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# Developments, challenges and future trends in advanced sustainable machining technologies for preparing array micro-holes

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The use of array micro-holes is becoming increasingly prevalent across a range of industries, including the aerospace, automotive, electronics, medical and chemical industries. The utilization of advanced sustainable machining technologies offers distinctive advantages and is pivotal for the sustainable manufacture of array micro-holes. This paper examines the sustainable machining techniques commonly employed in the production of array micro-holes, including electrical discharge machining, laser machining, electrochemical machining and composite machining technologies. The paper begins with an elaboration of the processing principles and characteristics of multiple non-traditional machining techniques. The performance indicators of the most commonly used processing technologies in industrial production are summarized from seven perspectives. Six significant avenues for the advancement of sustainable manufacturing technology for array micro-holes have been identified and categorized. This article provides a summary and evaluation of the previous relevant literature, with the aim of offering guidance for the development of array micro-hole processing technologies.

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## 1. Introduction

Array micro-holes have been widely used in various fields, including aerospace, automotive, electronics, medical, and chemical engineering,[1–6] as shown in Fig. 1. The demand for high-quality processing of array micro-holes has significantly increased because of the continuous expansion of their application field.[7] Meanwhile, the technology used for machining micro-holes in arrays is also advancing. In recent years, there

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**Fig. 1** Application of array micro-holes.

have been significant developments in the process of machining array micro-holes, as shown in Fig. 2.

The processing techniques commonly used can be divided into two categories based on their processing principles: traditional processing techniques and non-traditional machining techniques.[8] Traditional processing techniques for array micro-holes typically involve micro-drilling or micro-punching. Micro-punching is advantageous due to its simplicity, low cost, and high production capacity. Xu *et al.*[9] developed new metal foil punching equipment that could efficiently process arrays of micro-holes with high dimensional accuracy. However, manufacturing micro-scale dies was challenging, and the microstructure that could be produced through this process was limited.[10–12] To solve these problems, Xiao *et al.*[13] introduced ultrasonic vibration into the micro-punching process and used molten plastic as a flexible micro-punch to process micro-hole arrays on thin stainless steel plates. They found that the ultrasonic vibration time should be matched to the cylinder pressure and ultrasonic power, otherwise it would lead to a deterioration of the machining quality. Chou *et al.*[14] used a micro-punch to prepare an array of holes on Al5052 alloy. The sample was secured onto the lower die using vacuum adsorption for punching, ensuring precise coaxiality between the punches and the holes of the lower die. Chang *et al.*[15] proposed a sequential combination of micro-punching and laser machining to reduce the tool setting error between the two steps by using a specialized alignment device. The experimental results showed that the array micro-holes prepared by this combined machining process were better quality than those obtained by punching and laser machining. Although the above scholars have diminished the disadvantages of the traditional punching process through the optimization of the micro-punching process, its shortcomings cannot be eradicated, and it is difficult for it to meet the requirements of industrial applications in the short term. Although micro-drilling technology has a high production efficiency and low processing costs, it is not suitable for processing difficult-to-cut materials[16–18] because there are problems such as vibration[19–21] and difficulties in cooling and product removal.[22–24]

The fundamental reason for the above phenomenon is gradually increasing tool wear during the machining process. Khattare *et al.* conducted continuous drilling of straight and oblique holes on Inconel 718 high-temperature alloy with a thermal barrier coating. They found that the tool wear gradually intensified as the number of machining holes increased, leading to a gradual increase in cutting force. Specifically, compared to machining straight holes, tool wear is more severe during machining oblique holes.[33] To reduce the deterioration of machining quality caused by tool wear, Aamir *et al.*[22,34–36] conducted a series of studies on simultaneous drilling with multiple tools. They studied the effects of machining parameters on the multiple hole drilling process for different materials. The results indicated that selecting appropriate cutting tools and processing parameters based on different

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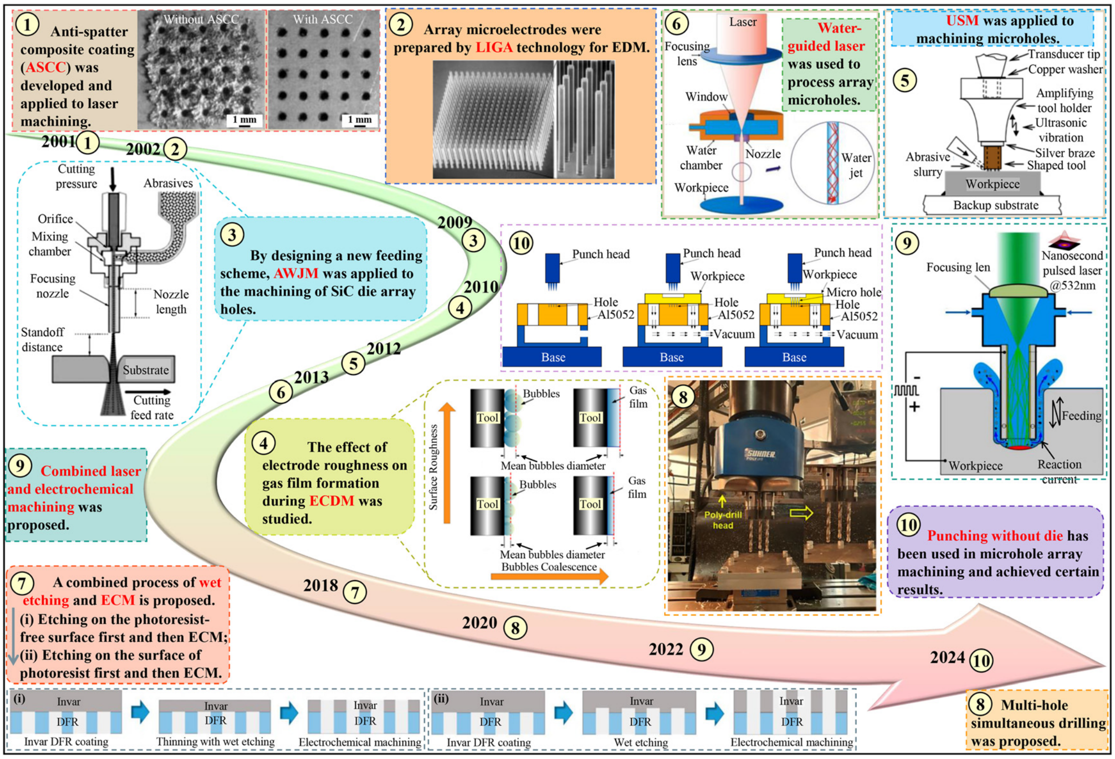


**Fig. 2** Development of important processes for array micro-hole machining.[14,22,25–32]

materials was helpful for obtaining excellent machining surface quality. Meanwhile, the machining efficiency could be greatly improved during machining a group of holes with multi-axis drill bits. Although multiple hole drilling has significantly improved processing quality compared to that of traditional single hole drilling, its processing flexibility and stability still need to be further improved.

Due to current problems with traditional processing methods, they cannot meet the actual processing needs of array micro-holes. Therefore, it is necessary to study non-traditional machining technologies suitable for processing array micro-holes. As for non-traditional machining technology, energy fields such as electricity, heat, sound, and light are utilized to process samples.[37,38] The commonly used non-traditional machining techniques for array micro-hole machining include electrical discharge machining (EDM), laser machining (LBM), and electrochemical machining (ECM).[39] This paper mainly discusses the mainstream non-traditional machining technologies and their composite processing technologies for array micro-hole processing. The processing principles, advantages and disadvantages, and existing problems of various processing technologies, are analyzed. The future development directions for array micro-hole processing technologies are discussed.

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# 2. Sustainable non-traditional machining technologies

## 2.1. Electrical discharge machining

Electrical discharge machining (EDM) is very important non-traditional machining technology that utilizes the high heat generated by instantaneous spark discharge to remove material.[40–42] The machining principle is shown in Fig. 3. Compared with traditional machining methods, EDM has the advantages of no cutting force and low processing costs. It is one of the effective techniques for machining array micro-holes on conductive materials.[43] However, there are still many problems in the machining of array micro-holes by EDM, such as tool electrode wear and recasting layers.[44–48] Solving these problems has become the key to further applying EDM in the processing of array micro-holes.

According to the number of machining electrodes, EDM can be divided into single electrode machining and multi-electrode simultaneous machining.[49] The preparation accuracy of micro-electrodes directly affects the machining quality of array micro-holes. Numerous researchers explored the high-precision preparation of a single micro-electrode. Li *et al.*[49] developed a new type of electrode wire grinding tool that effectively solved the problem of electrode wire vibration in wire electrical discharge machining, and a micro-electrode with a diameter of 40 μm was obtained. Subsequently, they used the prepared electrode and RC mode pulse generator to machine an array of micro-holes with a diameter of 50 μm on a stainless steel plate. But its machining efficiency was low, which meant it was unable to meet the requirements for the efficient preparation of micro-electrodes.[50] Jia *et al.*[51] proposed the dual mirror tangential feed WEDG method (TMTF-WEDG), which utilized dual wire discharge grinding to improve the efficiency of electrode preparation. And they produced tungsten micro-electrodes with a length to diameter ratio of fifty. They obtained a consistent array of small holes consisting of 800 holes on 304 stainless steel samples through EDM.

Simultaneous drilling with multiple electrodes resulted in higher efficiency compared to that with a single electrode. When machining with multiple electrodes, it was less affected by tool wear and there was no repeated positioning error, so it could meet the requirements for the efficient machining of array micro-holes. However, the preparation of multiple electrodes was more difficult than that of single electrodes. Exploring effective array electrode preparation processes was crucial for improving the EDM performance in array micro-hole processing. Gong *et al.*[52] used low-speed wire EDM with a wire speed of 2.7 m $s^{-1}$, and divided the preparation process for the array electrode into rough cutting (RC), trimming cutting (TC), and finishing trimming cutting (FTC). As processing progressed, the peak current, pulse conduction time, and open circuit voltage gradually decreased within the ranges of 40–180 A, 4–10 μs, and 85–100 V, respectively. They successfully obtained square tungsten copper alloy array micro-electrodes with small size errors, as shown in Fig. 4a. Compared to the traditional constant speed feed mode, the preparation efficiency of an array electrode prepared by new method was improved by 36.4%. Sun *et al.*[53] proposed a micro-array electrode self-loss precision machining method based on the principle of reverse EDM (R-EDM). They obtained square array electrodes by employing low-speed wire cutting technology. The inherent electrode wear was utilized to obtain an array of shaped holes with a square inlet and a circular outlet, as shown in Fig. 4b. They used the circular part of the irregular hole for R-EDM to obtain a cylindrical array electrode. The

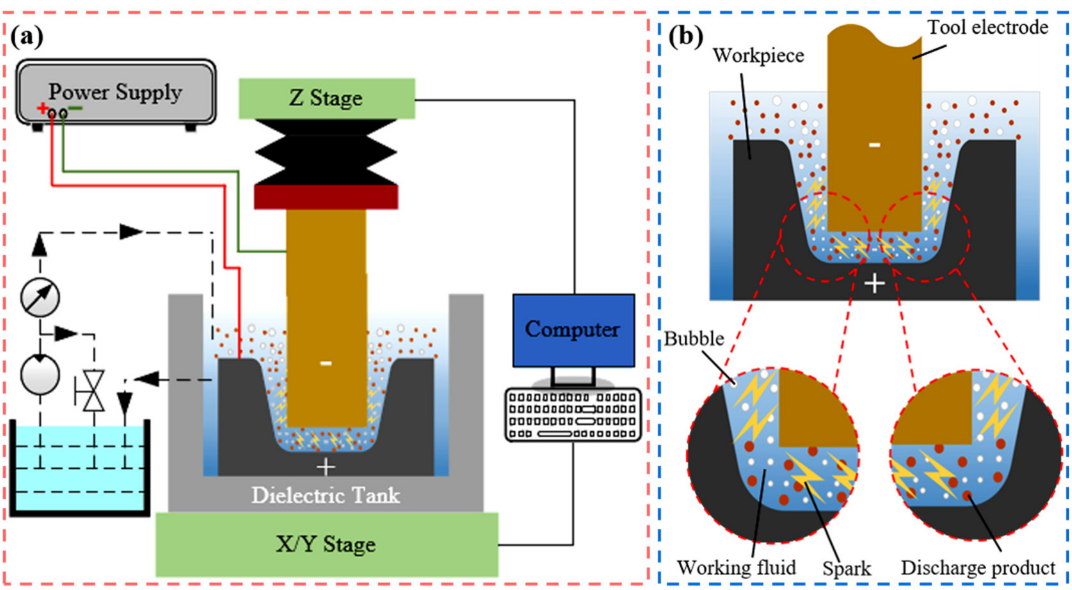


**Fig. 3** Principle of electric discharge machining (EDM): (a) schematic diagram of the overall device; (b) schematic diagram of the processing area.

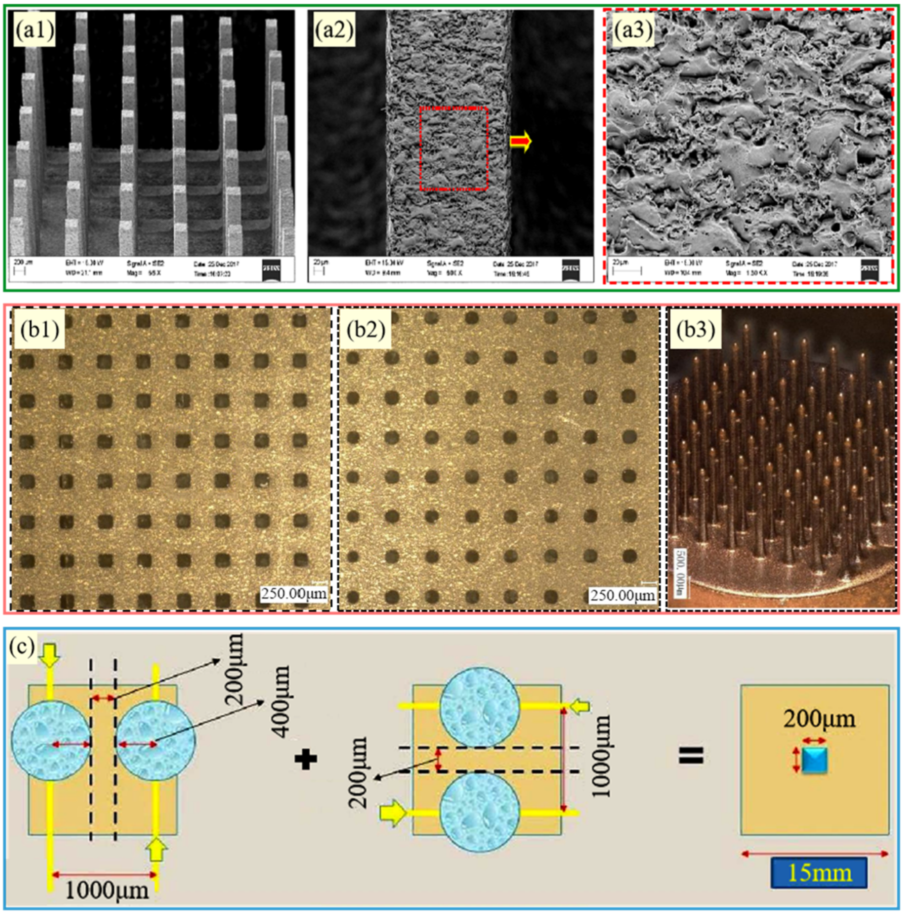


Fig. 4 (a1–a3) Array electrodes prepared by low-speed wire EDM: (a1) panorama; (a2) enlarged view; (a3) local morphology map.[52] (b1–b3) Cylindrical array electrodes prepared by self-loss precision machining: (b1) array micro-hole inlet; (b2) array micro-hole outlet; (b3) picture of array electrodes.[53] (c) Schematic diagram of the array electrode machining strategy.[54]

experimental results showed that this method improved the preparation efficiency and dimensional accuracy of cylindrical array electrodes. Pal *et al.*[54] obtained a square brass array electrode by employing abrasive water jet technology (AWJM). The micro-EDM experiments were carried out on Ti6Al4V, and a large square blind hole array was obtained. The machining strategy for AWJM is shown in Fig. 4c. It is worth noting that the distance between the two scanning lines selected in the AWJM process has a significant impact on the quality of micro-hole machining, and a larger distance of 1.1–1.5 mm is more conducive to ensuring geometric accuracy. However, the array micro-electrodes had a shape error because of inherent defects in abrasive running in during AWJM machining, which caused a deviation between the array micro-holes and the tool electrode.

In addition to the difficulty in preparing micro-electrodes, inevitable electrode wear during the EDM process led to a decrease in the formation accuracy and machining consistency of the micro-holes.[55,56] During the machining process, the tool electrodes continuously experienced axial and radial wear, which would affect the machining gap because of shortening of the electrodes. The radial wear of the electrode gradually transformed the shape of the electrode's end face into an arc, thereby affecting the shape accuracy of the hole,[57,58] as shown in Fig. 5(a and b). Therefore, minimizing the negative impact of electrode wear on the machining process was the key to improving the machining quality of array micro-holes. Research on this issue mainly focused on optimizing electrode wear compensation. Zou *et al.*[59] adopted an online contact measurement compensation strategy to reduce cumulative compensation errors during the machining process, as shown in Fig. 5(c). A radial compensation ($L_r$) of 6.7 μm, a fixed compensation length ($L_c$) of 16 μm, and an initial distance ($D_0$) of 20 μm were used to weaken the influence of electrode wear on machining accuracy, and an array of micro-holes with high machining accuracy was obtained.

Liu *et al.*[60] established a two-dimensional geometric model of electrode wear during machining of an array of holes. After machining 75 micro-holes, the relative errors of the calculated electrode wear length and axial electrode wear zone length were 2.1% and 2.5%, respectively. Subsequently, based on the electrode wear length calculated by the model, they applied a distance compensation to the axial feed rate of the tool electrode, thereby reducing the impact of electrode wear on

 

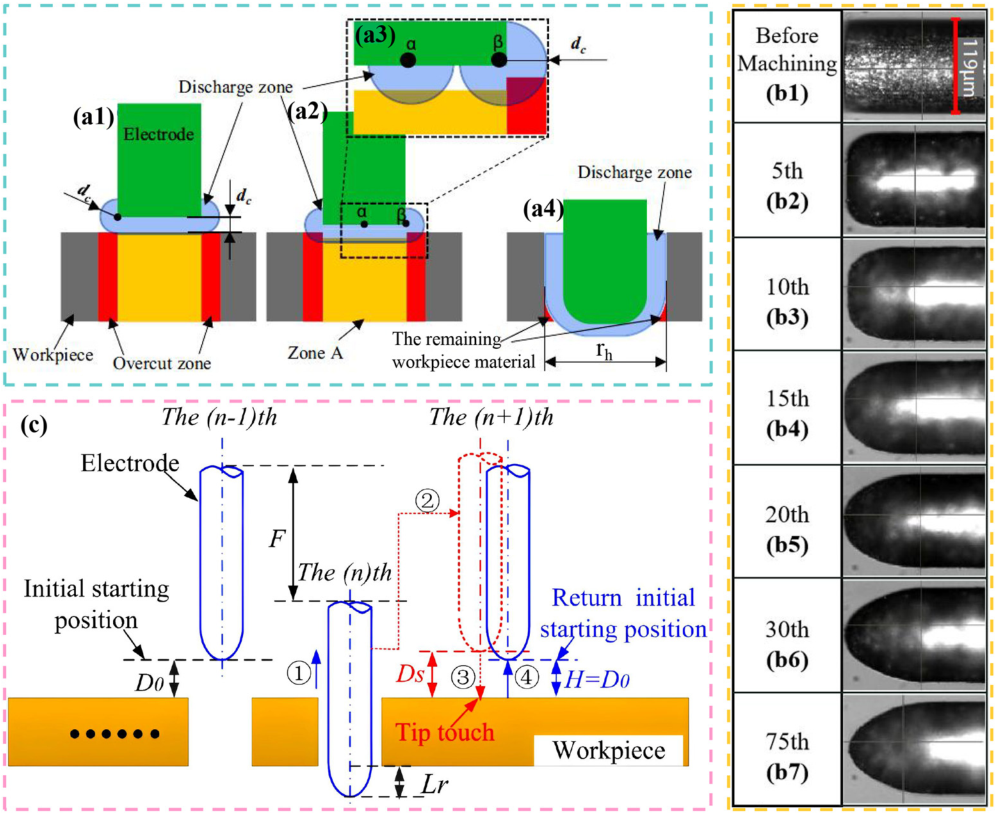


Fig. 5 (a1–a4) Schematic diagram of the electrode wear process: (a1) discharge start; (a2) electrode feed; (a3) partial enlarged view of the discharge gap; (a4) perforation formation.[57] (b1–b7) Evolution of electrode morphology during the array micro-hole machining process.[57] (c) Schematic diagram of the compensation strategy for online contact measurement.[59]

machining accuracy. Liang *et al.*[61] developed a numerical model for predicting the wear shape of square electrodes after multiple diffusion hole processing, and visualized the shape data for the electrode bottom. Due to the uneven distribution of electrode wear across the entire cross-section, they ensured uniform wear of the electrode by rotating the tool electrode at a specific angle based on the electrode wear results. Meanwhile, the axial wear error of the tool electrode was eliminated by controlling the axial feed rate of the tool electrode. This method was only suitable for single electrode machining of array micro-holes because of the difficulty of rotating the array electrodes during the machining process.

In addition, many researchers have attempted different methods to improve the machining quality and efficiency of the EDM of array micro-holes. Zhu *et al.*[62] explored the effect of the working medium on the EDM of array micro-holes. They found that deionized water was more suitable for machining array micro-holes than kerosene. Tanjilul *et al.*[63] developed a new type of metadielectric that could be used for electrical discharge drilling. Consistent array micro-holes were obtained on Inconel 718 alloy by optimizing processing parameters. Compared to deionized water, metadielectrics could improve the processing efficiency and reduce tool electrode wear under appropriate parameters. In addition, they also verified the possibility of processing array micro-holes in metadielectrics. Aruna *et al.*[64] optimized the voltage, frequency, current, and multi-electrode pitch to maximize the material removal rate (MRR) and achieve the lowest possible tool wear rate (TWR). They achieved an MRR of 813.48 μg min$^{-1}$ and a TWR of 82.03 μg min$^{-1}$ under the optimal parameter combination of a voltage of 40 V, a current of 3 A, a frequency of 6 kHz, and a pitch of 1.4 mm. Yu *et al.*[65] used distributed group electrodes and optimized parameters to machine a group of holes on thin-walled titanium alloy parts with high inclination angles. Under the optimal parameters, the processing efficiency increased by 1.5 times. Liu *et al.*[66] established a three-dimensional model of EDM drilling and simulated the changes in the gap flow field. The simulation results showed that the flow velocity of the medium in the gap increased after the penetration of micro-holes, which was conducive to the removal of processed products. Based on this, they accurately identified the perforation stage by detecting the changes in inter-electrode voltage during processing. By adopting the traditional variable feed rate servo control strategy (VFSC) before perforation and the indirect self-tuning control (ISTC) strategy after perforation, the processing efficiency and accuracy improved. Li *et al.*[67] developed a new type of piezoelectric device that could be used in the ultrasonic circumferential vibration (UCV) EDM process. The machining principle is shown in Fig. 6(a). By comparing it with synchronous rotating electrode

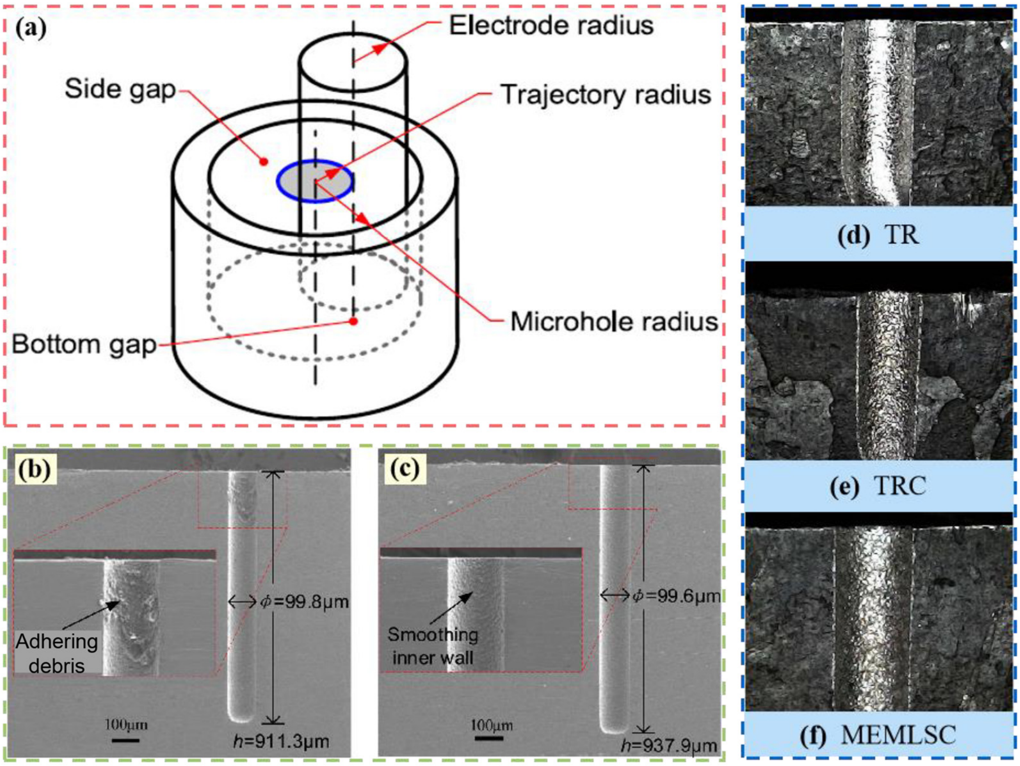


Fig. 6 (a) Schematic diagram of the UCV electrode machining principle. (b) SEM pictures of micro-holes processed by rotating electrodes. (c) SEM pictures of micro-holes processed by UCV electrodes.[67] (d–f) Profile diagram of micro-holes processed by different pulse generators: (d) TR pulsed generator; (e) TRC pulsed generator; (f) MEMLSC pulsed generator.[68]

EDM, they found that the UCV EDM process was beneficial for improving the flow field. This technology improved the efficiency of array micro-hole machining. The roundness error of the obtained array micro-holes was slightly higher than that of the rotating electrode. The surface quality and consistency at the inlet and outlet of the micro-holes were higher than those of rotating electrodes (Fig. 6b and c). Huang *et al.*[68] developed a multi-electrode multi-loop series capacitor pulse generator (MEMLSC), which could achieve uniform discharge from multiple electrodes during a single charging process. This method could improve the stability of the electrical discharge drilling process. Comparative experimental results indicated that the MRR was improved (Fig. 6d–f), and high-quality array micro-holes were obtained on 45-steel with optimized parameters.

## 2.2. Laser beam machining

Laser beam machining (LBM) is a processing technique that uses a high-energy-density laser beam to irradiate the surface of the sample, causing the sample material in the irradiation area to be heated, melted, evaporated, and then removed.[69–71] LBM has good flexibility, high processing efficiency, and high processing accuracy.[72–77] But there were inevitably defects such as a recast layer and a heat affected zone.[78–80] In addition, micro-holes machined by LBM followed a pattern of drilling holes one by one, which would result in repeated positioning errors.[81] The taper of the laser machined micro-hole was relatively large because of the Gaussian distribution of laser beam energy in space.[82]

To improve the quality of laser processed array micro-holes, researchers studied the effects of different processing parameters and then optimized the process of LBM. Rong *et al.*[83] optimized the laser parameters for quantitative micro-hole processing of PDMS thin films by using a UV nanosecond laser in orthogonal experiments. Under the optimal combination of a pulse frequency of 180 kHz and a drilling speed of 0.015 mm $min^{-1}$, the array micro-holes with the best roundness were obtained. The experimental results indicated that thermally induced carbonization was the intrinsic mechanism of the PDMS nanosecond laser micro-drilling process. Liao *et al.*[84] investigated the effect of different processing conditions on nanosecond laser processing of array micro-holes on CVD diamond films. The results indicated that the laser pulse width and laser scanning frequency had no significant effect on the hole entrance size. As the laser pulse width and laser scanning frequency increased, the diameter of the hole outlet increased, while the taper of the hole decreased. As the laser scanning speed increased, the entrance size of the machined hole slightly decreased, while the exit size and taper remained basically unchanged. Meng *et al.*[85] focused on exploring the effects of laser average power and laser scanning speed on blind array hole machining. They found that the average laser power had a significant impact on the diameter and depth of the machined hole. As the average power of the laser increased, the diameter and depth of the hole also increased. The aperture increased with an increase of the laser ablation time, but the depth of the hole remained almost unchanged. Wu *et al.*[86] investigated the effect of different laser wavelengths on the laser drilling of polyurethane synthetic leather. The machined sample exhibited photochemical ablation behavior under laser irradiation at a wavelength of 355 nm, which reduced the thermal impact. Liu *et al.*[87] used a truncated Bessel beam to directly write on the surface of fused silica to prepare square array nano-holes. The intensity distribution of the Bessel beam is shown in Fig. 7a. Numerical simulations and experiments were carried out to investigate the influence of existing holes on the propagation of Bessel beams. The processing parameters were optimized to obtain periodic array nano-holes with good repeatability.

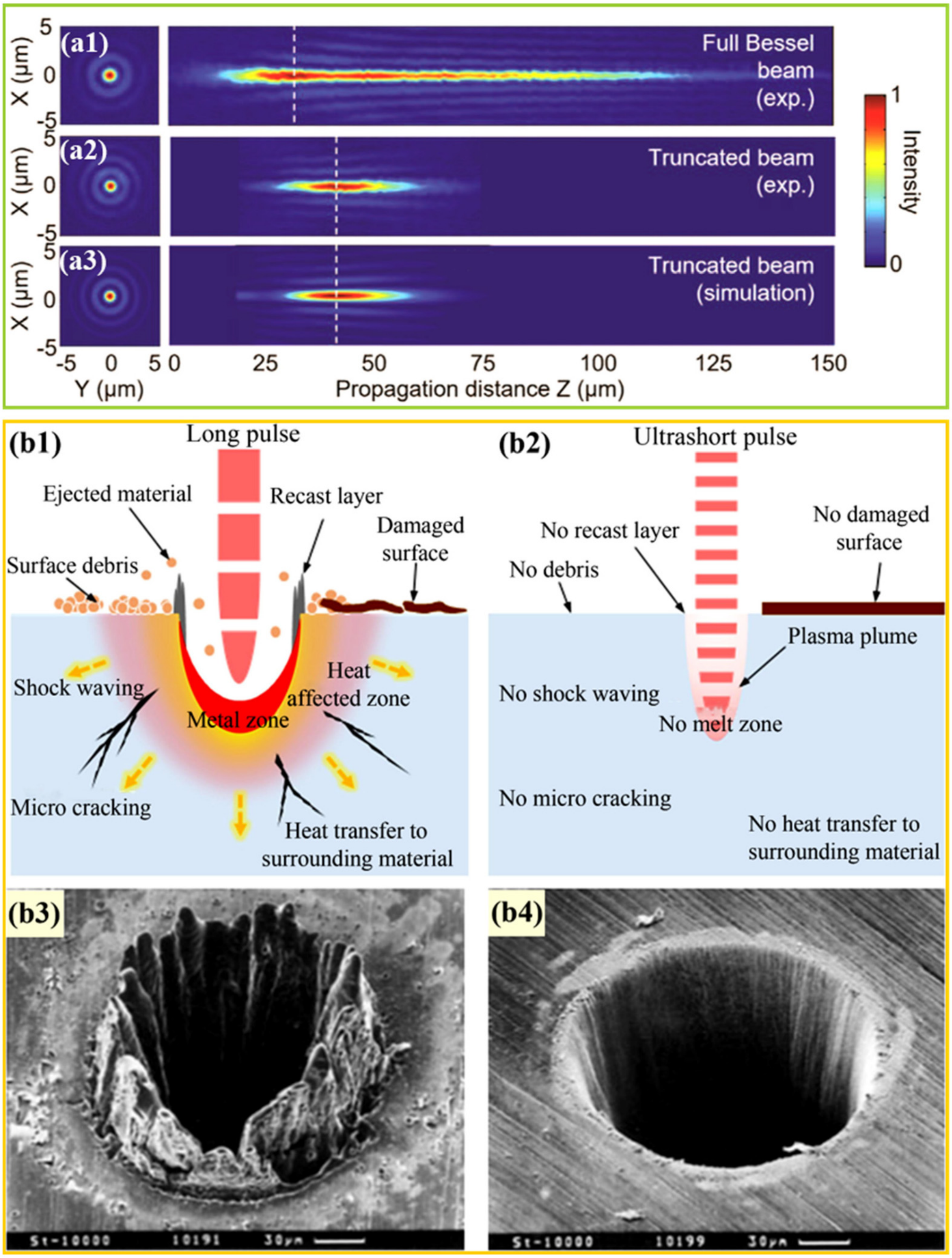


Fig. 7 (a1–a3) Distribution of Bessel beam intensity on the surface of fused silica: (a1) Bessel beam; (a2) experimental truncated Bessel beam; (a3) simulated truncated Bessel beams.[87] (b1–b4) Comparison of ultrafast laser and long pulse laser drilling: (b1) schematic diagram of long pulse laser drilling; (b2) schematic diagram of ultrafast laser drilling; (b3) SEM images of holes processed by a long pulse laser; (b4) SEM images of holes processed by an ultrafast laser.[88]

In addition to the methods of optimizing processing parameters to improve processing quality, ultra-short pulse lasers have received widespread attention in the field of array micro-hole processing in recent years. Compared to long pulse lasers, ultra-short pulse lasers have shorter pulse widths and a higher peak power.[89,90] The thermal effect during ultra-short pulse laser processing was relatively small (Fig. 7b) and was considered to be suitable for high-quality microfabrication.[88,91,92] Ji *et al.*[93] machined circular and triangular hole arrays without cracks on quartz glass by using a picosecond laser. Ahsan *et al.*[94] used a femtosecond laser to fabricate array micro-holes with good consistency on the surface of glass. By utilizing the loss of laser flux inside transparent glass, only the laser flux at the center of the laser's focus reached the material's ablation threshold, therefore, a hole with an aperture smaller than the diameter of the spot was obtained. Shangguan *et al.*[95] established a theoretical model of single pulse femtosecond laser ablation based on the Drude equation, and analyzed the mechanism of femtosecond laser ablation of transparent materials. Subsequently, they used a bottom-up drilling strategy to process array micro-holes on quartz glass. Under the conditions of a single energy pulse of 3 μJ, a scanning speed of 0.1 mm $s^{-1}$, and a defocusing distance of −0.3 mm, they prepared a 10 × 10 array of micro-holes with an aperture of 10 μm and a taper of 2°. Wang *et al.*[96] used a Michael interferometer device to convert a traditional Gaussian femtosecond pulse beam into a dual pulse laser beam with an energy ratio of 1 : 1 for preparing a periodic array of micro-holes on ZnS substrates, and found that the depth of the micro-holes could be controlled by adjusting the pulse energy. Zhai *et al.*[97] obtained array holes with good surface quality on Inconel 718 alloy by applying femtosecond laser shock drilling technology. The basic composition and metallographic structure of the processed thermal barrier coating were hardly changed. Zhang *et al.*[98] machined array micro-holes in PDMS thin films by femtosecond laser spiral drilling. The effects of laser pulse energy and scanning speed on micro-hole profiles were studied. The research results indicated that laser scanning speed significantly affected the geometric structure of micro-holes. As the laser scanning speed increased, the cross-sectional diameter of the hole decreased while the taper of the hole gradually increased. Li *et al.*[99] investigated the effect of different processing parameters on the machining process during femtosecond laser drilling of copper foil with a thickness of 8 μm. By using optimized processing parameters, array micro-holes with a smooth surface, high geometric accuracy, and good consistency were obtained. They found that a single pulse energy had a significant impact on the diameter of micro-holes, while laser frequency had the most significant impact on cumulative thermal effects. Yang *et al.*[100] used axon system shaping to obtain femtosecond Bessel beams for preparing micro-hole arrays on YAG crystals. The experimental results showed that Bessel beams could improve the aspect ratio of micro-holes. Meanwhile, the diameter of micro-holes could be controlled by adjusting the laser's single pulse energy.

In addition, the laser machining quality and efficiency of array micro-holes could be improved by optimizing the processing technology. Ha *et al.*[101] proposed a new process of laser drilling on cover plates for the processing of stainless steel foil. Other materials were coated on the workpiece as a protective layer to reduce material erosion and deformation. Compared with traditional laser processing, the average roundness of the micro-holes processed by this method increased by 77%, and thermal defects were significantly reduced, as shown in Fig. 8(a–e). Liu *et al.*[102] found that it was hard to improve the surface quality of the hole outlet by using single laser processing technology. Therefore, they proposed a new method, which used a protective layer and water to assist in femtosecond laser processing. Array micro-holes on 4H-SiC with smooth inner walls and good consistency were successfully obtained. The processing device is shown in Fig. 8(f). Wang *et al.*[103] achieved high-quality laser drilling on silicon wafers by coating them with aluminum film, resulting in a group of micro-holes with no recast layer on the surface of the machined micro-holes. Thereafter, they further explored the effect of laser flux on the processing of fused silica wafers coated with aluminum film. The results indicated that an increase in laser flux would lead to an increase in the average diameter of the array micro-holes.[104]

Zhao *et al.*[105] conducted a simulation study on the laser ablation of $Al_2O_3$ ceramic array micro-holes. When adjacent holes were continuously eroded, a small high-temperature area was generated, leading to crack propagation along the laser scanning path direction. Therefore, optimizing the scanning path was an effective means of laser processing array holes. Zhanwen *et al.*[106] proposed a thermal input adjustment strategy based on scanning path and parameter optimization to reduce local thermal accumulation effects in multi-beam laser parallel drilling processes. A schematic diagram of multi-beam laser processing is shown in Fig. 9(a). The traditional scanning path and the optimized scanning path are shown in Fig. 9(b and c). Compared with traditional scanning paths, the optimized scanning path had a more uniform temperature distribution with a maximum temperature decrease of 10%. By utilizing this strategy in conjunction with matching machining parameters, high-quality array micro-holes could be machined on stainless steel sheets. To further reduce the heat accumulation problem during the ultra-short pulse laser processing of micro-holes, Lutz *et al.*[107] optimized the laser scanning path using 100 000 generations of genetic algorithms, which reduced thermal defects by 45%. However, 100 000 algorithm iterations were complex and time-consuming. In recent years, new optimization algorithms have emerged continuously, such as the particle swarm optimization algorithm,[108,109] the ant colony optimization algorithm,[110] Bayesian optimization,[111,112] *etc.* This provides new ideas for optimizing laser scanning strategies, and they may be more effective. Zhang *et al.*[113] established an adaptive discrete grey wolf optimization laser drilling model with processing time as the evaluation index. With only 200 iterations, the processing times for 90 holes, 286 holes, and 649 holes were reduced by 38.9%, 53.6%, and 55.5%, respectively. Hartmann *et al.*[114] used different scanning strategies to perform picosecond laser array micro-hole proces-

 

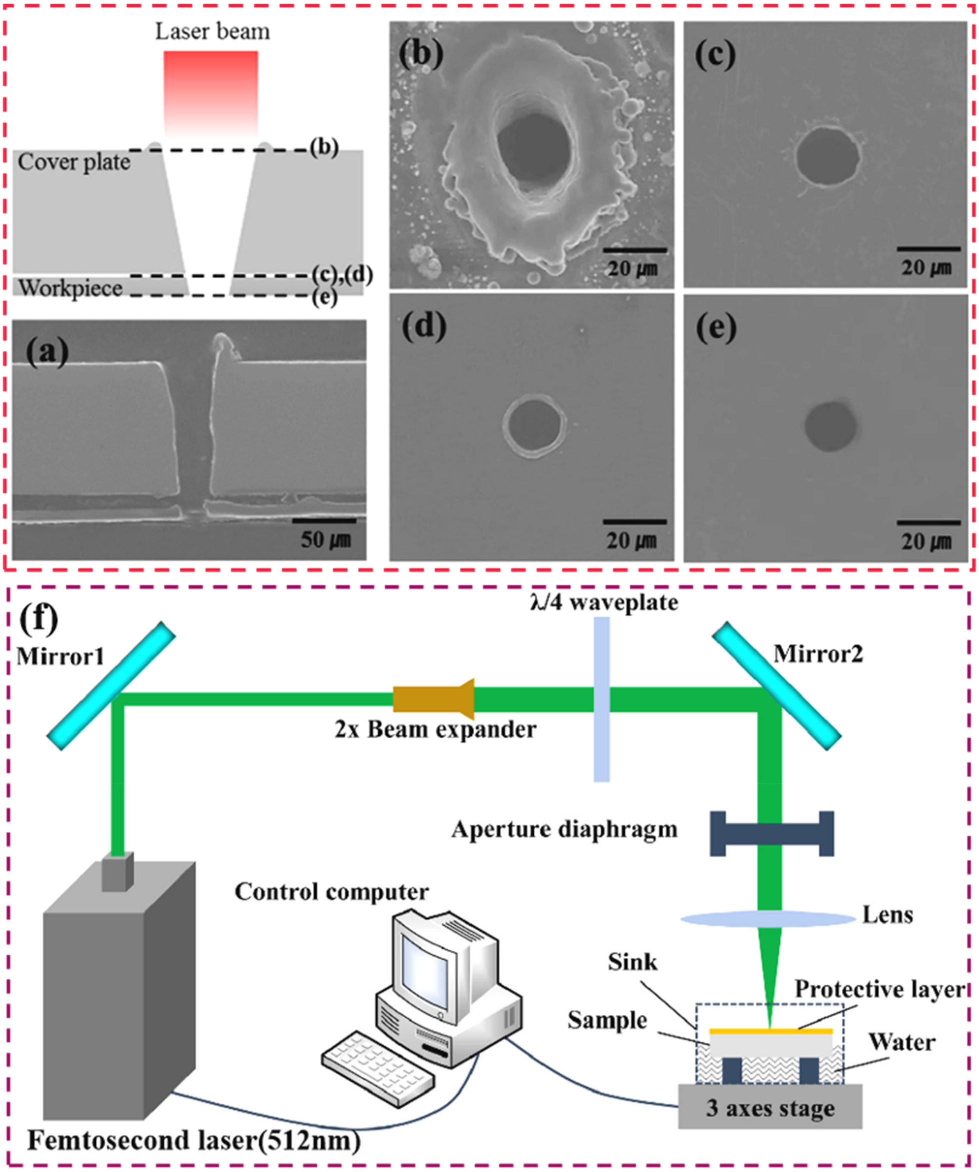


Fig. 8 Laser processed hole on the cover plate. (a) Overall morphology of holes; (b–e) hole morphology diagram at the corresponding cross-section;[101] (f) schematic diagram of a laser processing device assisted by a protective layer and a water layer.[102]

sing on aluminum foil. The experimental results indicated that the linear strategy (Fig. 9d) was more stable in the machining process than the random strategy (Fig. 9e). By studying the effect of picosecond laser frequency on micro-hole machining, it was found that the laser frequency had a significant impact on the ablation behavior during the machining process.[115]

### 2.3. Electrochemical machining

Electrochemical machining (ECM) is a non-traditional machining technique that utilizes the principle of anodic dissolution to remove surface materials from samples.[116–119] Compared with other machining techniques, electrochemical machining had advantages such as no tool wear, no cutting force, no residual stress, and no thermal defects.[120–124] Therefore, it is very suitable for machining array micro-holes.

**2.3.1. Maskless electrochemical machining and its variants.** Although traditional electrochemical machining has many unique advantages, there are problems such as stray corrosion, which seriously affect the machining quality of array micro-holes.[125,126] To reduce the problem of stray corrosion during the machining process, a series of new machining processes have been studied. Wang *et al.*[127] used a new type of disc electrode to machine array micro-holes by ECM on stainless steel (Fig. 10). The machining electric field of the disc electrode was mainly concentrated in the bottom gap of the electrode. The electric field in the side gap was weak, resulting in weaker stray corrosion. Fang *et al.*[128] introduced an auxiliary

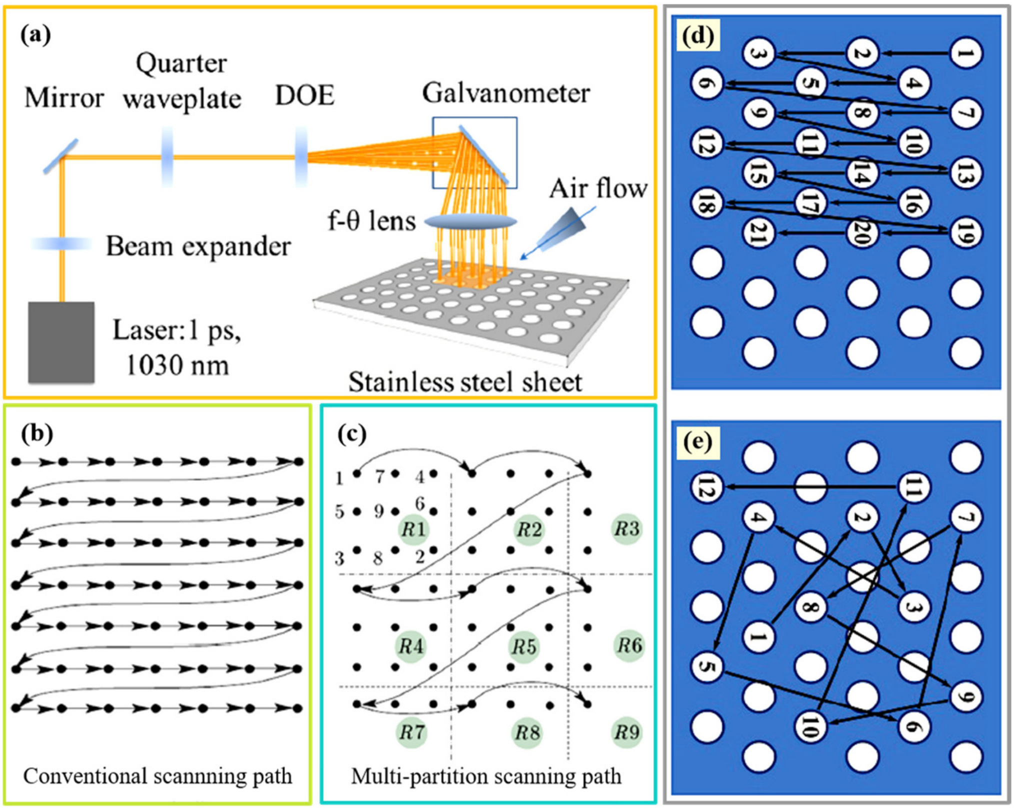


Fig. 9 (a) Schematic diagram of the multi-beam laser processing principle; (b) schematic diagram of the traditional scanning path; (c) schematic diagram of the heat input regulation path strategy.[106] (d) Linear scanning strategy; (e) random scanning strategy.[114]

anode into the ECM system and applied a potential difference between the auxiliary anode and the sample to reduce stray corrosion. The principle is shown in Fig. 11(a). Experimental results showed that this method could significantly reduce stray corrosion at the outlet of the hole. Kong *et al.*[129] conducted ECM experiments on 304 stainless steel and 18CrNi8 alloy in neutral salt solution to manufacture array holes. During processing, $H^+$ generated from the auxiliary electrode could acidify the processing interface, dissolve insoluble electrolytic products and reduce stray corrosion. The principle of interface acidization between the pulses is shown in Fig. 11(b). In addition, an asymmetric electrophoresis method was proposed for the preparation of an insulation layer on the side of the electrode,[130] as shown in Fig. 12. Compared with the electrodes prepared by a traditional electrophoretic coating method, the insulation performance of the electrodes prepared by this method was better, and the taper of the micro-holes processed by this method was reduced by 62%. Liu *et al.*[131] introduced a pulsed power supply and a rotating spiral electrode into traditional ECM systems. The high-speed rotation of the spiral electrode could promote the removal of electrolytic products in the machining gap, reduce stray corrosion, and improve machining efficiency. A micro-hole array with almost no taper was obtained under optimized processing parameters (machining voltage of 6 V, pulse period of 2.5 μs, pulse width of 0.5 μs, electrode speed of 25 000 rpm, feed rate of 1.2 μm $s^{-1}$).

In addition to stray corrosion, the machining replication errors and repetitive errors also have a negative impact on the application of ECM.[132] The existence of machining gaps is the fundamental cause of ECM replication errors. The fluctuations in the flow field, electric field, and electrochemical field in the machining gap led to changes in the machining state of ECM. Therefore, improving the stability of machining gaps could reduce machining errors.[133] To reduce this error, multi-electrode synchronous machining was proposed. During the multiple-electrode simultaneous machining of array micro-holes, the splitter significantly affected the flow distribution, thereby affecting the consistency of the machined array micro-holes.[134] The optimization design of the splitter was an effective means to improve the stability of the multi-electrode ECM. Fang *et al.*[135] used simulation technology to explore the influence of splitter pipe structural parameters on machining consistency. ECM was performed on 304 stainless-steel by using optimized diversion pipes, resulting in consistent array micro-holes. Luo *et al.*[136] developed an eight-channel flow control system, which could monitor and regulate the real-time flow rate of electrolyte through each electrode, as shown in Fig. 13a. The distribution of electrolyte between different electrodes was more uniform, and a consistent array of small holes was successfully processed, as shown in Fig. 13b. Additionally, Chen *et al.*[137] designed a novel tubular electrode with a half-wedge-

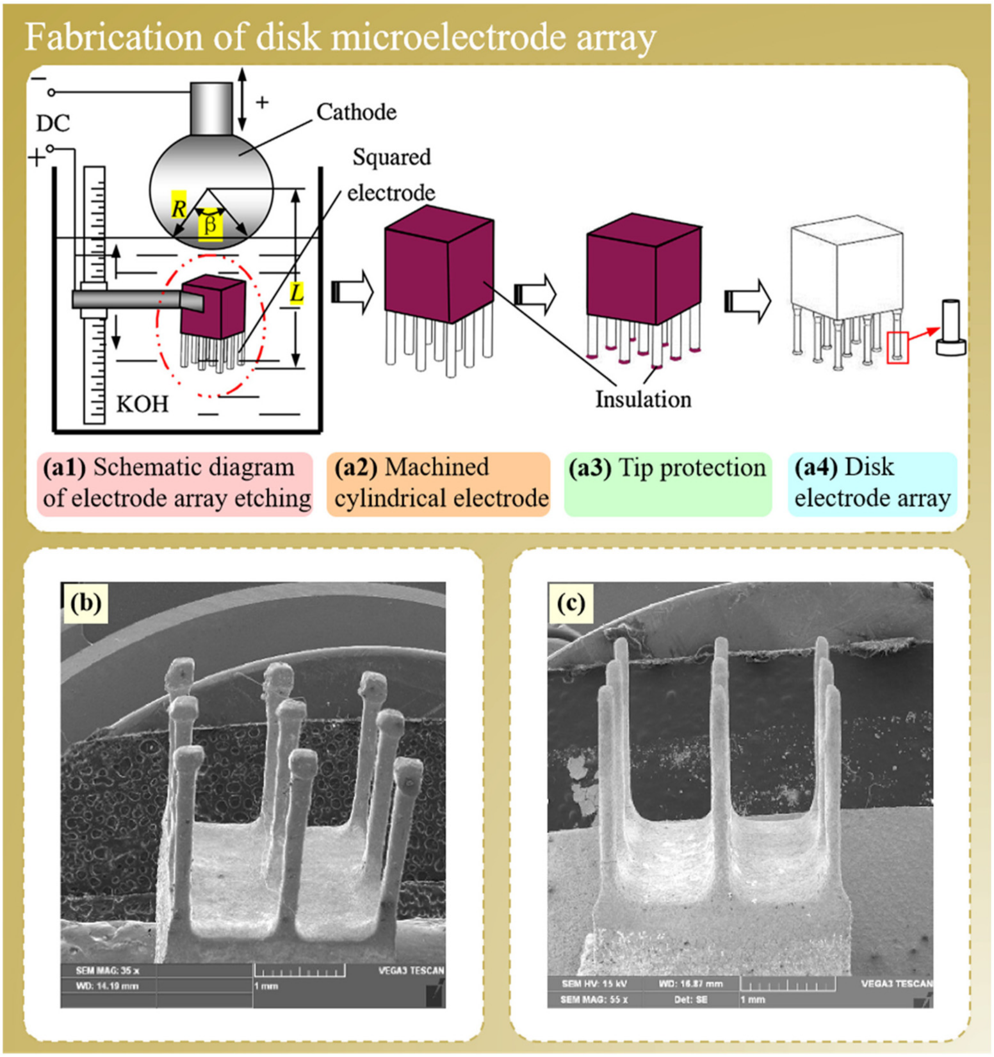


Fig. 10 (a1–a4) The manufacturing process of disk array electrodes; (b) SEM pictures of an array disk electrode; (c) SEM pictures of array cylindrical electrodes.[127]

shaped tip; the coupling of a pulsatile flow field and a pulsatile electric field within the inter-electrode gap was achieved by the rotating motion of electrodes. According to simulation and experimental results, the coupling of the physical pulsatile fields could improve the surface quality of the machined micro-hole.

2.3.2. **Mask electrochemical machining.** In mask electrochemical machining (TMEMM), it is necessary to apply a layer of photoresist to the surface of the sample. Then, the area of the sample that needs to be removed is exposed to achieve localized removal of the sample material.[138–140] The processing principle is shown in Fig. 14(a). In TMEMM, the controllability of the size, density, and position of the processed micro-holes was better because of the presence of masks, so this technology became a commonly used method for array micro-hole processing.[141–143] However, there were still problems such as overcutting, poor processing consistency, and difficulties in mask preparation during the TMEMM.[144,145] In response to these issues, researchers conducted a large amount of research to improve the machining quality of array micro-holes.

Many researchers achieved improved processing quality through parameter optimization during TMEMM.[141] Tsai *et al.*[148] established a finite element model of the machining process, and studied the effects of the electrolyte flow rates on array micro-hole machining. The research results indicated that under the same voltage, the faster the electrolyte flow rate, the smaller the average depth of the array micro-holes. Chun *et al.*[149] performed TMEMM processing on alloy materials. During processing, a magnetic rotor was used to stir the electrolyte. When the flow rate of the electrolyte was too low, the electrolytic products were not easily removed, which was harmful for the processing stability. When the electrolyte flow rate was too high, the hole overlap phenomenon would occur. Therefore, the electrolyte flow rate had a significant impact on the processing quality of TMEMM. Jin *et al.*[150] focused on the influence of the processing parameters on the current density

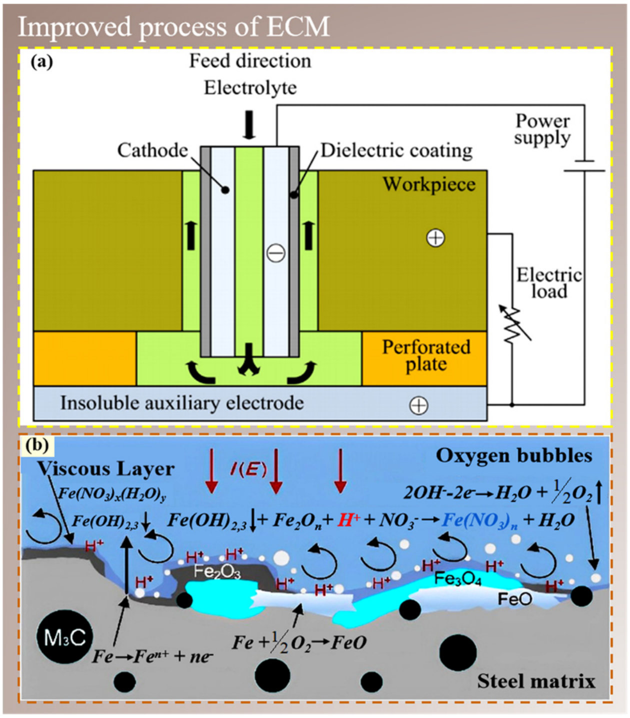


Fig. 11 (a) Schematic diagram of electrochemical machining with an insoluble auxiliary anode.[128] (b) Schematic diagram of the acidification principle at the pulse interface.[129]

distribution. The distribution of current density became uniform when the machining gap was large enough. The magnitude of current density would decrease with an increase of the machining gap, so it was necessary to determine a reasonable machining gap based on actual processing requirements. By utilizing optimized parameters, elliptical array micro-holes were obtained. Li *et al.*[151] measured the electrochemical behavior of molybdenum in $NaNO_3$ electrolyte and found that the surface dissolution uniformity of molybdenum was better when the current density was less than 16.89 A $cm^{-2}$. The machining quality of the array micro-holes on the molybdenum plate was significantly improved by controlling the current density. Li *et al.*[152] studied the influence of machining parameters and their composite effects on the machining process using orthogonal experiments. Under the optimal parameter combination of a voltage of 35 V, a pulse frequency of 400 Hz, and a duty cycle of 20%, a high-quality micro-hole array was obtained. He *et al.*[153] used polyaluminum chloride electrolyte to perform jet electrochemical machining of array micro-holes on Zr702 alloy plates. The effects of pulse voltage, electrolyte pressure, and jet scanning speed on machining results were explored using the multi-actor interaction response surface method. The experimental results indicated that pulse voltage had the most significant impact on the machining quality of array micro-holes. In addition, they used non-Newtonian fluid polyacrylamide (PAM) as an electrolyte to

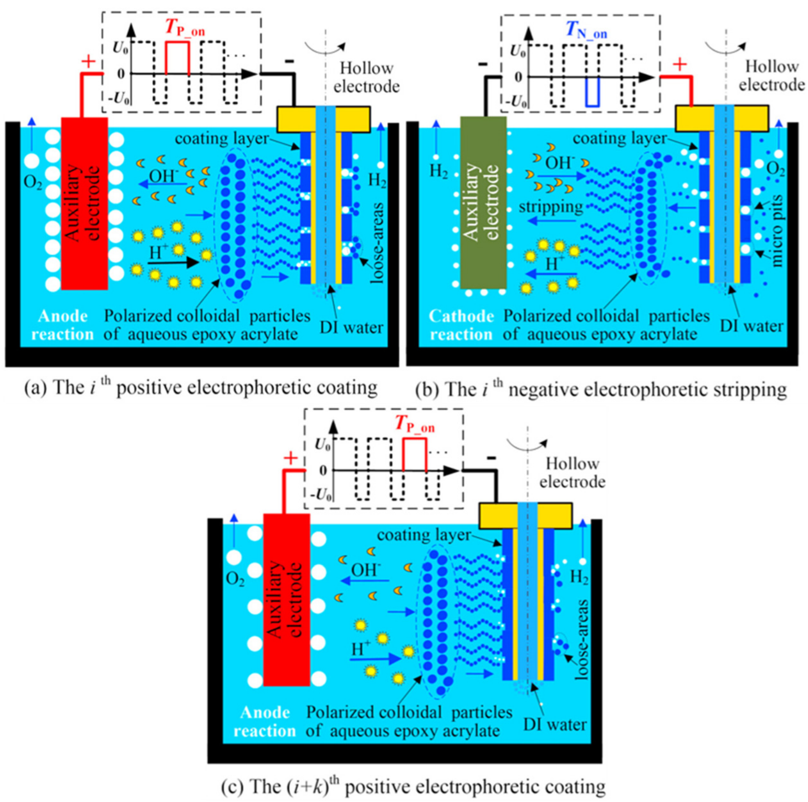


Fig. 12 Asymmetric timed bipolar electrophoresis coating process: (a) the $i^{th}$ positive electrophoretic coating; (b) the $i^{th}$ negative electrophoretic stripping; (c) the $(i + k)^{th}$ positive electrophoretic coating.[130]

 

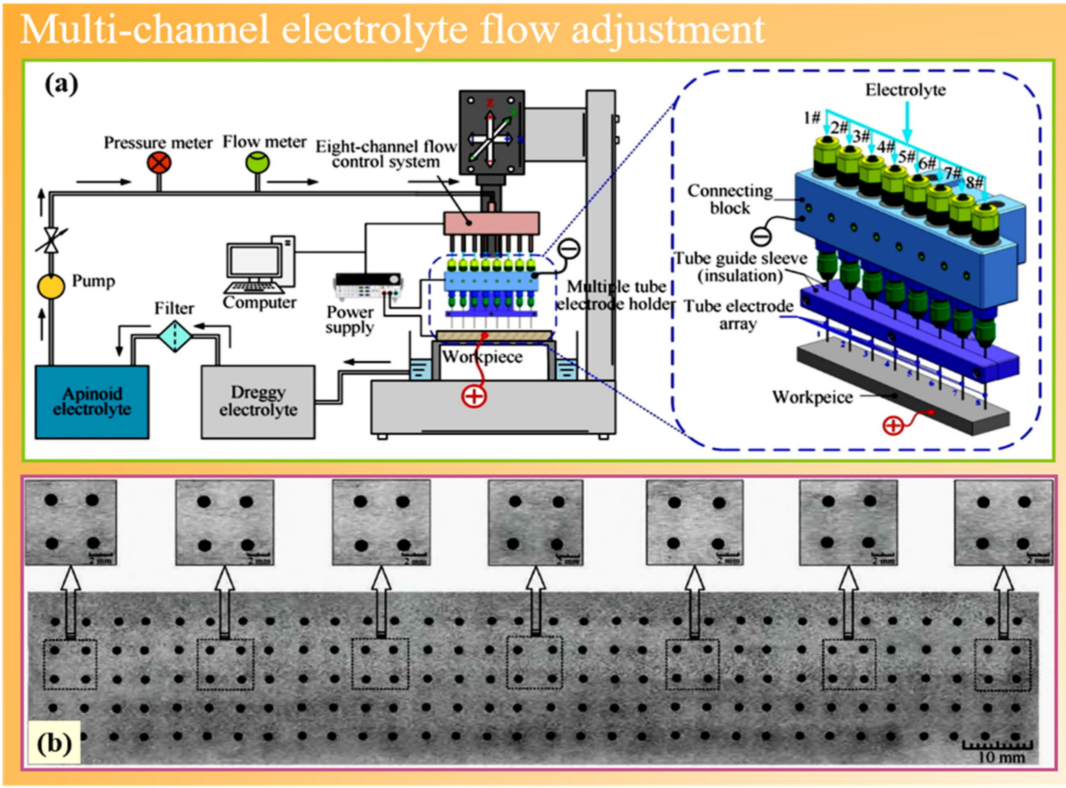


Fig. 13 (a) Schematic diagram of the eight-channel electrochemical machining device; (b) SEM pictures of array micro-holes.[136]

perform array micro-hole machining on SS304 stainless-steel.[154] The processing effect of SS304 stainless-steel in PAM, PAM NaOH, and $NaNO_3$ electrolytes was explored through comparative experiments. The experimental results showed that the PAM-NaOH solution had the best processing effect because of the dissolution effect of $OH^-$ on the processed products, and the properties of non-Newtonian fluids improved the processing accuracy. The continuous generation of bubbles and Joule heat during the machining process could cause an uneven distribution of electrolyte conductivity in the machining area, thereby affecting the distribution of current density.[155,156] Optimizing the electrolyte flow field and reducing the non-uniformity of electrolyte conductivity was beneficial for improving machining accuracy. Wang *et al.*[156] investigated the effect of electrolyte conductivity on the machining consistency of a group of holes. The research results indicated that using a pulsed power supply in TMEMM processing could reduce the variation of electrolyte conductivity, thereby improving the consistency of the group of holes. Li *et al.*[146] proposed a serpentine flow channel to improve the electrolyte flow state during the machining process. By reasonably placing guide plates in the flow channel, the optimization of the electrolyte flow field was achieved. A schematic diagram of the optimized serpentine flow channel is shown in Fig. 14(b). Consistent array micro-holes were obtained with this channel. Therefore, optimizing the electrolyte flow mode was necessary to improve the machining accuracy of array micro-holes.

In addition, masks had a significant impact on the distribution of electric and flow fields during TMEMM processing, which in turn affected the machining accuracy of array micro-holes.[157] Optimizing mask parameters was beneficial for improving processing quality and efficiency. Wang *et al.*[147] investigated the effect of different mask wall angles on the machining process, as shown in Fig. 14(c). The results indicated that the masks with conical holes were beneficial for the flow of electrolyte. Increasing the wall angle within a certain range could improve machining accuracy. However, if the mask wall angle were too large, it would exacerbate stray corrosion. Li *et al.*[158] established a finite element model for TMEMM processing of nickel based high-temperature alloys. The effect of the mask aperture on the hole formation process was explored. Simulation and experimental results showed that masks with large diameter holes reduced the taper of the processed holes. For nickel based high-temperature alloys with a thickness of 0.2 mm, the larger the mask hole diameter, the shorter the time required to form perforations. Wang *et al.*[159] used double-sided mask electrolysis technology to simultaneously process the upper and lower surfaces of the sample and established corresponding numerical models. Simulation and experimental results showed that this process could significantly improve the taper of the machined micro-holes. Array micro-holes with a maximum taper of 2.52° were successfully prepared on a 0.5 mm thick titanium alloy sheet.

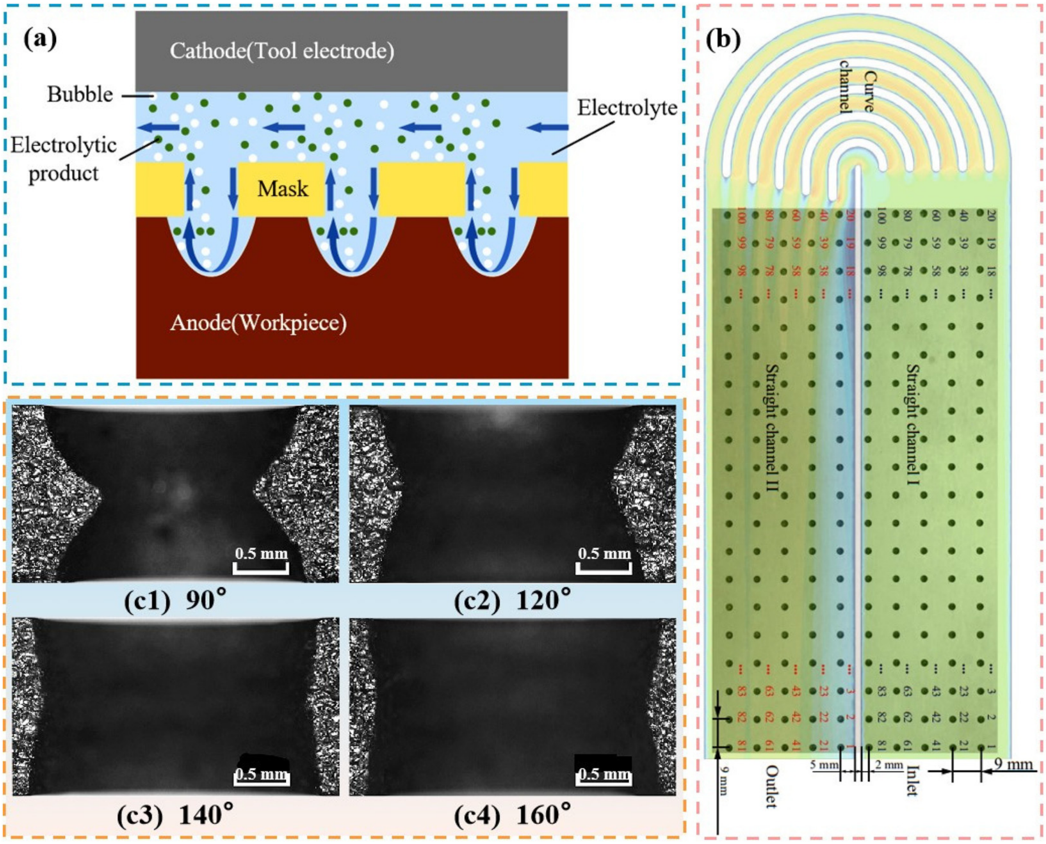


**Fig. 14** (a) Schematic diagram of the processing principle of TMEMM. (b) Schematic diagram of the optimized serpentine flow channel.[146] (c) Cross section of holes under different mask wall angles: (c1) 90°; (c2) 120°; (c3) 140°; (c4) 160°.[147]

## 3. Other non-traditional machining technologies

Due to the increasingly widespread application of hard brittle non-conductive materials such as glass and silicon in radio-frequency (RF) and microelectromechanical systems (MEMS), there is now an urgent need to process high-quality array micro-holes on these materials.[160,161] However, EDM and ECM cannot process non-conductive materials, while laser processing has defects such as thermal effects, which means that these mainstream non-traditional machining technologies are unable to meet the machining requirements for non-conductive materials.[162–164] Therefore, some other non-traditional machining techniques, such as ultrasonic machining (USM) and chemical etching, have begun to be explored for the processing of array micro-holes in non-conductive materials.

Ultrasonic machining (USM) is advanced manufacturing technology that uses the ultrasonic vibration of the cutting tool to drive abrasive particles in the slurry to impact the sample, causing brittle failure of the sample material and achieving material removal.[165,166] This technology is very suitable for processing hard brittle materials. The processing principle is shown in Fig. 15. Pandey *et al.*[167] used modal and harmonic analysis techniques to optimize the length of the amplitude rod to improve the uniform distribution of vibration at the tip of the array tool. Using SiC particles with a diameter of 1 μm as abrasives and optimized array tools, USM processing was carried out on glass and silicon wafers. The results indicated that the efficiency of USM machining was higher than that of plasma etching or electrochemical discharge machining. This confirmed the superiority of this technology in processing array micro-holes on hard and brittle materials.

Chemical etching is a special processing technique which removes material through chemical reactions.[168] The conventional chemical etching process has low efficiency and poor anisotropy, which limits its application.[169] To solve these problems, some novel etching methods were proposed for the processing of array micro-holes. Agrawal *et al.*[170] used a photochemical etching process (PCM) with ferric chloride aqueous solution to etch stainless steel array micro-holes. The Taguchi method was used to optimize the processing parameters. The array micro-holes with different diameters were successfully processed under optimized parameters. However, the consistency of the group of holes was poor because of the uncontrollability of the machining process. Michaels *et al.*[171] proposed a UV induced metal assisted chemical etching technique based on the chemical properties of SiC. This process utilized an etchant composed of potassium persulfate ($K_2S_2O_8$) and hydrofluoric acid as oxidants, and patterned Pt as a mask and

 

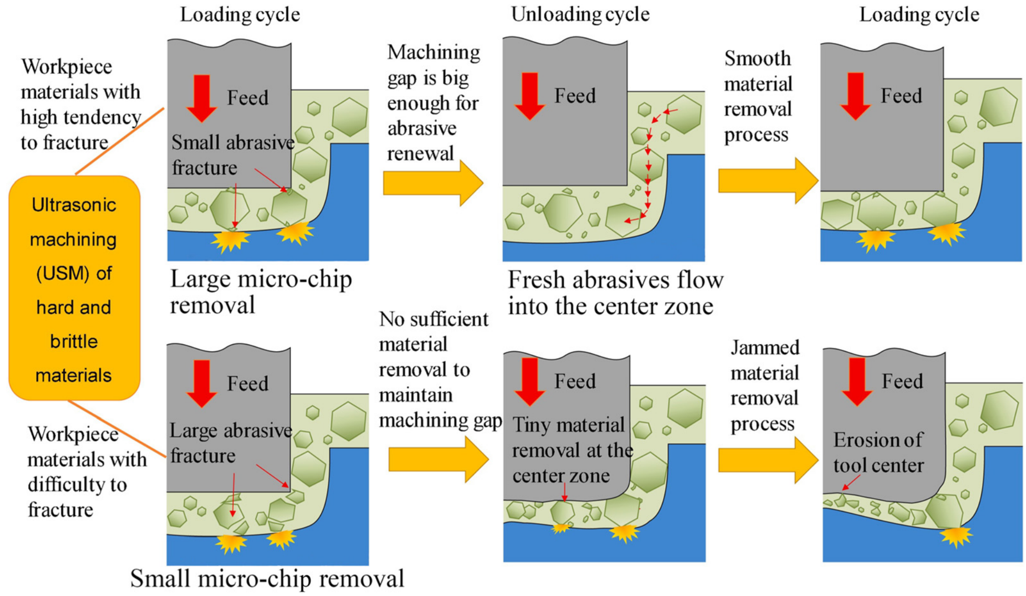


Fig. 15 Schematic diagram of material removal in ultrasonic machining.[165]

chemical reaction catalyst to achieve localized oxidation and acid etching removal of SiC under the induction of ultraviolet light. Liao *et al.*[172] further investigated the effect of metal pattern size on the hole formation process for 4H-SiC through photon enhanced metal assisted chemical etching. The research results indicated that the vertical etching rate accelerated with an increase of the coverage area of the Pt mask, providing a certain reference significance for improving the depth to diameter ratio of micro-holes. Chen *et al.*[173] proposed a double-sided metal assisted photochemical etching process, as shown in Fig. 16(a). A patterned Au metal layer was introduced on top of the SiC chip, while an Au metal layer was sputtered on the bottom of the chip, followed by wet-etch processing. The experimental results showed that compared to traditional metal assisted photochemical etching, the vertical etching rate of this process increased by 2.2 times. Kawamura *et al.*[174] deposited silver on a glass substrate and then removed the silver deposition area by a wet etching process. An array of micro-holes was formed on the glass substrate. A schematic diagram of the preparation process is shown in Fig. 16(b). The comparative experiments showed that KOH etchant was beneficial for improving the depth to diameter ratio of micro-holes, but its processing efficiency was relatively low. They believed that the lateral diffusion and deposition of silver ions could be suppressed by controlling the electric and thermal fields, thereby improving the depth to diameter ratio of micro-holes. Choi *et al.*[31] proposed a process combining wet etching and electrochemical processing. The uncoated photoresist surface of the sample was first thinned using wet etching, and the through-hole array was subsequently processed using ECM. They succeeded in obtaining tetragonal array micro-holes on Invar alloy films with high geometrical accuracy by rationally controlling the time of wet etching. However, the thinning step may result in a wider thickness tolerance of the sample because of the uncontrollable nature of wet etching, which does not meet the requirements of practical applications.

As the application fields of micro-holes became increasingly broad, other non-traditional machining techniques began to receive attention. At present, related reports in the literature on USM and chemical etching in the field of array micro-hole processing are few. These technologies have great potential in the processing of hard and brittle non-conductive materials, which are expected to become key processing technologies in this field.

Non-traditional machining techniques played an important role in the field of array micro-hole machining. The application and existing problems of EDM, laser machining, ECM, and other non-traditional machining technologies in array micro-hole machining were summarized. A comparison of mainstream non-traditional machining technologies in the field of array micro-hole processing is shown in Table 1. In the actual machining process, factors such as machining accuracy, machining efficiency, and machine costs should be comprehensively considered.

## 4. Composite machining technology

Although non-traditional machining techniques have multiple advantages, they also have various shortcomings. As for laser processing and EDM, the material is removed with thermal energy, so it is difficult to avoid thermal defects such as recast layers, micro-cracks, and heat affected zones.[175–177] In addition, there is a problem of tool wear in EDM. ECM has problems such as scattered corrosion and poor machining stability.[178,179] The efficiency of ultrasonic

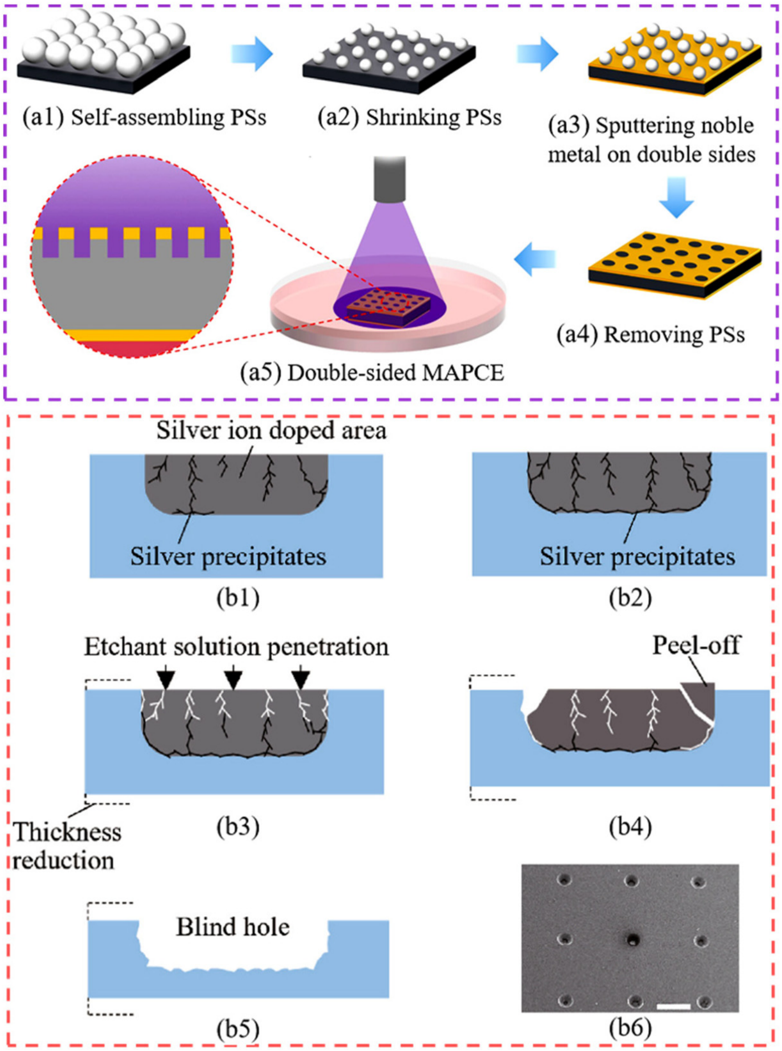


Fig. 16 (a1–a5) Schematic diagram of the double-sided metal assisted photochemical etching process.[173] (b1–b6) Schematic diagram of the etchant permeating along a network of silver precipitate to preferentially remove glass: (b1) silver precipitation on the surface of glass; (b2) expansion of the silver precipitation area; (b3) etching agent penetrates along the silver precipitate; (b4) edge peeling of the silver precipitation area; (b5) removal of the silver precipitation area and the formation of blind holes; (b6) SEM pictures of machined array micro-holes.[174]

Table 1 Comparison of common non-traditional machining technologies for array micro-holes[45,175]

| Machining characteristics | EDM | LBM | ECM |
|---|---|---|---|
| Minimum hole diameter (μm) | <50 | <10 | >100 |
| Maximum aspect ratio | 25 | 150 | 250 |
| Material removal rate | Slow | Fast | Medium |
| Cost | Medium | High | Low |
| Tool wear | Serious | Absent | Absent |
| Thermal defect | Serious | Serious | Absent |
| Tool complexity | High | Low | High |
| Type of material that can be drilled | Conductive materials | Non-reflective surface materials | Conductive materials |

machining is low. The chemical etching process is complex and harmful to the environment.[180,181] To solve the above problems and achieve high-quality processing of array micro-holes, composite processing technology has emerged and developed rapidly. Composite machining is a technique that integrates multiple technologies, which can achieve complementary advantages of different machining techniques. Composite processing is an important direction for achieving efficient and high-quality processing of array micro-holes.

 

### 4.1. Ultrasonic assisted electrochemical machining

Ultrasonic assisted ECM (UAECM) is a composite machining method that introduces ultrasonic vibration into traditional ECM systems.[182–185] During UAECM, the pumping and cavitation effects are used to improve the machining efficiency. As shown in Fig. 17(a and b), the electrolyte in the machining gap was periodically pumped.[39] The cavitation effect was caused by the presence of ultrasonic vibration, which continuously generated bubbles and ruptured the electrolyte. The rupture of bubbles could cause local jet action and stir the electrolyte in the processing area.[186–188] The above two effects could significantly promote the removal of electrolytic products and the renewal of electrolyte in the machining gap, which improved the machining efficiency and machining stability.

Shen *et al.* conducted a study on ultrasonic-assisted ECM of stainless-steel array micro-holes with an array tool electrode.[39] They found that the machining efficiency under the assistance of ultrasonic vibration could be increased by 5 times. However, the side of the electrode used in the experiment was not insulated, resulting in poor dimensional accuracy. Zhu *et al.*[184] proposed the ultrasonic assisted electrochemical drilling and

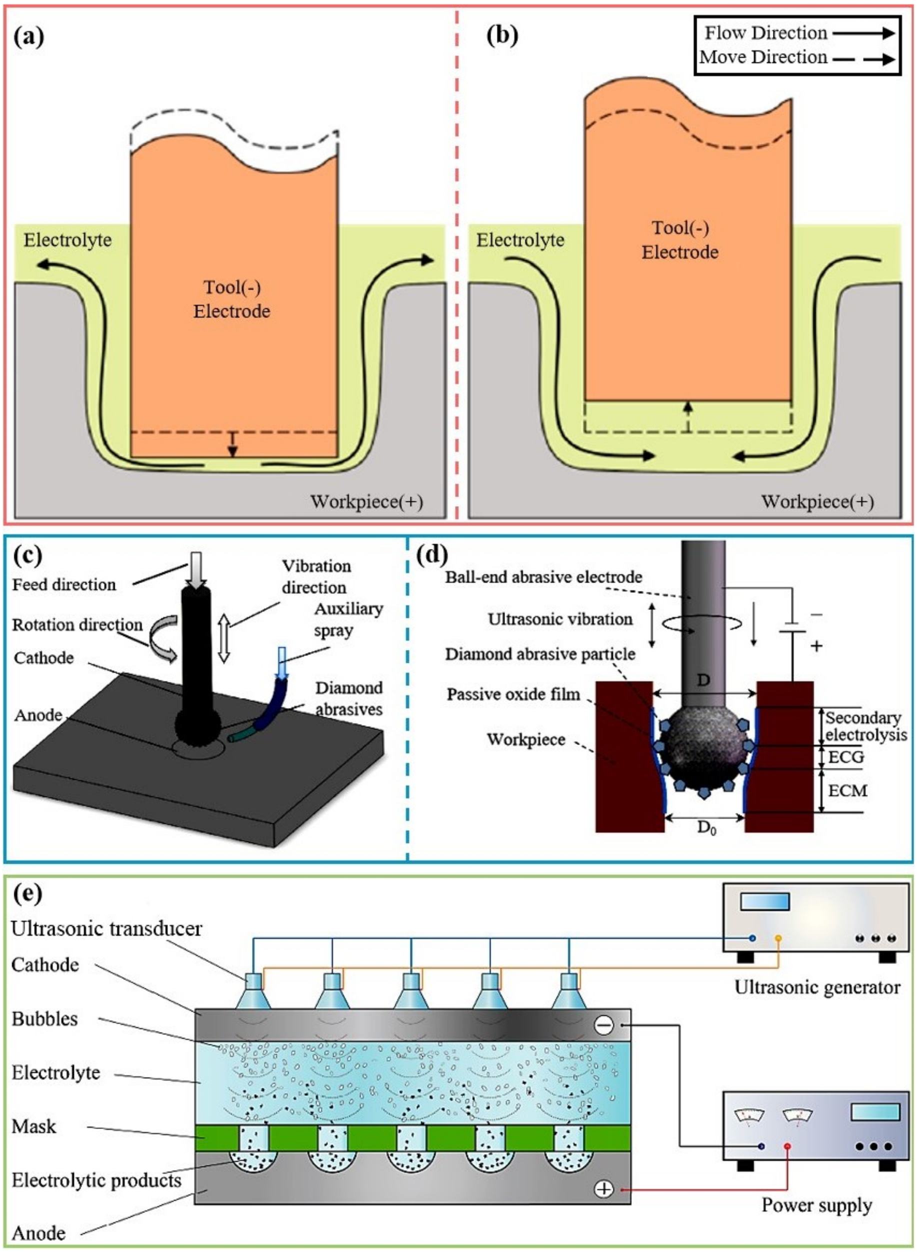


Fig. 17 (a and b) Schematic diagram of the ultrasonic pumping effect: (a) tool electrode moving downward; (b) tool electrode moving upward.[39] (c and d) Schematic diagram of the UAECDG machining principle: (c) schematic diagram of the processing area; (d) UAECDG processing mechanism diagram.[184] (e) Schematic diagram of the ultrasonic assisted mask electrochemical machining principle.[189]

grinding technology (UAECDG), which involved two steps for processing array micro-holes. Firstly, the array micro-holes were roughened by ECM with a spiral cathode tool. Then, the diamond abrasive particles embedded at the end of the spherical tool were used for ultrasonic assisted electrochemical drilling and grinding to complete the precision machining of the array micro-holes. A schematic diagram is shown in Fig. 17(c and d). The 304 stainless steel array micro-holes machined by this new method had good consistency, good surface quality, and a small taper. Wang *et al.*[190] used $NaHCO_3$ electrolyte and porous tube electrodes for UAECDG processing of glass. The range of process parameters was preliminarily determined through single factor experiments, and then key experimental parameters were selected through Plackett Burman experiments. Finally, multi-objective and multi-factor optimization was carried out through BOX-Bekken experiments to obtain the optimal combination of process parameters. Compared with ECDG, the overcutting, edge damage, and surface roughness of the microstructure produced through this method were reduced by 8.3%, 17.5%, and 70.6%, respectively. Under optimized parameter combinations, high-quality array micro-holes were prepared. This provided new ideas for the green manufacture of glass micro-structures. Kong *et al.*[191] processed multiple holes with perfect surface quality and a small taper on GH3030 alloy by UAECDG. The key to this technology was to achieve a balance between ECM and mechanical grinding, because this would directly affect the machining quality of micro-holes. Wang *et al.*[189] used ultrasound assisted mask ECM technology to process high-quality array micro-holes in high-temperature alloys. The machining principle is shown in Fig. 17(e). Through numerical simulation based on the bubble oscillation equation, they found that ultrasound frequency, ultrasound sound pressure amplitude, electrolyte incident pressure, and electrolyte temperature had a significant impact on ultrasound cavitation. The influence of electrolyte viscosity and surface tension on ultrasonic cavitation was relatively small. Li *et al.*[192] proposed a micro-rotation ultrasonic assisted electrochemical drilling method by introducing an ultrasonic field into traditional ECM systems. The simulation results showed that the introduction of ultrasonic vibration could make the electrolyte flow field more uniform, promote the renewal of electrolyte, and thus improve machining stability. The array micro-holes machined by this method had good consistency and a small taper.

### 4.2. Ultrasonic assisted electric discharge machining

The multiple-electrode simultaneous electric discharge machining method for array micro-holes is beneficial for improving processing efficiency. However, it is hard for the multiple electrodes to rotate during the machining process, making it difficult to remove debris from the machining gap, which seriously affects the machining accuracy.[52] Therefore, promoting the removal of debris during multiple-electrode simultaneous EDM is a key issue. Numerous studies showed that the introduction of ultrasonic fields could significantly improve the machining quality and efficiency.[193–195] Zhang *et al.*[196] conducted simulation analysis on the flow field under different ultrasonic amplitudes. As shown in Fig. 18, the simulation results indicated that the introduction of ultrasonic vibration could increase the flow rate of the working fluid in the bottom gap, promote the removal of debris, and thus improve the stability of the machining process. Xie *et al.*[197] explored the effects of the ultrasonic amplitude on debris removal. The research results indicated that increasing the ultrasonic amplitude appropriately was beneficial for the removal of debris, thereby improving the stability of array micro-hole processing. Zhang *et al.*[198] prepared a series of tungsten array electrodes by reverse electrical discharge technology. Ultrasonic assisted EDM experiments on array holes were carried out with the prepared tungsten array electrodes. The experimental results indicated that the diameter of the central hole was slightly larger than that of the surrounding holes. Through simulation analysis of the distribution of gap flow field, the removal of debris from the middle hole was less than that from the outer hole because of the interference effect of the working medium flow field, resulting in the accumulation of debris in the machining gap. This increased the probability of secondary discharge, resulting in an increase in the size of the intermediate hole. Hou *et al.*[199] proposed three-dimensional ultrasonic vibration assisted micro-electrical discharge machining technology (RTDUV) that combined the circumferential vibration of the electrode and the vertical vibration of the sample. The simulation results of the flow field indicated that PTDUV was beneficial for the removal of processed products. The experimental results confirmed the improved dimensional consistency of array micro-holes prepared by RTDUV-assisted EDM.

### 4.3. Electrochemical discharge machining

Electrochemical discharge machining (ECDM) is an advanced composite processing technology that combines ECM and EDM, and it is considered one of the main technical means for processing non-conductive hard and brittle materials.[200–202] ECDM can be divided into three steps.[203–205] The principle is shown in Fig. 19(a). In the first step, a large number of bubbles are generated between two electrodes because of electrochemical reactions. In the second step, hydrogen bubbles are continuously accumulated on the surface of the tool electrode to form a gas film, separating the tool electrode from the working medium. In the third step, the electric field strength between two electrodes increases to a very high value, and then the gas film is broken down and spark discharges occur.

Patro *et al.*[207] established a finite element model for the ECM preparation of microelectrodes, explored the effects of processing voltage and processing time on the tool profile, and conducted experimental verification. The experimental and simulation results showed that micro-electrodes with relatively uniform contours were obtained in 5% NaCl solution. Arab *et al.*[208] conducted ECDM on silica with the array electrode. The effects of machining parameters on the heat affected zone (HAZ) were explored. The research results indicated that the length of the array electrode should be designed reasonably, otherwise the machining stability would be

 

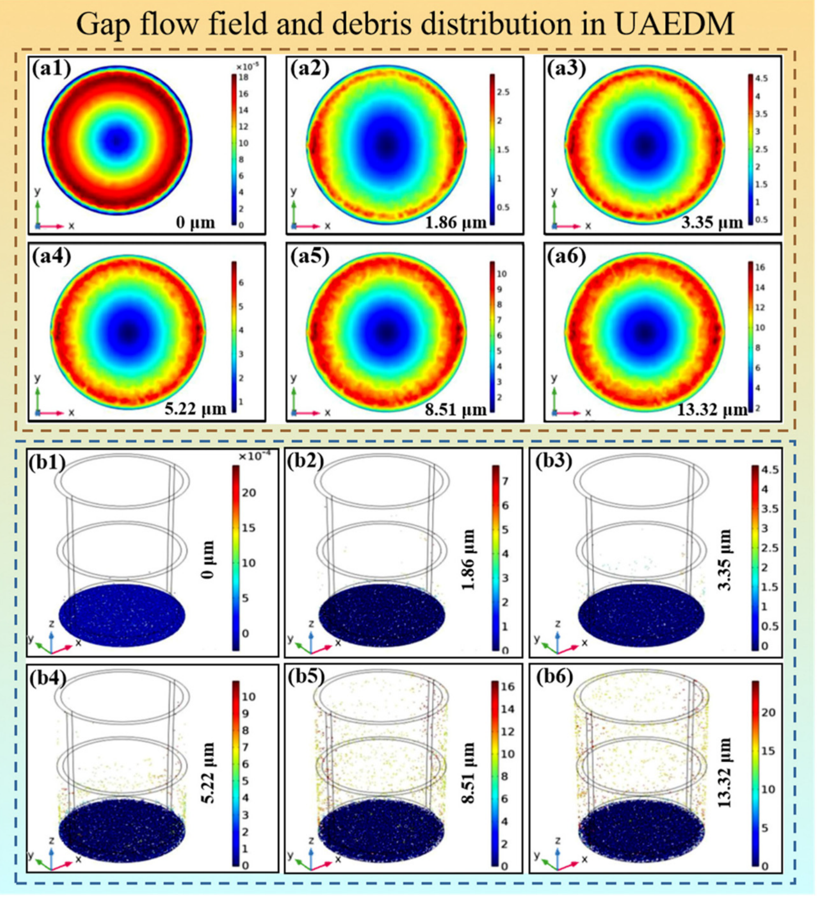


**Fig. 18** (a) Distribution of the gap flow field under different ultrasonic amplitudes: (a1) 0 μm; (a2) 1.86 μm; (a3) 3.35 μm; (a4) 5.22 μm; (a5) 8.51 μm; (a6) 13.32 μm. (b) Debris removal under two vibration cycles corresponding to different ultrasonic amplitudes: (b1) 0 μm; (b2) 1.86 μm; (b3) 3.35 μm; (b4) 5.22 μm; (b5) 8.51 μm; (b6) 13.32 μm.[196]

reduced. Afterwards, array electrodes of different lengths were used to explore the processing of micro-hole arrays on glass substrates.[209] The experimental results showed that a long electrode could reduce the occurrence of the bubble clamping phenomenon. Kannojia *et al.*[210] studied tool wear during ECDM of array micro-holes with array stainless steel electrodes. As the number of micro-hole machining groups increased, the volumetric wear of the tool continued to increased, while the ratio of volumetric material removal to volumetric tool wear decreased. Singh *et al.*[206,211] used a spherical tool cathode to repair the worn array tool electrodes through ECM. The repair accuracy of the pulsed power supply was higher than that of the DC power supply (Fig. 19c). ECDM machining experiments were conducted on glass substrates with the repaired array electrodes, and the feasibility of the repair technology was verified. Liu *et al.*[212] conducted ECDM drilling on ultra-white glass with a rotating spiral electrode. The side gap increased with the improved pulse voltage and duty cycle, and decreased with the improved pulse frequency and feed rate. They obtained high-quality array micro-holes with smaller diameters under optimized parameters. Zou *et al.*[213] used non-flowing fluid electrolytes instead of traditional KOH electrolytes, relying on the constraint effects of non-Newtonian fluids to improve the stability of the gas film, and thereby improving the quality of the glass array micro-holes. Compared with traditional KOH electrolytes, the width of the heat affected zone was reduced by 64.81%, and the repeatability was improved by 67.92%. Shen *et al.*[214] used a high-speed rotating helical tool electrode with a non-aqueous electrolyte to change the discharge processing principle from gas film breakdown discharge to low conductivity electrolyte breakdown discharge, which improved the area and intensity of the electrolytic reaction. Array micro-holes with no recast layer on the surface were obtained. Geng *et al.*[215] found that the discharge mode was basically continuous before perforation in the ECDM process, and the inter-electrode voltage was relatively stable. However, after perforations formed, the inter-electrode voltage showed fluctuation. By using the technique of variance statistics, the breakthrough of micro-holes was accurately identified by determining whether the average voltage variance exceeded the variance threshold.

The above research indicated the effectiveness of ECDM for micro-hole machining of non-conductive hard materials. However, when the depth of the micro-holes was large, the pro-

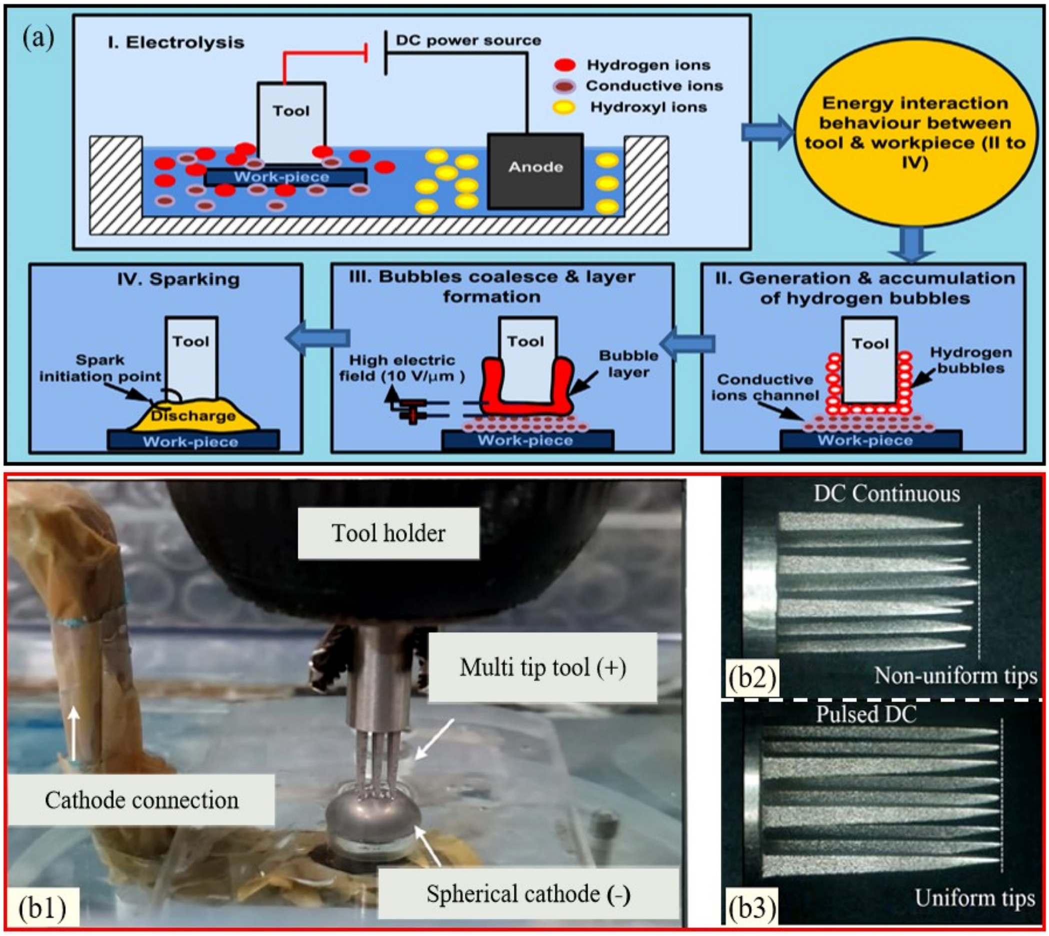


**Fig. 19** (a) Schematic diagram of the ECDM.[200] (b) Array electrodes of the ECDM: (b1) ECM equipment; (b2) repairing array electrodes with a pulse power supply; (b3) the restored array electrodes repaired with a continuous power supply.[206]

cessed holes appeared conical because of the difficulty of the working fluid entering the machining area.[216] To address this issue, ultrasonic vibration assisted electrochemical discharge machining (UAECDM) technology was proposed. The introduction of ultrasonic vibration could affect the formation of gas film and the distribution of spark discharge energy,[217] as shown in Fig. 20(a). A detailed study was carried out on the influence of key parameters on the processing of glass by UAECDM. A mathematical model of the relationship between micro-hole diameter and processing parameters was established. High-quality array micro-holes were obtained under optimized processing parameters. Compared with that of ECDM, array micro-holes produced by UAECDM had smaller diameters and better consistency, resulting in less tool wear. Yang *et al.*[218] used UAECDM to process array micro-holes on quartz chips, and found that the introduction of ultrasonic vibration could thin the gas film, thereby reducing the critical voltage required for gas film breakdown, and thus reducing the diameter of micro-holes. The optimal parameter combination (working voltage of 44 V, feed rate of 1 μm/6 s, pulse width of 30 μs, duty cycle of 30%) for UAECDM processing was determined through single factor experiments. Under this parameter combination, array micro-holes with good orifice morphology were obtained. Jia *et al.*[219] used an ECDM process with ultrasonic vibration to obtain high-quality array micro-holes on glass substrates. They found that the coupling effect of the electrolyte jet with ultrasonic vibration through numerical simulation could further optimize the gas film distribution on the tool electrode surface. Furthermore, the experimental results confirmed the effectiveness of the introduction of intra-electrolyte jets and ultrasonic vibrations in improving the performance of the conventional ECDM process. In addition, Sharma *et al.*[220] proposed a combined pulse feed method, as shown in Fig. 20(b). The feed rate and pulse frequency decreased sequentially, which solved the problem of electrolyte shortage when the hole depth was large. They used this method to process array micro-holes on alumina thin plates. The results showed that compared with a traditional constant speed feed, the processing time of array micro-holes was reduced by 40%, and the heat affected zone was significantly reduced. Hung *et al.*[221] proposed a new composite method based on an array of stepped tool electrodes, diamond abrasive electrolyte, and ultrasonic vibration. The combination of UAECDM, USM, and *in situ* cutting was achieved. They found

 

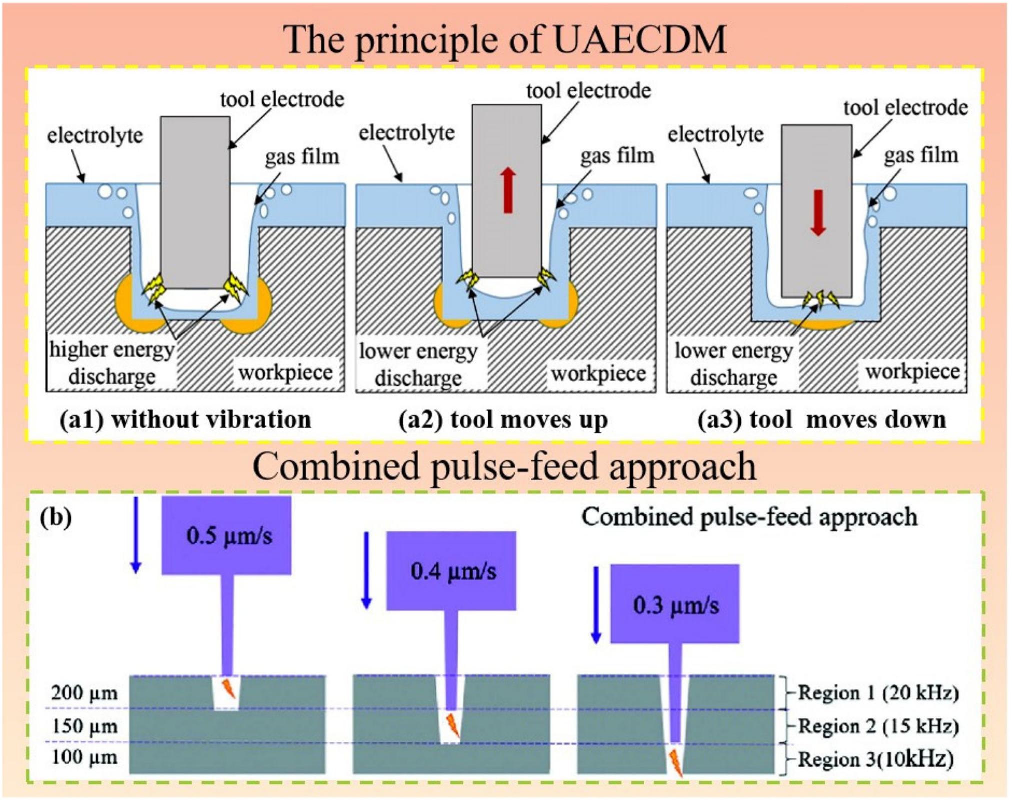


Fig. 20 (a) The effect of ultrasonic vibration on spark energy distribution: (a1) no ultrasonic vibration; (a2) upward movement of tools; (a3) downward movement of tools;[217] (b) schematic diagram of the combined pulse feed method.[220]

Table 2 Summary of research on composite machining technologies of array micro-holes

| Machining technology | Sample material | Key findings | Ref. |
|---|---|---|---|
| UAECM | 301 stainless steel | Higher ultrasonic amplitude leads to higher machining efficiency | Shen *et al.*[39] |
| | ODS superalloy | Ultrasonic frequency and sound pressure significantly affect the cavitation effect | Wang *et al.*[189] |
| UAEDM | Tool steel | Debris accumulation in the central hole | Zhang *et al.*[198] |
| ECDM | Silica | Electrode length should not be too short | Arab *et al.*[208] |
| | Glass | Non-NTF electrolyte can improve processing quality | Zou *et al.*[213] |
| UAECDM | Glass | Consistency of array holes is higher than ECDM | Wang *et al.*[217] |

that the concentration of abrasive in KOH solution had almost no effect on the formation of gas film. When the feed rate was high, bubbles were prone to accumulate at the entrance of the hole, which reduced the machining quality. They used this process to obtain array micro-holes with high dimensional consistency and a small taper. The application potential of this novel composite process was enormous, as the processing eliminated the need to change electrodes or electrolyte. In addition, this novel composite process improved the dimensional consistency of the array micro-holes.

### 4.4. Summary

Composite processing technology can address the limitations of single processing methods and enhance the processing efficiency of array micro-holes. Table 2 summarizes research conducted in the field of micro-hole composite processing. Most studies focus on exploring machining mechanisms and optimizing machining parameters. However, promoting composite processing technology for industrial applications still faces many difficulties.

Firstly, one of the main challenges is the lack of research on specialized equipment for various composite processing technologies. The majority of research is based on improving other equipment. The correlation between equipment and processing technology will have a direct impact on processing accuracy and efficiency.

Secondly, the practical engineering application of composite processing technology in array micro-hole processing is seriously limited due to an incomplete understanding of its mechanism and properties.

Additionally, there is a scarcity of quantitative analysis of the machining process, as an accurate mathematical model for the composite machining process has not yet been established.

## 5. Conclusion and future research directions

The continuous expansion of the applications of array micro-holes has made the sustainable manufacturing of array micro-holes an urgent necessity in multiple industries. This article presents a review of the principles, characteristics, and research progress for advanced sustainable non-traditional manufacturing technologies commonly used in array micro-hole machining. Presently, researchers are primarily focusing on enhancing the overall performance of a specific process through two avenues: parameter optimization and process improvement. The intrinsic limitations of the processing technology give rise to a range of inherent disadvantages associated with different processing techniques. Fig. 21 provides a detailed comparison of the performance indicators of six advanced manufacturing technologies. It is necessary to select an appropriate processing technique based on the specific performance requirements of the workpiece and the conditions of industrial production. Despite extensive research being conducted by scholars on advanced sustainable manufacturing technologies for array micro-holes, there are still some shortcomings in related fields and numerous challenges that require urgent attention (Fig. 22). The following recommendations are provided for the processing of array micro-holes.

(1) It would be beneficial for subsequent research to place a greater emphasis on the processing mechanisms of advanced sustainable manufacturing technologies. At present, the primary focus of research in the field of array micro-hole processing is on the optimization of processing parameters, with the objective of achieving enhanced processing outcomes within a constrained process window through comprehensive experimental investigation. However, advanced non-traditional and composite processing techniques involve energy fields that differ from those involved in traditional mechanical processing, such as light, sound, electricity, and so forth. The interaction between these energy fields and the workpiece is highly intricate, encompassing a plethora of processing parameters that interact with one another. It is challenging to enhance process performance through the exclusive optimization of process parameters. To advance process performance, it is essential to conduct comprehensive research on the processing mechanisms of diverse advanced manufacturing technologies. The development of an accurate mathematical model of the machining process through simulation technology, coupled with the real-time capture and analysis of exceptional phenomena during the machining process, represents a pivotal avenue for achieving this objective.

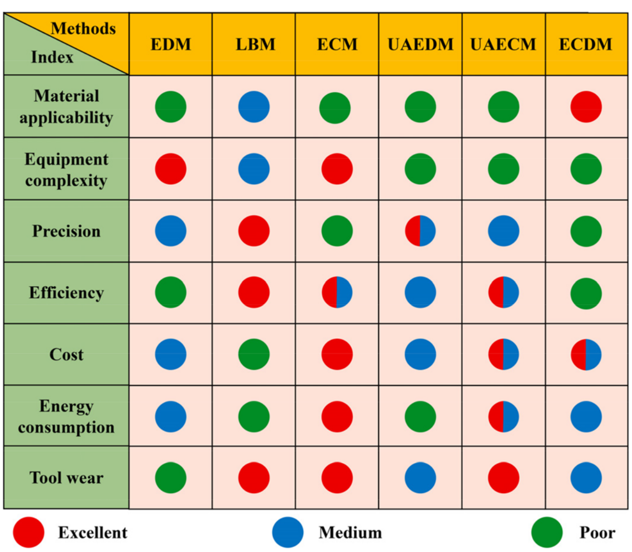


Fig. 21 Comparison of key performance indicators for different processing techniques.

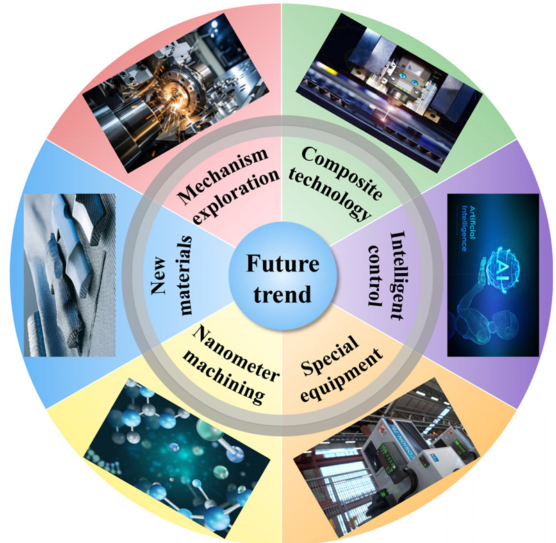


Fig. 22 Prospects for the future development of advanced sustainable manufacturing technology for array micro-holes.

(2) It is imperative to pursue the advancement of novel composite processing technologies. The constraints inherent to individual processing techniques render composite processing technology a promising avenue for addressing these challenges. Nevertheless, in comparison with standalone micro-hole processing technology, the current composite processing technology employed for array micro-hole processing remains scarce, with the majority still in the nascent stages of process development. This hampers the ability to meet the demands of industrial production. Consequently, the development of innovative composite processing techniques is of paramount importance.

(3) The digitization and intelligent control of processing represent significant avenues for future research. The progressive advancement of computer and automation technology has

rendered the precise automatic control of the machining process a feasible proposition. In particular, the recent exponential growth of artificial intelligence has opened up a vast array of unprecedented opportunities across numerous fields. The small size, large quantity and strict position accuracy requirements of array micro-holes mean that manual control of the processing process can easily lead to positioning errors. Furthermore, manual operation is time-consuming, resulting in a high scrap rate. Therefore, adopting digital and intelligent control methods is beneficial for the timely detection and handling of problems that arise during the machining process, thereby improving the machining accuracy and efficiency of array micro-holes, and enhancing the adaptability of the machining process.

(4) The development of specialized equipment is a crucial factor in the advancement of diverse advanced manufacturing technologies. The utilization of processing equipment has a considerable impact on the accuracy and efficiency of the processing itself. The deployment of specialized equipment enables the precise control of processing parameters and the optimization of process flow, which in turn reduces the wastage of raw materials and energy consumption, improves the efficiency with which resources are utilized, and aligns with the overarching objective of sustainable manufacturing. Furthermore, the deployment of specialized equipment ensures the stability, reliability, and high degree of control that are essential in the field of micro- and nano-manufacturing.

(5) Research and development of nanoscale array micro-hole processing technology should be the primary focus. In light of accelerated developments in fields such as microelectronics, biomedicine, and materials science, coupled with the growing demand for practical applications of workpieces and the ongoing enhancement of material service performance, the dimensional precision of micro-hole arrays is witnessing a shift from the micro-metre domain to the nano-metre range. It is, however, important to note that existing reports in the literature indicate that only a limited number of processing techniques have been successfully applied in the manufacture of nanoscale micro-hole arrays. Consequently, the development of efficient processing techniques suitable for nanoscale micro-hole arrays will not only address this technological gap but also act as a significant driving force for the advancement of technology and industrial upgrading in related fields.

(6) Develop micro-hole processing technology suitable for new materials. In recent years, with the widespread application of new materials such as structural ceramics, composite materials, and additive manufacturing metals, it is often necessary to process array microstructures on them to achieve some special functions. However, current mainstream array micro-hole processing technology generally faces the challenge of limited material applicability, for example, laser processing technology faces difficulties in processing transparent materials, while electrical discharge machining and electrochemical machining are only applicable to conductive materials. Although electrochemical discharge machining has a wide range of material applicability, it is still difficult for its machining accuracy to meet the requirements for the preparation of array micro-holes. Therefore, developing suitable processing methods based on the physical, chemical, and mechanical properties of different materials is beneficial for further expanding the application of array micro-holes.

Sustainable manufacturing technology for array micro-holes is still in its infancy, with numerous avenues that require urgent attention or further investigation. As this field and its associated technologies continue to evolve, processing technology for array micro-holes will undoubtedly improve, enhancing its practical applicability.

## Data availability

The authors confirm that the data supporting the findings of this study are available within the article.

## Conflicts of 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.

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