAECDG process, several groups of comparative experiments were carried out. Machining efficiency is characterized by the optimal feed rate, which is the maximum feed rate without short circuit in UAECDG process. The experimental results are shown in Fig. 10a.

As shown in Fig. 10a, with increasing of machining voltage, optimal feed rate increases correspondingly, due to the enhancement of electrochemical etching when the voltage increases, and the increase of the etching material at the same time, so the optimal feed rate increases correspondingly. With increasing of duty cycle, optimal feed rate increases, which is similar to the principle of voltage increase, it is caused by the increase of energy density of material etching. When the voltage and duty cycle are maximum, the optimal feed rate is maximum. However, at the same time, stray corrosion becomes more and more serious due to the high energy density of erosion. Moreover, passivation film is easy to be broken down and large pieces of erosion material fall off, resulting in a serious decline in surface quality.

![Simulation results of ECDG process.](image-url)
Therefore, in the case of a certain feed rate, the electrical machining parameters with smaller energy density should be selected. At present, there are two choices, one is high voltage with low duty cycle, the other is low voltage with high duty cycle. When the duty cycle reaches 100%, the pulse signal becomes a DC voltage stabilized signal. As shown in Fig. 7, it is obvious that the shape of small holes produced by DC voltage stabilization at low voltage is superior to that produced by high frequency pulse at high voltage. Although high frequency pulse can enhance the localization of machining, stray corrosion is still serious under high voltage, resulting in worse hole shape, so the hole shape under low voltage DC voltage stabilization machining is better. At last, DC voltage stabilization under low voltage was chosen as the machining parameter of hole-enlarging process in this paper. As shown in Fig. 10a, optimal feed rate is moderate and stable at low voltage of 3–3.5 V. Finally, 3–3.5 V was chosen as the next step to explore the more suitable voltage range for UAECGD, and the feed rate is 2.5–4.5 μm/s.

Matching of ECM and mechanical grinding

The electrical parameters mentioned above have a great influence on hole-enlarging process. Similarly, if there is no good cooperation with other machining parameters, the advantages of UAECGD cannot be reflected. In this paper, the electrochemical grinding process removes most of the material by electrochemical machining, and a brittle passivation film is formed on the surface of the material. The diamond abrasives attached to the ball-end scrape the passivation film away by the rotation of the spindle, and a new passivation film is produced on the exposed material. Thus, along with the electrochemical corrosion reaction, passivation-grinding also takes place. Continuously alternating, the final hole is produced by this compound machining method. However, if electrochemical machining and mechanical grinding do not match, there will inevitably be the following poor machining situation as shown in Fig. 8.

As shown in Fig. 8a, when the electrochemical effect is too strong, it can be seen that the inlet of the hole wall has a large stray corrosion, and the diamond abrasives cannot touch the material, and the finishing effect of mechanical grinding cannot be reflected. As shown in Fig. 8b, when the mechanical grinding effect is too strong, although the hole wall is steep, there are obvious scratches on the inner wall caused by mechanical grinding. It is caused by
the direct grinding of the material substrate by diamond abrasives, which lead to increasing of the surface roughness of inner wall. Moreover, due to the direct contact between tool electrodes and the substrate, a lot of scratches are produced. The mechanical grinding force can desorb a large amount of diamond, cause serious electrode wear, and greatly reduce the repeatability. Therefore, the direct grinding of the material substrate by diamond abrasives, which lead to increasing of the surface roughness of inner wall. Moreover, due to the direct contact between tool electrodes and the substrate, a lot of scratches are produced. The mechanical grinding force can desorb a large amount of diamond, cause serious electrode wear, and greatly reduce the repeatability. Therefore,
matching of electrochemical machining and mechanical grinding is very important. It is reflected in the matching of machining parameters, for example, the matching of applied voltage and feed rate. Therefore, in order to determine better machining parameters, several groups of experiments were conducted. As shown previously, the machining voltage is determined to be 3–3.5 V, and the feed rate is 2.5–4.5 μm/s.

Firstly, the effect of feed rate and applied voltage on small holes’ diameter machined by UAECGD is discussed. The experimental results are shown in Fig. 10b. The diameter increases with the applied voltage. As the increase of applied voltage, the amount of material eroded by electrochemical effect increase in the same machining time, so the diameter becomes larger. Secondly, the diameter decreases with the feed rate increasing, it results in reduction of erosion per unit time and reduction of diameter.

For researching the influence of applied voltage and feed rate on surface roughness of small holes’ inner wall, Wyko NT9300 white light interferometer is used to observe and measure the surface roughness of small holes’ inner wall. The measurement results

| Item                  | Value          |
|-----------------------|----------------|
| Applied voltage       | 3.3 V          |
| Feed rate             | 4 μm/s         |
| Electrolyte           | 20 wt% NaNO₃  |
| Rotation speed        | 12000 r/min    |
| Number of diamond abrasives | 1200#    |
| Ultrasound amplitude  | 0–10 μm        |

Table 3: Machining parameters for UAECGD.

![Fig. 11. Typical small holes machined by UAECGD.](image-url)
are shown in Fig. 10c, when applied voltage is 3.3 V and feed rate is 4μm/s, ECM matches the mechanical grinding best.

As shown in Fig. 9b, after UAECGD process, the inner wall of the small hole is smooth and the wall is steep as applied voltage is 3.3 V and feed rate is 4μm/s, it verifies that these parameters are the best which match electrochemical machining and mechanical grinding.

**Effect of ultrasonic vibration on machining quality of small holes**

In this paper, ultrasound is transmitted to spindle from ultrasonic generator, and then to the tool electrode, which makes the electrode produce periodic up-and-down vibration, then improves the removal and renewal of electrolyte during hole-enlarging process, optimizes the machining environment, and improves the machining stability and quality.

The main controlling factors of ultrasonic machining are ultrasonic amplitude and frequency, in which the resonant frequency obtained by sweeping the tool electrodes is generally 24.9–25.1 kHz, and the ultrasonic amplitude is the controlling factor in this section. In order to explore the influence of ultrasonic vibration on the optimal feed rate in UAECGD, this paper used the parameters of Table 3 as the machining parameters, in which the ultrasonic amplitude is varying from 0 to 10μm. The machining results are shown in Fig. 10d.

As shown in Fig. 10d, with increasing of ultrasonic amplitude, optimal feed rate increases correspondingly. This is because the increase of amplitude leads to the enhancement of mass transfer effect of electrolyte and the improvement of electrochemical machining environment, which reduces the probability of short circuit and increases the optimal feed rate accordingly. And then, optimal feed rate increases sharply and reaches a relatively stable state when ultrasonic amplitude changes from 0μm to 2.5μm, that is, from no ultrasonic to ultrasonic. The increased optimal feed rate shows that the machining efficiency of hole-enlarging process has been significantly improved by ultrasonic vibration. In addition, it can be seen from Fig. 10d, when the ultrasonic amplitude is 5μm, the optimal feed rate is 5.5μm/s.

For researching the influence of ultrasonic vibration on surface roughness of small holes, experiments which employ machining parameters in Table 3 are carried out in this section.

As shown in Fig. 10d, with increasing of the ultrasonic amplitude, surface roughness of small holes inner wall decreases continuously. When the ultrasonic amplitude reaches 5μm, it reaches the minimum of 0.31μm. In addition, it can be seen that when the ultrasonic amplitude changes from 0μm to 2.5μm, i.e. from non-ultrasonic to ultrasonic vibration, the surface roughness of small holes inner wall decreases from 0.65μm to 0.35μm, and reaches a relatively stable state, which indicates that the surface roughness of the hole-enlarging process has been significantly improved by ultrasonic vibration.

**Typical machining results**

Combined with the previous experiments and analysis, by choosing the following machining parameters of UAECGD, the best quality holes can be obtained on 304 stainless steel plate. The applied voltage is 3.3 V, the feed rate is 4μm/s, the electrolyte is 20 wt% NaNO₃, the electrode rotation speed is 12000r/min, the number of diamond abrasives is 1200#, and the ultrasonic amplitude is 5μm. The typical machining results are shown in Fig. 11.

As shown in Fig. 11, the holes obtained by UAECGD has good dimensional consistency, good surface quality and minimal taper. Compared with the pre-holes, there are almost no electrochemical flow mark and pitting corrosion, and the machining quality has been greatly improved. Therefore, by means of UAECGD, small holes with diameter of 1.1 ± 0.01 mm, taper of less than 0.6 degrees and surface roughness of 0.31μm can be machined on 304 stainless steel plate.

**Conclusions**

In this paper, a brand-new technology UAECGD was proposed, the conclusions can be summarized as follows:

1. Through the study of the anode polarization curve of 304 stainless steel, it is concluded that 20 wt% NaNO₃ solution can produce the most stable passivation reaction and reduce the stray corrosion, which is most conducive to hole-enlarging by UAECGD.

2. The electric field simulation results of the ECDG process revealed that the ball-end electrode used in this paper can effectively improve the machining localization and reduce the secondary electrochemical corrosion.

3. Experimental study of ultrasonic amplitude in UAECGD process proved that combined the ECDG technology with reasonable ultrasonic vibration can effectively improve the machining efficiency and the surface roughness of small holes.

4. Influence of electrical parameters, ultrasonic amplitude and matching degree between electrolysis and mechanical grinding on the machining quality of small holes are discussed experimentally, which demonstrated that the small holes with the hole diameter of 1.1 ± 0.01 mm, the taper of less than 0.6 degree, the surface roughness of 0.31 μm can be obtained on 304 stainless steel plate by UAECGD with the optimal parameters.

5. For further research, UAECDM technology in this paper could be rapidly applied to the field of metal additive manufacturing, in order to significantly improve the machining accuracy and surface quality of small hole structures in metal additive manufacturing parts.

**Declaration of Competing Interest**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

**Acknowledgements**

Authors acknowledge financial support from the National Key R&D Program of China (No.2018YFB1105900), the Key R&D Program of Shandong Province (No. 2019GGX104023), the Natural Science Foundation of Shandong Province (No. ZR2018MEE018), the China Postdoctoral Science Foundation (Nos. 2018M630772, 2019M662347), and the Young Scholars Program of Shandong University, Weihai (No. 2015SWLJH03).

**References**

[1] Gurav MM, Gupta U, Dahade UA. Quality evaluation of precision micro holes drilled using pulsed Nd:YAG laser on aerospace nickel-based superalloy. Mater Today: Proc 2019;19:575–82.

[2] Wang Y, Jiang P. Fluctuation evaluation and identification model for small-batch multistage machining processes of complex aircraft parts. Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture 2015;231(10):1820–37.

[3] Geng D, Teng Y, Liu Y, Shao Z, Jiang X, Zhang D. Experimental study on drilling load and hole quality during rotary ultrasonic helical machining of small-diameter CFRP holes. J Mater Process Technol 2019;270:195–205.
[4] Sen M, Shan HS. Analysis of Roundness Error and Surface Roughness in the Electro Jet Drilling Process. Mater Manuf Processes 2006;21(1):1–9.

[5] Jia BX, Wang ZL, Zhao WS. Micro hole machining technology based on non-traditional machining. Electromachining Mould 2005;02:1–5 (in Chinese).

[6] Ai DM, Jia ZX. Development status of small hole machining technology. Mechanical Engineer 2000;01:8–10 (in Chinese).

[7] Chari NJ, Pei ZJ, Treadwell C. Rotary ultrasonic machining of titanium alloy: effects of machining variables. Machining Science and Technology 2006;10 (3):301–21.

[8] Shao-Hsien C, Tsai K-T. Predictive Analysis for the Thermal Diffusion of the Plasma-Assisted Machining of Superalloy Inconel-718 Based on Exponential Smoothing. Adv Mater Sci Eng 2018;2018:1–9.

[9] Guodong L, Yong L, Quancun K, Hao T. Selection and Optimization of Electrolyte for Micro Electrochemical Machining on Stainless Steel 304. Procedia CIRP 2016;42:412–7.

[10] Liu Y, Wu X, Hong H. Investigation of Electrochemical Nanostructuring with Ultrashort Pulses by Using Nanoscale Electrode. Curr Nanosci 2019;15(3):279–88.

[11] Wu Q, Ma Y, Jie J, Yu Q, Liao Y, Fang R, et al. Hole drilling of Inconel 718 by high intensity pulsed ultraviolet laser. J Laser Appl 2003;15(3):168–71.

[12] Morar NI, Roy R, Mehnen J, Marimuthu S, Gray S, Roberts T, et al. Investigation of recast and crack formation in laser trepanning drilling of CMSX-4 angled holes. The International Journal of Advanced Manufacturing Technology 2018;95(9–12):4059–70.

[13] Tao X, Liu Z, Qiu M, Tian Z, Shen L. Research on an EDM-based unitized drilling process of TC4 alloy. The International Journal of Advanced Manufacturing Technology 2018;97(1–4):867–75.

[14] Li C, Zhang B, Li Y, Tong H, Ding S, Wang Z, et al. Self-adjusting EDM/ECM high speed drilling of film cooling holes. J Mater Process Technol 2018;262:95–103.

[15] Kumar J, Khamba JS, Mohapatra SK. Investigating and modeling tool-wear rate in the ultrasonic machining of titanium. The International Journal of Advanced Manufacturing Technology 2008;41(11–12):1107–17.

[16] Zhao J, Wang F, Zhang X, Yang Z, Lv Y, He Y. Experimental Research on Improving ECM Accuracy and Stability for Diamond-hole Grilles. Procedia CIRP 2018;68:684–89.

[17] Qu NS, Zhang QL, Fang XL, Ye EK, Zhu D. Experimental Investigation on Electrochemical Grinding of Inconel 718. Procedia CIRP [Internet]. Elsevier BV 2015;35:16–9.

[18] Judal KB, Yadava V. Electrochemical magnetic abrasive machining of AISI304 stainless steel tubes. Int J Precis Eng Manuf 2012;14(1):37–43.

[19] Zhu D, Zeng YB, Xu ZY, Zhang XY. Precision machining of small holes by the hybrid process of electrochemical removal and grinding. CIRP Ann 2011;60(1):247–50.

[20] Ge Y, Zhu Z, Wang D, Ma Z, Zhu D. Study on material removal mechanism of electrochemical deep grinding. J Mater Process Technol 2019;271:510–9.

[21] Niu S, Qu N, Yue X, Li H. Effect of tool-sidewall outlet hole design on machining performance in electrochemical mill-grinding of Inconel 718. J Manuf Processes 2019;41:10–22.

[22] Zaborski S, Lupak M, Poroń D. Wear of cathode in abrasive electrochemical grinding. J Mater Process Technol 2004;149(1–3):414–8.

[23] Wang T, Du K, Liu W, Zhu Z, Shao Y, Li M. Enhanced electrocatalytic activity of Mo/P microparticles for hydrogen evolution by grinding and electrochemical activation. J Mater Chem A 2015;3(8):4368–73.

[24] Curtis DT, Soo SL, Aspinwall DK, Sage C. Electrochemical superabrasive machining of a nickel-based aeroengine alloy using mounted grinding points. CIRP Ann 2009;58(1):173–6.

[25] Hutli E, Nedeljkovic MS, Bonyár A, Légrády D. Experimental study on the influence of geometrical parameters on the cavitation erosion characteristics of high speed submerged jets. Exp Therm Fluid Sci 2017;60:281–92.

[26] Nagalingam AP, Yeo SH. Effects of ambient pressure and fluid temperature in ultrasonic cavitation machining. The International Journal of Advanced Manufacturing Technology 2018;98(9–12):2883–94.

[27] Zhao Q, Deng Z, Yang D, Gu X, Zhu Y. Study on Multi-effect Synergy Mechanism of the Ultrasonic Compound Electro-discharged and Electrochemical Machining and Real Time Optimal Controlling of On-line Parameters. Procedia CIRP 2018;68:150–5.

[28] Wang D, Zhu Z, He B, Ge Y, Zhu D. Effect of the breakdown time of a passive film on the electrochemical machining of rotating cylindrical electrode in NaNO 3 solution. J Mater Process Technol 2017;239:251–7.

[29] Xu H, Wang L, Sun D, Yu H. The passive oxide films growth on 316L stainless steel in borate buffer solution measured by real-time spectroscopic ellipsometry. Appl Surf Sci 2015;351:367–73.

[30] Zhang B, Wang J, Wu B, Guo XW, Wang YJ, Chen D, et al. Unmasking chloride attack on the passive film of metals. Nature. Communications 2018;9(1).