The International Journal of Advanced Manufacturing Technology (2022) 118:703–735
https://doi.org/10.1007/s00170-021-07976-6

CRITICAL REVIEW

A comprehensive review on fabrication of ultra small micro tools via electrical discharge machining-based methods

Yao Sun[1] · **Liya Jin**[1] · **Mingjun Liu**[1] · **Yadong Gong**[1] · **Xuelong Wen**[1] · **Guoqiang Yin**[1] · **Quan Wen**[1]

Received: 27 April 2021 / Accepted: 29 August 2021 / Published online: 8 September 2021

Abstract
At present, the production of micro parts and components with characteristic sizes ranging from micron to millimeter mainly relies on micro machining technology, but the dimensional size of micro tools (including micro cutting tools, micro grinding tools, and microelectrodes) involved in micro machining is ultra small and made of super hard material like cemented carbide and polycrystalline diamond, which makes the preparation of ultra small micro tools have become the main bottleneck restricting the development of micro machining technology. The non-contact nature of electrical discharge machining (EDM) process makes it more competent in fabricating micro tools with relatively high efficiency and low cost; especially the wire electrical discharge grinding (WEDG) invented in 1985 provides a new approach and direction to fabricate micro tools; following this trend, numerous new design requirements and theoretical concepts of EDM-based processes utilized in fabricating micro tools have been proposed and studied successively, but, very few studies have been proceed from an integrated perspective. To address the gap, this study provides a comprehensive and well-arranged literature survey of the advancements made in the fabrication of micro tools using various EDM-based methods to date along with an insightful discussion on the science and application of EDM process. The critical factors influencing process performance, different numerical models, limitations, as well as possible future research direction and development in the field of micro tools fabricated by various EDM-based methods are identified and reviewed. This article is expected to help the researchers in identifying the existing gaps and contributing towards making EDM-based processes more competent in catering the trend of parameterized and non-standardized fabrication of ultra small micro tools.

Keywords EDM · Ultra small micro tools · Micro machining · Fabrication

Nomenclature

EDM	Electrical discharge machining
WEDG	Wire electrical discharge grinding
x	The changed discharge gap (cm)
j	Varied field electron emission density (A/cm^2)
E	Electric field intensity (V/cm)
φ	Electrons escape work (eV)
ρ	Material density (g/cm^3)
V	Electrode leaving volume of the made by electrostatic field (cm^3)
U	Interelectrode voltage (V)
F	Mechanical stress of electrode material (N)
S	Cross-sectional area of electrode made by destructive force (cm^2)
$K1$, K_2	Coefficient
j_a	Current density of anode spots (A/cm^2)
j_p	Current density of positive ions (A/cm^2)
j_e	Electron current density (A/cm^2)
V_a	Anode voltage drop (V)
V_i	The ionization potential of positive ion (V)
φ_a	Electron work of anode material (J)
φ_k	Electron work of cathode material (J)
d	Diameter of discharge crater (μm)
MCT	Micro cutting tool
MGT	Micro grinding tool
ME	Microelectrodes
BEDG	Block electrical discharge grinding
S-BEDG	Stationary block electrical discharge grinding

✉ Yao Sun
sy547515291@163.com

✉ Yadong Gong
gongyd@mail.neu.edu.cn

[1] School of Mechanical Engineering and Automation, Northeastern University, Shenyang 110819, China

M-BEDG	Moving block electrical discharge grinding
HER-MBEDG	High electrical resistivity moving block electrical discharge grinding
ISEDM	Slab electrical discharge milling
e	Electronic charge
k	Boltzmann constant
T	Discharge gap temperature (K)
S_a	Area of anode spots (cm^2)
S_k	Area of cathode spots (cm^2)
I	Discharge current (A)
m_e	Electronic quality (g)
U_c	Electronic voltage drop before collision (V)
U_a	Anode voltage drop (V)
T_k	Cathode boiling point (K)
μ	Atomic mass of metals (kg)
A	Avogadro constant
T_o	Temperature at a point on the electrode (°C)
z	The coordinates of this point
$g_{3\Phi}$	The effective power of the heat source (W)
a	Temperature coefficient
C	Heat capacity (J/K)
k	Characterized curve
t_u	Pulse on time (μs)
I_m	Pulse current amplitude (A)
TW-WEDG	Twin wire electrical discharge grinding
TF-WEDG	Tangential feeding wire electrical discharge grinding
RF-WEDG	Radial feeding wire electrical discharge grinding
R-EDM	Reverse electrical discharge machining
WEDM	Wire electrical discharge machining
LS-WEDT	Low speed wire electrical discharge turning
CWEDT	Cylindrical wire electrical discharge turning
EDG-TBE	Electrical discharge machining grinding by two block electrodes

1 Introduction

In recent years, precision three-dimensional micro parts and components with featured size ranged from micrometers to millimeters, and meeting the requirements of high shape accuracy and good surface quality have broad application in aerospace, defense and military, automotive electronics, biomedicine, precision instruments, etc., and Fig.1 presented some miniature products and structures including the micro aircraft, micro wall, micro trench, and micro gears [1–3]. These micro parts usually involved in a variety of materials such as metals, ceramics, and resins, and micro structures often relate to grooves, thin walls, micro pores, and special-shaped curved surface [4, 5]. Therefore, the realization of high precision and low cost processing of micro parts and components made of various materials and complex structures has become the key to micro-miniature processing technology.

The micro machining technology is the mainstream technique to achieve the fabrication of micro parts and components, and it mainly can be classified into micro cutting, non-cutting, and unconventional machining techniques; and the micro cutting processes contain micro cutting, micro milling, micro drilling, and micro grinding; the micro non-cutting processes include micro stamping, micro injection, etc; and the micro unconventional machining techniques include micro electrochemical, micro ultrasonic, micro-EDM, etc., and the unconventional machining and micro cutting processes have received extensive attention [6–8]. The micro-EDM makes the use of electro-corrosion generated by the pulse discharge immersed in the working fluid to remove conductive materials, and it has the characteristics of the non-contact, not limited by strength and hardness of material and can achieve the desired removal by controlling discharge energy, which makes it have unique advantage in fabricating micro part and structures, but it fails to fabricate micro parts and structures made of non-conductive material and consist of complex three-dimensional shapes [9–14]. Thus, the micro parts and structures made of conductive materials can be directly fabricated by EDM method. However, as for the fabrication of micro parts and structures made of non-conductive materials still relies on micro cutting technology including micro turning, micro milling, and micro grinding [15–20], and micro cutting technologies have advantages of relatively high efficiency, strong three-dimensional processing ability, and a wide range of applicable workpiece materials [21, 22].

However, the diameter of micro tools involved in micro cutting technologies is generally smaller than 1mm, and the smaller the size is, the more difficult it is to prepare, so the successful preparation of micro tool is the key to micro cutting technologies to achieve high precision and low cost manufacture of micro parts and structures [6, 23]. The non-contact nature of EDM processes makes it more competent in preparing micro tools and has been drawn wide attention of scholars around the world. This article provides a critical overview of the broad field of EDM processes involved in the fabrication of micro tools and the present achievements and limitations to provide grounds for future research works.

2 Physical process, classification, and short chronological review of EDM methods involved in fabricating micro tools

2.1 Physical process and material removal mechanism

The physical process of EDM machining is very complicated and short-lived, and the microscopic process of each spark

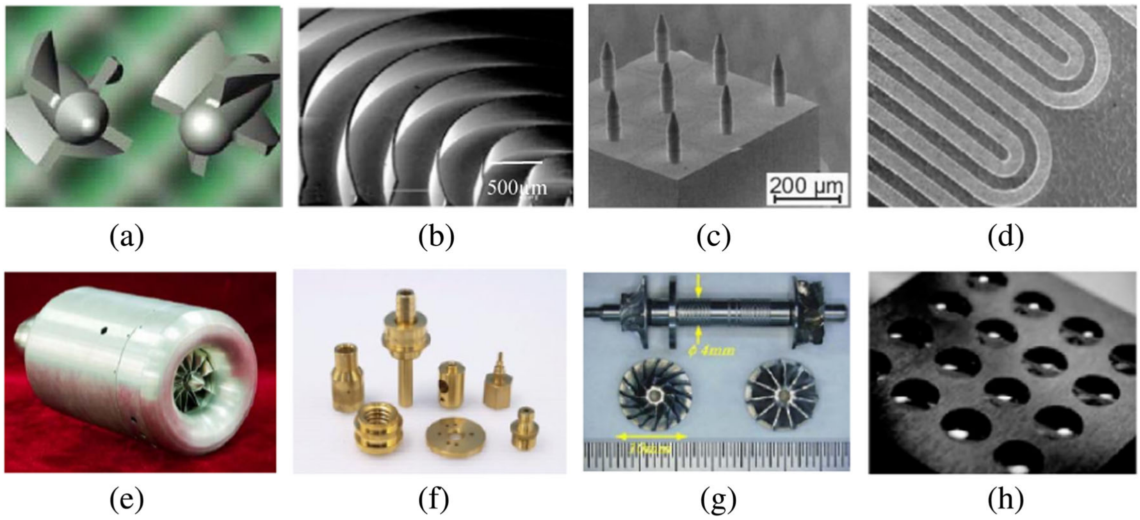


Fig. 1 Micro products and structures: **a** micro air vehicle parts, **b** micro wall, **c** microarray, **d** micro sensor, **e** micro turbine engine with diameter of about 12cm, **f** aerospace micro products, **g** micro impeller parts and rotor, **h** microarray

discharge is integrative result of thermal power, electric power, electromagnetic force, and fluid power. In the process of EDM, the material erosion mainly can be divided into dielectric breakdown, channel formation, electrical discharge thermal erosion, and deionization throwing as presented in Fig. 2 [24, 25]. Firstly, an electric field is established between tool electrode and workpiece, and the field strength depends on the interelectrode voltage and distance. When the field is strong to a certain extent, working fluid molecules are polarized to form the low resistance channel. At the same time, impurities in the working fluid such as metal particles and micro bubbles will gather and form chains in the place of strongest field. When the field strength is further increased, the cathode may also emit electrons. The electrons are accelerated under action of electric field and hit neutral molecules or atoms to cause ionization. This ionization develops rapidly from the cathode to the anode in an avalanche manner. When electrons flow to the anode, the medium is broken down to form a discharge

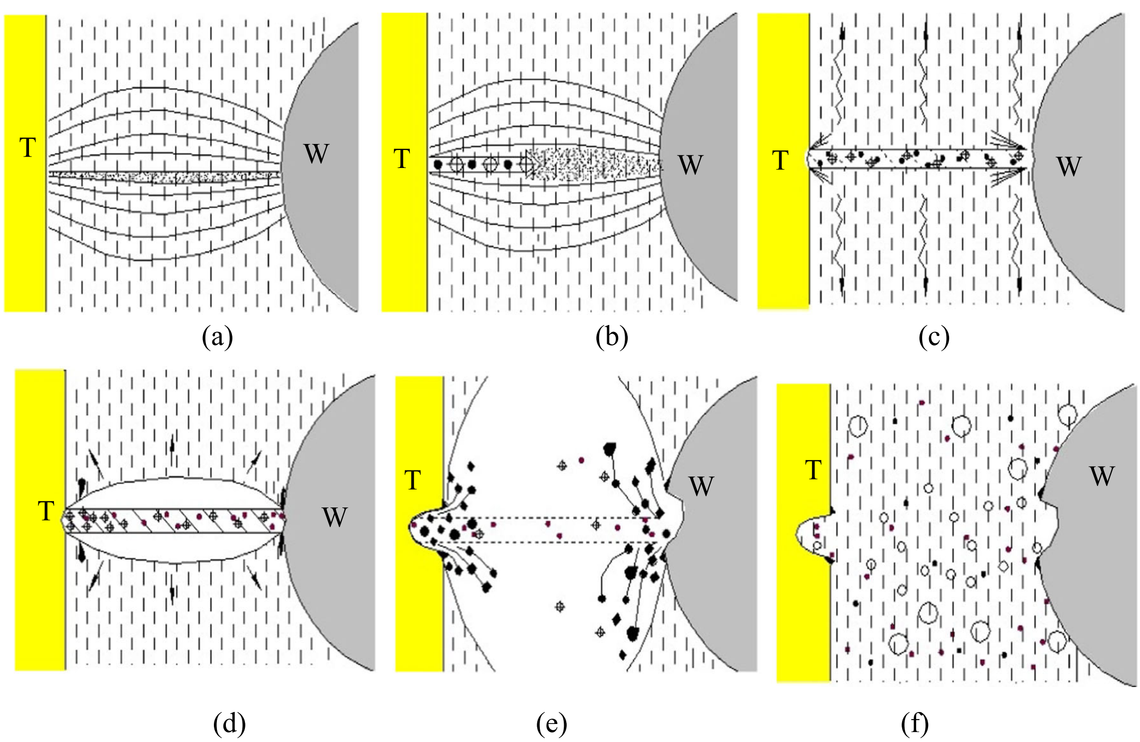


Fig. 2 Diagrammatic sketch of material removal process for EDM process; T is tool electrode, and W is workpiece electrode; **a** establishment of electric field, **b** electron emission, **c** channel formation, **d** channel expansion and bubble formation, **e** channel collapse and bubble expansion, **f** deionization

channel. The dielectric breakdown under a very thin gap is the result of the mass and dynamic interaction of field emission and static electric field, and there is a positive feedback relationship between them as shown in Eq. (1), and they can be calculated from Eq. (2) [26].

$$\begin{cases} x = f(t) \\ j = \phi(t) \end{cases} \tag{1}$$

$$\begin{cases} \dfrac{d_x^2}{d_t^2} = \dfrac{S(t)}{K_1 \rho V(t)} \left[\dfrac{U^2}{x^2} - K_2 F(t) \right] \\ j = 1.55 \times 10^{-6} \dfrac{E(t)^2}{\phi} e^{-\frac{6.8 \times 10^7 \phi^{2/3}}{E(t)}} \cdot \psi \left(\dfrac{3.62 \times 10^{-4} \sqrt{E(t)}}{\phi} \right) \end{cases} \tag{2}$$

where x represents the changed discharge gap (cm), j is varied field electron emission density (A/cm^2), E is electric field intensity (V/cm), φ is electron escape work (eV), ρ is material density (g/cm^3), V is electrode leaving volume of the made by electrostatic field (cm^3), U is interelectrode voltage (V), F is mechanical stress of electrode material (N), S is cross-sectional area of electrode made by destructive force (cm^2), and K_1 and K_2 are coefficient.

The entire energy of pulse is released in two electrodes and discharge gap. The energy gained by anode is primarily passed by electron bombardment, and radiation heat transfer and thermal shock of gas particles are relatively small, so it can be neglected, and then anode energy per unit time can be expressed as Eq. (3); in addition, the cathode energy is supplied by positive ions, and electrons consume cathode energy; thus, the power input on the cathode P_k is represented by Eq. (4) [27].

$$P_a = j_a \left(V_a + \frac{\phi_a}{e} + \frac{2kT}{e} \right) S_a \tag{3}$$

$$P_k = \left\{ j_p \left[d \left(V_k + \frac{2kT}{e} \right) + V_i - \frac{\phi_k}{e} \right] - j_e V_e \right\} S_k \tag{4}$$

where the j_a and j_p respectively are current density of anode spots and positive ions (A/cm^2), j_e is electron current density (A/cm^2), V_a is anode voltage drop (V), V_i is the ionization potential of positive ion (V), φ_a and φ_k respectively are electron work of anode and cathode material (J), e is the electronic charge, k is the Boltzmann constant (k=1.38×10^{-23}J/K), T is discharge gap temperature (K), S_a and S_k respectively are area of anode and cathode spots (cm^2), and I is discharge current (A).

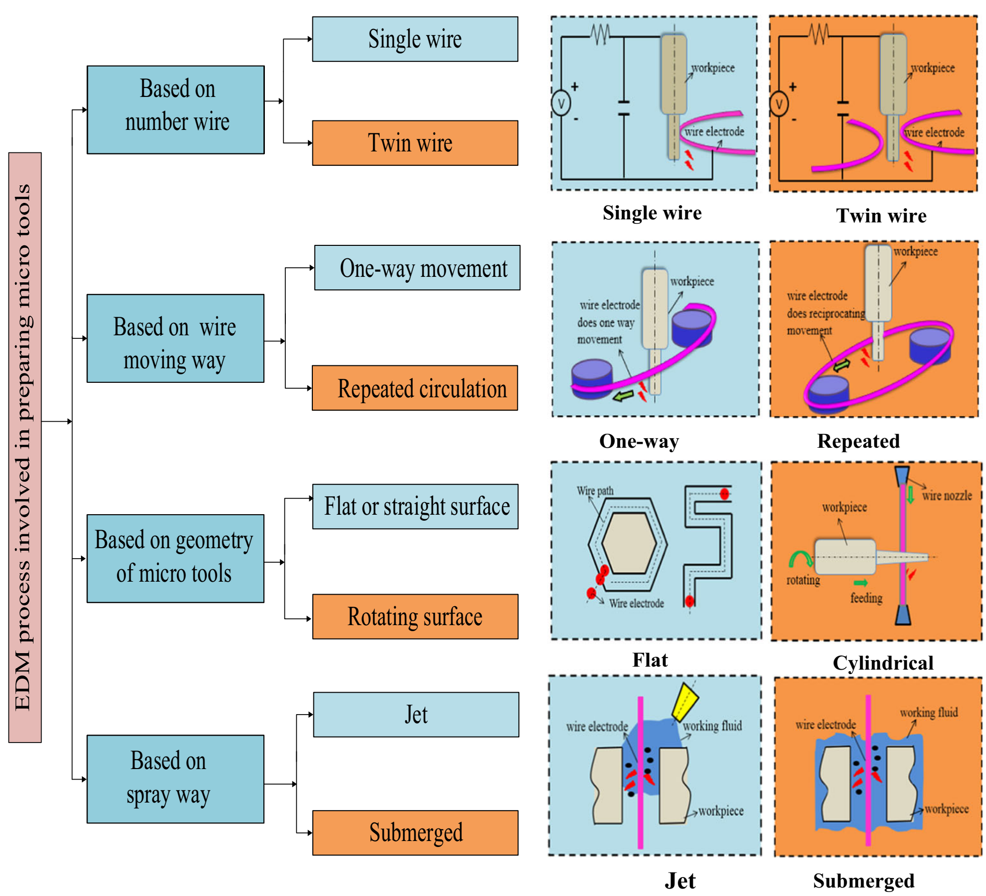


Fig. 3 Classification of EDM process involved in fabricating micro tool

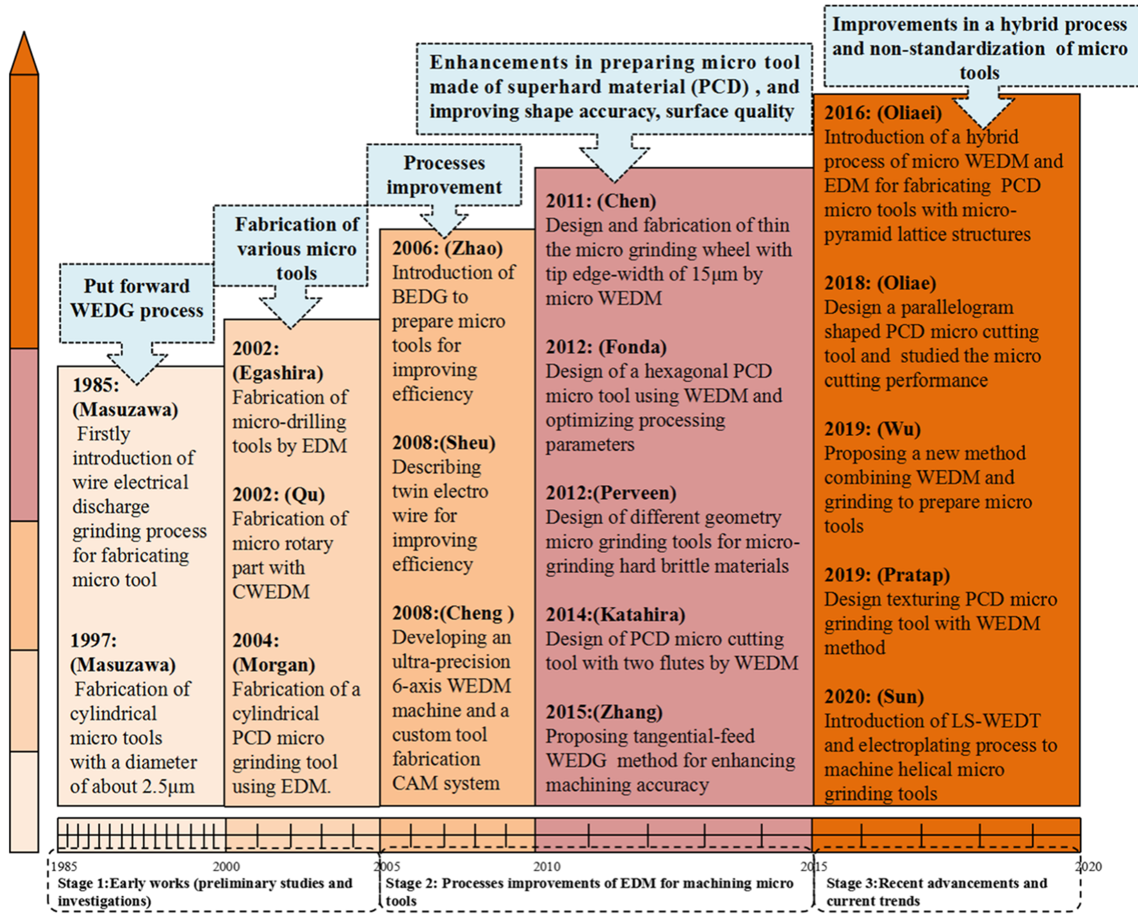


Fig. 4. A short chronological review of EDM process involved in fabricating micro tools

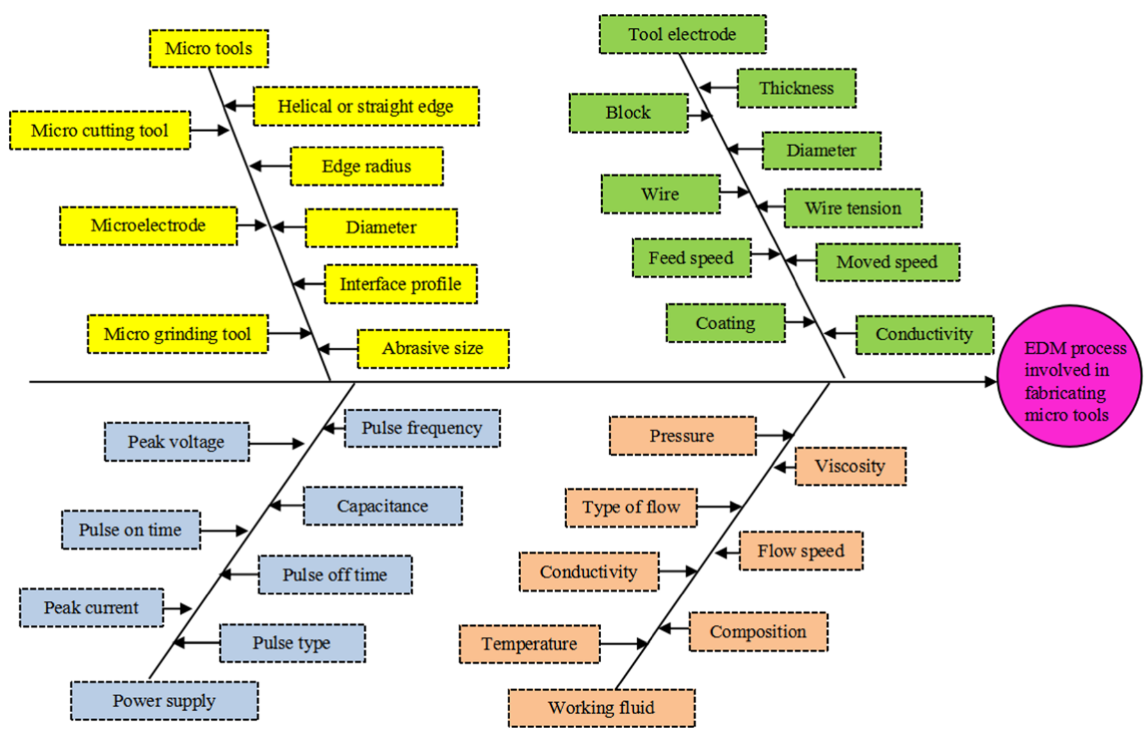


Fig. 5 Ishikawa diagram showing the classification of process parameters in machining micro tools by EDM process

The extremely high temperature and pressure of discharge channel can strongly heat the cathode spot and make metal near the point become overheated material and then occur explosive melting, vaporization, and metal throwing phenomena, and the bubbles gradually expand outward. Then the cathode pressure under the action of ion flow p_k and the anode pressure under the action of electron flow p_a can be respectively expressed by Eq. (5) [26].

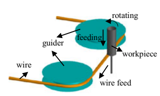
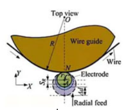
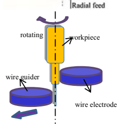
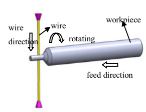
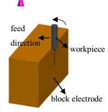
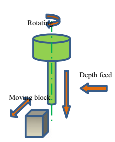
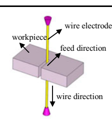
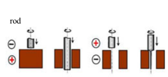
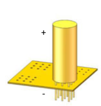
$$\begin{cases} p_a = j_a\sqrt{\dfrac{m_e(2eU_a-3kT_k)}{e^2}} \\ p_k = j_p\sqrt{\dfrac{\mu(2eU_c-3kT_k)}{Ae^2}} \end{cases} \tag{5}$$

where m_e is electronic quality (kg), U_c is electronic voltage drop before collision (V), U_a is anode voltage drop (V), T_k is cathode boiling point (K), μ is atomic mass of metals (kg), and A is Avogadro constant.

In addition, the electrode obtained heat from the discharge channel namely surface heat source. Assuming that the radial distribution of heat flow in the surface heat source can be described by the Gaussian distribution, the solution of the temperature field can be obtained by the superposition principle and expressed as Eq. (6) [26].

$$T_o(r,z,t) = \frac{8g_{3\varphi}\alpha k}{C\rho(4\pi a)^{3/2}}\int_0^{t_u}\frac{1}{\sqrt{t}\sqrt{4akt+1}}e_{-\left(\frac{kr^2}{4akt+1}+\frac{z^2}{4at}\right)}d_t \tag{6}$$

Table 1 Main EDM processes involved in fabricating micro cutting or grinding tools and microelectrodes

EDM types	Machining schematic diagram	Characteristics	Application and remarks
WEDG		High machining accuracy and non-taper, low efficiency, high investment	Fabricating micro electrodes with 2.5μm in diameter and micro cutting or grinding tools with various shapes; Masuzawa et al.[31-32], Li et al.[99], Kuo et al.[100], Egashira et al.[33,67,101], Yan et al. [92, 103], and Rees et al.[104], Wang et al.[106]
TF/RF-WEDG		High machining accuracy, good surface roughness, complex setup	Fabricating micro electrodes with 26μm in diameter; Zhang et al.[134]
Twin-WEDG		High machining efficiency and non-taper, poor surface quality	Fabricating microelectrodes with 5μm in diameter; Sheu et al.[37]
LS-WEDT		Flexibility space movement and not restricted by the regulating wheel	Fabricating helical microelectrodes and helical micro cutting tools; Su et al.[79], Sun et al.[52,86]
S-BEDG		High efficiency, simple setup, but low machining accuracy	Fabricating cylindrical microelectrodes with 150μm in diameter, D-shaped micro cutting tools, and triangular and square micro grinding tools; Ravi et al.[107], Lim et al.[108], Zhao et al [36] and Siddhartha et al.[109],Perveen et al.[43]
M-BEDG		Good machining accuracy and simple setup	Fabricating microelectrodes with various shape; Jahan et al.[110], Rahman et al. [111] , Hourmand et al.[112] and Jahan et al.[113] Koyano et al. [114]
WEDM		High accuracy, low investment, be competent in fabricating complex straight surfaces, but failure of forming rotary surface	Fabricating micro grinding tools and micro cutting tools; Yan et al.[44], Katahira et al.[45], Nakamoto et al. [46], Gao et al.[47], Oliaei et al.[50], Ganesh et al.[72],Zhan et al.[73], Katahira et al.[41], Fonda et al.[40], Cheng et al.[38,74, 75]
Self-drilled		Simple setup, low investment, low accuracy and taper	Fabricating cylindrical micro electrode with 4μm in diameter; Minoru et al. [118]
R-EDM		Good surface roughness, low machining accuracy and taper, low efficiency	Fabricating cylindrical array micro electrodes; Kim et al. [121] and Singh et al.[122]

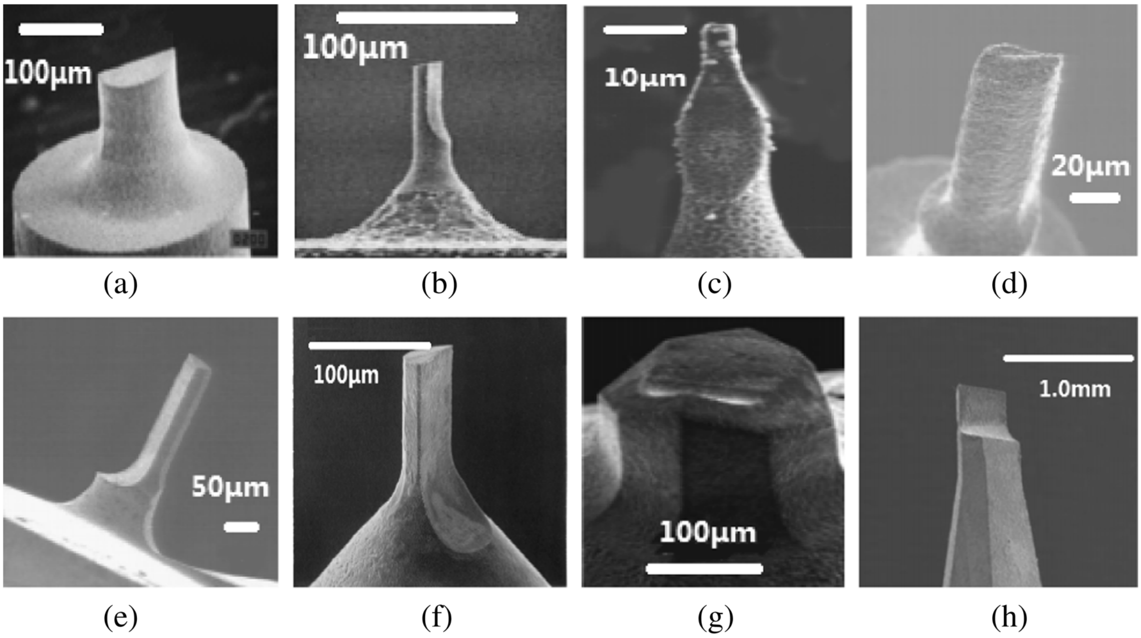


Fig. 6 **a** MCT in tungsten carbide and diameter of 100μm[64], **b** MCT with the clearance angle of 20° and cutting edge radius of 0.5 μm[32], **c** MCT with diameter of 3μm[65], **d** micro cutter with diameter of 50 μm[67], **e** semi-circular micro cutter with diameter of 100 μm, **f** D-shaped micro cutter [43], **g** custom designed single edge PCD micro end mill[45], **h** quadrilateral micro cutter[46]

T_o is the temperature at a point on the electrode (°C); z is the coordinate of this point; $g_{3\Phi}$ is the effective power of the heat source (W); a is temperature coefficient; ρ is material density (g/cm^3); C is the heat capacity (J/K); t_u is the pulse width (μs); and k is characterized curve.

Finally, the discharge channel rapidly shrinks and collapses when the discharge pulse ends, and then deionization is performed. Meanwhile, the bubbles continue to expand to its maximum size, and the pressure in bubble drops to close to atmospheric pressure, and the overheated molten material is

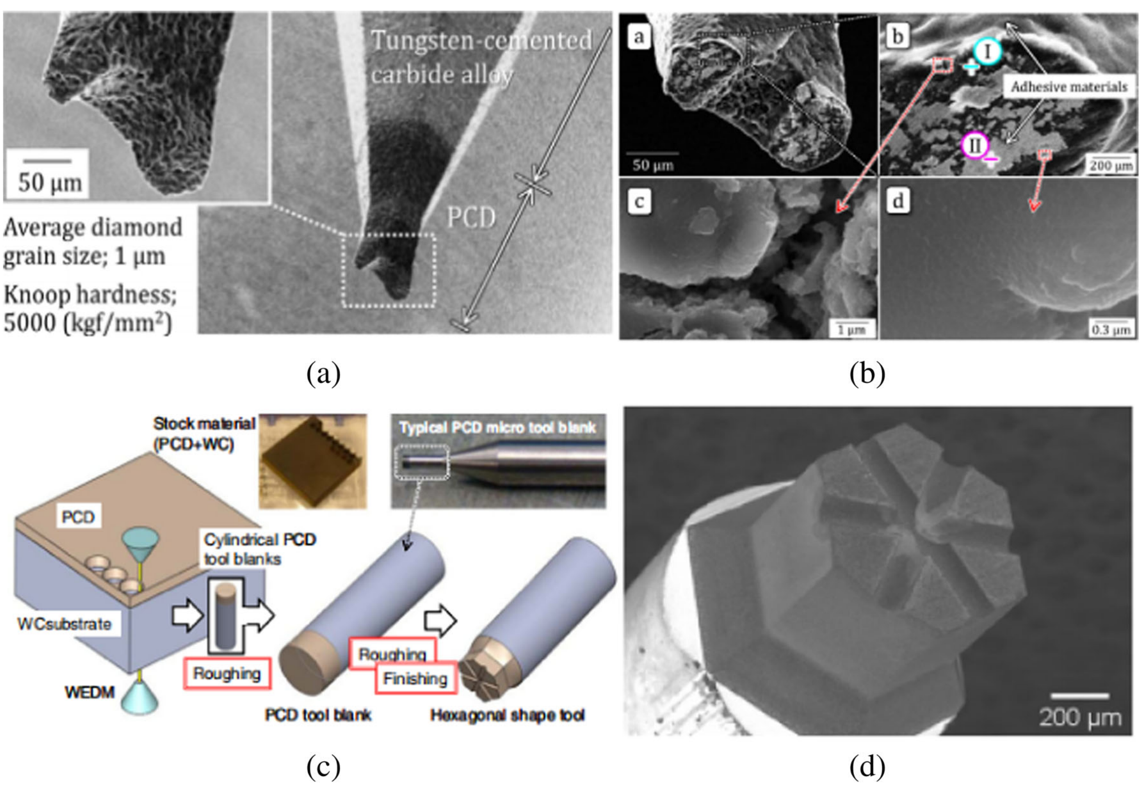


Fig. 7 **a** Square-shaped PCD end mill, **b** micro cutting tool after machining, **c** PCD tool fabrication process, **d** a hexagonal micro cutting tool

thrown out in EDM process. Metal particles are scattered inside and outside of the bubble to form processing chips. After the bubble expands to the maximum size, it begins to shrink due to the low pressure until it bursts. After the discharge corrosion is completed, the metal particles, carbon black, and small bubbles will be left in the liquid between the electrodes, and discharge craters are formed on the workpiece and tool electrodes, and the diameter of discharge crater can be expressed as Eq. (7) [28].

$$d = 0.151 I_m^{0.4} t_u^{0.4} \quad (7)$$

where d is diameter of discharge crater (μm), I_m is pulse current amplitude (A), and t_u is pulse width (μs).

2.2 Classification of EDM involved in fabricating micro tools

The non-contact nature of EDM processes makes them competent to machine electrical conductive materials regardless of their hardness and strength with precise shape and good surface quality, which mainly can be classified into the WEDM, die-sinking EDM, EDM drilling, EDM milling, WEDG, etc.[29], but not all EDM methods are suitable for the fabrication of micro tools. For visualizing the spectrum of ongoing research in EDM methods for machining micro tools, processes are classified into four categories in this research, which is the basis of the number of tool electrodes, moving way of tool electrode, micro tool geometry, and liquid way as shown in Fig. 3.

2.3 A short chronological review

The EDM process was invented by Soviet scholar Lazarenko in 1943, and this new processing technology has gained rapid development and wide application in the world and usually was used for the machining of various metal materials such as carbon steel, stainless steel, and high temperature alloy. Until 1985, the Japanese scholars Masuzawa proposed WEDG method which provided a new approach to the fabrication of micro tools by EDM process and meet the rapid requirements of micro tools applied in micro cutting technologies [30]. To give a holistic viewpoint of field related to EDM processes involved in fabricating micro tools, primary reports are chronologically presented in Fig. 4, and a brief description is presented as follows:

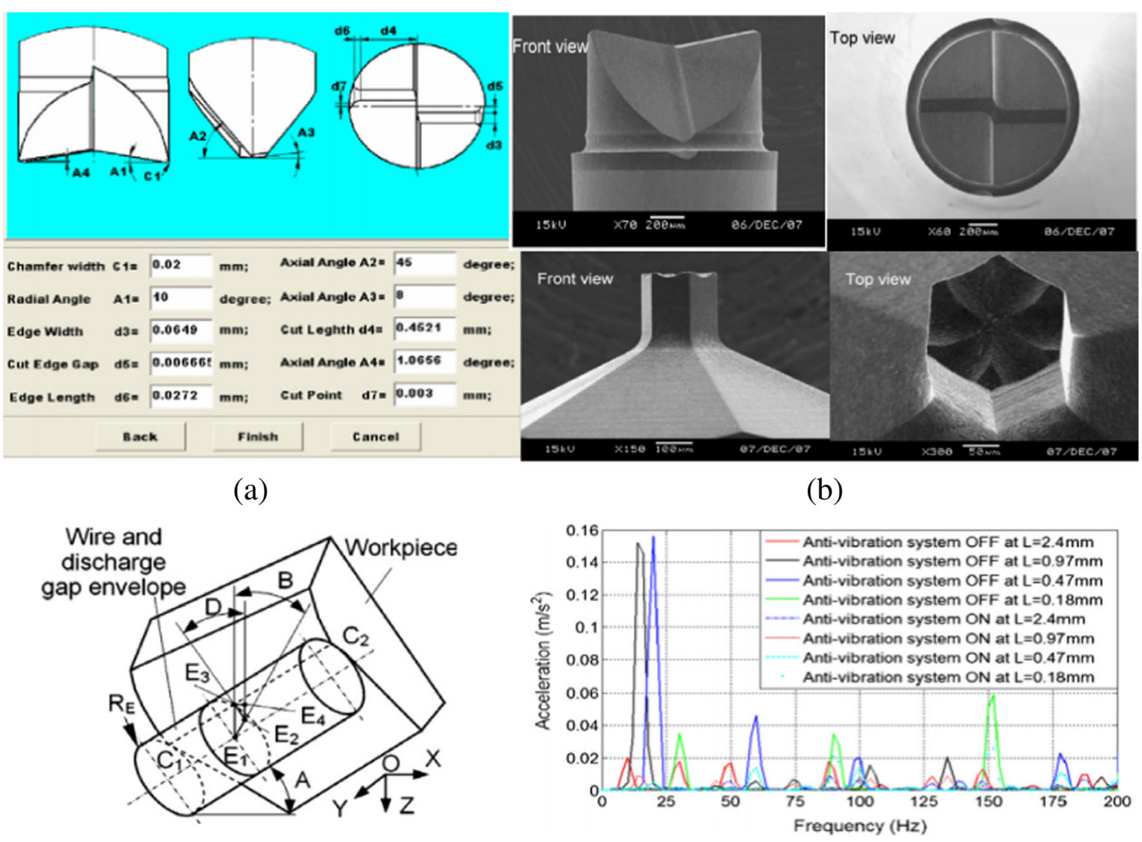


Fig. 8 **a** Micro tool fabrication CAM system, **b** fabricated results of micro cutting tool, **c** wire offset calculation, **d** frequency response components

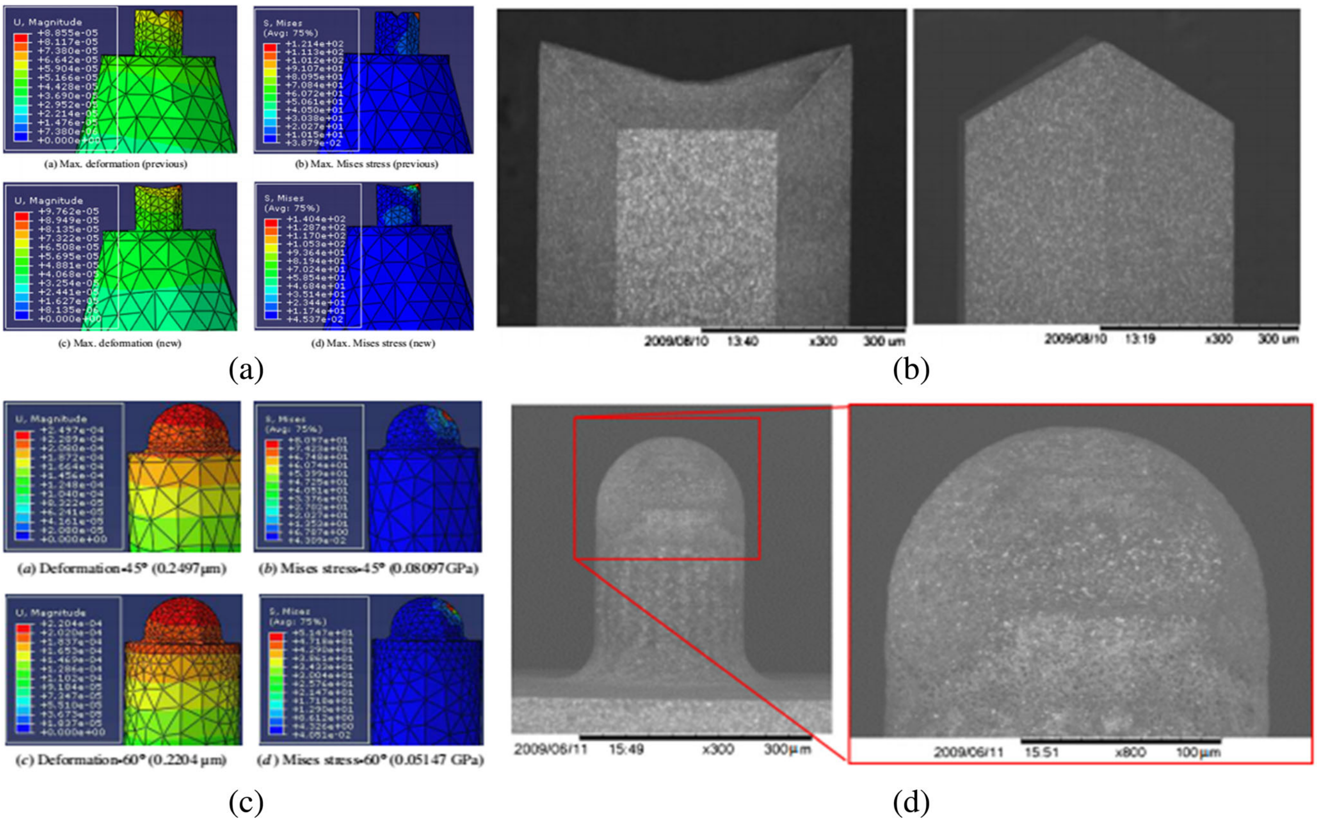


Fig. 9 **a** The FEM static analysis, **b** new hexagonal end mill made of PCD, **c** static FEM analysis, **d** fabricated new ball end mill.

2.3.1 Stage 1: Early works (preliminary studies and investigations) (1985–2005)

The early works mainly focused on the introduction of WEDG [30], fabricating the cylindrical micro rods and adjusting discharge parameters for minimizing its diameter [31] and preparing simple rotating parts or micro tools [32–34].

2.3.2 Stage 2: Process improvements (2005–2015)

In this stage, the significant study is reported related to improvements of EDM methods involved in fabricating micro tools, for example, in order to improve machining efficiency, the BEDG method [35], twin electro wire [36], and custom tool fabrication CAM system [37] are successively put forward. Besides, the process improvements are obtained in the fields of machining accuracy [38],surface roughness [39], super hard material [40], complexly parametric design [41] and the application of EDM fabricated micro tools in hard brittle materials [42]. Additionally, the majority of work is also reported on analyzing influencing factors and optimizing process parameters involved in micro tool fabrications of using EDM process [43–46], and a classification of parameters directly associated with process performance in the EDM fabrication of micro tools is shown in Fig. 5.

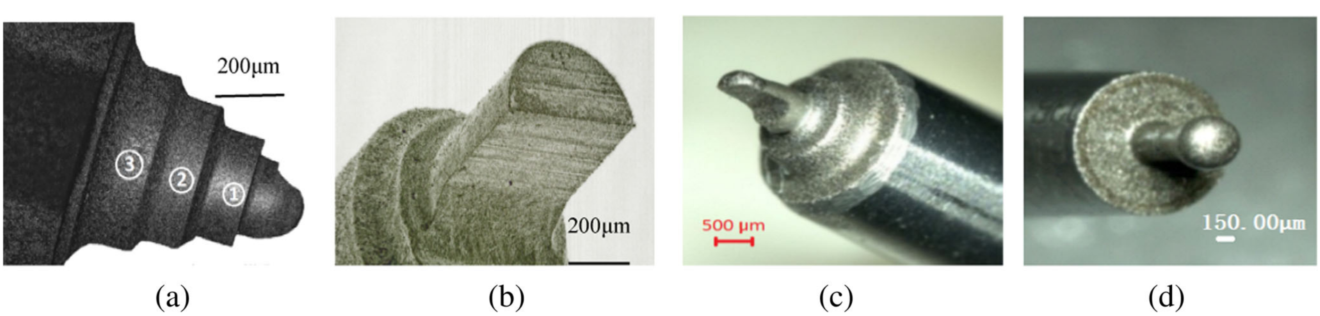


Fig. 10 **a** Stepped WC micro tool, **b** D-shaped flat end cylindrical PCD micro tool, **c** micro ball end mills, **d** lollipop end mill

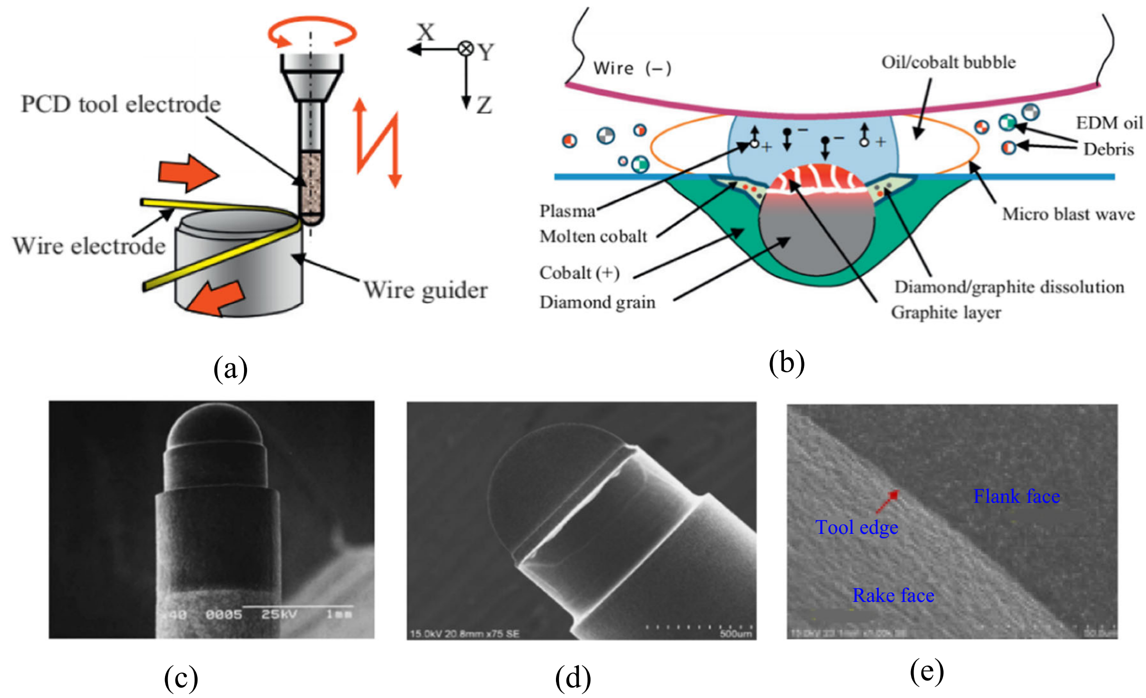


Fig. 11 **a** Schematic of tool shape generation; **b** detailed diagram showing graphitization, dissolution, and gradual removal of a diamond grain; **c** EDM-fabricated hemispherical tool; **d** PCD micro cutting tool; **e** tool edge and flank

2.3.3 Stage 3: Recent advancements and current trends (2015–2020)

In this stage, the majority of published papers are related to improvements in hybrid processes and non-standardization design of micro tools. The design of texturing micro grinding tool [47] and helical edged micro cutting tools [48] are introduced for enhancing the machining stability and surface quality. Apart from this, a significant volume of work is also reported on the fabrication of micro tools using the hybrid technology combining more than two individual processes [49, 50].

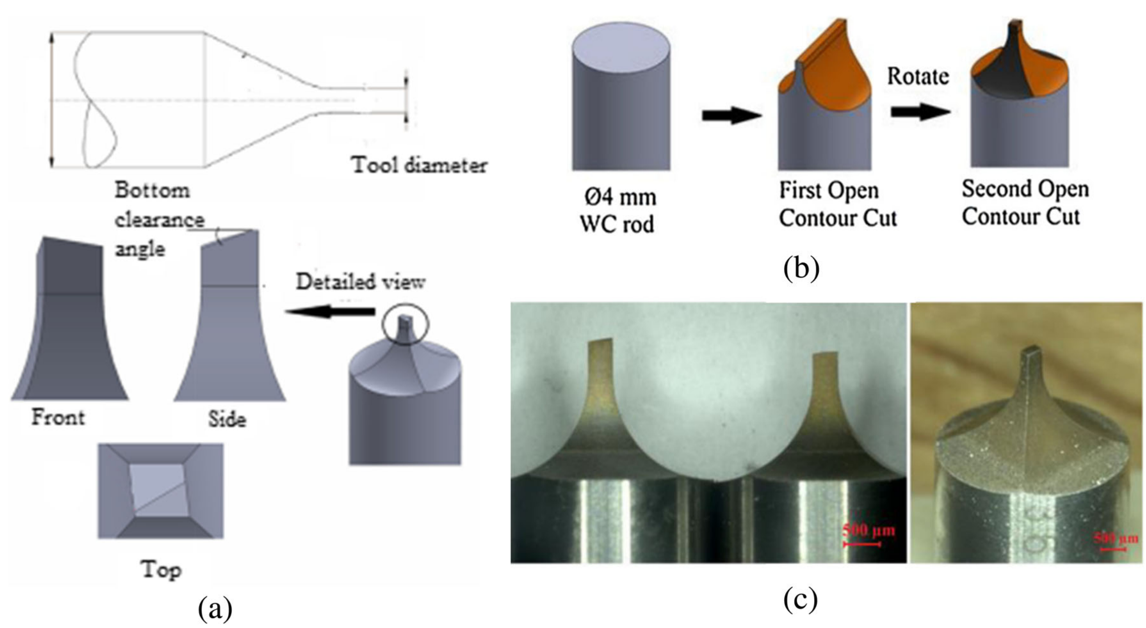


Fig. 12 **a** Geometry of designed micro cutting tool, **b** schematic of micro cutting tool fabricated

3 EDM methods applied in fabricating micro tools

3.1 Micro cutting tools

In micro machining, the micro milling is a dominant process to achieve the fabrication of micro parts and components, and micro cutting tools (MCT) involved in micro milling process are usually very slender with the diameter less than 1mm, which makes the preparation of micro cutting tools difficult, and the complex structures and ultra-hard materials will further increase the difficulty of preparation [51, 52]. The fabrication techniques of MCT are the basis of ensuring the machining accuracy and capacity of micro milling, which is also one of the main bottlenecks restricting the development of micro milling [53, 54]; at present, the fabrication technology of MCT mainly includes the precision micro-grinding, focused ion beam, laser machining and electrical discharge machining, etc [55–57]. Among them, the minimum diameter of MCT cannot be stably obtained with precision micro-grinding due to the limited by grinding force [43, 58]; the processing efficiency of focused ion beam is low, and the cost is expensive; the hot melt zone in laser machining is difficult to control resulting in low forming accuracy [59]; while the advantages of good controllability, non-contact, no macroscopic force, and low machining cost make EDM process more competent to fabricate micro cutting tools, it can ignore material hardness and prevent undesired problems such as chatter, mechanical stresses, and vibration [60–63]. Thus, many scholars all over the world paid attention to fabricate micro cutting tools using various EDM processes, which includes WEDG, TW (twin)-WEDG, TF/RF-WEDG, S/M-BEDG, R-EDM, Self-drilled, LS-WEDT, WEDM, etc, and specific EDM processes involved in fabricating micro tools and their machining principles, characteristic, applications, and remarks are summarized in Table 1.

For reducing the preparation difficulty of micro cutting tools, some researchers adopted EDM methods to fabricate

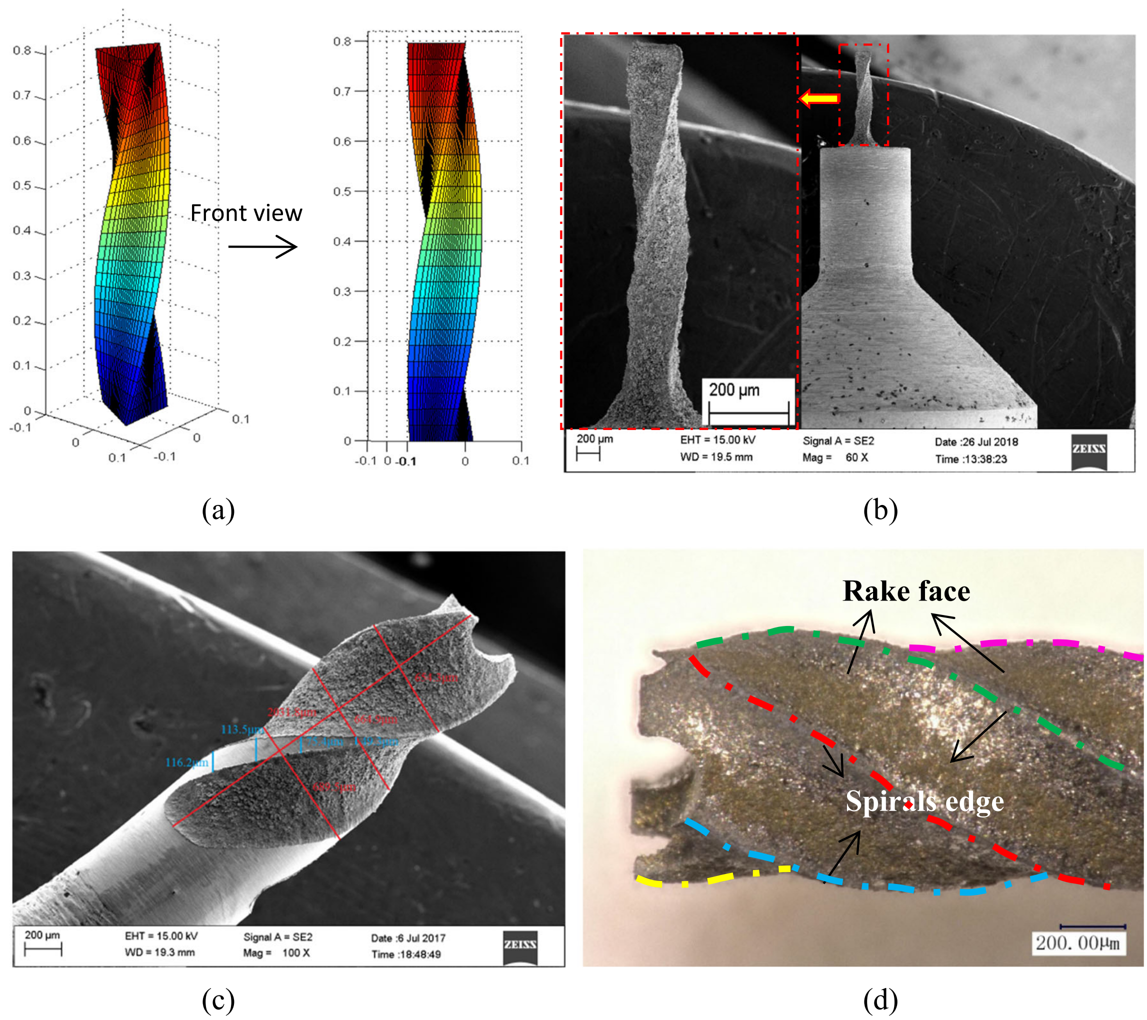


Fig. 13 **a** Simulated results and **b** experimental results of micro cutting tool with three spirals, **c** three edge spirals micro end tool with varied spiral angle, **d** micro cutting tool with six spirals

micro cutting tools with simple polygon structure and straight cutting edge. Fleischer et al. [64] found that the WEDG method has the potential to machine micro cutting tools with a diameter smaller than 100 μm, and the results meet requirements of necessary surface roughness and sharpness of the cutting edge as displayed in Fig. 3a. Egashira et al. [32, 65], Ali et al. [66], Chern et al. [67], and Fleischer et al. [68] adopted WEDG method to prepare micro cutting tools with different cross-section shape (such as D-shaped and circular) and high aspect ratio made of tungsten carbide material as presented in Fig.3. Yan et al. [43], Katahira et al. [44], Nakamoto et al. [45], Gao et al. [46], Oliaei et al. [69], Ganesh et al. [70], and Zhan et al. [71] respectively adopted the WEDM method to fabricate various kinds MCT as shown in Fig. 6 and controlled geometrical error and tool edge radius of the cutting edge by optimizing electrical discharging parameters including peak current and peak voltage.

In recent years, the structural design of micro cutting tools has been presented a trend of non-standardization and parameterization; for example, Katahira et al. [40] fabricated a square-shaped PCD micro cutting tool with two flutes by WEDM method as presented in Fig. 7 a and b, and the micron-sized wells and groove structures on silicon carbide with surface roughness of R_a=1.7nm were successfully machined by using this PCD tool, and amorphous silicon dioxide can be detected onto the surface of the PCD tool by SEM and EDS analyses. Fonda et al. [39] investigated effects of WEDM parameters on machining speed for roughing and surface roughness for finishing by using signal to noise ratios, and a hexagonal MCT made of the PCD material was fabricated by WEDM optimized condition, and chemical composition is detected as shown in Fig. 7 c and d. In addition, Cheng et al. [37] developed an ultra-precision machining system of six-axis WEDM machine and custom tool fabrication CAM system; before fabricating micro cutters, the effectiveness of counter motion system is conducted and the detected frequency components obtained by an accelerometer located on workbench when X-axis is driven by acceleration or deceleration pattern. For cutting accurately, the wire offset is considered and calculated by Eqs. (8)~(10). Finally, they fabricated a 2-flute special cutter with diameter of 1mm and hex-polygon cutter with diameter of 0.2mm made of PCD material as shown in Fig. 8. Moreover, Cheng et al. [72–74] designed a new kind of PCD ball micro cutting tool and utilized WEDM tool with four axes to fabricate it and proposed to use negative rake angle to cut brittle materials for achieving the purpose of plastic cutting. Through FEM simulation analysis, it is concluded that this ball micro cutting tool has the

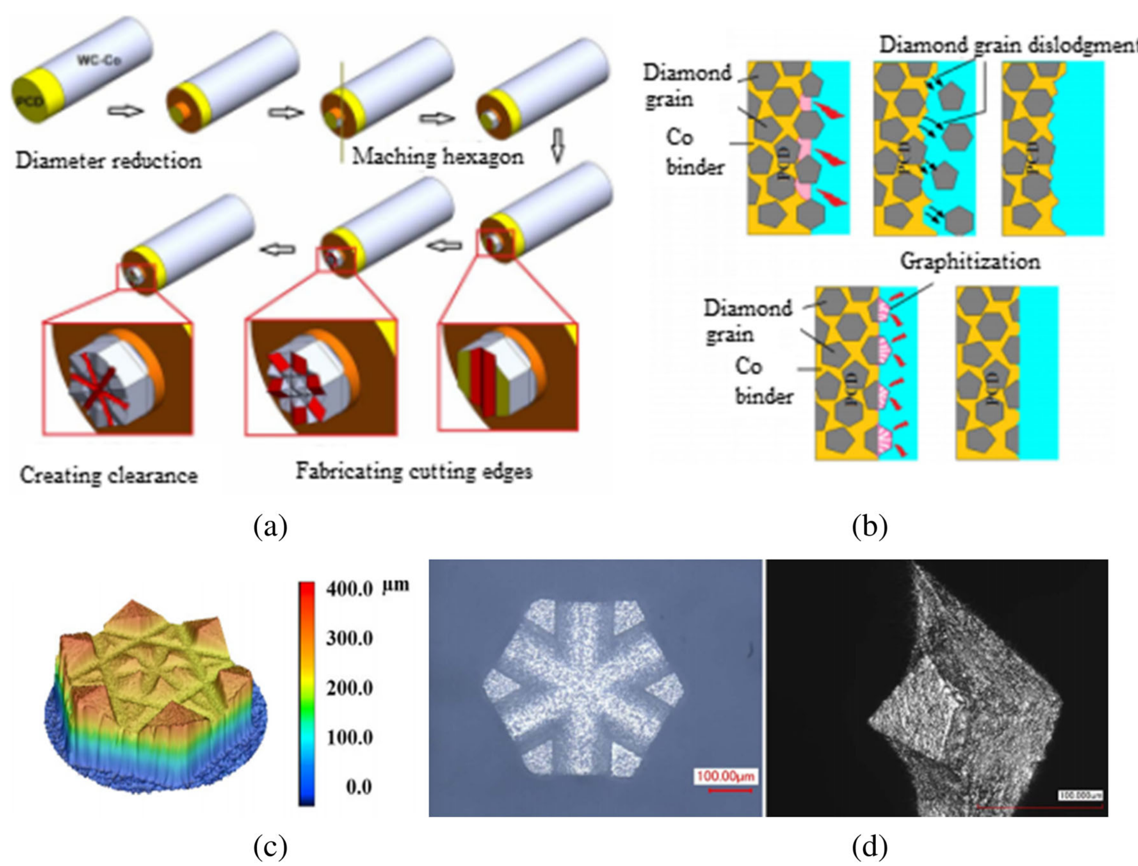


Fig. 14 **a** Schematic of micro tool fabricated steps, **b** material removal mechanisms of PCD during WEDM process, **c** 3D profile of the fabricated PCD tools, **d** hexagonal PCD micro end mill

Table 2 The specifications of various micro tools fabricated using EDM processes

Type of micro tools	Performance (dimensions and material)	EDM-fabricated method	Application	Remarks
Shape with a polygon with 36 corners	Less than 100μm in diameter, tungsten carbide	WEDG	Fabricating micro slots	Fleischer et al. [64, 68]
Shape with a D-shaped cross section	About 20m in diameter, and clearance angle and cutting edge radius of approximately 20° and 0.5 μm, tungsten carbide	WEDG	Fabricating micro holes on monocrystalline silicon	Egashira et al. [32, 65]
Shaped with double cutting edges	Less than 100 μm, tungsten carbide	WEDG	Fabricating micro slots and thin-walled structure on Al 6061-T6 material	Chern et al.[67]
Shape with two cutting edges and no helical grooves	About 20μm in diameter; made of high speed steel and tungsten carbide	WEDG+FBI	Fabricating micro channels on polymer	Ali et al.[66]
Shape with a polygon with 8 corners and inclination clearance angle	About 50μm in diameter , the geometrical error and roundness of cutting edge are controlled below 1 μm, tungsten carbide	WEDM	Fabricating micro grooves on electroless nickel plating	Yan et al.[43]
Shape with ball head and four straight flutes	Ball head radius of 0.25 mm, made of PCD diamond grains with 0.5μm in size	WEDM	Fabricating hemispherical cavity with a radius of 0.4 mm and depth of 0.4 mm	Katahira et al.[44]
A custom single edge micro cutting tool with axial relief and angle	About 300μm in diameter and made of PCD material	WEDM	Fabricating narrow groove with high aspect ratio on tungsten carbide	Nakamoto et al. [45]
A quadrilateral micro cutting tool	About 300μm in diameter, tool edge radius of 6.7μm. and CTB002 PCD material	WEDM	Can be used to fabricate micro structures	Gao et al.[46]
Micro turning tool with rake face and angle	Edge radius of around 2μm and clearance angles of 7° and 14°, made of uncoated carbide	WEDM	Milling titanium alloy (Ti6Al4V) plane	Oliaei et al.[69]
A four edged micro cutting tool	About 100 μm in diameter and 476 μm in length, tungsten carbide	WEDM	Fabricating micro-channel on SS304L and Aluminum 6061	Ganesh et al.[70]
A costumed hexagon micro cutting tool	The diameter of 1 mm. the rake angle, flank angle, and inclination angle for the end cutting edge respectively of 0,20, and 10 °, made of PCD	WEDM	Milling tungsten carbide plane	Zhan et al.[71]
A square-shaped micro cutting tool with two flutes	About 150 μm in diameter and made of PCD with average diamond grain size of 1μm	WEDM	Fabricating micron-sized wells and groove structures on silicon carbide	Katahira et al.[40]
A hexagonal micro cutting tool with six chip removal slots at the bottom	About 1mm in diameter and made of tungsten carbide substrate and PCD layer	WEDM	Of great promise for micro machining hard and brittle materials	Fonda et al.[39]
A 2-flute, hex-polygon, flat, ball head micro cutting tools	With diameter ranged from 0.2mm to 1mm, made of PCD material.	WEDM	Fabricating 3D freeform geometry milling on tungsten carbide and silicon wafer	Cheng et al. [72–74]
D-shaped square end cylindrical, ball head and lollipop micro cutting tools	About 400μm in diameter and made of tungsten carbide and PCD with 5μm grain	BEDM + WEDG	Fabricating prototypes of microfluidics chips and micro channel on fused silica	Oliaei et al.[75]
A hexagon micro cutting tool with flank and rake angle	About 700μm in diameter, cutting edge radius of 3μm, cutting edge length of 0.5 mm, flank and rake angle of10°	WEDM+ Grinding	Milling cemented carbide plane	Wu et al.[50]

Table 2 (continued)

Type of micro tools	Performance (dimensions and material)	EDM-fabricated method	Application	Remarks
	and 0°, made of PCD with grain size of diamond particles of 2~4μm			
Single flute spherical micro end mill	About 1000μm in diameter, the radius of the spherical surface of about 400μm and edge radius of about 1.8μm, made of PCD	WEDG	Fabricating micro dimples and micro grooves on tungsten carbide mold substrates	Zhang et al[57]
Ball micro end mills with four cutting edges	Radius of less than 200 μm and cutting edge radius of 5.16μm, made of hard alloy	LS-WEDT	Fabricating micro dimples on brass	Su et al.[76]
A single cutting edge micro cutting tool with bottom and side clearance angles, neck taper angle	About 200μm in diameter, surface roughness of 0.15μm and edge radius of 1.5~2.5μm	WEDM	Fabricating micro slots on titanium alloy Ti6A14V	Samad et al [77]
Three or six spirals and varied spiral angle micro cutting tools	About 123.8μm in diameter and 800μm in length, made of hard alloy	LS-WEDT	Fabricating micro slots on Nickel based superalloyDD5	Sun et al.[48]
Micro cutting tools with a hexagonal geometry with a large negative rake angle on the bottom of the tool	About 500μm in diameter and cutting edge radii of 1.8 μm, made of PCD	WEDM	Fabricating micro slots on silicon	Oliaei et al.[78]

best cutting performance when the rake angle is −60°, and three-dimensional solid model before and after optimization of ball micro cutting tool and fabricated results are displayed in Fig. 9; besides, Cheng also designed a PCD flat micro cutting tool and used it to machine brittle materials, and the quality of side and bottom of the brittle workpiece verified the effectiveness of this new designed micro cutting tools.

$$Offset_x = |E_1E_2| = R_E\sin(B)\sin(D) \tag{8}$$

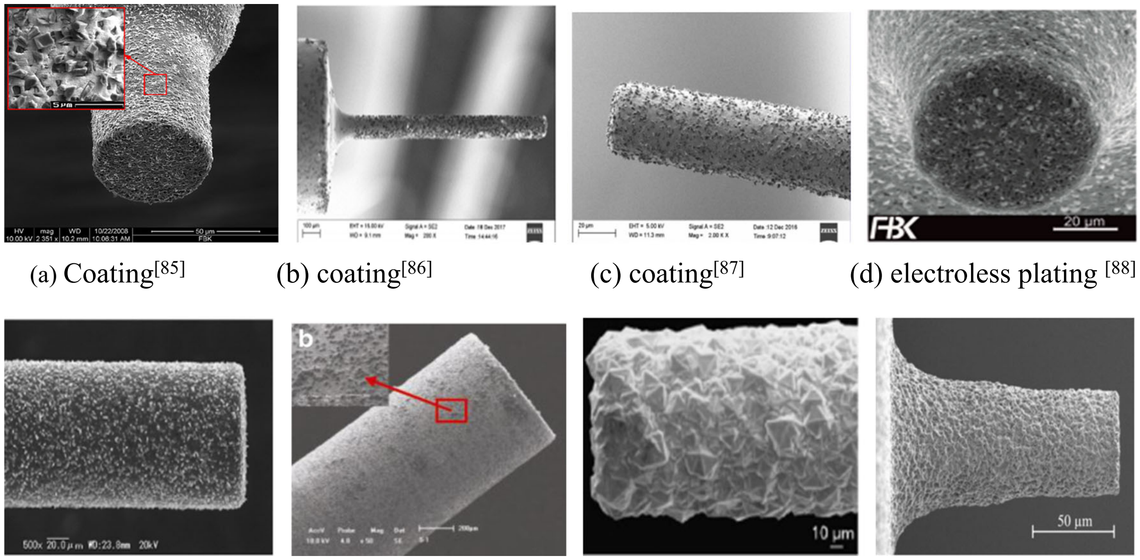
$$Offset_y = |E_2E_4| = R_E\cos(B) \tag{9}$$

$$Offset_z = |E_3E_4| = R_E\sin(B)\cos(D) \tag{10}$$

where B is cutting point central angle, D has the same value as wire rotation angle A, C_1C_2 the tangential line between workpiece and wire discharging envelope, and R_E is the wire radius plus the discharge gap under current machining conditions.

Ball micro cutting tools have good geometric adaptability and simple tool path algorithm, which is the main micro cutting tool for machining complex curved micro surfaces involved in micro parts and components used in aerospace, automobile, etc. Nowadays, some studies are focused on preparing ball micro cutting tools using EDM processes. Oliaei et al. [75] proposed a new method combining BEDM and WEDG techniques to fabricate ball micro cutting tools with different geometries as shown in Fig. 10 and studied the effects of EDM process parameters on MRR and Ra of MCT, and they found that this MCT can be used to fabricate microfluidic channels on fused silica with acceptable quality and accuracy. Wu et al. [50] proposed multistep fabricated process of MCT made of PCD for satisfying the efficiency and tool quality; firstly, the PCD plate is welded on the tool shank. Then, the PCD micro cutting tool is machined with WEDM method to generate its main shape and structure. Finally, the MCT is further sharpened with a diamond wheel. Besides, Zhang et al. [57] used continuously feeding wire electrode through a wire guider to fabricate PCD tools as presented in Fig. 11, and the resistor-capacitor discharge circuit is adopted, and for realizing extremely low discharging energy, the stray capacitance of the circuit C0 (~1pF) is used, and PCD tool with the radius of the spherical surface of about 400 μm and the edge radius of about 1.8μm is obtained. Su et al. [76] proposed two different schemes to machine ball MCT with four straight cutting edges using LS-WEDT method; after the electrode wire path and parameter optimization, the ball MCT with the radius less than 200μm, Ra of 1.13μm, and cutting edge radius of 5.16μm can be obtained.

Compared to the conventional micro cutting tools, which are produced through grinding process to have helical flute geometry, these tools usually have straight



(a) Coating[85] (b) coating[86] (c) coating[87] (d) electroless plating [88]

(e) electroless plating [89] (f) cold spraying [90] (g) chemical vapor deposition [91] (h) EDM[35]

Fig. 15. Cylindrical micro-grinding tools fabricated by various methods

edges, which improves the stiffness but limits the chip evacuation. The use of straight edges can be justified by considering low depth of cut values in micro milling. Samad et al. [77] adopted Sodick AP250L high precision WEDM machine with a brass wire of 0.1 mm diameter to fabricate a single cutting edge micro cutting tool as displayed in Fig. 12, and the best surface roughness of 0.15μm and edge radius of

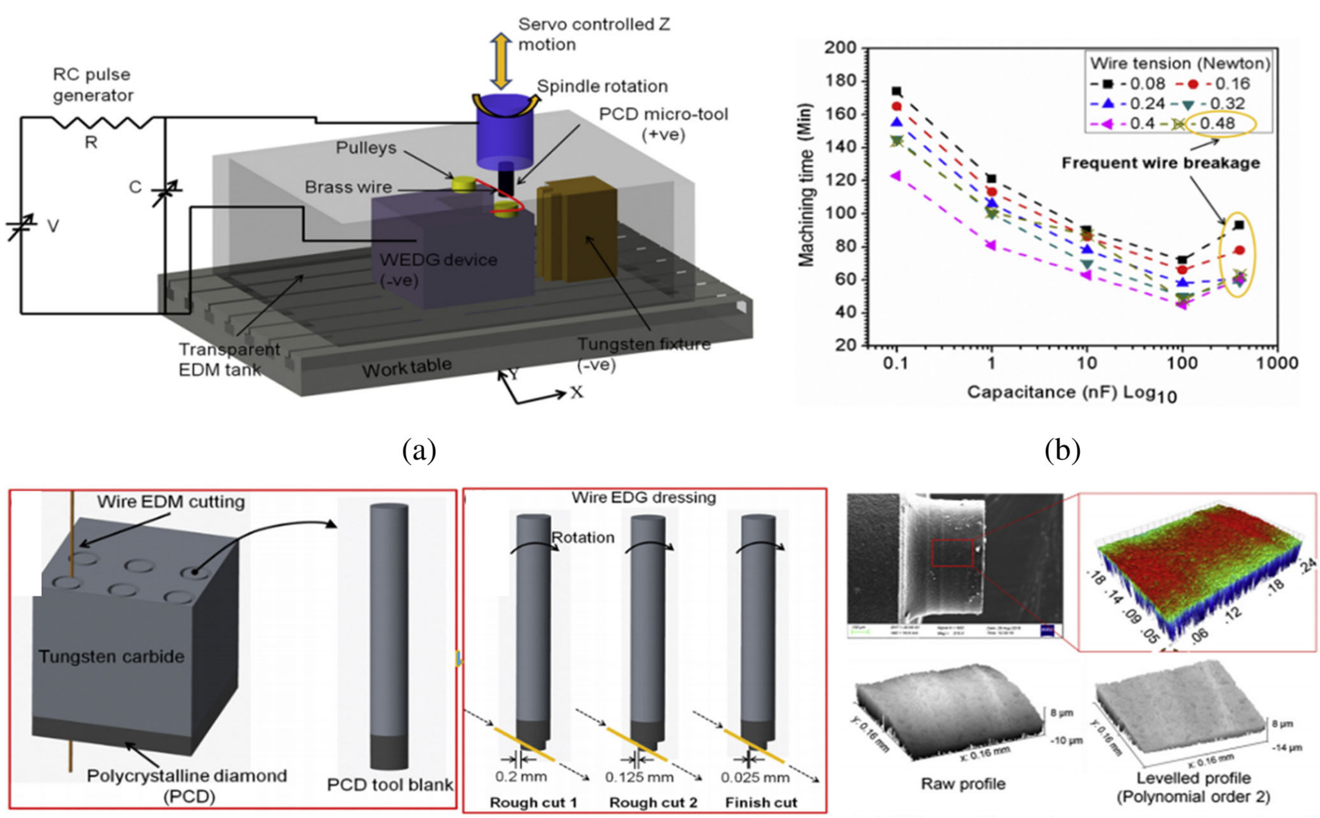


Fig. 16 **a** Wire electrical discharge grinding setup for polycrystalline diamond tool, **b** machining time and wire breakage at wide range of wire tension and capacitance, **c** machining processes of PCD micro tool, **d** 3D view and surface leveling of micro tools

1.5~2.5μm can be obtained after a design of experiments approach on WEDM process parameters. Sun et al. [48] realized visual predictability of helical micro end mills fabricated by LS-WEDT method, and they found that feeding amount of electrode wire, feeding, and rotating speed have key influence on the shape of spirals micro end tool, and their experimental results showed that the three spiral MCT with 123.8μm in diameter and 800μm in length, MCT with six spirals, and varied spiral angle MCT are efficiently prepared using this method as presented in Fig. 13.

process, **c** fabricated results of WC single edge micro cutting tools

In addition, Oliaei et al. [78] adopted WEDM method to fabricate a PCD end mill with a hexagonal geometry, and its micro cutting geometry has been modified to have a parallelogram shape featuring a large negative rake angle on the bottom of the tool, and they found that the PCD micro cutting tool geometry significantly affects the process outputs as displayed in Fig. 14. Based above mentioned contents, the type of EDM processes involved in fabrication of micro cutting tools and their performance, application, and remarks are summarized in Table 2.

3.2 Micro grinding tool

In grinding process, the surface quality, grinding hardening, residual stress, micro hardness, and machining accuracy of workpiece directly affect its machining performance and service life [79–83]. In recent years, with the increasing requirements of machining size and surface quality of micro parts, the micro grinding technology has been widely concerned. The design and preparation of grinding tools are the most important factor in grinding process. At present, the main preparation methods of micro-grinding tools mainly include the super hard abrasive coating method and the diamond or CBN usually selected as abrasives and coating methods always involved in the electroplating [84], electroless plating [85, 86], cold spraying [87], chemical vapor deposition [88], etc. And the other fabricated methods refer to EDM-fabricated polycrystalline diamond [34] as displayed in Fig. 15a–h. Besides, Pratap et al. [47] analyzed effects of discharge energy and wire tension on surface roughness and diametrical error involved in the fabrication of micro-grinding tool using WEDM as shown in Fig.16, and they found that defects will be increasing at low wire tension and high

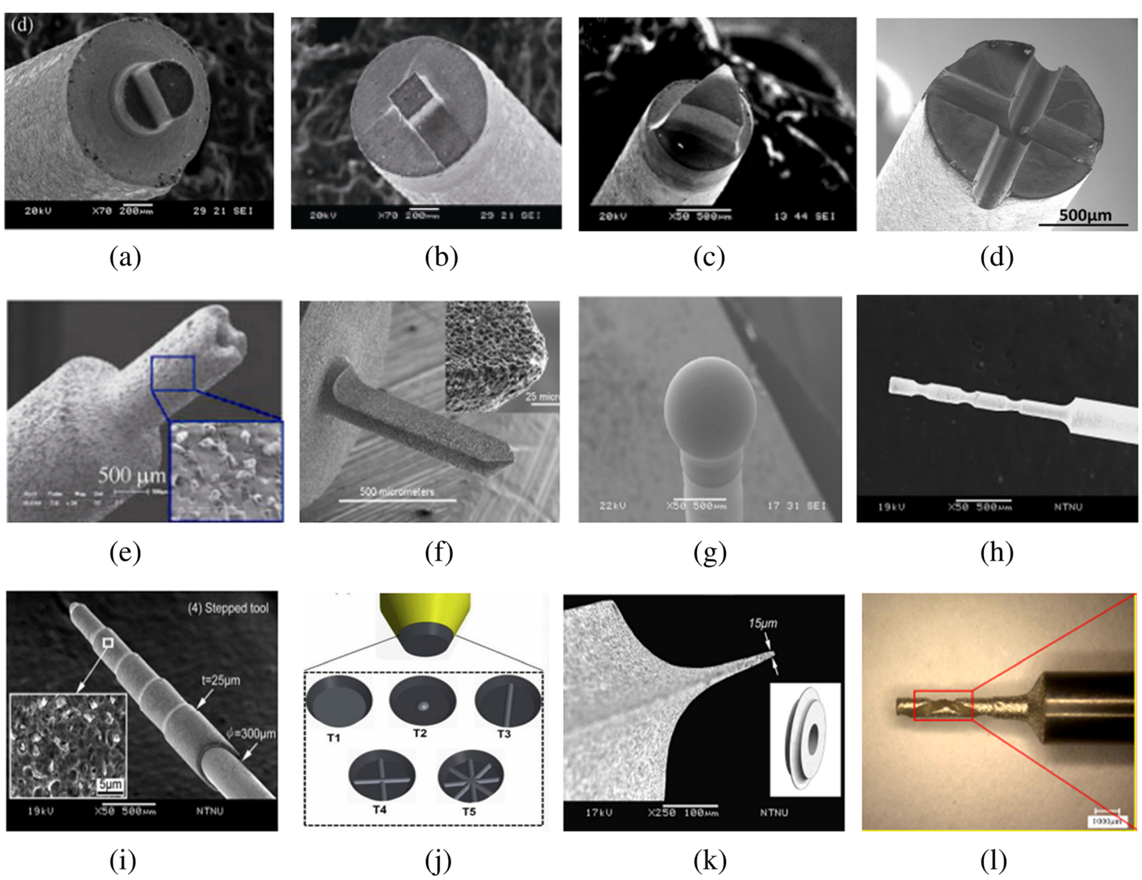


Fig. 17 Special shape micro-grinding tools: **a** "D" shape[42], **b** square shape[42], **c** triangle shape[42], **d** cross-shaped[89], **e** conical shape[90], **f** a conical tipped PCD micro-grinding tool[92], **g** ball end MGT [93], **h** fluted MGT[90], **i** ladder shaped MGT[90], **j** five types of MGT[93], **k** formed extremely thin diamond wheel[94], **l** MGT with helical slots[95]

discharge energy, and diametrical error of micro tools is found to be large at low wire tension.

(a) Coating[82] (b) coating[83] (c) coating[84] (d) electroless plating [85]

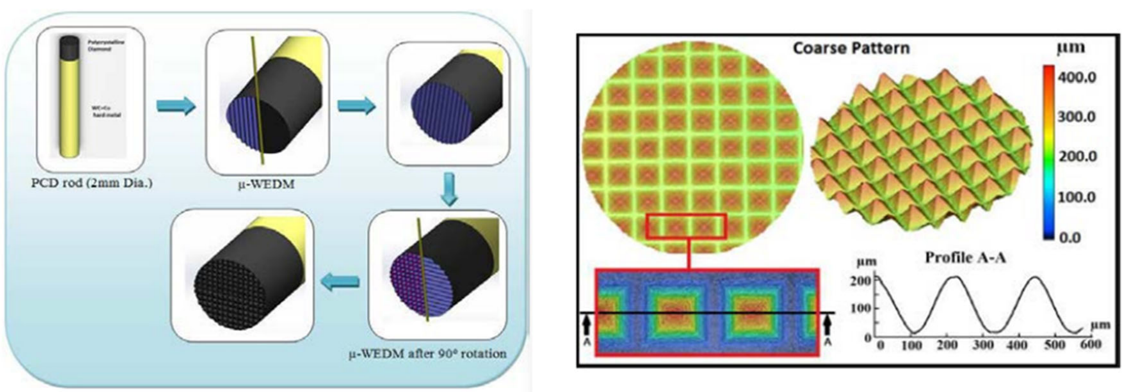
(e) electroless plating [86] (f) cold spraying [87] (g) chemical vapor deposition [88] (h) EDM[34]

Based on above analysis, it can be seen that the design of micro-grinding tools is still dominated by cylindrical shape without chip groove. But, in recent years, the design of micro-grinding tool has been presented a trend of non-standardization and parameterization; for example, Perveen et al. [42], Yan et al. [89], Chen et al. [41, 90], Morgan et al. [34, 91], Masaki et al. [92], and Pratap et al. [93], respectively, adopted various EDM processes to prepare the D-shaped, four prism, conical, cross, ball, fluted, ladder shaped micro grinding tools as displayed in Fig. 17; in another research of Chen et al. [94] employed micro WEDM to fabricate thin the micro grinding wheel with tip edge width of 15μm as shown in Fig.17k, and then it is used to grind micro-grooves on optical glass. Additionally, Sun et al. [95] proposed hybrid process combining the LS-WEDT and electroplating process to fabricated diamond MGT with helical chip removal slots and diameter of about 800μm, and firstly the WEDM with high precision rotating unit to prepare MGT substrate and slots and then diamond abrasive is uniformly coated by electroplating process as displayed in Fig.17l. In addition, Oliaei et al. [49] used micro WEDM and EDM methods to fabricate two kinds of PCD micro tools with micro-pyramid lattice structures as presented in Fig.18, and these micro tools can be employed as post-processing tools in a wider range of feed per revolution and cut depth. Based on above mentioned contents, the type of EDM processes involved in the fabrication of micro grinding tools and their performance, application, and remarks are summarized in Table 3.

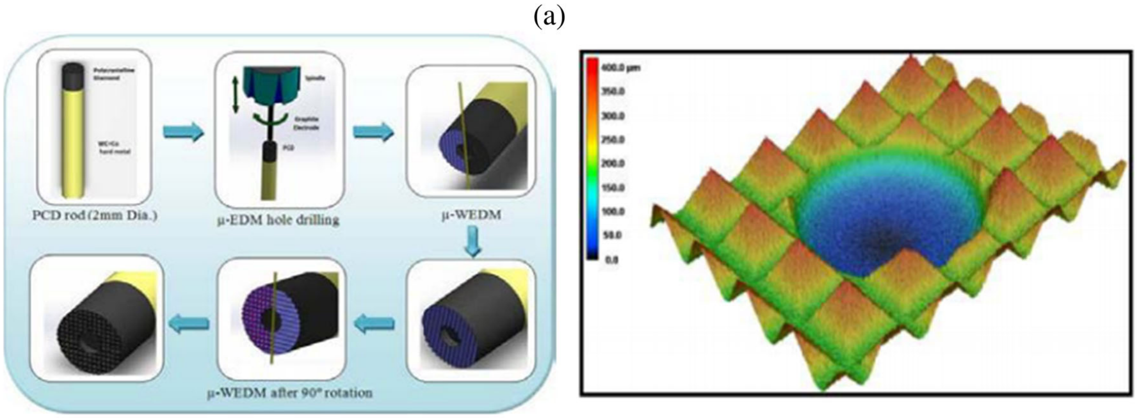
4 EDM methods involved in preparing microelectrodes

4.1 Single microelectrode

The size and surface quality of tool microelectrodes directly affect the machining of micro holes and complex micro three-dimensional structure cavity. Therefore, the preparation



(a)



(b)

Fig. 18 **a** Schematic of micro tool fabricated steps and results of micro tools with micro-pyramid lattice structure **b** micro tool fabricated steps and results of hole drilling tools

Table 3 The specifications of various micro grinding tools fabricated using EDM processes

Type of micro tools	Performance (dimensions and material)	EDM-fabricated method	Application	Remarks
Micro grinding tool with cylindrical shape or a conical tipped shape	About 50μm in diameter and made of sintered poly crystalline diamond (PCD)	WEDG	Grinding micro grooves on soda-lime glass	Morgan et al.[34, 91]
Micro grinding tool with cylindrical shape, one or several micro-grooves along the end face	About 1mm in diameter and made of PCD	WEDG	Grinding micro-slot on the BK7 glass	Pratap et al. [47, 93]
Micro grinding tools with four different geometry including circular, D-shaped, triangular, and square	About 500μm in diameter and made of PCD	BEDG	Grinding micro-slot on the BK7 glass	Perveen et al. [42]
Micro grinding tools with bottomed crossed microgrooves	About 1mm in diameter and made of PCD	EDM	Of great promise for micro machining hard and brittle materials	Yan et al.[89]
Micro grinding tool with six negative back rake-angles and thin diamond grinding wheel-tool	About 1mm in diameter and made of diamond abrasives and the edge-width of the grinding wheel at its tip of only 15 μm	WEDM+WEDG+REDM	Forming micro-hole on optical grade glass and quartz, and fabricating crisscross microgrooves on optical glass	Chen et al. [41, 90, 94]
Micro grinding tools with spherical head	Radius of less than 500 μm and made of PCD	Micro-EDM	Forming a flat plane and a convex spherical surface on silicon	Masaki et al. [92]
Micro grinding tools with helical chip removal slots	About 500μm in diameter and made of carbide base and diamond abrasives	LS-WEDT + electroplating process	Grinding flat surface on Nickel based superalloy DD5	Sun et al.[95]

Table 4 The specifications of various microelectrode fabricated using EDM processes

Type of EDM	Performance		Characteristics	Remarks
	Dimensions	Shapes		
WEDG	About 2.5μm in diameter	Various	High machining accuracy and nontaper, low efficiency, high investment	Masuzawa et al.[30], Li et al.[96], Kuo et al. [97], Egashira et al.[98], Chern et al. [67], Yan et al.[99], and Rees et al.[100], Wang et al. [101]
Twin-wire EDM	About 5μm in diameter	Cylindrical	High machining efficiency and nontaper, poor surface quality	Sheu et al.[36]
TF-WEDG	About 26μm in diameter	Cylindrical	High machining accuracy, good surface roughness, complex setup	Zhang et al.[38]
BEDG	About 150μm in diameter	Various	Simple setup, good surface roughness, low investment, low machining accuracy and taper	Ravi et al.[102], Lim et al.[103], Zhao et al [35] and Siddhartha et al.[104]
MBEDG	About 40μm in diameter	Various	Simple setup, high accuracy, low efficiency	Jahan et al.[105], Rahman et al. [106] , Hourmand et al.[107] and Jahan et al.[108]
HER-MBEDG	About 0.4μm in diameter	Cylindrical	Extreme dimension, low efficiency	Koyano et al. [109]
EDG-TBE	About 45μm in diameter	Cylindrical	Low investment, simple setup, high machining efficiency, poor surface quality	Yin et al.[110]
ISEDM	About 200μm in diameter	Cylindrical	High efficiency, large machinable diameter	Gil et al. [111, 112]
Self-drilled holes	About 4μm in diameter	Cylindrical	Simple setup, low investment, low machining accuracy and taper	Minoru et al. [113]
Scanning EDM	About 40μm in diameter	Cylindrical	High efficiency, low accuracy	Naotake et al[114], Tani et al. [115]
REDM	About 35μm in diameter and 1.5mm in length	Various	Good surface roughness, low machining accuracy and taper, low efficiency	Kim et al. [116] and Singh et al.[117]
CWEDM	About 58μm in diameter	Various	High accuracy, low efficiency	Qu et al. [33], Matoorian et al.[118], Haddad et al. [119],Krishnan et al.[120] and Janardhan et al.[121],Sun et al.[122, 123]
Strip-EDM	About 1.5mm in diameter	Various	High efficiency, large machinable diameter	Song et al.[124, 125]
LIGA and micro-EDM	About 200μm in diameter	Various	High machining accuracy, complex setup, high investment	Takahata et al.[126]
Micro-turning and micro- EDM	About 19 μm in diameter	Cylindrical	Good surface roughness, high efficiency, complex setup, high investment	Asad et al.[127]
WEDG and ECM	About 0.3μm in diameter	Cylindrical	Good surface roughness, complex setup, high investment	Kai et al.[128]
TF-WEDG and self-drilled hole	About 27μm in diameter	Cylindrical	High efficiency, complex setup	Zhang et al.[38]
BEDG and WEDG	About 30μm in diameter	Paraboloid-shaped	High efficiency, complex setup	Li et al.[129]

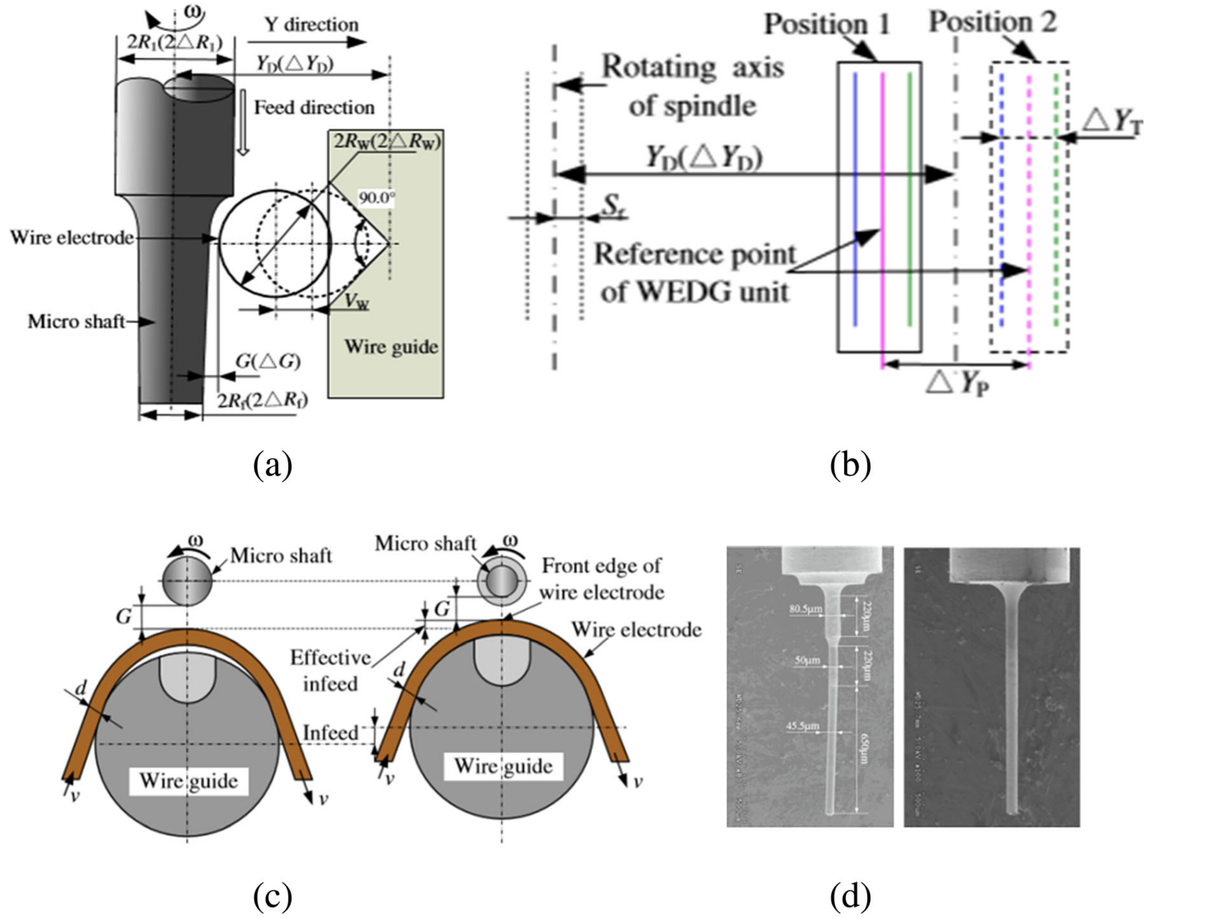


Fig. 19 **a** Effects of vibration of wire electrode, **b** factors affecting $\triangle Y_D$, **c** effects of relaxed wire electrode when electrical contact occurs on $\triangle R$, **d** fabricated results [2]

of tool microelectrodes with high efficiency, high quality, and high precision is the key to achieve the fabrication of micro hole and complex micro structure. The efficiency of preparing the tool microelectrode by traditional machining method is very low or even cannot be processed at all. Therefore, at present, the preparation of tool microelectrode mainly relies on the non-traditional techniques especially the EDM method. The microelectrode can be divided into cylindrical, edge cutting, D shaped, spiral electrode, and so on. Scholars at home and abroad have done a lot of research on the preparation of

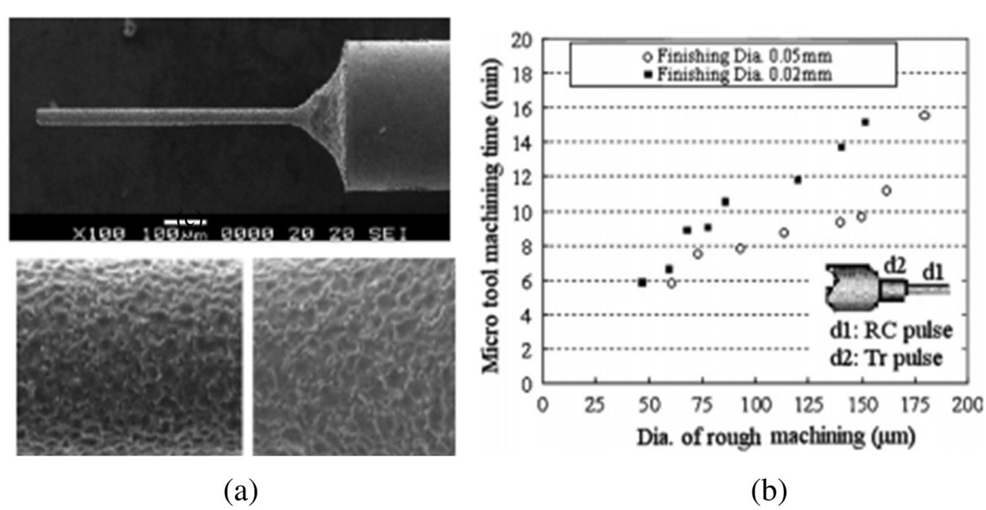


Fig. 20 **a** View of microelectrode tool machining by the twin-wire EDM system, **b** micro tool machining time of the twin-wire EDM system

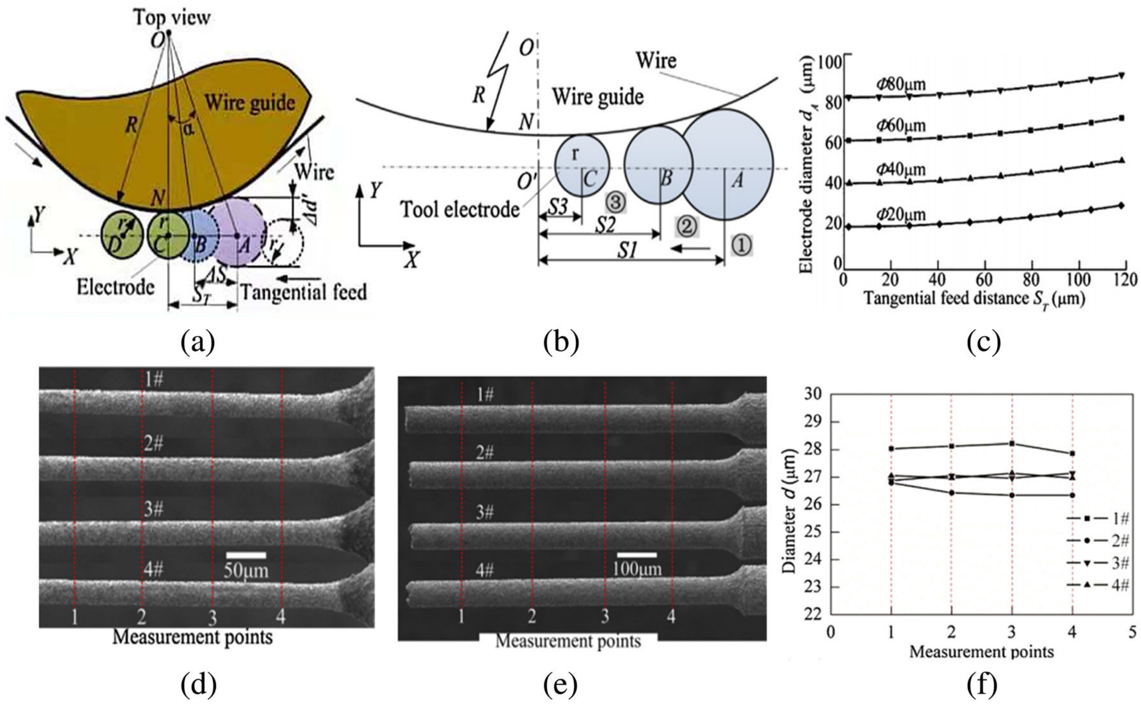


Fig. 21 **a** The TF-WEDG process, **b** three steps of TF-WEDG method, **c** error analysis of TF-WEDG, **d** microelectrodes with diameter of 27μm, **e** microelectrodes with diameter of 64μm, **f** diameter deviation

tool microelectrode, and Table 4 demonstrated the type of EDM processes involved in the fabrication of microelectrodes, machining size and shapes, and characteristics studied by previous researchers.

The WEDG method was introduced by Professor Masuzawa of the Tokyo University in 1985 [31], which provides an effective approach for fabricating micro pins, micro spindles, and micro tools, and they adopted this method successfully to fabricate several microelectrode with a diameter of about 2.5μm, 15μm, and 25μm, respectively, and their measured results indicated that the accuracy and repeatability of WEDG method are high with the error of less than 1μm [32]. Li et al. [96], Kuo et al. [97], Egashira et al. [98], Chern et al. [67], Yan et al.[99], Rees et al. [100], and Li et al. [130], respectively, used the WEDG method to fabricate all kinds of microelectrodes of different cross-sectional shapes and the sacrificial electrode involved in wire, block, disk etc. and studied the influences of different machining parameters on the surface quality and machining accuracy of microelectrodes by statistical methods and parameter optimization. For improving machining repeatability, Wang et al. [101] studied primary error sources of diameter accuracy of microshafts obtained by WEDG, and the empirical models of evaluating the relationship of infeed and radial direction ($\triangle R$) are set up as shown in Eq. (11), and based on empirical models and machining strategy, the micro shafts with diameters of 45±2μm are successfully fabricated as displayed in Fig.19, which verifies the model to be effective and can be applied in improving machining repeatability.

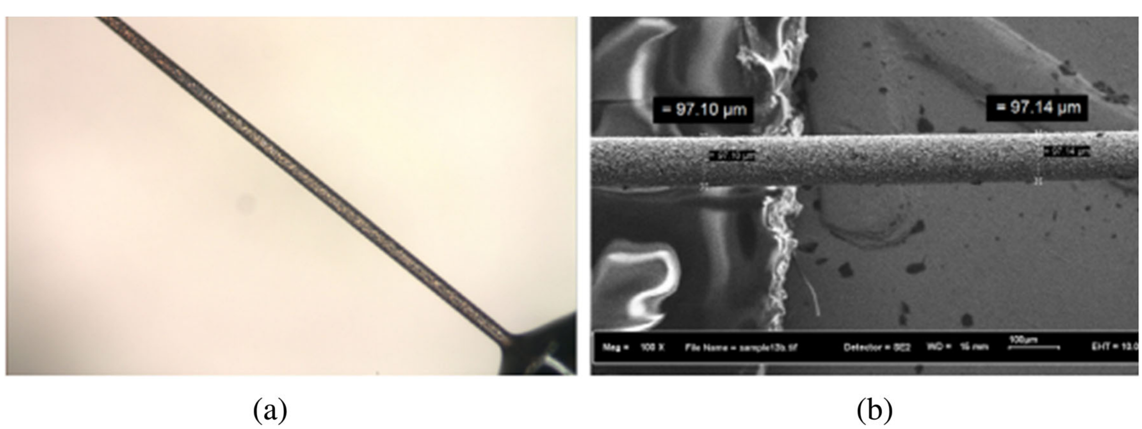


Fig. 22 **a** Illustration of horizontal moving BEDG process, **b** micro-electrode with diameter of 97.14μm [107]

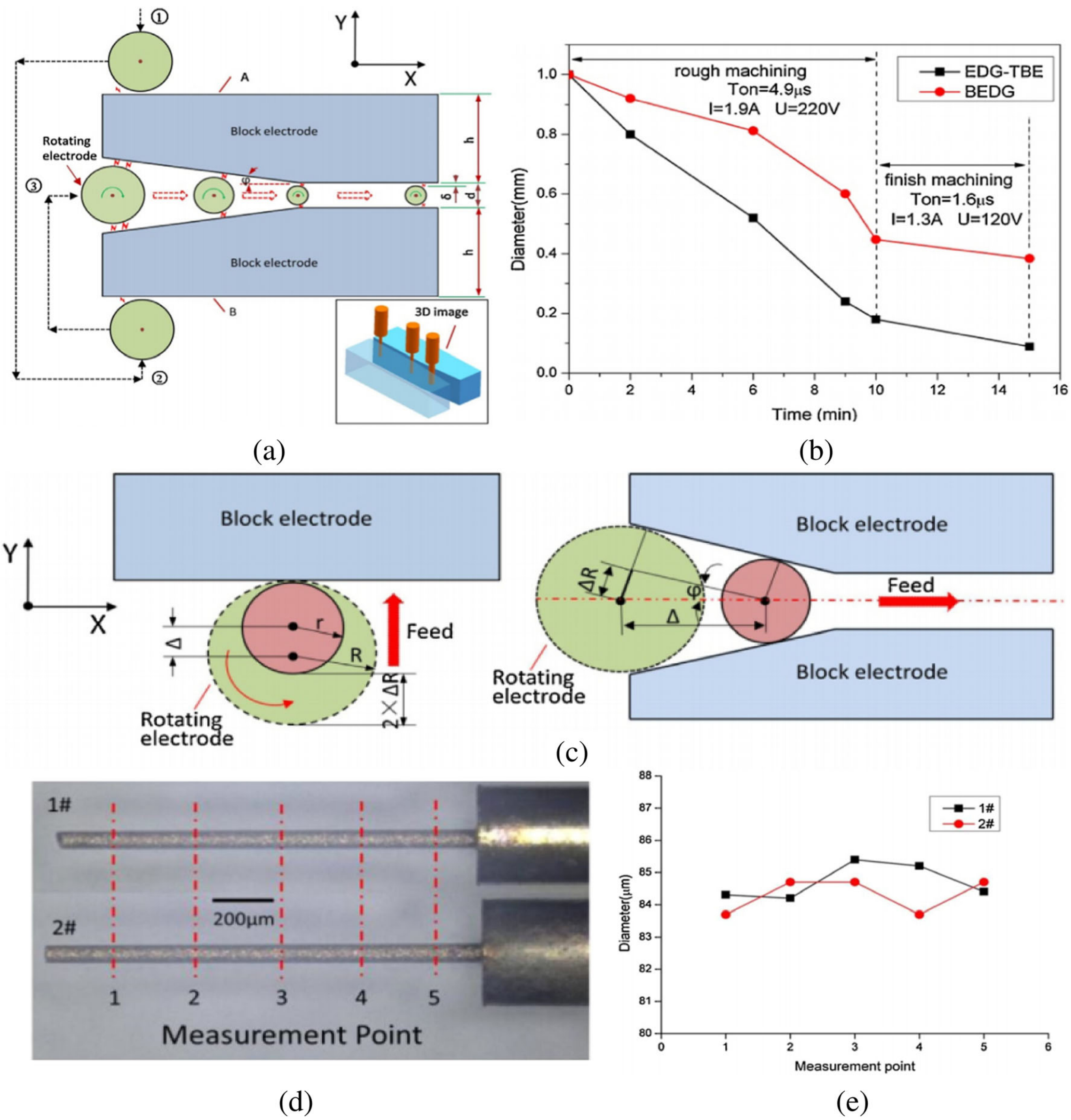
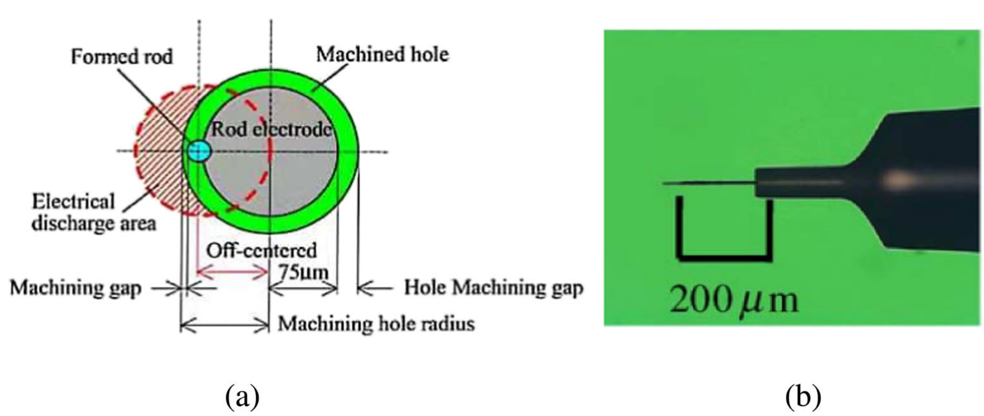


Fig. 23 **a** Schematic diagrams of EDG-TBE process, **b** comparison of efficiency of BEDG and EDG-TBE, **c** schematics of removal resolution according to machining types of BEDG and EDG-TBE, **d** experimental results of microelectrode of 86μm, **e** diameter deviation

Fig. 24 **a** Off-centering concept chart, **b** fabricated results of cylindrical microelectrodes



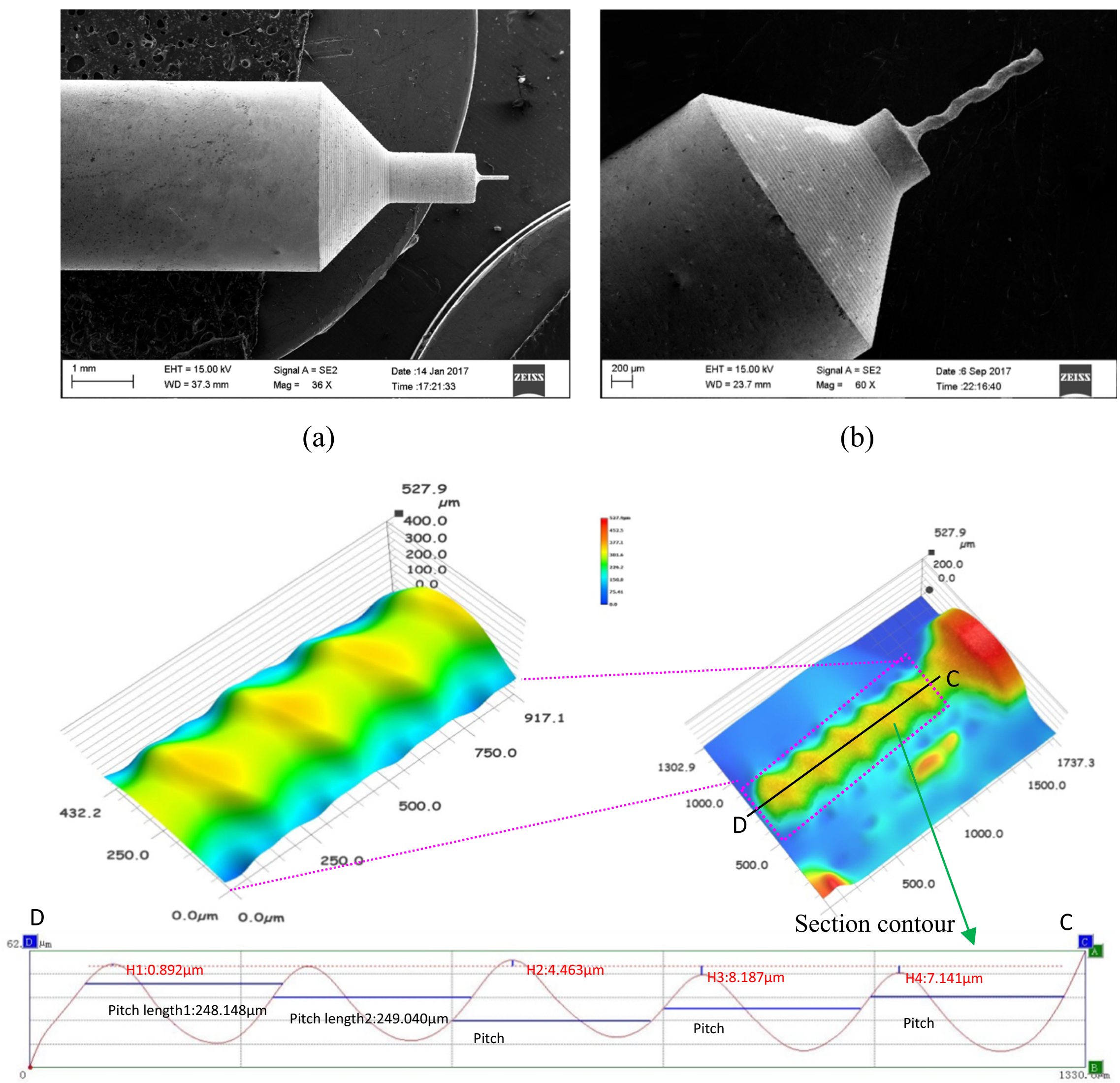
$$2\Delta R_f = 2\left(\Delta Y_P + \Delta Y_T + S_r + \left(\sqrt{2}+1\right)\Delta R_W + V_W + \Delta G\right) \quad (11)$$

where the G and $\triangle G$ are spark gap and its variations, respectively, V_w is wire electrode vibration amplitude, S_r is the runout of spindle, $\triangle Y_P$ is position variations of WEDG unit, and $2R_f$ and $2\Delta R_f$ are diameter and its tolerance of micro shaft, respectively.

To improve the prepared efficiency of microelectrodes, Sheu et al. [36] described a new method combining twin electrode wire with two discharge circuits to fabricate microelectrode tools as presented in Fig. 20, and their experimental results found that this twin-wire EDM system can significantly improve machining efficiency of microelectrodes compared to conventional WEDG technology.

For reducing the effect of positioning error on machining accuracy of microelectrodes, the tangential-feed WEDG (TF-WEDG) method is proposed by Zhang et al. [38], and its principle is illustrated as shown in Fig. 21, the microelectrode is fed from position A to B and to C, and the distance of A and C position is defined as S_T and can be calculated as Eq. (12). Several microelectrodes with diameter less than 70µm were machined repeatedly, and the consistent accuracy of microelectrode along axial direction can be confined to be 1µm, and the negative polarity machining involved in TF-WEDG process can further enhance the resolution and surface roughness of microelectrodes...

$$d_A = 2(OA - R) = 2\left(\sqrt{(R+r)^2 + S_T^2} - R\right) \quad (12)$$



(c)

Fig. 25 **a** Slender microelectrode with diameter of 58µm, **b** spiral microelectrode with diameter of 150µm, **c** three-dimensional topography and section contour

Based on the reports mentioned above, it can be seen that machining efficiency of WEDG is low, and in order to improve the prepared efficiency of micro tools, Ravi et al. [102], Lim et al. [103], Zhao et al [35], and Siddhartha et al. [104] proposed block electrode discharge grinding (BEDG) to fabricate microelectrodes or micro rods at a higher machining speed.

Although machining efficiency is significant by the use of block electrodes and the process is simple, but, the fabricated micro tools fail to possess dimensional accuracy due to the existence of block electrode wear. Therefore, in order to solve this problem, Jahan et al. [105], Rahman et al. [106], Hourmand et al. [107], and Jahan et al. [108] proposed moving BEDG method, and the illustration of horizontal MBEDG (moving BEDG) process developed by Hourmand as shown in Fig. 22, and the microelectrodes with diameter of 97.14μm and 78.19μm are fabricated, and their experimental results disclosed that this MBEDG process is more beneficial for machining straight and thin microelectrodes with smooth surface, short time, and low cost. In order to decrease the discharge crater diameter of micro rods machined by MBEDG process, Koyano et al. [109] proposed HER (high electrical resistivity)-MBEDG method namely adopting the silicon tool electrodes for increasing the electrical resistivity, and they found the discharge craters diameter formed on micro-rods can be decreased to approximately 0.4 μm, and finally the cemented tungsten carbide micro-rod with diameter of 0.8 μm was manufactured.

In order to enhance both the efficiency and accuracy of microelectrode using the conventional machine tool with low cost, Yin et al. [110] developed the electrical discharge machining grinding by two block electrodes (EDG-TBE) method without measuring device on-line as shown in Fig. 23 and desired diameter of microelectrodes mainly determined by the width of narrow slit and the discharge gap. They found that machining efficiency of microelectrode machined by EDG-TBE is higher than that of BEDG, and the error between machined diameter and target diameter is less than 2μm, and the cylindrical error of microelectrode also can be confined to be 2μm. In addition, Gil et al. [111, 112] presented the inverse slab electrical discharge milling (ISEDM) method and studied the influence of process variables including rotational speed and discharge energy on the efficiency, surface finish, and accuracy of micro pins machined by the ISEDM process. Their results showed that the micro pins with diameter of 200μm and aspect ratio of 90 can be economically manufactured. Minoru et al. [113] proposed self-drilled holes to form micro-rods which does not need initial positioning of the tool electrode, and the operation is easy and short as shown in Fig. 24. Their experimental results indicated that

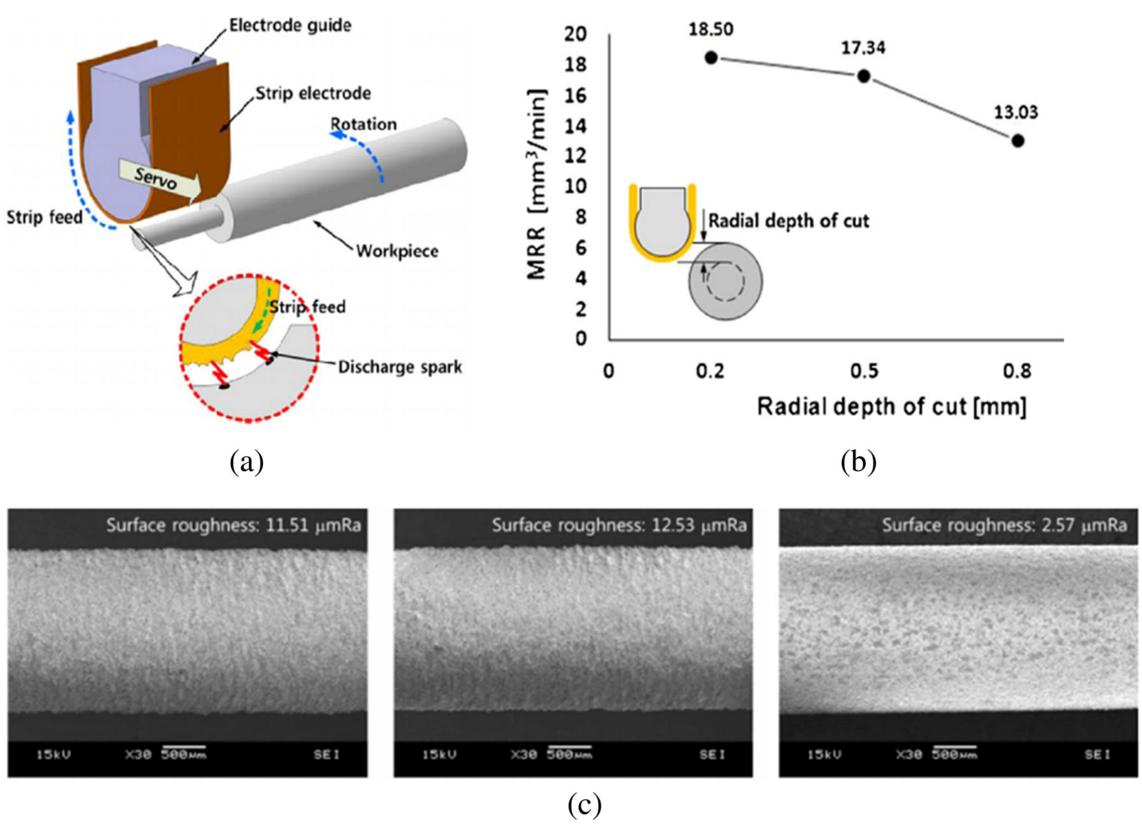


Fig. 26 **a** Schematics of strip-EDM turning, **b** material removal rates according to radial depth of cut, **c** the SEM images of the machined surfaces of micro rods

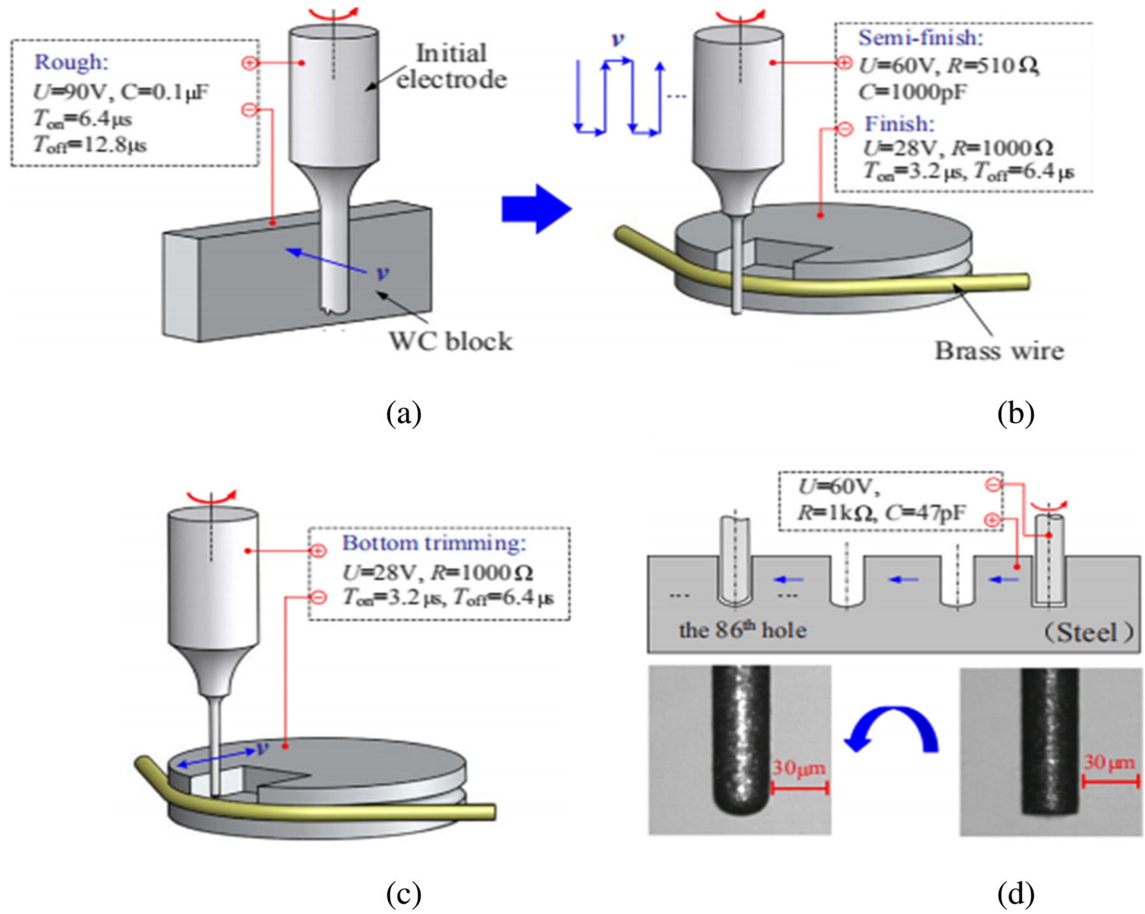


Fig. 27 **a** Schematic of microelectrode preparation processes, **b** rough grinding by BEDG, **c** semi-finish and finish grinding by WEDG, **d** self-drilling holes process and image of microelectrode with a paraboloid-shaped tip.

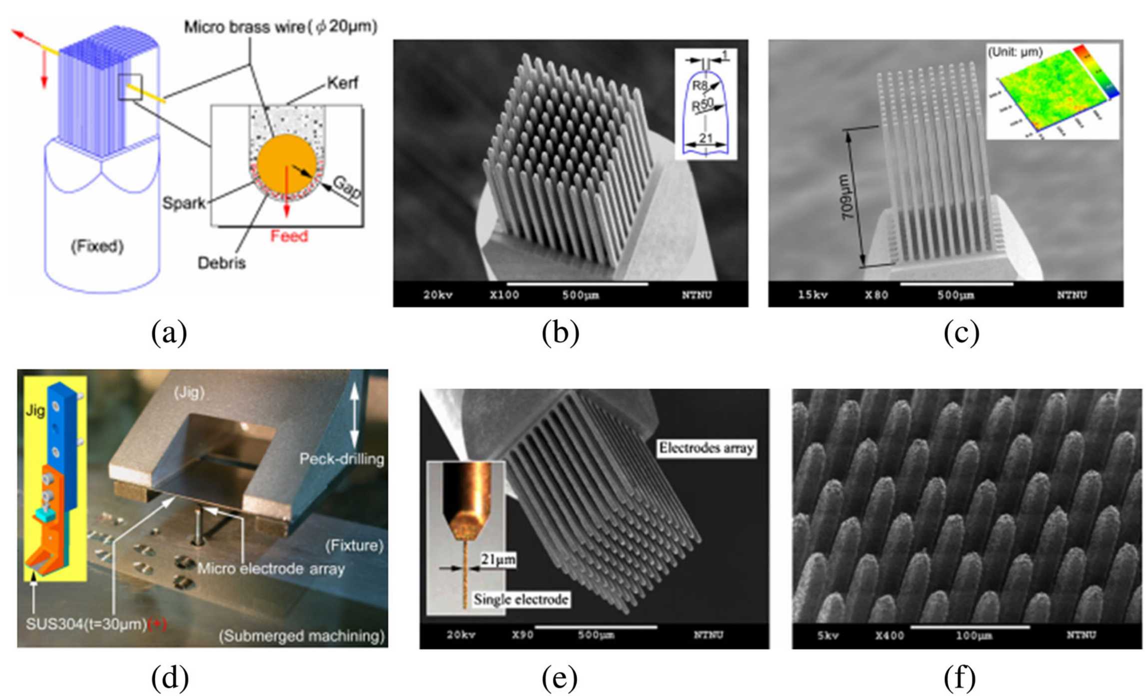


Fig. 28 **a** Machining diagram of microelectrode array, **b** electrode arrays from an isometric view, **c** electrode arrays from a front view, **d** machining live by an upward mode, **e** 10×10 microelectrode array, **f** enlarged view

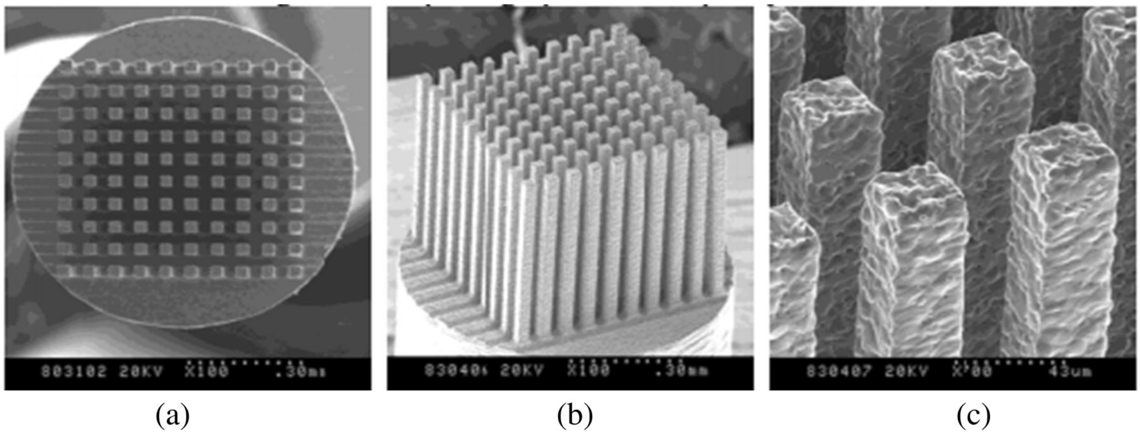


Fig. 29 The squared microelectrode array fabricated by the WEDM: **a** top view, **b** 10×10 squared microelectrode arrays, **c** enlarged view

microelectrodes obtained by this method still existed taper errors after reverse copying many times. Naotake et al. [114] and Tani et al. [115] demonstrated a new method of microelectrode formation by scanning EDM, and a micro pin WC-Co electrode is formed with a diameter of about 40μm, and the machining time of tool electrode with diameter of 300μm that was changed to be 50μm only takes 3 min. Kim et al. [116] and Singh et al. [117] adopted reverse electrical discharge machining (REDM) to prepare microelectrodes or micro rods with various shapes and investigated the effect of capacitance and voltages on machining characteristics of REDM, and then optimal conditions for obtaining stable machining were provided.

As we all know, the WEDM process including LS (low speed)-WEDM and HS (high speed)-WEDM can realize the machining of parts with abnormalities and complex ruled surfaces, but it fails to manufacture parts with incomplete penetration surface or partial micro rotating structure. So in order to achieve the function of machining rotary surfaces on the WEDM workbench, Qu et al. [33], Matoorian et al. [118], Haddad et al. [119], Krishnan et al. [120], and Janardhan et al. [121] developed the cylindrical wire electrical discharge machining (CWEDM) to fabricate simple rotary parts and investigated effects of parameters on surface quality, roundness, and material removal rate; on this basis, Sun et al. [122,

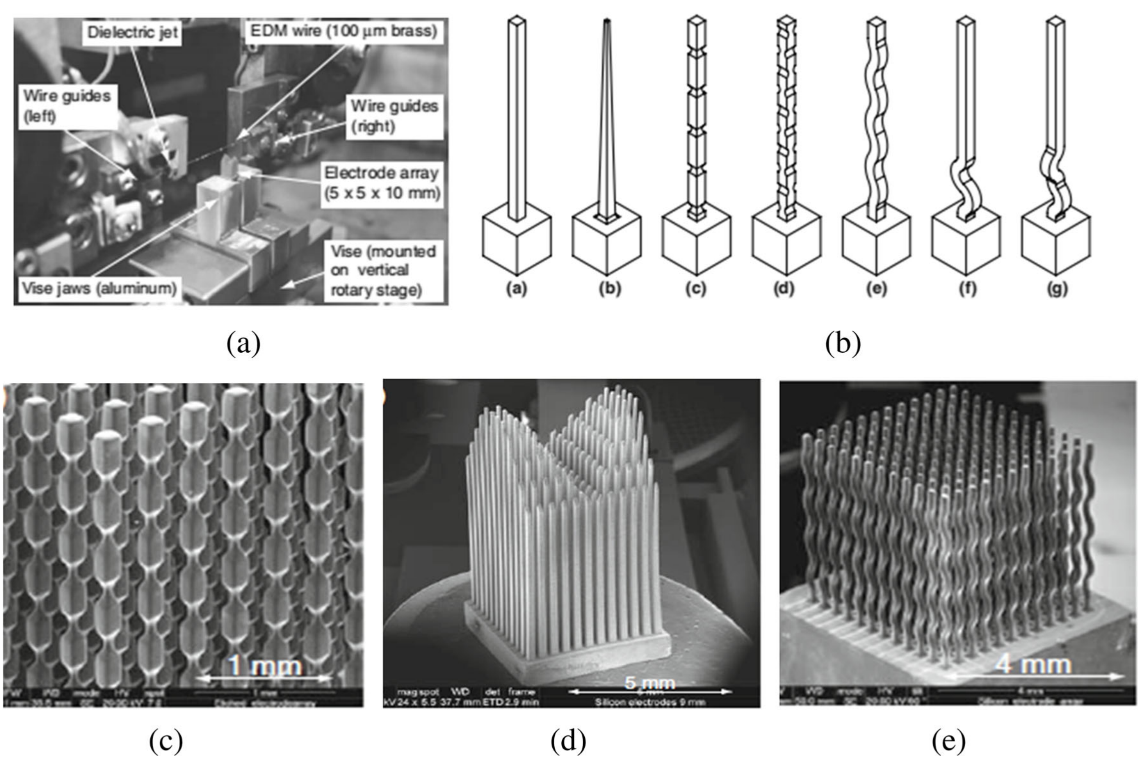
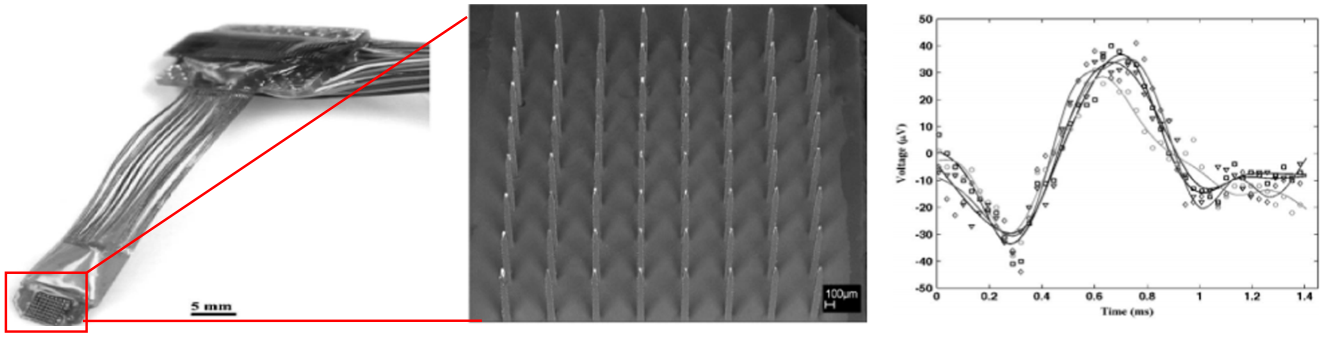


Fig. 30 The microelectrode array with different shape fabricated by the WEDM: **a** experimental setup for micro-electrode array fabrication using WEDM, **b** designed electrode geometries, **c** hourglass, **d** variable length, **e** wavy



(a) (b) (c)

Fig. 31 **a** Assembly equipment, **b** 8×8 microelectrode array made by WEDM, **c** voltage curve

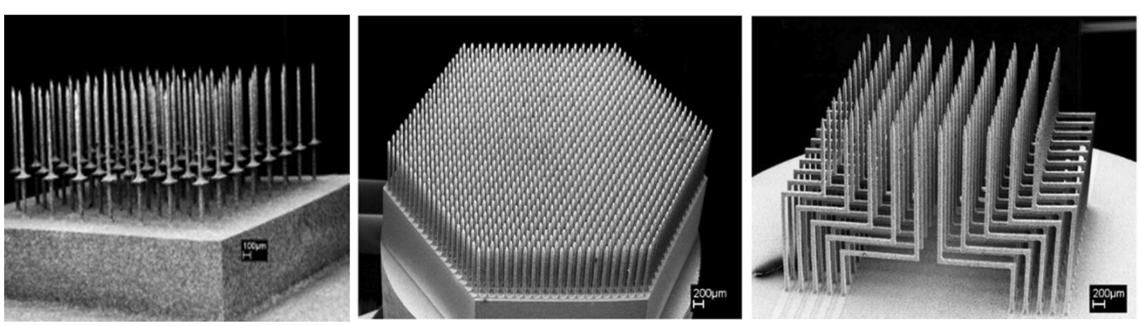
123] make full use of the advantages of multiple cutting and the electrode wire unidirectional motion for LS-WEDM machine and proposed the LS-WEDT (low speed wire electrical discharge turning) method and adopted this method to fabricate slender cylindrical and spiral microelectrodes as displayed in Fig. 25, and the measured results disclosed that the errors of pitch length and thread angle respectively can be confined to less than 3μm and 3° due to in-existence of electrode loss, which indicated that the LS-WEDT method has superiority in fabricating complicated structure not just limited to the simple cylindrical parts, but in this method, the wire does one-way movement and cannot be reused, resulting in the relatively high cost.

The wire electrode used in WEDG and CWEDM methods has the disadvantages of low material removal rate and easy wire breaking, so for the sake of increasing the material removal rate and avoiding wire electrode broken, Song et al. [124, 125] proposed the strip-EDM turning method, and a wide conductive strip is selected as an EDM electrode, and the strip was fed continuously as shown in Fig. 26; compared to CWEDM and LS-WEDT processes, the strip-EDM turning does not cause electrode vibration, electrode breakage or cusps on machined surfaces due to the strip are wide and flat. Their experimental results disclosed that the MRR of the strip-EDM turning was 74.3% higher than of CWEDM, and this method is competent to fabricate complex shapes, like a taper pin, a cylinder, and a polygon.

Moreover, for circumventing the limitation of single processing method and balancing the contradiction between processing efficiency and surface quality, some researchers developed the hybrid technique to prepare microelectrodes. Takahata et al. [126] developed a new process combining LIGA and micro-EDM process to fabricate a high-aspect-ratio tungsten carbide super hard alloy micro structure. Asad et al.[127] combined the micro-EDM and micro turning technology to produce the high aspect ratio electrodes. Kai et al. [128] fabricated some tungsten electrodes by combination of WEDG and electrochemical machining. Zhang et al. [38] developed the hybrid process combining the TF-WEDG and self-drilled hole method to fabricate microelectrodes for improving efficiency. Li et al. [129] prepared microelectrodes with paraboloid-shaped tip by four steps including the rough BEDG, semi-finish and finish WEDG, bottom trimming, and formation of paraboloid-shaped tip. In previous three steps, the microelectrode worked as the anode, and in the fourth step, the positive polarity machining was adopted, and microelectrode with paraboloid-shaped tip is formed after machining of 86 holes as displayed in Fig. 27.

4.2 Microelectrode array

At present, the microelectrodes array mainly can be prepared by the LIGA, R-EDM and micro WEDM techniques, and the LIGA process contains several different processes which



(a) (b) (c)

Fig. 32 **a** Chemically etched array electrodes, **b** 1141 microarray electrodes, **c** 10×10 microarray electrode fabricated by the WEDM

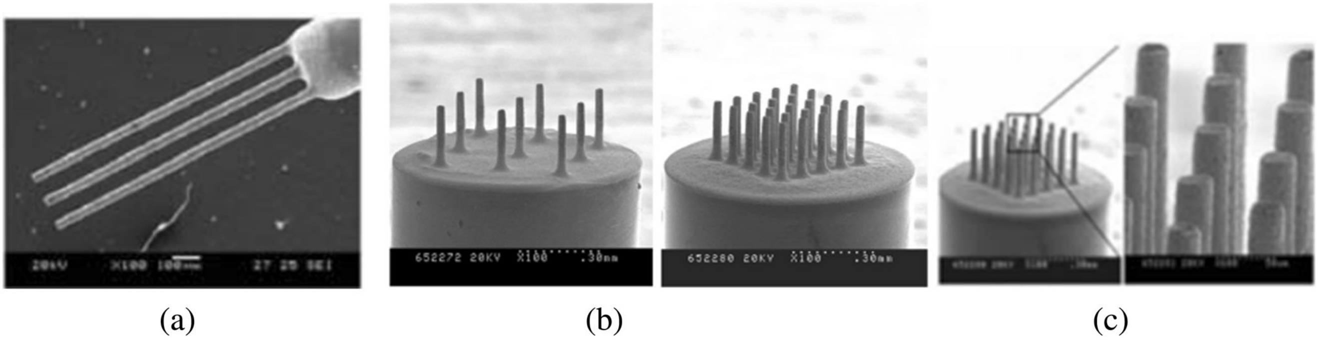


Fig. 33 **a** Microelectrodes of 35 μm in diameter, **b** WC micro-rods, **c** 5 × 5 microelectrodes

makes the equipment cost high and machining efficiency low; micro WEDM method is primarily utilized in fabricating microelectrodes array with polygon structures but failure of rotary structures; R-EDM method namely forming microelectrodes array by replacing polarity of workpiece and tool electrodes, which is mainly used in the preparation of cylindrical microelectrodes array. Chen et al [131, 132] proposed a set of micro WEDM mechanisms and mounted it on the developed precise tabletop CNC machine tool, and in order to reduce wire electrode jitters, and the vibration suppression system is developed for effectively suppressing micro vibrations of the wire during discharging and then preparing the 10×10 squared microelectrodes with width of 21μm, height of 700μm, and spacing of 24μm between two electrodes as shown in Fig. 28. Zeng et al. [133] fabricated 10×10 squared microelectrode array with the width of about 30μm and the length of about 600μm and the distance between neighborhood electrodes of about 70μm using WEDM method as shown in Fig.29. Rakwal et al [134] adopted WEDM method to prepare high length-width ratio silicon microarray electrodes as displayed in Fig.19, where the tip size of taper electrode is about 95×94 μm and the cross section size of wave electrodes is about 220×220 μm. Arab et al [135] used reciprocating wire-EDM machine to fabricate multi-tip array tool and selected sufficient tension for avoiding wire wobbling and reducing overcut, and then the high aspect ratio 3×3 multi-tip array tool electrodes were obtained as shown in Fig.30. Fofonoff et al [136] fabricated an 8×8 microelectrode array WEDM process, and these 64 microelectrode array were used to record the voltage changes in the cerebral cortex of mice for studying the inhibitory and excitatory activities of neurons in the cerebral cortex of mice as shown in Fig. 31; besides, in another study [137], they also prepared array electrode with length of 1mm, width of 80μm, and spacing of 500μm by WEDM process, the number of electrodes was 8×8 after chemically etching, and the material was titanium, and microelectrode array of 1141 are obtained as displayed in Fig. 32.

Additionally, cylindrical array micro holes are commonly used in components and parts of micro electro mechanical system, such as instrument components in aerospace inertial gyroscope, chemical fiber spinnerets, and high speed printer nozzles; for preparing these array micro holes, some scholars have prepared cylindrical array electrodes by REDM method. Kim [116], Mastud [138], Talla [139], Zhang [140], and Zeng

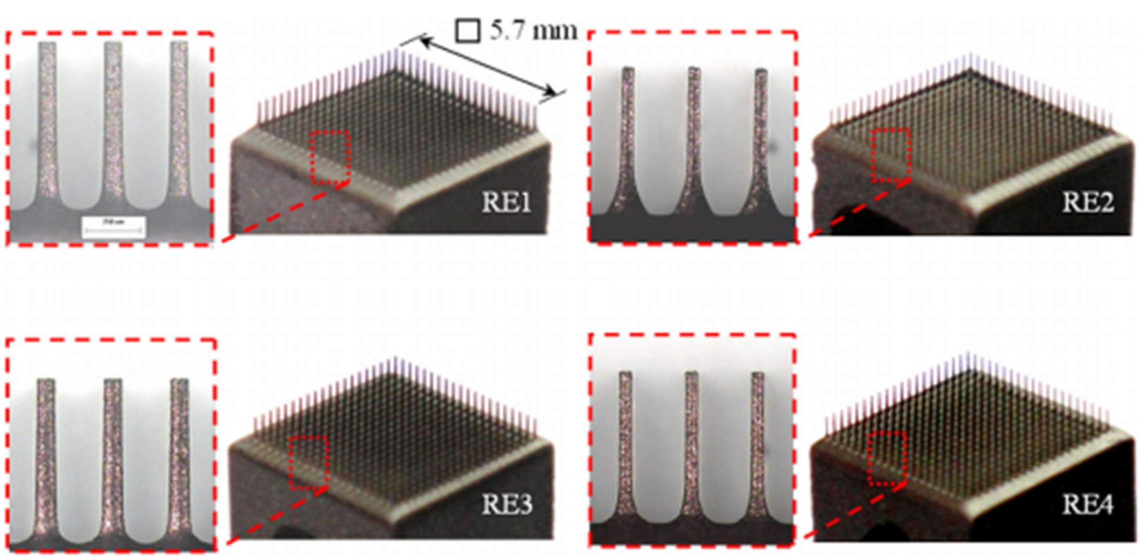


Fig. 34 The 1600 micro-pin array with an average diameter of 30μm and a length of 625μm

[141], respectively, adopted reverse EDM process to fabricate cylindrical array electrodes, and the three microelectrodes of 35μm in diameter, the 3×3 tungsten electrode arrays, and 5×5 tungsten electrode arrays are shown in Fig. 33 a and b.

The microelectrode array fabricated by R-EDM process existed the problem of electrical corrosion products removal difficulty, secondary discharge, and instability discharge due to the large number of microelectrode array and cannot be rotated. Therefore, in order to improve chip removal performance and reduce the occurrence of electric arc and short-circuit involved in process of fabricating microelectrode array machined by R-EDM, the ultrasonic vibration is introduced to R-EDM by Zeng et al. [141], and they prepared 5×5 arrays of microelectrode with the diameter of less than about 30μm and height-to-width aspect ratios of larger than 8, and measured results disclosed that these microelectrode arrays have good coaxiality and surface quality as shown in Fig. 33c. For the preparing efficiency of microelectrode array, Hwang et al. [142] proposed the method of combining mechanical peck-drilling and R-EDM to fabricate micro-pin array, and their results indicated that the 1600 micro-pin array with an average diameter of 30μm, a length of 625μm, and a pitch of 100μm can be efficiently produced introducing working fluid spraying, vibration assisted electrode, and shake-down type workpiece as shown in Fig. 34.

5 Conclusion and outlook

This paper extensively reviews the application of EDM-based processes in fabricating micro tools as well as their characteristics, performances, measurements, remarks, existing problems, and future development direction based on previous researchers, and the following conclusions can be identified:

The EDM-based process is the most widely used and proved to be a promising technique for fabricating micro tools due to its versatile and non-contact nature. Dimensional accuracy, machining efficiency, and surface quality of micro tools are significantly affected by various tool and workpiece electrode factors, power factors, flushing fluid parameters, tool/workpiece electrode feed rate or way, etc. Besides, the analytical and predicted models for diameter, edge radius, runout error, and surface roughness of micro tools machined by EDM process are established, but the predicted results differ greatly from the test results. The preparation of micro tools has to enter into the scope of micro machining scale, the influences of micro defects or in-homogeneity of material, the flow of working liquid in discharge area, and the formation and annihilation of spark discharge channel on the machining precision and quality of micro tools fabricated by EDM processes are not clear; until now, the effective theoretical model for the EDM fabrication process of micro tools has not yet been established, which needs further investigation.

Some hybrid techniques have been proposed to fabricate micro tools, like WEDG along with micro-EDM, combination of WEDM, and diamond grinding. So it needs to vigorously develop the micro tool preparation techniques of compound processes in the future, such as integrating the laser, EDM, electrochemical, and ultrasonic vibration, and meanwhile combining the real-time monitoring, on-line detection, and CAD/CAM advanced technologies, which can satisfy the processing requirements of high precision and continuous development of new materials for micro tools as well as improving the machining efficiency and machining quality.

The WEDG method is firstly proposed to fabricate micro tools; for enhancing its machining accuracy, the TF-WEDG and RF-WEDG methods are developed; for improving fabricated efficiency, the twin-WEDG, strip-EDM, S/M-BEDG, etc. have been successively put forward; for getting rid of the limit of regulating wheel and realizing the process of complicatedly rotary surface, the CWEDT, EDT, LS-WEDT, etc. have been invented. Based on continuous enhancements of EDM-based process, the micro tools with straight or helical cutting blades and various cross sectional geometry made of super hard material (including PCD, cemented carbide, etc) can be successfully prepared. However, the experimental studies of micro tools prepared by EDM based processes are carried out the EDM test platform at home and abroad, but there is little research on overall development of special EDM machine tool for micro tool preparation. In order to meet the requirements and the actual production needs of micro tools made of increasingly diverse materials, gradually specialized structures, and continuous high-precision size, the micro tool EDM-fabricated techniques will develop towards the direction of high precision in nanometer scale and high efficiency in macro scale, which needs to develop high-performance micro tool special EDM machine.

Acknowledgements The authors would like to thank the support of the National Natural Science Foundation of China (No. 52005092), the Fundamental Research Funds for the Central Universities (No. N2103013), the China Postdoctoral Science Foundation (No. 2019M661111), the National Natural Science Foundation of China (No. 51775100), and the Fundamental Research Funds for the Central Universities (No. N2003024).

Author contribution Yao Sun and Liya Jin developed the idea of the study; Mingjun Liu and Yadong Gong participated in its design and coordination and helped to draft the manuscript. Xuelong Wen, Guoqiang Yin, and Quan Wen contributed to the acquisition and interpretation of data. Wen provided critical review and substantially revised the manuscript. All authors read and approved the final manuscript.

Funding This study has been funded by the National Natural Science Foundation of China (No. 52005092), the Fundamental Research Funds for the Central Universities (No. N2103013), the China Postdoctoral Science Foundation (No. 2019M661111), the National Natural Science Foundation of China (No. 51775100), and the Fundamental Research

Funds for the Central Universities (No. N2003024).), and the postdoctoral scientific research funds of Liaoning (2021-BS-053).

Data Availability The data sets supporting the results of this article are included within the article.

Declarations

Ethical approval Not applicable.

Consent to participate Not applicable.

Consent to publish All authors agree that the manuscript be published.

Competing interests The authors declare no competing interests.

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