REVIEW ARTICLE

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Recent advances in micro- and nano-machining technologies

Abstract Device miniaturization is an emerging advanced technology in the 21st century. The miniaturization of devices in different fields requires production of micro- and nano-scale components. The features of these components range from the sub-micron to a few hundred microns with high tolerance to many engineering materials. These fields mainly include optics, electronics, medicine, bio-technology, communications, and avionics. This paper reviewed the recent advances in micro- and nano-machining technologies, including micro-cutting, micro-electrical-discharge machining, laser micro-machining, and focused ion beam machining. The four machining technologies were also compared in terms of machining efficiency, workpiece materials being machined, minimum feature size, maximum aspect ratio, and surface finish.

Keywords micro machining, cutting, electro discharge machining (EDM), laser machining, focused ion beam (FIB)

1 Introduction

In recent years, the demand for micro-scale components and products has increased rapidly, particularly in the fields of electronics, communications, optics, avionics, medicine, and automobiles [1,2]. Typical applications of such products include micro-engines, micro-reactors, micro-heat exchangers, medical implants, drug delivery devices, and diagnostic devices [3,4]. The fabrication of these products usually requires micro- and sub-micrometer

components. Given this demand, many studies in manufacturing have focused on developing micro- and nano-machining technologies [3]. This emerging trend requires a new micro-manufacturing platform that not only integrates different fabrication technologies but also develops new machining technologies for micro and nano-components. Furthermore, the micro-manufacturing platform should produce different materials in a high throughput and cost-effective manner.

Lithography-based microelectromechanical systems (MEMS) technologies are the most commonly used micro- and nano-manufacturing technologies in the past few decades and can fabricate micro-components with micro- and nano-feature sizes [5]. However, they are generally employed to fabricate two-dimensional and two-and-half-dimensional microstructures in a narrow range of workpiece materials [6,7]. Given this limitation, MEMS technologies are unable to meet the demand for fabrication of complex three-dimensional microstructures made of different materials. New micro- and nano-machining technologies were developed to address these demands. This paper reviews recent developments in new machining technologies, including micro-electro discharge machining (micro-EDM), micro-cutting, laser micro-machining, and focused ion beam (FIB) micro-machining [5,8,9].

2 Classification of micro- and nano-machining technologies

Micro- or nano-machining refers to the fabrication of components or products with at least one feature size in the micrometer or nanometer scale. In the past two decades, a wide range of micro- and nano- machining technologies based on different principles were developed to manufacture complex microstructures. Several classification methods were proposed to classify these technologies. For example, Masuzawa [10] summarized the micro-machining technologies and categorized them based on different machining characteristics. Madou [11] classified micro- and nano-manufacturing technologies into lithographic or non-lithographic techniques. Brinksmeier et al. [12],

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Brousseau et al. [13], and Qiu et al. [14] classified these technologies into two types, namely, microsystem technologies (MST) and micro-engineering technologies (MET). MST is generally employed to produce MEMS, such as photolithography, electroplating, silicon micromachining, micro-electroforming, and chemical-etching. By contrast, MET mainly refers to some processes related to mechanical machining, such as cutting, milling, grinding, laser machining, micro-EDM, and FIB machining. The MET can be used to produce high-precision mechanical components and surfaces. Depending on the type of machined materials, micro- and nano-machining technologies can also be classified as silicon-based or non-silicon-based manufacturing technologies [14]. Dimov et al. [15] and Brousseau et al. [13] classified these technologies on the basis of the processing dimension. In their classification, one-dimensional technologies include micro-cutting, micro-grinding, micro-milling, micro-EDM and FIB machining. These technologies fabricate micro-components by performing material removal in a single dimension. Two-dimensional technologies fabricate micro structures in a plane by employing masks, including photo/UV lithography, X-ray lithography, and electron beam lithography. Three-dimensional technologies are mainly employed for conducting surface modification and deposition or fabricating volume structuring. Processes under this classification include physical vapor deposition (PVD), chemical vapor deposition (CVD), microinjection molding (MIM) and nano-imprint lithography (NIL). The present paper focuses on the recent development of one-dimensional micro-machining technologies, including micro-cutting, micro-EDM, laser micro-machining, and FIB machining.
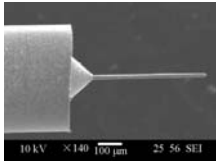
3 State-of-the-art technologies
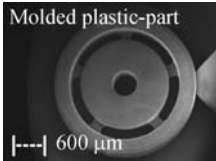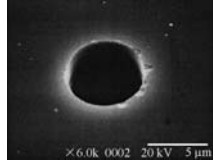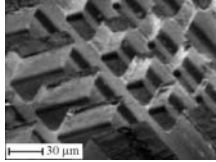
3.1 Micro-cutting

The machining principle of micro-cutting is essentially similar to that of conventional macro-cutting. It refers to the process of mechanical micro-machining employing micro-tools with geometrically defined cutter edges to remove materials directly. This process must be performed on ultra-precision machines or specifically designed micro-machines. Given that micro-cutting can achieve micro-form accuracy and nanometer finish, this process is widely used to machine micro-components or micro-features in different engineering materials [16–18]. Typical micro-cutting processes include micro-turning, micro-milling, micro-drilling, and micro-grinding [19]. Various geometries and high surface quality can be achieved with the application of different micro-cutting processes to produce micro-components; these advantages are shown in Table 1 [19–29]. The machining principle of micro-cutting is similar to that of conventional macro-cutting, but new

challenges, such as predictability, producibility, and productivity, must be resolved [30]. Moreover, micro-cutting exhibits several different characteristics because of significant reduction in size. These characteristics include cutting chip formation, minimum chip thickness, cutting force, and tool wear.

The depth of cut in conventional macro-cutting is significantly larger than the radius of the cutting tool edge. Thus, macro-chip formation models are created under the assumption that the cutting tool can completely remove the surface material of a workpiece and form cutting chips. The depth of cut in micro-cutting is close or even smaller than the edge radius of the cutting tool; this feature results in a large negative rake angle during cutting, as shown in Fig. 1 [25]. It should be noted that the negative rake angle can be observed in both micro- and macro-grinding processes. This negative rake angle significantly influences the magnitude of shearing and ploughing forces because the elastic-plastic deformation of workpiece materials is more apparent in micro- than in the macro-cutting process [31,32]. According to Liu et al. [6,33], Bissacco et al. [34], and Kim et al. [35], the workpiece material can undergo pure elastic deformation during micro-cutting. Kim et al. [35] also observed a new non-detached chip when the depth of the cut in the tool exceeded the critical minimum chip thickness. Further, when the depth of cut is less than a critical minimum chip thickness, the surface material only deforms elastically and cutting chips are not generated during machining.

Minimum chip thickness is an important measure that determines the formation of cutting chips. According to Weule et al. [36], minimum chip thickness primarily depends on the edge radius of a cutting tool and the material property of the workpiece. They further indicated that once the depth of the cut of the cutting tool reaches the minimum chip thickness, surface roughness can be predicated based on the spring back of the elastically deformed material. Liu et al. [37] established an analytical model for predicting minimum chip thickness; this model is based on the thermo-mechanical properties of the machined material, which include cutting temperature, strain, and strain rate. Vogler et al. [38,39] used finite element modeling approach to investigate the minimum chip thickness of steel; they found that the minimum chip thickness is approximately 0.2 and 0.3 times of the edge radius of a cutting tool for pearlite and ferrite, respectively. This finding validates the assumption that material property affects minimum chip thickness. Son et al. [40] examined the influence of friction between the workpiece and the cutting tool and established an analytical model for determining minimum chip thickness. This model established the correlations among minimum chip thickness, edge radius of cutting tool, and friction angle between the cutting tool and the uncut workpiece. Chen et al. [29] performed a parametric investigation and developed micro-grinding technologies for micro aspherical molds

Table 1 Machining capabilities of typical micro cutting processes

Process	Machining shape	Feature size	Surface roughness Ra	Reference
Micro-turning	Rotational convex shape with high aspect ratio	Diameter > 5 μm, but > 100 μm more applicable	0.05–0.30 μm	[19–21]
Micro-milling	Convex and concave shapes with high aspect ratio	Slot width > 3 μm, but > 50 μm more applicable	< 10 nm	[22,23]
Micro-drilling	Round blind- and through-holes	Diameter > 5 μm, but > 50 μm more applicable	0.05–0.30 μm	[24,25]
Micro-grinding	Convex and concave shapes of hard-brittle materials	Structure width > 13 μm, but > 50 μm more applicable	< 10 nm	[26–29]
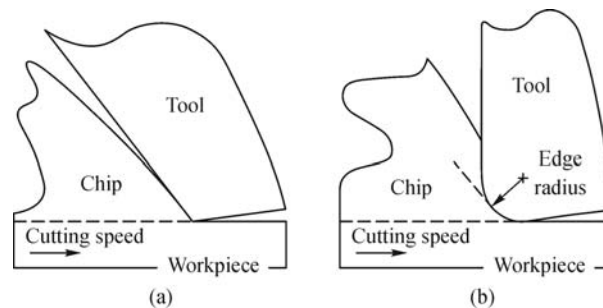
Fig. 1 Schematic of chip formation in (a) macro-cutting and (b) micro-cutting [25]

made of tungsten carbide. They found that the thickness of an undeformed chip at nanometric scale had insignificant influence on the surface finish of ground inserts, whereas grinding trace spacing had a slightly stronger influence on surface finish. They also developed a new truing and dressing technique for micro grinding wheels that achieved satisfactory wheel form accuracy and high grain packing density. These technologies were applied to fabricate a micro aspherical insert with a diameter of 200 μm, a surface finish of 4 nm, and a form error of 0.4 μm.

Many studies investigated cutting force in micro-cutting and the significant effect of size on chip formation, cutting tool deflection, and bending stress [41]. Kim et al. [31] analyzed differences in cutting force between macro- and micro-cutting. Shear occurred along the shear plane during macro-cutting. By contrast, shear stress in micro-cutting gradually increased around the edge radius of the cutting tool. This study also established a micro-cutting force model that considered the elastic recovery of workpiece material, which resulted in sliding along the clearance face of the cutting tool. Liu et al. [6] demonstrated that the forced vibration of the cutting tool and the elastic recovery

of the machined material significantly affected the magnitude of cutting force at low feed rates. They found that low feed rates resulted in unstable micro-cutting because of the elastic deflection of the machined material thereby leading to the forced vibration of the cutting tool. To calculate the chip thickness of the machined material, Bao and Tansel [42,43] proposed a cutting force model that considered the effect of tool tip trajectory. However, this model did not consider the effect of the negative rake angle of the cutting tool and elastic-plastic deformation of the workpiece material in micro-cutting; both of these factors significantly differ from that in macro-cutting. The interaction between the cutting force and the corresponding deformation of the cutting tool is a key issue in micro-cutting. Dow et al. [41], Duan et al. [44], and Ma et al. [45] analyzed the effect of tool deformation on cutting force; they established cutting force models that compensated for the error induced by cutting-tool deflection during micro-cutting.

Cutting tools are critical to micro-cutting processes because these tools can considerably affect surface quality and the feature size of micro-components. In the past few years, a continuous effort has been directed toward developing efficient micro-cutting tools. Diamond materials are often employed in micro-turning and micro-grinding, but these materials are unsuitable for cutting ferrous workpiece materials [46]. Micro-cutting tools in micro-milling and micro-drilling are usually made of tungsten carbide because of the high hardness and strength of this material at elevated temperatures [47]. At present,

commercially available micro-cutting tools with a helix angle that can reach a diameter of 50 μm are fabricated by ultra-precision grinding [48]. Micro-cutting tools with less than 50 μm diameter generally have a special zero helix angle to increase the strength of the tool and mitigate the limitations of machining methods [23,48]. Onikura et al. [49] fabricated carbide tools with 11 μm diameter through ultrasonic vibration grinding to reduce grinding forces without breaking the cutting tools. Adams et al. [50] used FIB sputtering to fabricate micro-milling tools with 25 μm diameter at different cutting edges, as shown in Fig. 2. They used these tools to machine micro-channels with 25 μm depth and width. Egashira et al. [51] employed EDM to develop cemented tungsten carbide drilling and milling tools with 3 μm diameter. They used these tools to fabricate holes with diameters of 4 μm and slots with 4 μm width and 3 μm depth, as shown in Fig. 3 [51].

3.2 Micro-EDM

EDM is a thermo-electric machining process that removes workpiece material through high-frequency, repeated electrical discharges between the electrode tool and the workpiece material. Both materials are submerged in liquid dielectric bath. The development of EDM has been directed toward machining of features in the micrometric scale. This development led to the widespread utilization of micro-EDM to fabricate micro-components, micro-tools, and parts with micro-features. Micro-EDM can machine various materials, such as hardened steel,
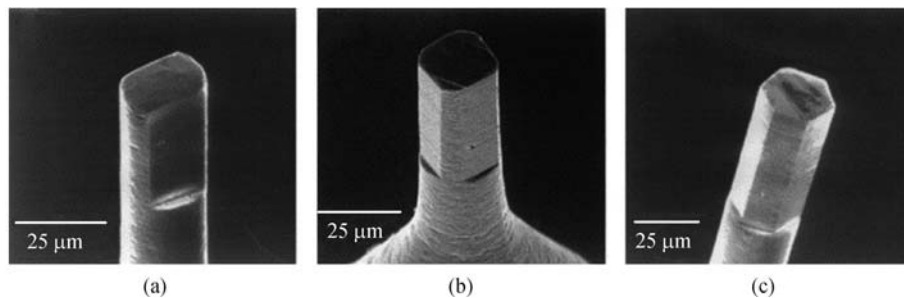

Fig. 2   Micro-cutting tools of 25 μm in diameter made by FIB micro-milling having (a) 2, (b) 4 and (c) 5 cutting edges [50]
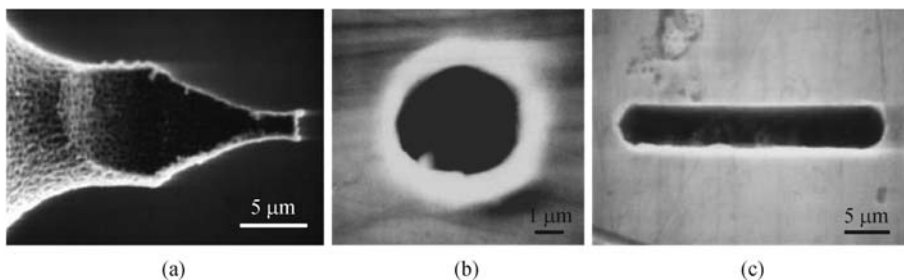

Fig. 3   (a) A micro-cutting tool of 3 μm in diameter made by EDM and the fabricated (b) micro-hole and (c) micro-slot [51]

cemented carbide, and electrically conductive ceramics with sub-micron precision [8,52]. Given its small machining force and good repeatability, micro-EDM is one of the most valuable processes for fabricating micro-structures with high aspect ratios [53]. Figure 4 [9,13,54] shows micro-features machined by micro-EDM. Current micro-EDM technologies primarily include die-sinking micro-EDM, micro-wire EDM, micro-EDM drilling, and micro-EDM milling [13]. The removal mechanism of micro-EDM is similar to that of macro-EDM, but micro-EDM has unique features in tool fabrication, discharge energy, and dielectric fluid flushing [55,56]. Unlike conventional macro-EDM, the application of micro-EDM is hindered by limitations in handling of electrodes, preparation of workpiece-electrode, and planning of the machining process [53].

Machining error induced by electrode wear is generally disregarded in conventional macro-EDM. However, electrode wear in micro-EDM significantly affects the machining accuracy of fabricated micro-features. Researchers investigated electrode wear mechanism and compensation approaches to overcome this issue. Pham et al. [53] investigated the influence of different sources of errors, including machine, electrode dressing, electrode wear, and fixture, on the machining accuracy of micro-EDM milling; they found that electrode wear compensation was critical to achieving highly accurate micro-features. They also proposed a micro-EDM milling approach that did not rely on complex mathematical calculations. This approach is shown in Fig. 5 [53]. As shown in Fig. 5, cavity volume is only partially completed after the first milling passes through Path 1 [53] because electrode wear primarily appears on the edge and face of the tool. $Z_{contact}$, which denotes the point where the electrode tip comes in contact with the workpiece, is reset. The paths for the next milling passes are then designed (Paths 2 and 3). If electrode wear is small or negligible (after Path 4 in Fig. 5), a newly dressed electrode is employed to conduct finishing milling passes. In addition, Pham et al. [57,58] also investigated the influence of different factors that contribute to electrode wear in micro-EDM drilling with micro-rod and micro-tube electrodes.

They discussed possible methods for wear compensation and calculated electrode wear ratios using a simple method. This method is based on geometrical variations during machining. Dimov et al. [59] presented a new tool-path generating method for layer-based micro-EDM milling. This method integrates uniform wear method and adaptive slicing to compensate for electrode wear by varying layer thickness. Complex three-dimensional cavities were fabricated by micro-EDM milling using simple-shaped electrodes. Tasi and Masuzawa [60] studied the influence of thermal properties on the electrode wear of various materials in micro-EDM. They found that the boiling point of an electrode material played a significant role in electrode wear. Motivated by this finding, they proposed an index based on boiling phenomenon to evaluate the erosion property of electrode material. To reduce electrode wear, Uhlmann and Roehner [61] applied novel electrode materials to fabricate tool electrodes; these materials include boron doped CVD-diamond (B-CVD) and polycrystalline diamond (PCD). They investigated the performance of B-CVD and PCD and the effect of electrode materials on tool wear and workpiece surface quality. However, further investigation must be conducted on the effects of micro-feature and element concentration in PCD and B-CVD on material removal and wear mechanism for industrial applications. Aligiri et al. [62] employed an electro-thermal model to estimate material removal volume in real time during micro-EDM drilling; in this study, the compensation length of electrode wear was determined by comparing the estimated material removal volume with the targeted material removal volume. Bissacco et al. [63] also proposed a new electrode wear compensation method for micro-EDM milling based on discharge counting and discharge population characterization. They found that electrode wear can be effectively compensated based on discharge counting without implementing a pulse discrimination system.

Electrode preparation is important in achieving high accuracy and good repeatability in micro-EDM [53]. Thus, many researchers have focused on tool-electrode preparation in the past years. Masuzawa et al. [64] proposed a new technique called wire electro-discharge grinding (WEDG)
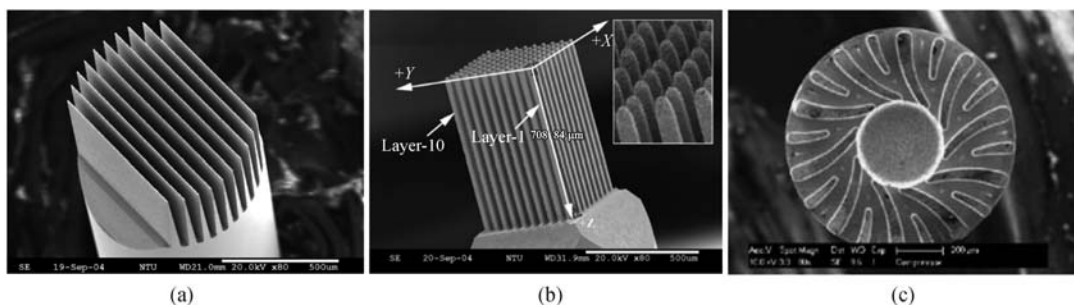

Fig. 4 (a) A sharp-edge microstructure array, (b) a high aspect ratio pillared microstructure array and (c) a micro-compressor machined by the micro-EDM [9,13,54]
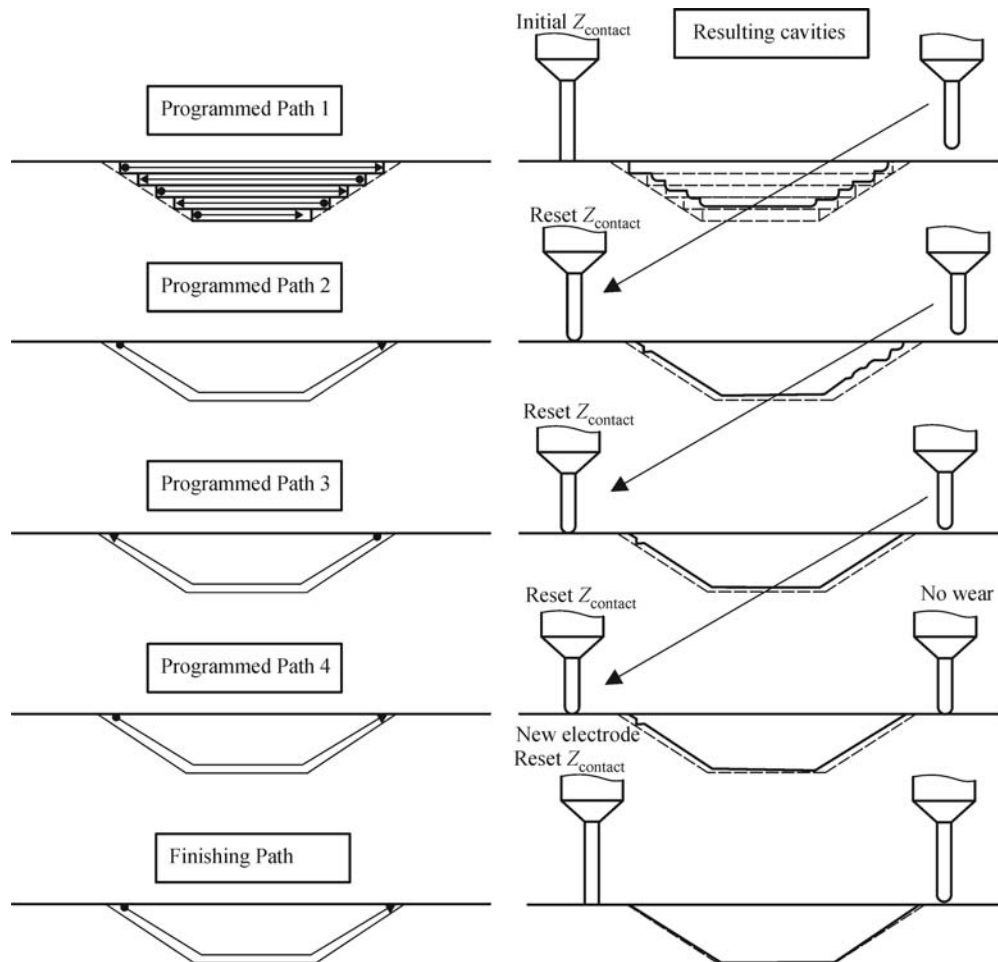
Fig. 5   Process strategy for wear compensation in micro-EDM milling [53]
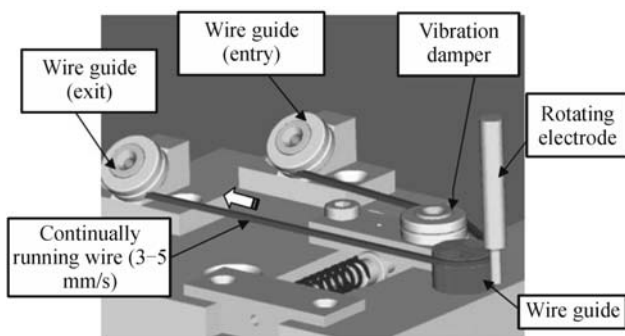

Fig. 6   Schematic of a WEDG system [65]

to facilitate on-the-machine electrode generation. WEDG is similar to wire EDM given that both approaches used a traveling wire as tool electrode; however, the wire guide and the machining setup of WEDG differ from that of wire EDM, as shown in Fig. 6 [65]. The continually running wire is fed at a constant speed from the wire pool to the dressing system. Thus, the wire pool applies constant tension to the running wire throughout the entire dressing

process. The running wire then passes through a vibration damper and a fixed wire guide to maintain stability during the dressing process. The electrode is dressed by a rotating electrode at the position of the wire guide. Finally, the running wire goes through a number of wire guides and is deposited. Using this technique, they investigated the machining characteristics, including accuracy and repeatability. They demonstrated that WEDG can achieve high accuracy and good repeatability with an error of less than 1 µm. This method can successfully machine materials into electrodes of less than 15 µm in diameter. Rees et al. [65] investigated the effects of electrode material, process strategy, and machine accuracy on the surface finish, electrode quality, and aspect ratio of the fabricated electrode. They demonstrated that tungsten carbide and tungsten electrodes made by WEDG can achieve high aspect ratio and good surface finish, respectively. They also proposed a compensation method based on an optical verification system to significantly improve the machining accuracy of tool electrodes.

WEDG is widely used for electrode generation in micro-EDM, but conventional WEDM still encounters issues in

producing cylindrical electrodes with high aspect ratios. Considerable research effort has been directed toward implementing WEDG with a wire micro-EDM. Uhlmann et al. [66] studied the machining performance of three different methods for producing cylindrical parts, namely, electro-discharge turning (EDT), electro-discharge grinding (EDG), and WEDG; they particularly examined pulse stability, hydrodynamic behavior of dielectrics, machine dependent gap, and feed control. However, this study did not attempt to optimize surface quality. Using a similar method to machine cylindrical parts, Qu et al. [67,68] improved traditional WEDM by integrating an additional rotary axis into the micro-EDM machine. They studied the influences of pulse on-time, part rotational speed, and wire feed rate on the surface finish and roundness of machined components. Nonetheless, the approach developed was employed to fabricate macro-components, not directly applicable at the micro scale. Rees et al. [69] and Brousseau et al. [13] used wire micro-EDM combined with a rotating submergible spindle to perform WEDG. As shown in Fig. 7 [69], a wire guide was not required at the contact point between the electrode running wire and the rotating test-piece. This approach improved the flexibility of machine cylindrical parts. The use of WEDG set-up can achieve better surface integrity than that by traditional WEDG under the same discharge energy levels. Figure 8 [13] shows the micro electrode machined by the WEDG implemented into micro-wire EDM.
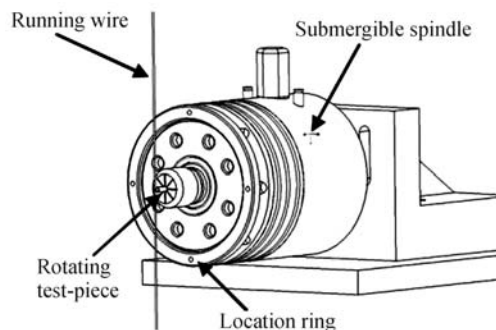

Fig. 7   WEDG principle implemented into micro-wire EDM [69]

3.3   Laser micro-machining

Laser micro-machining is a widely-used energy-based machining process, wherein a laser beam is focused to melt and vaporize unwanted materials from the workpiece [70]. Laser micro-machining is an efficient micro-manufacturing process because of its high lateral resolution, low heat input, and high flexibility [14]. Laser micro-machining integrated with a multi-axis micro-machining system can be used for drilling, cutting, milling, and surface texturing. This process is suitable for machining micro-components made of different kinds of workpiece materials, such as metals, polymers, glasses, and ceramics [71]. Figure 9 [72] shows typical micro-features fabricated by laser micro-machining. Laser micro-machining is primarily used for drilling, cutting, and milling. Specially, laser micro-milling is gradually gaining recognition as an important micro-manufacturing technology in rapid prototyping, component miniaturization for different applications, and serial production of micro-devices by batch fabrication methods [71,73].
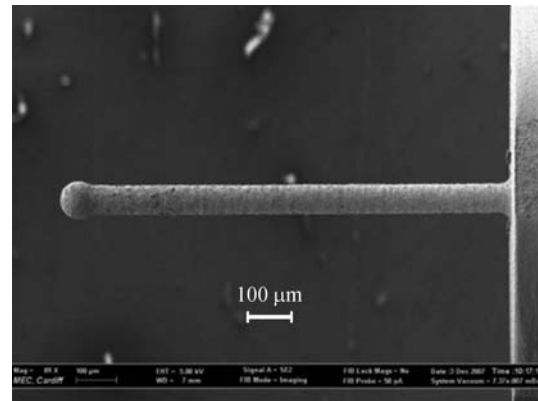

Fig. 8   Micro electrode machined by micro-wire EDM [13]

Laser micro-drilling is an economical process for making closely spaced micro-holes. Laser micro-drilling typically includes two types of processes, namely, percussion drilling and trepan drilling; the schematic of
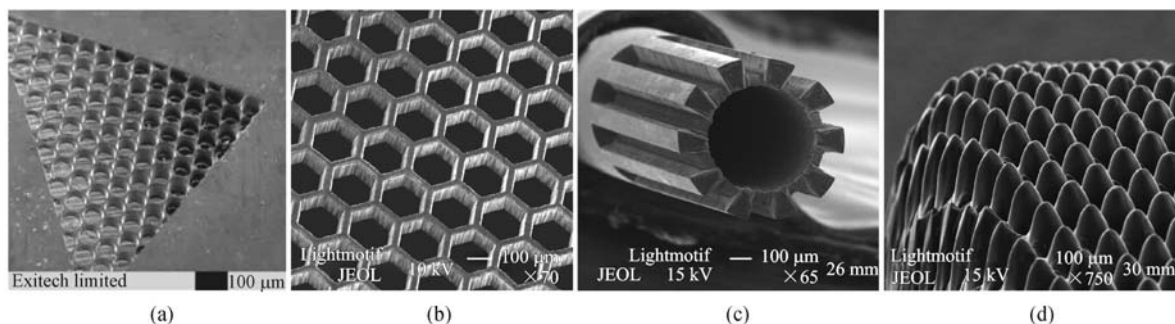

Fig. 9   (a) Micro-through-hole arrays, (b) honeycomb micro-structures, (c) a micro-spinneret, and (d) cone-like-protrusions fabricated by the laser micro-machining [72]
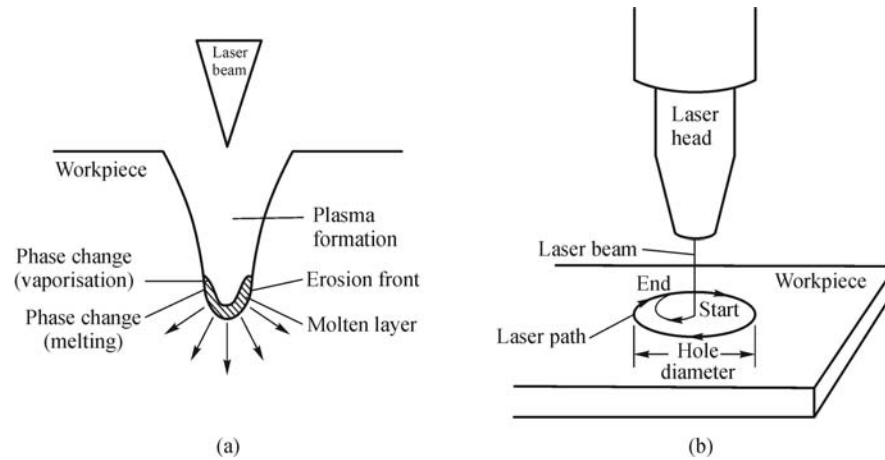
Fig. 10 Schematic of (a) percussion laser micro-drilling and (b) laser micro-drilling [74]

these two processes is shown in Fig. 10 [74]. Percussion drilling is generally used for fabricating micro-holes, wherein the laser spot remains stationary on the workpiece material and a series of pulses is released. Thus, the diameter of the micro-hole depends on the laser spot size, which ranges from several micro-meters to tens of micro-meters. The micro-hole made by laser drilling is tapered because the diameter of the hole at the exit of the laser beam is smaller than that at the entrance of the laser as shown in Fig. 11(a). The tapered shape may be improved by optimizing the processing parameters [75,76]. The smallest micro-holes that have been made by the Light-motif B.V. Corporation have a diameter of sub-microns at the laser exit. Zheng and Huang [77] proposed a novel approach for improving laser hole drilling quality by using an ultrasonic vibrator to excite the work material during laser drilling. They found that the aspect ratio and wall surface finish of the micro-holes machined by ultrasonic-vibration-assisted laser drilling were improved compared with that without ultrasonic vibration assistance. To machine holes larger than the laser spot size in diameter, trepan laser micro-drilling technology can be used, in which the laser beam cuts the workpiece material around the circumference of the hole. Figure 11(b) shows the

micro-holes machined by trepan laser micro-drilling, which exhibits perfectly smooth walls with the absence of burrs. The machining principle of laser micro-cutting is similar to that of trepan laser micro-drilling. This approach also removes the workpiece material by scanning the contour of the desired cut through the use of pulse lasers to achieve highly accurate cuts with good surface quality and low damage [78]. By using fast galvanometer scanners, laser micro-cutting can facilitate accurate, flexible, and fast cutting processes.

Laser micro-milling is a new machining process that employs a focused laser beam to scan over workpiece and remove workpiece material layer-by-layer through laser ablation effect [13]. Unlike conventional micro-milling, scanning pattern in laser micro-milling may vary for each layer. This feature indicates that this machining process can fabricate three-dimensional surface structures. In addition, laser micro-milling can machine different kinds of engineering materials. This technique is particularly suitable for hard workpiece materials that are difficult to machine using traditional machining methods. Laser parameters in laser micro-milling significantly influence the machining process. An accurate control of the laser parameters combined with the optimization of the scan
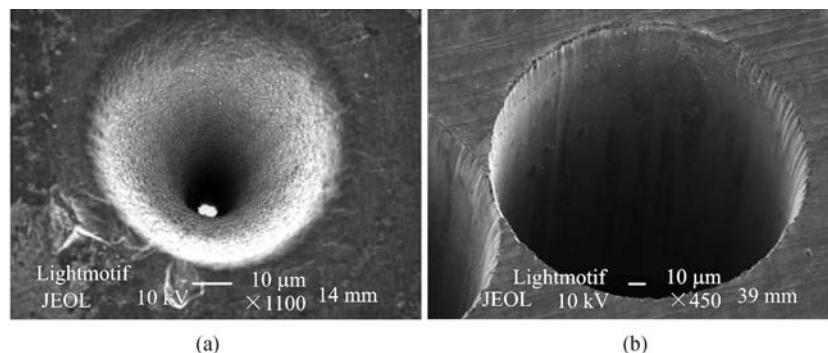

Fig. 11 Micro-holes machined by (a) percussion laser micro-drilling and (b) trepan laser micro-drilling

pattern is the key to achieving high-quality laser micro-milling. Petkov et al. [79] proposed two major material removal mechanisms based on laser pulse length (i.e., ultrashort pulses and long pulses) in laser micro-milling. Ultrashort pulses refer to femtosecond and picosecond pulses, whereas long pulses comprise nanosecond and longer pulses. When ultrashort pulses are used in laser micro-milling, the duration of laser pulse is less than the time needed for the electrons and the atomic lattice to reach thermal equilibrium; thus, laser ablation can be considered a solid-plasma or solid-vapor transition, having a small or negligible heat-affected zone [80,81]. However, the absorbed energy from the laser beam in long pulses melts the workpiece and heats it to a high temperature enabling atoms to obtain enough energy to enter a gaseous state. In this case, the thermal wave has sufficient time to propagate into the workpiece material, which results in the evaporation of the liquid state of a material. After performing laser micro-milling with long pulses, heat quickly dissipates into the work material, and a recast layer is generated. Various defects, such as microcracks, debris, surface layer damage, shock waves, and recast layers, are also generated [82]. Huang et al. [83] studied the effect of femtosecond laser micro-milling on the surface characteristics and microstructures of a Nitinol alloy. They demonstrated that this process can achieve better surface quality as well as thinner re-deposited material and heat-affected layers. Thus, laser micro-milling using ultrashort pulses can improve surface quality. Pham et al. [73] investigated laser micro-milling for machining ceramic micro-components; they demonstrated that laser micro-milling with microsecond pulses can machine micro-components with feature sizes as small as 40 μm. However, their investigation was still in its infancy and did not reveal the material removal mechanism and the interactions between the laser beam and the workpiece involved in the machining process. Dobrev et al. [84] developed a model to simulate the material removal process involved in laser ablation. Using this model, they revealed the formation mechanism of crater defects on metal materials machined using microsecond laser pulses. They also employed laser micro-milling to machine ceramics and silicon nitride micro-components [85]. These previous works verify the machining accuracy of laser micro-milling at the micrometric scale. Machining accuracy and surface quality depend on the process parameters and the composition and initial surface finish of the workpiece. In general, decent results can be obtained on workpiece materials that have a fine grain or amorphous structure and a polished surface.

3.4 FIB-machining

FIB machining can fabricate complex micro- and nano-features using a focused beam of ion with in situ scanning electron microscopic (SEM) monitoring to remove unwanted workpiece material layer by layer. FIB can also be used to deposit materials via ion beam-induced deposition when precursor gas exists [86]. Ion beam is irradiated on the workpiece surface and the surface atoms receive energy during FIB micro-milling. The workpiece surface of atoms is sputtered if the received energy exceeds the surface binding energy [87]. FIB micro-milling can fabricate complex micro-features on nearly all workpiece materials with high surface quality and dimensional accuracy because of ultra-low ion scattering effect. In particular, FIB micro-milling can machine micro-features of less than 50 nm in lateral size [13]. At present, FIB micro-milling technology is widely used in the semiconductor industry for modifying electronic circuits, preparing transmission electron microscope (TEM) specimens, and debugging integrated circuits with increasing circuit density and decreasing feature dimension [88–90]. FIB is also employed to fabricate high-quality and high-precision micro-components for optical, mechanical, thermofluidic, and biochemical applications [88,91,92]. Figure 12 [88,92,93] shows the micro-structures and micro-tools fabricated by FIB micro-milling.
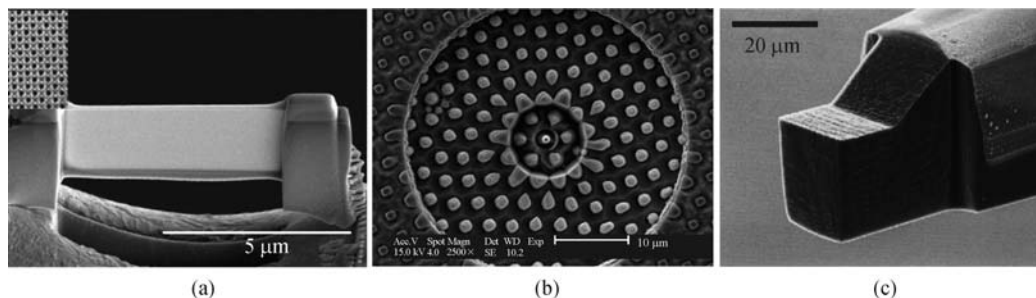

Fig. 12 (a) A TEM specimen, (b) Mo-alloy micro-pillars and (c) a monocrystal diamond micro-tool fabricated by FIB micro-milling [88,92,93]

FIB micro-milling is popularly used in micro-tool fabrication because of its high accuracy and resolution. This technology induces small or negligible machining stress and damage layer comparing with conventional ultra-precision machining methods. Picard et al. [92] employed the FIB micro-milling to produce micro-tools with non-planar materials. These micro-tools were made of different materials including tungsten carbide, high speed steel, and single crystal diamond. They successfully fabricated a variety of micro-cutting tools with dimensions in the range of 15–100 μm and a cutting edge of 40 nm in radius. To machine micro-diffractive optical elements, Xu et al. [94] used FIB micro-milling to fabricate micro-cutting tools with edge radius of around 25 nm with complex shapes as shown in Fig. 13. Wu et al. [95] optimized the fabrication process of diamond cutting tools with edge radius at nanometric scale by direct writing of FIB micro-milling. The FIB-induced lateral damage of diamond micro-tools could be reduced using the optimized process to improve the cutting ability and prolong the lifetime of micro-cutting tools.

FIB micro-milling was successfully employed to fabricate micro- and nano-structures in recent years. Li et al. [96] studied the FIB micro-milling capacity to machine micrometer and nanometer scale features on Ni-based substrates. This paper demonstrated that the micro- and nano-features machined by FIB micro-milling process can replace lithography-based pattern transfer techniques to fabricate Ni-based masters for injection molding and hot embossing. Li et al [97] further investigated machining capacity of FIB micro-milling for micro- and nano-features on fused silica substrates coated with a 15 nm thick Cr layer. Their study indicated that FIB micro-milling could also replace e-beam lithography for fabricating fused silica templates for UV nanoimprinting. According to Wu and Liu [98], well-defined, laterally site-positioned arrays of silicon islands could be directly fabricated using the FIB micro-milling without mask-removal or etching steps. They also fabricated silicon islands with different shapes

and sizes; nanoscale Si island arrays with hexagonal symmetry were also fabricated as shown in Fig. 14 [98]. Chang et al. [99] developed a fabrication method of ZnO-based micro-cavities with different shapes by FIB micro-milling and systematically investigated the optical characteristics of different shaped micro-cavities. Their experimental results demonstrated that ZnO-based micro-cavities with different shapes were fabricated by FIB micro-milling with high quality. Lu et al. [100] used FIB micro-milling to fabricate a series of cantilevers with different dimensions to investigate the facture strength characterization of protective intermetallic coating on AZ91E Mg alloys as shown in Fig. 15. FIB micro-milling has found a number of applications that require complex micro-structures made of various engineering materials.

3.5 Comparison of micro- and nano-machining technologies

A series of micro- and nano-machining technologies were reviewed, including micro-cutting, micro-EDM, laser micro-machining and FIB machining. Those machining technologies are essential for the manufacture of micro- and nano-components. Table 2 shows a comparison between the four machining technologies discussed earlier in terms of material removal rate, workpiece materials being machined, minimum feature size, maximum aspect ratio and surface finish. Micro-cutting technologies, which include micro- turning, milling, drilling and grinding, have the highest machining efficiency. These technologies can machine various engineering materials including metals, polymers, ceramics, silicon, and glass. However, micro-cutting has limitation in terms of achieving the minimum feature size. Machining features of sizes less than 25 μm remain challenging. Micro-EDM can achieve the highest aspect ratio and micro holes with an ultra-high aspect ratio of more than 30 can be fabricated using micro-EDM drilling with ease. Nevertheless, micro-EDM can only machine conductive materials. Laser micro-machining can
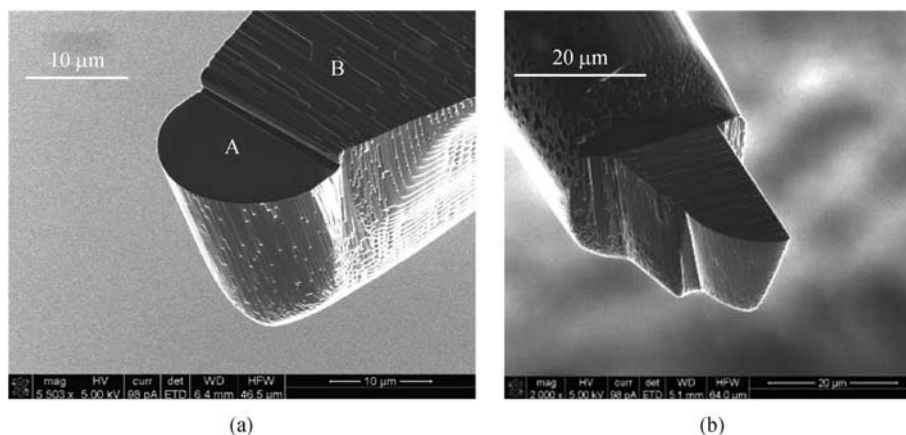

Fig. 13 (a) Spherical and (b) hemi-spherical micro-cutting tools fabricated by the FIB micro-milling [94]
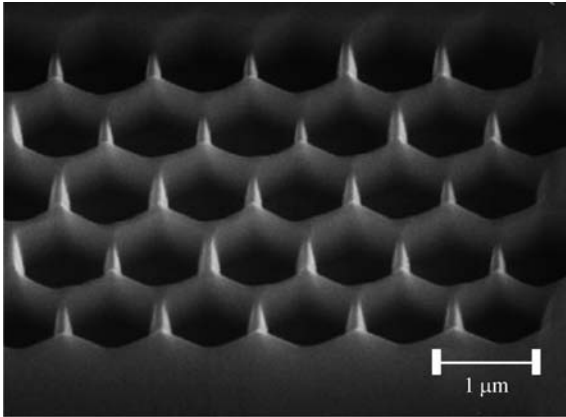
Fig. 14 Nanoscale Si island arrays with hexagonal symmetry fabricated by the FIB micro-milling [98]

be employed to machine the widest scope of workpiece materials. There are two main ablation regimes in laser machining based on the pulse length of laser, which directly influence machining efficiency and feature size. When using ultrashort pulses, laser micro-machining can achieve a feature size of less than 3 μm, but it also has the lowest material removal rate. FIB machining can fabricate both micro- and nano-scale components or features and is suitable for various engineering materials. The limitation

of this process is the lowest material removal rate among the four technologies. FIB machining and laser micro-machining with ultrashort pulses lasers have relatively low material removal rate but both approaches can provide a removal process with high resolution. Overall, the four technologies can complement each other for the manu-facture of micro- and nano- components.

4   Conclusions

This paper summarized the processing principles and applications of four primary micro-machining technolo-gies, which include micro-cutting, micro-EDM, laser micro-machining, and FIB machining. Comparison was conducted among the four machining technologies in terms of machining efficiency, workpiece materials being machined, minimum feature size, maximum aspect ratio and surface finish. Among four machining technologies, micro-cutting provides the highest material efficiency and can be employed to machine various engineering materi-als. However, this approach has limitation in achieving the minimum feature size. Micro-EDM can achieve the highest aspect ratio. Laser micro-machining with ultrashort pulses lasers and FIB machining can perform high resolution processing to achieve sub-micrometer features.
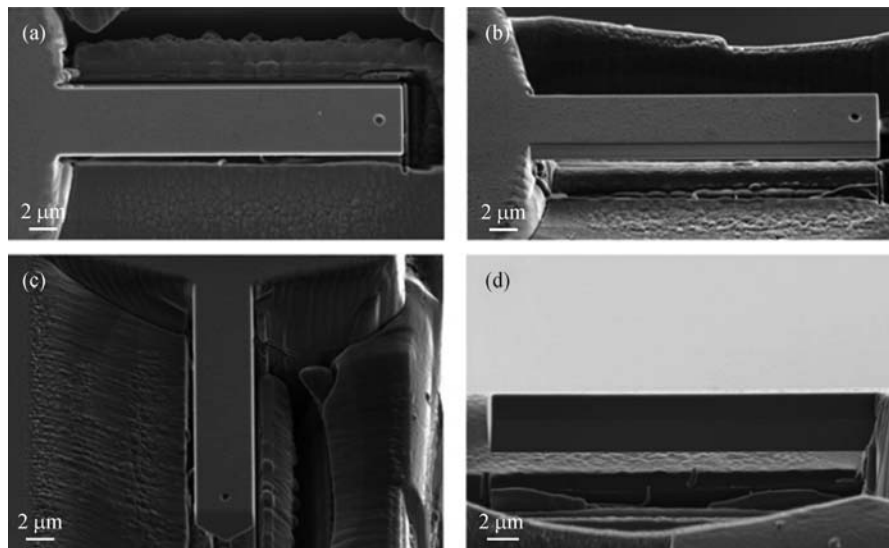

Fig. 15   A typical micrometer-sized cantilever machined by FIB micro-milling: (a) 0° tilt/top view, (b) and (c) 40° tilt, (d) 90° tilt/side view [100]

Table 2   Machining capabilities of micro- and nano-machining technologies

Machining technology	Material removal rate	Workpiece materials being machined	Minimum feature size	Maximum aspect ratio	Surface finish
Micro-cutting	Better	Average	Worse	Worse	Average
Micro-EDM	Average	Worse	Average	Better	Average
Laser machining	Average	Better	Average	Average	Average
FIB machining	Worse	Better	Better	Worse	Better

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