

## Micro tool design and fabrication: A review

S.N.B. Oliaei<sup>a</sup>, Y. Karpas<sup>b,e,f,g</sup>, J. Paulo Davim<sup>c</sup>, A. Perveen<sup>d,\*</sup>

<sup>a</sup> Atılım University, Department of Mechanical Engineering, Incek, Ankara, Turkey

<sup>b</sup> Bilkent University, Department of Industrial Engineering, Bilkent, Ankara, Turkey

<sup>c</sup> University of Aveiro, Department of Mechanical Engineering, Portugal

<sup>d</sup> Nazarbayev University, Department of Mechanical & Aerospace Engineering, Kazakhstan

<sup>e</sup> Department of Mechanical Engineering, Bilkent University, Ankara, Turkey

<sup>f</sup> UNAM – Institute of Materials Science and Nanotechnology, Turkey

<sup>g</sup> Department of Industrial Engineering, Bilkent University, Ankara, Turkey

### ARTICLE INFO

#### Keywords:

Miniaturization

Coating

Electro discharge machining

Laser

Grinding

Hybrid

### ABSTRACT

Mechanical micromachining is considered as a cost-effective and efficient fabrication technique to produce three dimensional features and free-form surfaces from various engineering materials. Micro cutting tools are an essential part of mechanical micromachining and they are exposed to harsh conditions which reduces tool life and adversely affect the economics of the process. The challenge is therefore to maintain the tool rigidity and cutting edge sharpness for extended period of time. Thus, the design, fabrication and durability of micro cutting tools are of significant importance for successful micromachining operations. This review paper aims to provide a comprehensive understanding about the capabilities, characteristics, and limitations of different fabrication techniques used in the manufacturing of micro cutting tools. State-of-the-art micro cutting tool design and coating technology has been presented for various micromachining applications. Possible future research direction and development in the field of micro tool design and fabrication has also been discussed.

### 1. Introduction

The miniaturization trend in recent years across many industries such as aerospace, automotive, microelectromechanical systems (MEMS), optics, electronics, biotechnology, and communications requires manufacturing of small parts having micro scale features [1–4]. There are numerous key advantages of miniaturization from both manufacturer and customer perspectives, including portability (which reduces the risk of sample contamination and problems due to mishandling for users of analytical devices), disposability, heat transfer enhancement due to high surface to volume ratios, lower cost of raw material and reduced power consumption [5,6].

In order to realize miniature components, several micro fabrication techniques have been developed. The developed techniques can be classified according to different criteria. In general, they can be divided into two groups [7,8]: micro-system technologies (MST, mask-based fabrication of MEMS(micro-electromechanical system) and integrated circuits) and micro-engineering technologies (MET, tool-based micro-machining techniques). Tool-based micro-fabrication techniques encompass a large variety of processes, some of them have been developed by scaling-down of conventional machining processes such as

micro-turning, micro milling and micro-drilling. These processes are known as mechanical micromachining processes. There are other processes, which are based on non-traditional machining technologies such as micro-electrical discharge machining ( $\mu$ -EDM), micro-electro-chemical machining ( $\mu$ -ECM) or a combination of these processes known as hybrid processes, such as EDM/ECM, ultrasonic assisted EDM (US/EDM), etc. [9]. These techniques have been emerged as a promising technology for the fabrication and realization of miniaturized components from different engineering materials. These processes not only eliminate the requirements for very expensive clean room facilities but also leave a smaller environmental footprint by completely eliminating chemical materials such as etching solutions, etc. [9], which makes them economically suitable for the fabrication of small batches or single products and prototypes [10].

Among various tool-based micro fabrication technologies, mechanical micromachining which uses micro cutting tools with diameters smaller than 1 mm [11–13] plays a key role in producing complex 3D micro-features and free-form surfaces with tight dimensional and geometrical tolerances and relatively high material removal rates [14–16]. Although these processes are considered as the scaled-down version of conventional machining processes, the mechanics of machining at

\* Corresponding author.

E-mail address: [perveen.asma@gmail.com](mailto:perveen.asma@gmail.com) (A. Perveen).

<https://doi.org/10.1016/j.jmapro.2018.10.038>

Received 4 December 2017; Received in revised form 29 August 2018; Accepted 27 October 2018

Available online 16 November 2018

1526-6125/ © 2018 The Society of Manufacturing Engineers. Published by Elsevier Ltd. All rights reserved.

micro scale is quite different [17,18] and there are many challenges which should be considered. In micromachining, the uncut chip thickness and the grain size of the work material are usually in the same order of magnitude, the feed per tooth value set in the process may be less than the cutting tool edge radius, and the runout of the tool/tool holder/spindle system may be larger than feed per tooth value. These characteristics of micromachining lead to process uncertainties and deviations from expected process outputs due to so called size effects [19]. The effect of material microstructure must be considered where isotropic and homogeneous material assumptions are no longer valid [14,20]. Polycrystalline material should be considered as heterogeneous and discrete material [21], where elastic modulus and flow stress (deformation resistance) changes with respect to the direction of the cutting edge [22,23].

In mechanical micromachining processes, micro tools are the most flexible part of the micro-cutting system, and they have the lowest stiffness in the whole micro cutting process chain. Their geometry and material properties have a substantial effect on the material removal process, micromachining forces, heat generation, tool wear, surface quality [6], burr formation. These are also considered to be the main drawbacks of the mechanical micro machining process due to tool wear and tool deflection [24] which affects part accuracy significantly. Tool condition monitoring of micro cutting tools is different than conventional tools as it is difficult to identify worn cutting edges or broken micro tools [25–27]. Since the machined micro-features are achieved and realized as a result of a direct interaction between micro cutting tool and workpiece, the quality and accuracy of the machined features are highly influenced by the strength, dimensional and surface quality of the micro tools. The significant influence of micro tool tolerances and process uncertainties are the main factors responsible for the low predictability of micromachining. Therefore, continuous research efforts in design and fabrication of micro-tools have been reviewed in this paper which is considered tremendously paramount in the area of micromachining.

## 2. Applications of micro tools

Due to miniaturization trend, there is an increased demand in fabrication of micro components. Examples of these kind of micro-features could be micro holes for fiber optics, biomedical filter, micro nozzles used in jet engines, micro mould/die either for micro optics or micro-fluidic devices [28]. There are many studies in the literature where  $\mu$ -EDM technique has been used to fabricate tools or electrodes which are employed to create micro scale features. Ravi et al. used block EDM fabricated micro-electrode to manufacture circular, triangular, square micro-holes using micro-EDM technique. Kim et al. [29] has exploited reverse EDM to fabricate multiple electrode which later on used to fabricate micro holes array, channel, grooves using micro ECM technique [29]. Kim et al. [30] also fabricated 3D microstructure like micro hemisphere, micro-channel, micro column using micro ECM milling. Ahn et al. used electrochemical micro-drilling to fabricate 8  $\mu$ m diameter, 20  $\mu$ m thickness hole on stainless steel. Wu et al. [31] also fabricated micro cavity with rectangular and semi-cylindrical island using vibration assisted micro-ECM. Rathod et al. [32] used electrochemical micromachining to fabricate complex micro grooves which may have their application in micro-coolers, micro-reactors, and micro-mixers. Ghosal et al. [33] fabricated micro features of various shape using micro electrochemical sinking and milling. Yong et al. [34] also fabricated microelectrode to manufacture micro holes and microstructure using micro ECM as well as electrochemical milling. Similar investigation is also done by Liu et al. [35] with fabrication of complex structure using micro electrochemical milling. MEMS applications use micro holes to facilitate the passing of wire for the interfacing [36]. Other customized micro-features/shapes, 3D features, channels are also paramount for the applications mentioned earlier. Therefore, these applications inevitably require new fabrication techniques, relevant

machine tools technology, and precision metrology as well as micro-scale tools. In order to keep pace with miniaturization trend of micro scale tools, innovative fabrication techniques need to be explored extensively [37]. Another specific applications for micro-scale parts include micro-channels for lab-on-a-chip devices [2], micro heat exchangers as compact devices for heat transfer enhancement [38], miniaturized gas analysis systems [39], micro-scale rate integrating gyroscopes for navigation systems in aircrafts and guided weapons [40,41], micro-pumps for flow-controlled delivery in micro-fluidic systems [42], micro nozzles for high-temperature jets [1] and micro-cantilevers for scanning tunneling microscopy [43].

## 3. Materials and coatings

Micro cutting tools can be fabricated from different super hard materials including high speed steel (HSS) [44,10], cubic boron nitride (CBN) [45,46], cermet [4], single crystal diamond (SCD) [47] and polycrystalline diamond (PCD) [48–51]. At the first glance, single crystal diamond seems to be the most suitable material of choice for micro end mill fabrication due to its extreme hardness and the possibility to produce very small cutting edge radii (smaller than 100 nm) and consequently reduces machining forces due to smaller minimum uncut chip thickness values, however attritious wear, low fracture toughness and cleavage fracture have been reported as the main drawbacks of SCD cutting tools [52,53]. Furthermore, extremely high hardness of SCD makes the fabrication of SCD tools a difficult task [54]. A second concept for the usage of diamond as a cutting tool material is polycrystalline diamond (PCD) which is mainly fabricated by high-pressure/high temperature sintering process [55]. Due to the presence of cobalt as a binding phase in PCD, it has a superior toughness, or resistance to chipping. Another important advantage of PCD is that, it is isotropic without the crystal orientation dependent cleavage of single crystal diamond [56]. Owing to its high hardness and strength, PCD is extremely difficult to be machined by mechanical methods, especially for feature sizes smaller than 100  $\mu$ m [57]. Very low G-ratio (the ratio of the volume of material removed from PCD to the volume of material removed from the grinding wheel) is the characteristics of PCD grinding [58], which further hinders its widespread application as a material for micro tool fabrication. Additionally, the reactivity of diamond in both SCD and PCD and its chemical-thermal degradation when machining transition metals such as iron or nickel limits their application to the machining of nonferrous materials only [59]. The limitations associated with the use of PCD and SCD, have pushed the industry to use cemented tungsten carbides as the most common material for micro tool fabrication. Consequently, most of the micro cutting tools available in the market are composed of cemented tungsten carbide with cobalt as a binder which is fabricated using powder metallurgy technique [60,61]. Therefore, widespread acceptance of tungsten carbide as a material of choice for micro cutting tools is mainly due to its ease of processing, ability to machine ferrous and non-ferrous materials along with its hardness over a broad range of temperatures [2].

The fact is that despite the high strength and hardness of micro tool materials, micro-scaled features fabricated by the end mills can easily be damaged because of various reasons such as: brittle nature of tool materials, harsh micro machining conditions; excessive micromachining forces due to the ploughing of the material ahead of the cutting tool as a result of large effective negative rake angle and large cutting edge radius to uncut chip thickness ratios along with inefficient design and fabrication. Therefore rapid tool degradation and even catastrophic failure is almost unavoidable [62]. When machining soft and ductile materials, the adhesion and accumulation of materials at the rake face of the cutting tool may result in clogging the micro-sized flutes, which eventually results in high cutting forces and force spikes, and therefore a drastic reduction in tool life [63]. For micro milling of difficult-to-cut materials the major process constraints are unpredictable tool life and premature failure of micro end mills [44].

Therefore, depending on the characteristics of workpiece materials, different tool failure mechanisms may be involved including fatigue, chip clogging and excessive stresses due to different wear mechanisms [44,64,65]. In micromachining, all of the aforementioned factors which results in a difference between an up-sharp tool and the used tool is referred to as “wear” [44]. Tool wear is quite critical since it dictates the accuracy of the machined parts and achievable tolerances, surface roughness and micromachining cost [12]. In order to overcome such issues of tool wear and failure associated with micro cutting tools, Takacs et al. [66] proposed coating of micro cutting tools which enables longer tool life and improved cutting performance. It is expected the coating to reduce the friction coefficient, adhesion, abrasion, diffusion and also act as a thermal barrier.

Several coatings have been successfully exploited so far for macro-scale cutting tools; including TiN, TiAlN and CrN. Since microscale cutting differs from conventional cutting from several aspects such as forces, temperature and strain rate, the protection mechanism of coatings is influenced differently by such process conditions [12] making tool wear and failure mechanisms complicated [44]. It has been mentioned by Yang et al. [67] that for micro cutting tools the conventional coating techniques may not be applicable, because some of the defects that could be negligible for coating of macro-tools can have a detrimental effect on the performance of the micro cutting tools. Two typical issues affecting the coating quality of micro end mills are droplets and coating defects at the cutting edges as shown in Fig. 1 [68]. The creation of droplets is considered as an inherent disadvantage of arc based deposition technique such as arc-PVD processes [69]. These small droplets or defects when placed at the cutting corners can cause considerable failure of coated micro cutting tools because of the local loss of the coating adhesion [70]. An example of droplets bounded to the coating surface can be seen in Fig. 1. Reducing the size and density of droplets on the surface of the coatings for micro cutting tools can be considered as an important technological challenge. Another important technological challenge in the coating process of micro cutting tools is to apply the coating evenly around the cutting edges [12]. The increased edge radius due to the applied coating is also of significant importance. The increased cutting edge radius will result in larger micromachining forces, larger effective negative rake angle and can promote ploughing dominant cutting.

According to Torres et al. [62], having the potential of eliminating the many of the restrictions hindering the performance of micro end mills and their operational life, diamond coating can be considered to be a promising coating for micro end mills. This is mainly due to the unique physical and tribological properties of diamond coatings such as extreme hardness which increases the resistance to abrasive tool wear,

low coefficient of friction which results in a reduced cutting forces, and chemical inertness and low adhesion which prevents built-up edge (BUE) formation and clogging of the flutes [71]. However, poor adhesion between diamond coating and substrate due to strong catalytic effect of the cobalt (binder phase) in the substrate is considered as the main limitation of the CVD diamond coated tools [72]. Additionally, the large thickness of the conventional microcrystalline diamond (MCD) coatings ( $> 2 \mu\text{m}$ ) results in an increased cutting edge radius, which in turn changes machining mode to ploughing dominant cutting, and as a result machining forces increase. The increased machining forces adversely affect the cutting process as well as tool life and may promote premature tool failure. To overcome these issues, Torres et al. [62], investigated the performance of hot-filament chemical vapor deposition (HF-CVD) of nano-crystalline diamond coatings during micro machining of 6061-T6 aluminum alloy by a 0.3 mm two flute micro end mill. The results of their micromachining experiments revealed that with lower wear rate the tool integrity can be dramatically improved making it possible to achieve a significant reduction in the cutting forces (50%), and adhesion of aluminum to the diamond-coated micro tool can be prevented. Similar results has also been reported in the micro milling experiments conducted by Heaney et al. [71] with the same workpiece material and cutting tool specifications.

In a study conducted by Aramcharoen et al. [12] five different coatings (TiAlN, CrN, TiN, TiCN, and CrTiAlN) achieved by reactive closed field unbalanced magnetron sputter ion plating on 500  $\mu\text{m}$  diameter ultra-fine grain tungsten carbide two-flute flat micro end mills has been investigated and their machining performances are tested during micromachining of hardened H13 tool steel with a hardness of 45 HRC. Their measurements revealed that TiCN has the lowest friction coefficient of 0.16, while the highest friction coefficient of 0.46 has been reported for TiN. For all coating materials, edge rounding and edge chipping has been reduced compared to uncoated tool. TiN has shown the best performance in terms of edge chipping and minimum flank wear, while delamination has been observed in CrN and TiC coatings. In another study conducted by Kim et al. [73], a hybrid coating system which combines sputtering and arc ion plating (AIP) is used to deposit CrCN, CrSiN, and CrSiCN. A maximum hardness of 45 GPa has been achieved for CrSiCN coatings with silicon content of 9.2 at. %. Their results showed that during micromachining of brass with 0.2 mm micro end mill, CrSiCN and CrSiN have the best resistance to wear. A bi-layer coating (SiC + diamond) is synthesized by Hei et al. [72] on 0.8 mm diameter cemented carbide micro end mills and used for dry micromachining of aluminum alloys. Their results indicated that SiC as an interlayer, successfully suppresses detrimental effects of cobalt through some chemical reactions leading to the formation of cobalt silicide. Table 1 shows the application of different coatings for micro milling of different workpiece materials. It is completely evident from the given classifications that uncoated tools have been used almost as extensive as coated micro end mills. Also, it is clear that, among different coatings for micro end mills, TiAlN is shown to be the most commonly used coating, which has been used for a wide range of materials having different hardness, mechanical and thermal properties. Another important fact which is worth mentioning here is that plenty of publications in the field of micro machining lack of detailed information about coating technique, coating thickness, hardness, etc. This makes the comparison of performance of different coatings a difficult task. Therefore, for future researches in the field of micromachining it is quite necessary to include more details about the micro end mills coating. Additionally, it can also be seen that there is no systematic guideline to select a suitable coating for specific workpiece materials.

#### 4. Design methodologies

According to Li et al. [107] and Aurich et al. [15] an efficient micro end mill design needs to accomplish various, partly conflicting requirements. It must:

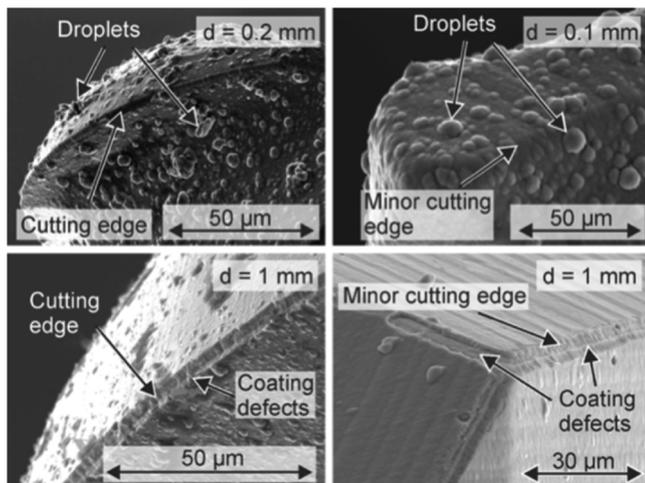


Fig. 1. Droplets and defects at the surface and edges of the micro end mills after PVD coating [68].

**Table 1**  
Application of Coating materials.

#	Coating Type	Coating Technique	Workpiece Material
1	Diamond	CVD [74,75], HFCVD [71]	Single Crystal Silicon [76], ZrO <sub>2</sub> Ceramic [74], ZrO <sub>2</sub> [75], Al 6061-T6 [71]
2	DLC	(PECVD) [77]	Inconel 718 [77]
3	TiNAl	Not Reported [78,79], PVD [80]	AISI 1045 steel [78], austenitic stainless steel (X5CrNi18-10) [80], AISI D2 (~62 HRC) Hardened Steel [79]
4	AlTiN	RPDCUMS PVD [80,81] Not Reported [28,44,82–91]	Nimonic 75 [88], super duplex stainless steel (UNS S32750) [92], Ti-6Al-4 V [44,93], Inconel 718 [81], AA 6262-T6 [82], hardened high-speed steel (S6-5-2, 63 HRC) [83], polymer polymethyl methacrylate (PMMA) [84], austenitic stainless steel (X5CrNi18-10) [80], crown glass [85], soda-lime glass [86], Nickel-Chromium stainless steels (JIS SUS304, ISO X5CrNi18-10) [87], NiCrBSiFe coated AISI M2 high-speed steel [56], PM X190CrVmo 20, 52 HRC [89], H13 Tool Steel [44], Rochling 2316 (Pre-hardened steel-s 32.5 HRC) [90], Sintered tungsten–copper composite [91]
5	TiAlSiN	RPDCUMS	Ti-6Al-4 V [93]
6	AlTiN/Si <sub>3</sub> N <sub>4</sub>	PVD [81]	Inconel 718 [81]
7	CBN	Not Reported [46]	Ti-6Al-4 V [94], Single Crystal Silicon [46]
8	TiN	PVD [80]	austenitic stainless steel (X5CrNi18-10) [80]
9	TiSiN	Not Reported [95]	AISI P20 (29 HRC) [95], AISI H13(45 HRC) [95]
10	AlCrN	PVD [80]	austenitic stainless steel (X5CrNi18-10) [80]
11	CrN	PVD [80]	austenitic stainless steel (X5CrNi18-10) [80]
12	Uncoated		Brass [66], temper-grade steel [66] carbon steel [66], Ti-6Al-4 V [93,94,96–103], Nimonic 75 [88], Inconel 718 [81], Hardened A2 tool steel (62 HRC) [104], Unhardened A2 tool steel (annealed) (15 HRC) [104], Cold work tool steel (X155CrVmo12-1, 50 HRC) [79], Aluminum 7075 [105], AISI 1015 Steel [105], Aluminum alloy (RSA 6061-T6) [106], Inconel 718 [77], Invar 36 steel alloy [43]

- **RPDCUMS**: Reactive pulsed direct current unbalanced magnetron sputtering.
- **PVD**: Physical Vapor Deposition; **CVD**: Chemical Vapor Deposition; **DLC**: Diamond Like Carbon.
- **HFCVD**: Hot filament chemical vapor deposition; **PECVD**: Plasma enhanced chemical vapor deposition.

- Have a high stiffness to reduce the amount of tool deflections and minimize the risk of chatter.
- Have sharp edges with elevated strength to avoid chipping, to reduce ploughing effects and improve tool life.
- Prohibit contact with the side walls of the workpiece having a flank geometry.
- Have a simple geometry, so that it could be manufactured easily and accurately in an economically feasible way, since complex features cannot be realized accurately on the micro end mills.
- Allow for good chip formation, removal and evacuation.

In addition to the above-mentioned requirements there are some key factors which are necessary to be taken into account in the design phase of micro end mills. The first important key design factor for micro cutting tools is the tool size, which defines the minimum achievable feature size of micromachining and thus determines the length scale of the process [11]. Commercial micro tools are designed based on the scaling down of macro-scale cutting tools which makes the cutting edge corners the weakest part on the tool [107]. According to Huo [11], conventional two-fluted micro-milling tools are available in diameters between 100  $\mu\text{m}$  and 1 mm, while single-fluted type micro-milling tools are available in diameters in the range of 25  $\mu\text{m}$  and 100  $\mu\text{m}$ . A common feature of all available conventional micro tools is their identical geometry obtained by scaling down of macro-scale end mills. A similar situation exists in the academic side of research in the area of micro-tool design and fabrication, and limited researches are reported in this area, where simple geometries are fabricated and used for micromachining without too much attention into geometric optimization of cutting tools to achieve better tool performance. Therefore, design and fabrication of new cutting tool geometries based on the knowledge of interaction between cutting tool and workpiece at micro-scale seems to be a challenging task. Successful implementation of mechanical micromachining for high precision manufacturing purposes requires high performance, high precision cutting tools with optimized geometries specifically designed based on the requirements of certain machining task. To fulfill all these requirements, novel cutting tool geometries and highly efficient and accurate fabrication methods are always the major requirements. The knowledge about the interaction between micro cutting tool geometry and workpiece material, stress levels being developed during material removal and performance measures and robustness characteristics of the micro tools are among the factors which

need to be identified when designing efficient micro cutting tools. It is known that, when micromachining ductile materials positive rake angle is preferred in order to reduce the cutting forces and promote shearing dominant cutting, whereas negative rake angle is used for machining brittle materials. For instance, large negative rake angles are helpful in ductile mode micromachining of silicon, where there is a possibility of forming metallic phase during cutting process due to the high hydrostatic pressure associated with large negative rake angles.

In the literature, different methodologies have been implemented for the design of various cutting tools. In a study conducted by Cheng et al. [48] a micro end mill with straight cutting edges has been designed. The stiffness and natural frequencies of cutting tools with different rake angles have been identified by using static and dynamic finite element analysis. Their designed straight edge micro end mill has been shown in Fig. 2 from different views. Their FEM results showed that small rake angles resulted in increased tool stiffness and reduced tool wear. The negative rake angle has been used by Cheng et al. [49] to design micro ball end mills for micromachining of hard and brittle materials. They also showed that, the negative rake angle not only makes ductile mode machining possible but also increases the strength of the cutting edge.

A systematic finite element analysis of cutting tools with various geometries (commercial two flute, triangular and D-shaped) (Fig.3) has been carried out by Fang et al. [108] in order to study tool failure modes and improve tool life. The results of their FE analysis revealed that the stiffness of a two-flute end-mill is 8 times weaker than tapered triangular shaped micro tools and 12 times weaker than a tapered D-shaped micro end mill. Although these increases in the stiffness by introducing a taper angle is quite promising, however it should be mentioned that straight walls cannot be machined using tapered cutting tools, which restricts their use for specific applications. The experiments of Fang et al. [108] also revealed that D-shaped end-mills are capable of producing feature sizes smaller than 50  $\mu\text{m}$ . Recently, straight D-shaped and helical D-shaped micro tools have also been used by Reichenbach et al. [109] to produce micro channels on thermo-plastic polymethyl methacrylate (PMMA). The results of their study showed that axial and radial runout are more influential than increasing cutting speeds to obtain better surface roughness and minimize burr formation. Although D-shaped micro end mills have shown to be quite promising, however, zero clearance angle is the major shortcoming of these kind of micro end mills which may result in accelerated

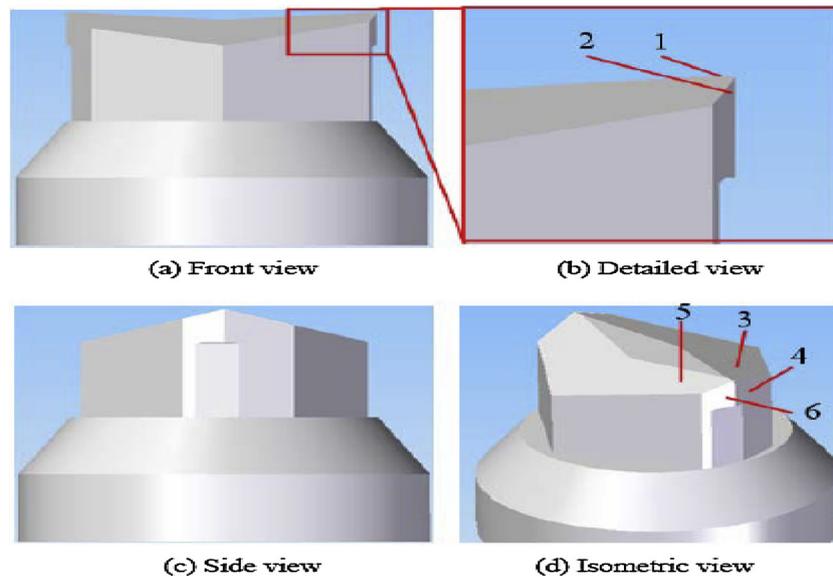


Fig. 2. Straight edge micro end mill designed by Cheng et al. [48]. (1) Bottom cutting edge; (2) Side cutting edge; (3) Axial rake face; (4) Radial rake face; (5) Axial clearance face; (6) Radial clearance face (with the kind permission from Springer).

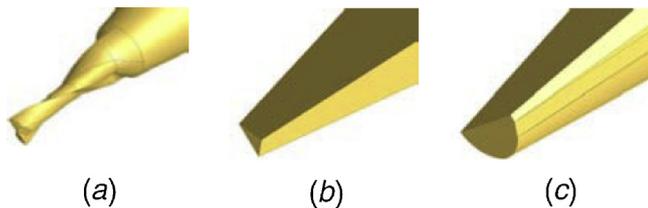


Fig. 3. Micro end mills with various geometries : (a) Two-flute micro end-mill, (b) triangular shaped micro end mill with a tapered body and (c) D-shaped micro end mill with a tapered body [108]. (with the kind permission from Iopscience).

tool wear and increased micromachining forces. Therefore, the geometry of D-shaped tools can be further modified by removing some materials from its bottom face and side walls to create a clearance angle without significantly reducing its stiffness. This approach has been used by Yan et al. [110], where a relief angle of  $30^\circ$  is machined on the side wall of a D-shaped micro end mill of  $50\ \mu\text{m}$  in diameter. Their tool is designed to have a rake angle of  $0^\circ$ , a bottom clearance angle of  $10^\circ$  and edge inclination angle of  $7^\circ$ .

Uhlmann and Schauer [89] carried out a load analysis on commercial micro end mills using finite element method (FEM). The tools are used to machine tool steel (PM X190CrVMo 20) with a hardness of about 62 HRC. The main idea in their investigation was to reduce the length of the cutting portion of the tools, thereby eliminate the influence of helical flutes on the tool stability. In their study, they came into a conclusion that inappropriate tool design was the main cause of low reliability of the commercial micro tools. Based on the results of FEM analysis and experiments, they came up with an innovative tool design with optimized under-neck length and diameter. As it can be seen in Fig. 4, for optimized tool design, the bending stresses have been reduced about 30%. Their experimental results have also confirmed a longer tool life of about 10% for the optimized design, which is not as significant as expected, meaning that in addition to bending stresses other factors are also needed to be taken into account. Oliaei and Karpat [18] also used finite element method to analyze tool deflection and failure of commercial two flute micro end mills of  $0.8\ \text{mm}$  diameter. In their study, the transverse rupture strength (TRS) is used as failure criterion. Their results showed that finite element model is capable of producing results in a good agreement with the experimental observations as depicted in Fig. 5.

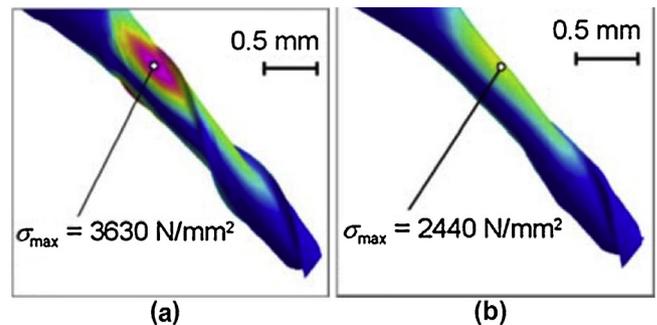


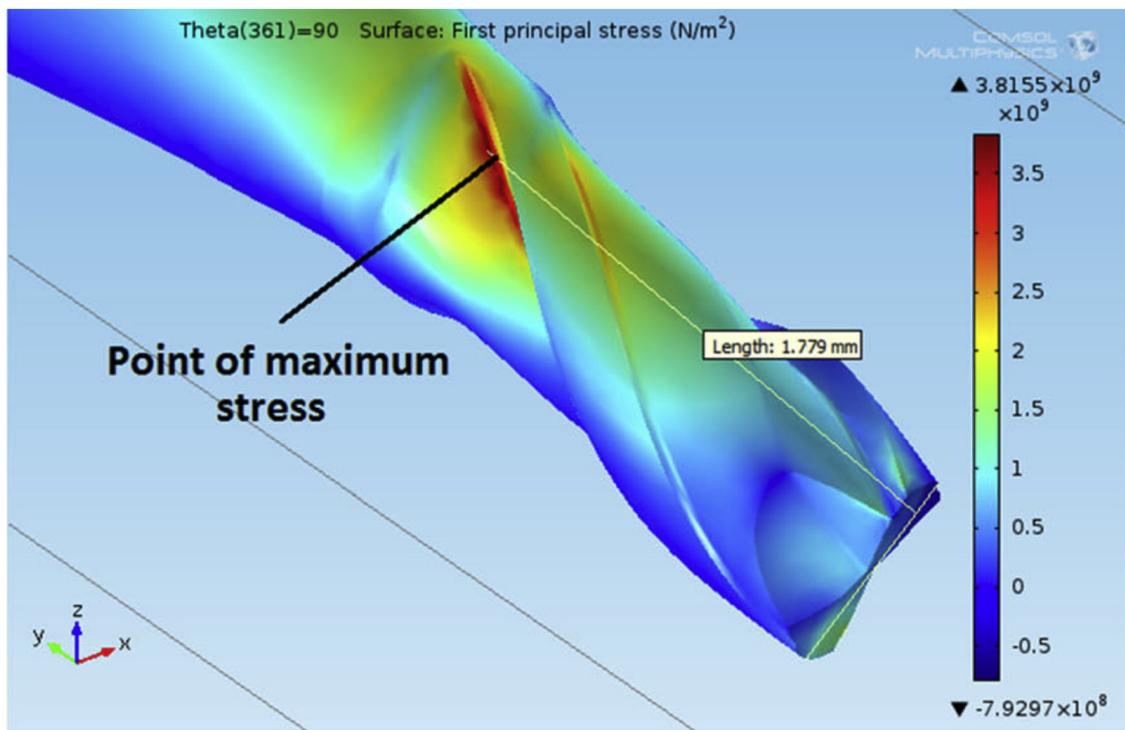
Fig. 4. (a) Conventional, (b) Optimized micro-end mills [89] (with the kind permission from Elsevier).

Li et al. [107] used analytical modeling and finite element analysis to improve micro tools stiffness and strength. They showed that a larger neck angle, negative rake angle and optimized tool core geometry are needed to achieve this goal. They also set some guidelines to redesign micro end mills, including increased stiffness to avoid bending and chatter, cutting edge corners strengthening to avoid chipping at initial stage of the machining, using simpler geometries for ease of fabrication and compensation for runout by proper tool design. Fig. 6 illustrates micro end-mills designs proposed by Li et al. [107] together with a commercial micro end mill.

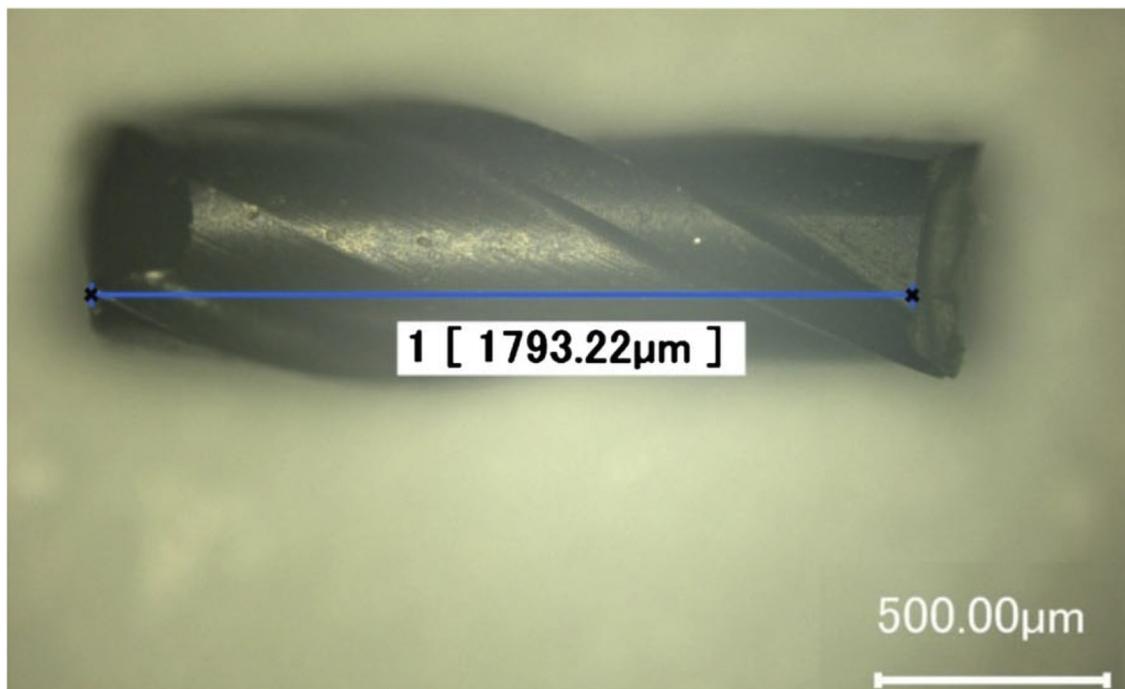
In order to eliminate the effect of tool runout, a single-edge geometry has been proposed by Fleischer et al. [111] to guarantee perfect adjustment of the micromachining process parameters such as lateral infeed and feed per tooth values. The stability of three different geometries depicted in Fig. 7 has been investigated. Their findings revealed a 30% higher stability for the semi-circular geometry (geometry 3 of Fig. 7) when compared to the trapezium-shaped geometries (geometry 1 and 2 of Fig. 7), meaning that due to the smaller deflection of the third geometry, more accurate machining can be achieved.

Oliaei and Karpat [58] also designed a single-edge cutting tool for micromachining of titanium alloy as depicted in Fig. 8. They exploited WEDM to fabricate micro tools with controlled surface and edge radius values and to promote built-up edge formation. In their study, the protective effect of built up edge (BUE) has been explored during micro machining of Ti6Al4V titanium alloy.

It can be seen that, the publications in the field of micro tool design



(a)



(b)

Fig. 5. (a) Maximum principal stresses on two flute commercial micro end mill predicted by FEM, (b) Broken micro end mill and its measurement [18].

are focused on different issues. Uhlmann and Schauer [89] have been concentrated on the bending stresses and optimization of tool geometry in terms of under neck length and diameter; Li et al. [107] have been focused on cutting tool cross-section optimization and tool wear, Oliaei and Karpat [58] have been focused on tool runout elimination and built-up edge (BUE) promotion. The work of Fang et al. [108] addresses stiffness issues and ease of manufacturing, while the work of Fleischer

[111] devoted to the elimination of tool runout. Table 2 provides brief summary of the work reported in the literature. It can be seen that, there is no systematic approach for designing micro-cutting tools. Hence, it is essential to develop a systematic approach for micro cutting tool design which takes into account various aspects and challenges concerning micro tools. It seems that, tailoring micro-end mills based on the requirements of particular machining operations in terms of

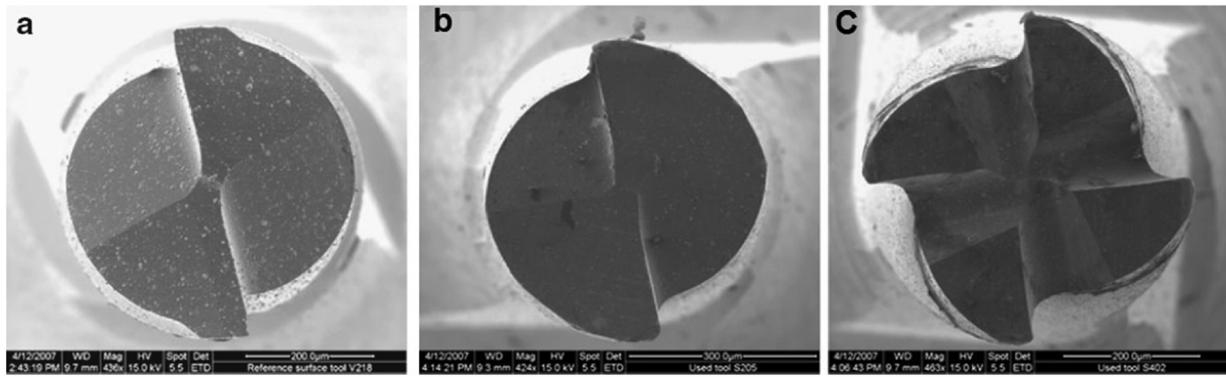


Fig. 6. (a) Commercial micro end mill, (b) newly designed two-flute micro end mill, (c) newly designed four-flute micro end mill [107] (with the kind permission from Springer).

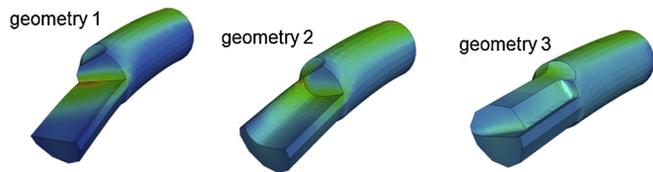


Fig. 7. FE simulation of different micro cutting tool geometries designed by Fleischer et al. [36]. (With the kind permission from Springer).

workpiece material properties, machining strategies and part dimensional and surface quality requirements will be a necessary step for designing novel micro cutting tools in the future. Table 2 shows the summary of the literature done in this area.

5. Fabrication techniques

Micro tool fabrication is the most important part of realization of micro tools for micromachining applications. Successful fabrication demands for a thorough understanding of design requirements and specifications such as tool diameter, cutting edge radius, number of edges, tool geometric specifications (rake and clearance angle) and tool materials along with the capabilities, characteristics, advantages and limitations of different fabrication techniques. In the selection of fabrication method for mass scale used, in addition to design requirements, the reliability and economic feasibility of the process need also to be considered, however for the sake of research novelty, cost aspect can be ignored. The subsequent sections are devoted to the various fabrication techniques which are used for the realization of micro cutting tools. These fabrication technologies include, EDM, Focused Ion beam

machining, Laser machining, Mechanical machining, Hybrid machining.

5.1. EDM-based techniques

Electro discharge machining uses electro-thermal energy to remove material and experiences no cutting force due to its noncontact nature. It has the advantages of removing material regardless of material hardness. Therefore, EDM has been a preferred fabrication technique for difficult-to-machine materials since its invention. Non-contact nature of the process also gives extra advantages when it comes to the fabrication of downscaled tool. During EDM; voltage is applied to the gap between electrode and workpiece, depending on the gap distance, electric field breaks down the dielectric properties of the oil and series of sparks start moving as plasma between the electrodes. The temperature of the plasma can go as high up to 10,000 °C which melts the materials from both electrode and results in the formation of crater on both electrodes. Dielectric flush helps removing this debris from the machined area and starts preparing for the next cycle during the spark off time.

Ravi et al. [113] was the first to propose block EDM method to fabricate symmetrical electrodes for the application of array of different shape micro holes. As per this method, a piece of rectangular metal block is used along with indexing facility to fabricate electrode. For fabrication of square electrode, the cylindrical tool electrode is fed against the block along z axis and change the orientation of the tool to 90° using indexing attachment. This change of orientation will repeat three times to finish the four faces of square tool. Using similar method, triangular tool is produced (120° orientation of tool) with tool rotation. Since this method uses multi-pass machining strategies to remove

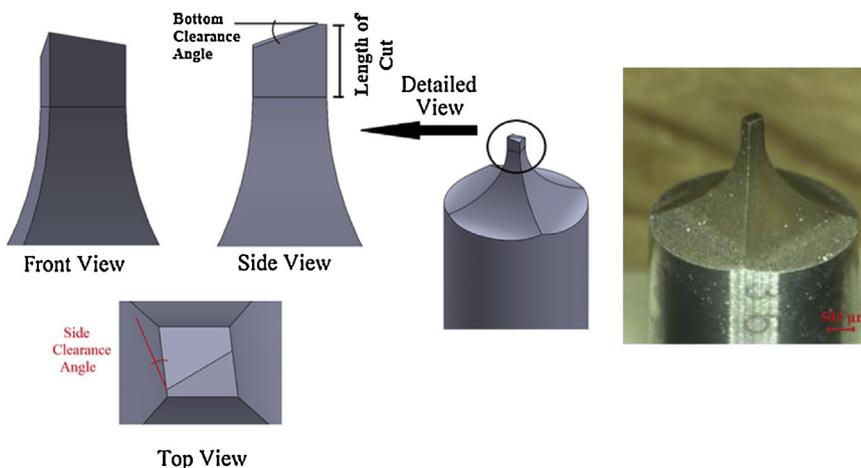


Fig. 8. Single edge micro end mill designed and fabricated by Oliaei and Karpap [112].

**Table 2**  
Summary of micro-tool design.

Tool design	Optimization target	Techniques used	Results
Cheng et al. [49], micro end mill with straight cutting edges	Stiffens, rake angles	Static & dynamic finite element analysis	Small rake angle causes increased stiffness and reduced tool wear, negative rake angle improves strength of cutting edge
Fang et al. [108], commercial two flute, triangular, D- shaped tool	Tool failure mode & improved tool life	Finite element analysis	Two flute tool is 8 times weaker than tapered triangular tool and 12 times weaker than tapered D shaped tool. D shaped tool experience accelerated tool wear due to zero clearance angle.
Uhlmann and Schauer [89], micro-end mill	Innovative tool design with optimized under neck length and diameter	Finite element analysis	30% reduction in bending stress, 10% increase in tool life
Oliaei & Karpat [18], commercial two flute micro end mill	Tool deflection and failure	Finite element analysis	Experimental observation of failure matches FEM results
Li et al. [107], commercial micro end mills	Stiffness & strength	Analytical modeling & Finite element analysis	Larger neck angle, negative rake angle and optimized tool core geometry assist in better stiffens
Fleischer et al. [111]	Tool runout	Finite element analysis	Single edge geometry tool assists in proper adjustment of lateral infeed as well as feed per tooth
Oliaei & Karpat, [112], Single edge cutting tool	Promote built up edge formation	Tool design & experimental analysis	Micro tool with controlled surface and edge radius promotes built up edge formation during Ti alloy micro machining

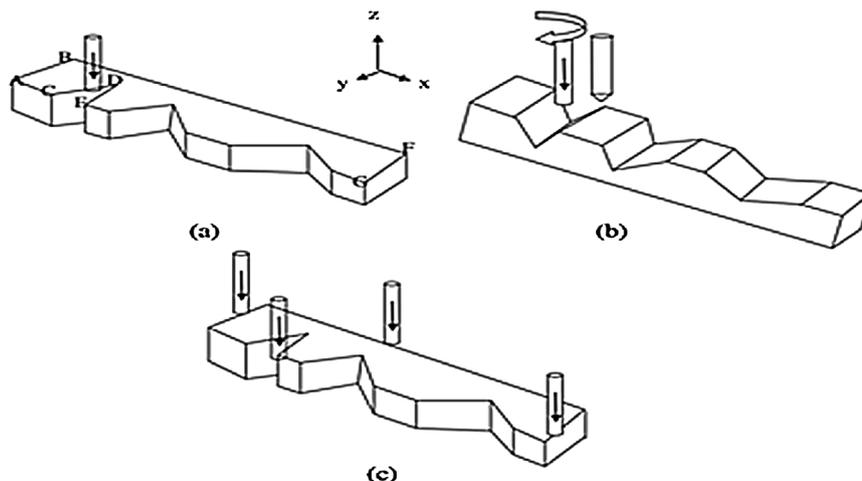
material, it is especially suitable for fabrication of microscale electrodes of few tens of micron. In addition, proposed method also reduces the chances of electrode breakage.

Perveen et al. [114] designed and fabricated special block (Fig. 10) containing three V slots using wire EDM for fabrication of different shape tool. Mikrotool multipurpose machine facilitated both wire EDM and block EDM set up in the same machine. The use of different edge and orientation of this specially designed block made it possible to fabricate circular, D- shaped, triangular, tapered and square shape tool as shown in Fig. 9. This method eliminated the indexing attachment used by Ravi et al. Examples of fabricated tools are presented in the Fig. 10. Perveen et al. [115] also studied tool wear associated with these fabricated tools. Their study used acoustic emission signal to monitor tool condition in order to decide tool dressing requirement. This kind of micro tool, loses their shape and therefore become unfit to continue machining process well before it reaches to its end of life. Dimensional variation in the machined part acts as an indication for stop using the tool for further machining.

Oliaei et al. [58] reported on the fabrication of PCD planarization tool with pyramid pattern using micro WEDM (30  $\mu\text{m}$  tungsten wire). Fig. 11 presents the fabrication technique and the fabricated tool. Extremely low discharge energy was used during the fabrication, which facilitated lower surface roughness of 120 nm. This fabricated PCD tool was exploited successfully later on for ductile mode silicon grinding to remove subsurface damage originating from earlier machining.

Masuzawa et al. [116] proposed the principle of wire electro

discharge grinding (WEDG) (Fig. 12a). The advantages offered by this process are possible geometric modification and miniaturization of the tools. As this process uses a moving wire (diameter of 50–200  $\mu\text{m}$ ), the machined area is always exposed to fresh wire which reduces the effect of wear during machining. Fleischer et al. [117] implemented this principle and fabricated the end mills (Fig. 12b) using brass wire of 100  $\mu\text{m}$  with the travel speed of 15 mm/min. Using NC coding, initially the bottom of the milling tool was reduced, following that diameter of the end mill was reduced from 0.3 mm to 0.1 mm. Next step was to machine to reach d-shape end mill. Finally, the clearance angle of 10° was machined at the end of milling tool. Average surface roughness of 60 nm was obtained using machining process parameters of 80 V and stray capacitance. Morgan et al. [118] also fabricated cylindrical PCD tool using similar technique for glass machining. Dong-Yea Sheu et al. [119] proposed twin-wire EDM system where resistance capacitance circuit is combined with Transistor electro discharge circuit for facilitating rough and finish machining simultaneously using same machine. With this new EDM system, precise micro-tool can be fabricated which also reduces fabrication time two third of conventional WEDM. On another study, Kim et al. [29] fabricated array of WC electrode using reverse EDM techniques. These array of electrode is useful in fabrication of micro holes array or micro-structure using micro-ECM techniques which does not suffer much from tool wear aspect, thus increasing the efficiency. Yamazaki et al. [120] also proposed another simple EDM technique to fabricate micro-tool using self-drilled hole (as shown in the Fig. 13). Micro-rod with negative polarity is used to fabricate hole using



**Fig. 9.** Schematic diagram: (a) Fabrication of PCD triangular micro tool using a dedicated fixture, (b) Tapered micro tool fabrication using a dedicated fixture at different orientation, and (c) The orientation of the fixture for fabricating D-shaped and square micro tool [114] (with the kind permission from Springer).

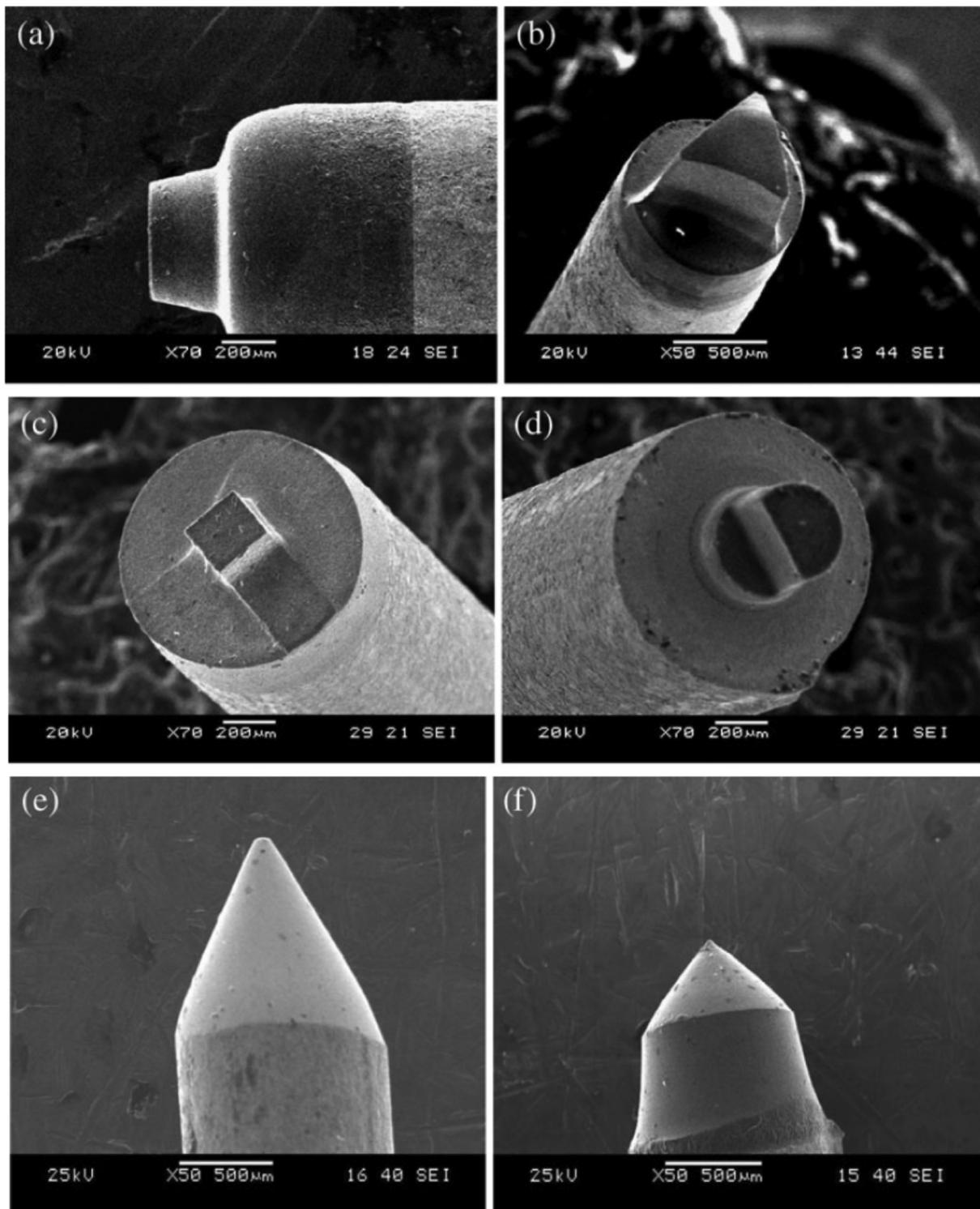


Fig. 10. (a) Circular micro tool, (b) triangular micro tool, (c) square micro tool, (d) D-shaped micro tool, (e) tapered micro tool of  $60^\circ$ , and (f) tapered micro tool of  $90^\circ$  [114] (with the kind permission from Springer).

micro EDM. In the second step, same tool with reversed polarity is off centered and fed downward inside the hole to create straight rod electrode without causing wear in hole outlet but the inlet. This new technique offers advantage of not requiring the adjustment of initial point over other conventional method thus increases machining efficiency.

According to Oliaei et al. [58] the relative motion of the workpiece (micro tool) with respect to the wire electrode is quite challenging when using WEDG process to fabricate micro ball end mills. This is

mainly because the wire diameter and tool size are of the same orders of magnitude, consequently the wire curvature can cause some inaccuracies in the fabricated ball end mill geometries. In an attempt to compensate for wire curvature, Oliaei et al. [58] modified the tool trajectory to produce micro ball end mills. Their results showed that by the developed trajectory, accurate micro ball end mills can be produced by WEDG process. The same issue with WEDG has also been reported by Masaki et al. [121]. They mentioned that the fabrication of precision spherical tool for using micro shape grinding requires high precision,

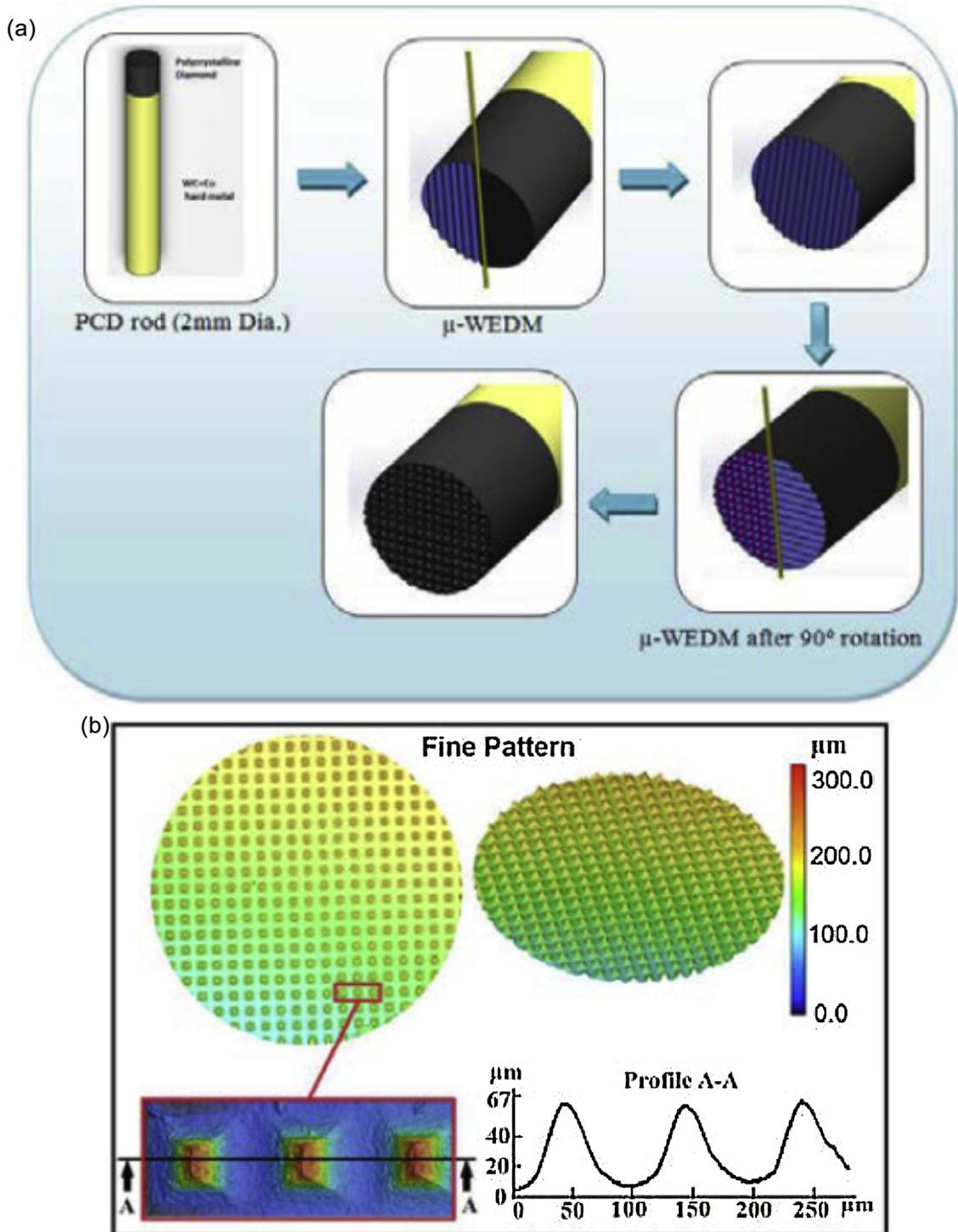


Fig. 11. (a) Tool Fabrication steps (b) Fine patterned planarization tool [58] (with the kind permission from Elsevier).

and it is extremely difficult when using WEDG process. They used a precise tungsten carbide pin gauge (precise diameter and straightness) as a sacrificial electrode to form spherical shaped PCD tools. In this process, a rotating PCD blank follows a cylindrical shape machining path along the pin gauge in order to fabricate spherical PCD tool.

In another study by Oliaei et al. [122], micro end mills of various geometries are being fabricated by a multi-processing approach which combines block-EDM and WEDG techniques (Fig. 14). They studied the effect of EDM input parameters on material removal rate (MRR) and surface roughness. Their fabricated micro end mills have been successfully used for micromachining of fused silica and silicon.

The possibility of applying micro wire electro-discharge machining ( $\mu$ -WEDM) to fabricate dual helix cutting tools has been studied theoretically by Cheng et al. [123]. To do so, they built a mathematical model between tool and wire. As a result of their mathematical analysis, they came into a conclusion that for fabricating such complex geometries six axes machines are necessary. The graphical representation of their simulation is illustrated in Fig. 15. Although their proposed solution and six axis machine tool configurations seem to be promising and shows a great potential for fabrication of micro tools with complex geometries, their concept has not yet been experimentally verified. An accuracy analysis method has been proposed by Cheng et al. [124] in

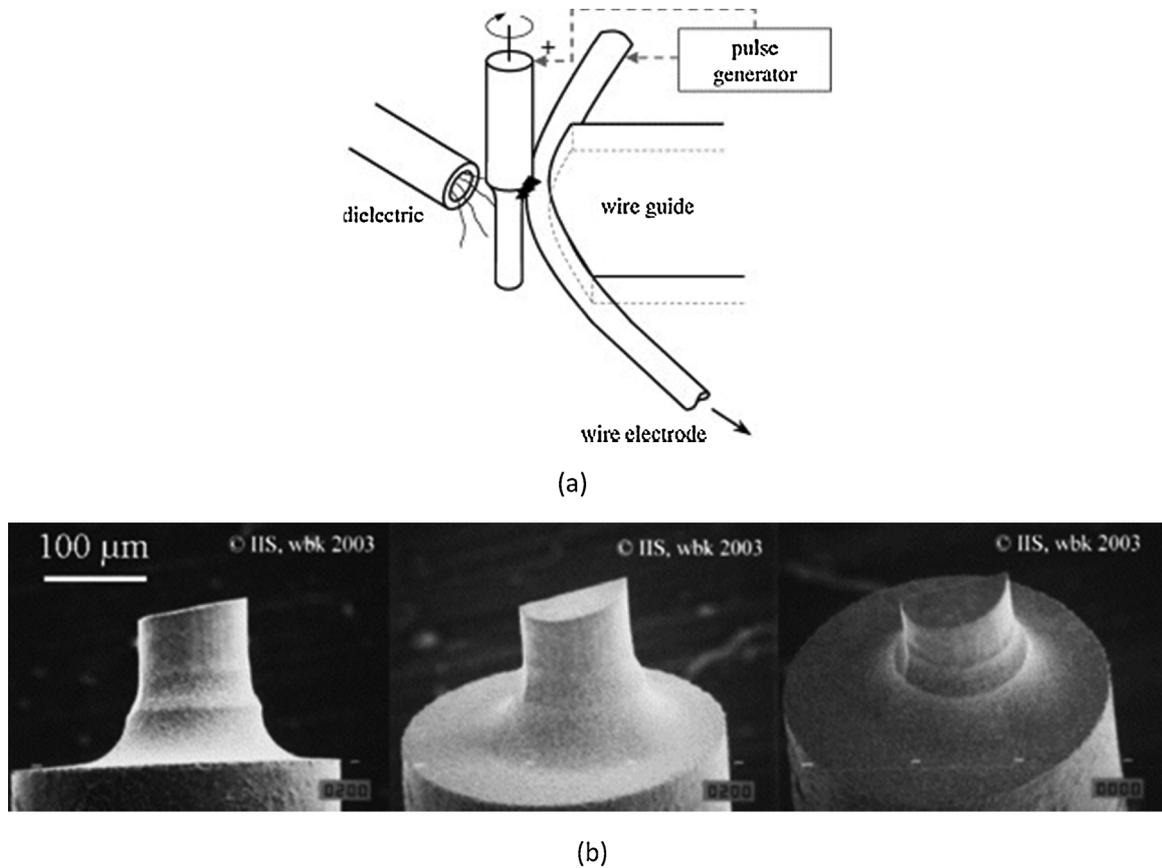


Fig. 12. (a) Principle of WEDG. [116] (b) WEDG Machined 100 μm Tungsten carbide End mills [117](with the kind permission from Elsevier).

the fabrication of super finish ball end mills (SFBs) and micro ball end mill with uniform rake angles in axial cross-section (URB) by kinematic modeling and analysis of WEDM process. The results of their kinematic analysis revealed that SFBs cannot be realized since they require a

simultaneous five-axis CNC WEDM machine tool for their fabrication, while URBs has been fabricated by a simultaneous three-axis CNC WEDM machine. Their fabrication accuracy analysis showed that higher geometrical accuracies can be achieved by appropriate design of

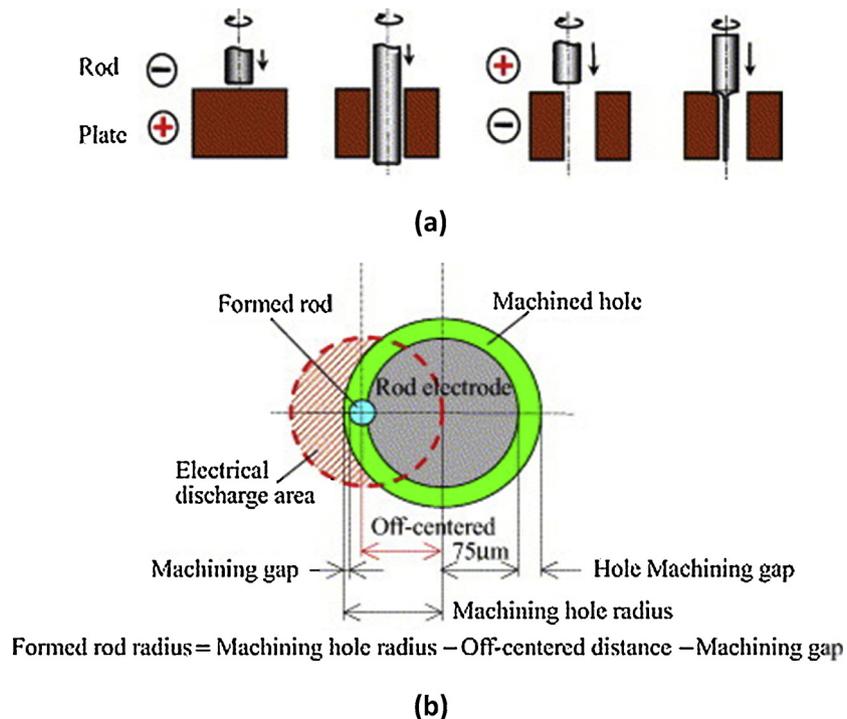


Fig. 13. (a) Principle of obtaining micro-rods(b) Off-centering concept chart [120].

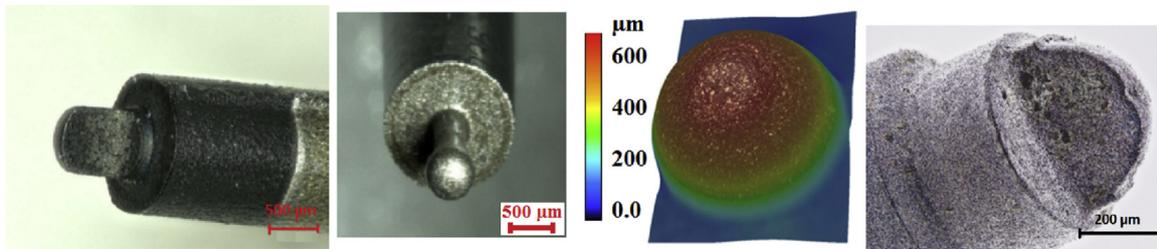


Fig. 14. Fabrication of ball end mills and Lollipop end mill by Oliaei et al. [122].

micro cutting tool geometries and by arranging the corresponding fabrication procedures accordingly.

Recently Oliaei and Karpat [125] designed a polycrystalline diamond micro end mill with a hexagonal geometry having a parallelogram shape featuring a large negative rake angle on the bottom of the tool. The micro end mill has been fabricated by WEDM process and used for micromachining of single crystal silicon. With their proposed geometry (Fig. 16) a fourfold increase in critical depth of cut has been achieved. They also used the same approach [51] to design and fabricate a PCD mechanical planarization tool capable of ductile-mode machining of silicon as depicted in Fig. 16(c). In their study, in order to decrease the area between the tool and the work material without introducing a negative rake angle, some changes have been made. Firstly, the number of edges are increased which, decreases the contact between the tool periphery and the workpiece. In addition, the profile of the slots between edges is modified so that a V-shaped channel is produced. This modification further decreases the surface area between the tool and the workpiece at the bottom of the tool.

As an improvement of WEDM method, Yao Sun et al. [126] proposed low speed wire electrical discharge turning (LS-WEDT) along with multiple cutting strategies for fabrication of micro-tools. Principle of LS-WEDT is explained in the Fig. 17 with respect to LS-WEDM method. Authors reported successful fabrication of D-shaped as well as spiral micro tools using proposed method which offers better geometric accuracy compared to WEDG due to non-existence of wire deflection as a result of gravity.

A single edge 0.2 mm in diameter PCD micro end mill has been designed and fabricated by Nakamoto et al. [127] using a custom-made 6-axis WEDM machine as shown in Fig. 18 and has been used for micro milling of tungsten carbide. A preconditioning has been performed after certain machining period and is shown to have a significant role in

improving surface quality. Their results revealed that after certain amount of machining the machining mode has been changed from milling to micro grinding due to the creation of wear lands on the cutting tool. Tool wear is shown to have no detrimental effect on surface quality.

A three step multi-processing approach which combines WEDM, WEDG and  $\mu$ -EDM processes has been used by Morgan et al. [128] to fabricate micro end mills from PCD (Fig. 19(b) & (c)), which are used to machine grooves in soda-lime glass and pockets in ultra-low expansion (ULE) glass. The WEDM process is used to cut tool blanks of 1 mm in diameter from PCD blanks. The diameter of tool blanks is reduced to about 50  $\mu$ m using WEDG process followed by  $\mu$ -EDM using a sacrificial block electrode to improve the geometric accuracy of the cutting surface. PCD micro tools are shown to produce a surface roughness of 0.3 nm and a flatness of 1.5  $\mu$ m over a length of 500  $\mu$ m.

Gao et al. [129] have tried to optimize WEDM process parameters for rough and finish cutting of PCDs. For rough cutting peak current and voltage pulse width are found to be the dominant WEDM process parameters while for finishing operation the peak current and peak voltage are shown to be the most important parameters affecting the machining speed. Using optimum parameters, they fabricated a quadrilateral PCD micro milling tool as depicted in Fig. 19. Although the authors didn't report the diameter of the fabricated micro cutting tool, however they reported a cutting edge radius of 6.7  $\mu$ m. EDM fabrication summary are provided in Table 3.

## 5.2. Focused ion-beam machining

Focused Ion beam machining (FIB) as a Micro/Nanofabrication process which uses accelerated ions to remove surface atoms of the workpiece [146] which can be used for micro-tool fabrication. It can be

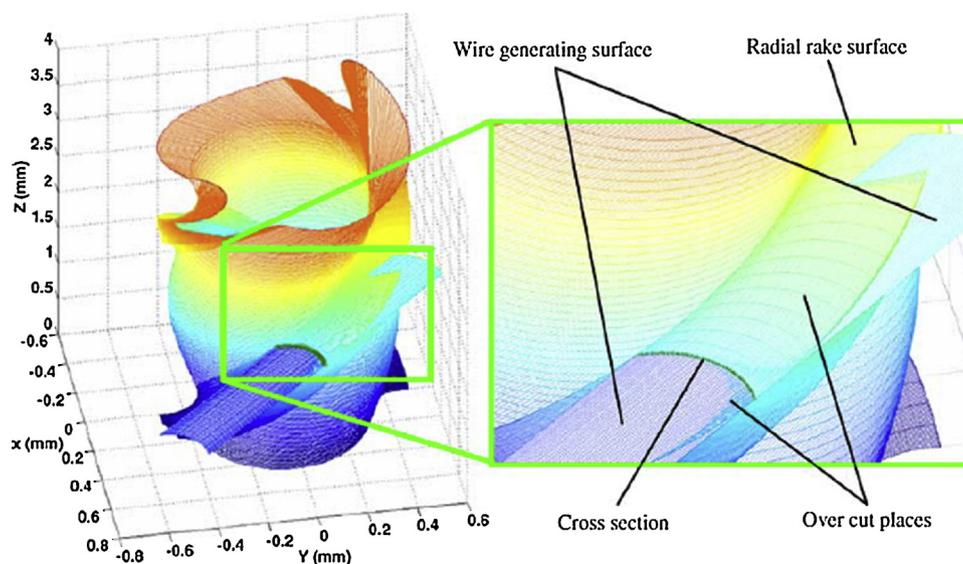


Fig. 15. Simulation of micro-tool fabrication by micro-wire EDM process [36] [123] with the kind permission from Springer).

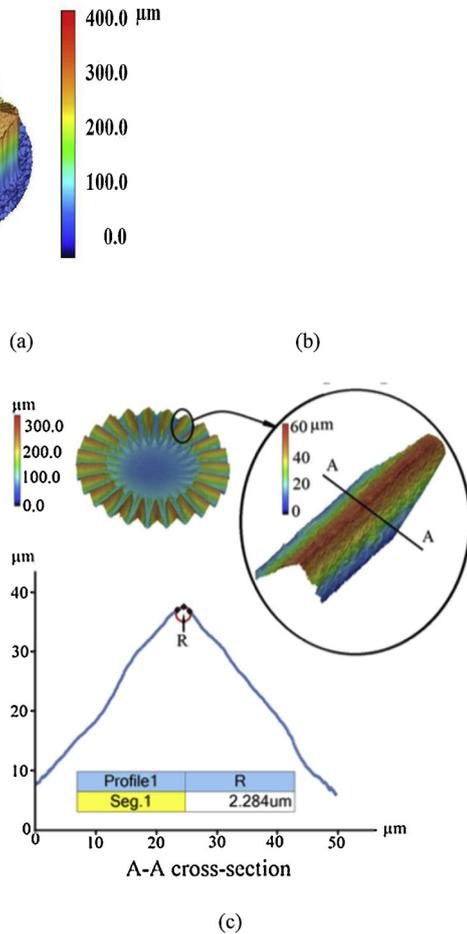


Fig. 16. Micro end mill designed and fabricated by [125], Oliaei and Karpat, (a) Solid Model; (b) Fabricated micro end mill (c) Mechanical planarization tool [51].

considered as a compound platform with ion beam of tens of nanometer in diameter as a cutting tool and an imaging microscope with a nanometer resolution for positioning. In a study conducted by Adams et al. [95], focused gallium ion beam is implemented to fabricate micro cutting tools with a diameter of 25  $\mu\text{m}$  having different cutting edge numbers of 2, 4 and 5 cutting edges on micro grain tungsten carbide. They managed to obtain very sharp cutting edges with an edge radius of 0.1  $\mu\text{m}$ . Vasile et al. [147], also used FIB to produce micro end mills of 25  $\mu\text{m}$  diameter using high speed tool steel. Examples of micro end mills produced by FIB are shown in Fig. 20.

An important advantage associated with FIB process is its ability in producing very sharp cutting edges, with edge radii in the order of nanometer. This edge sharpness can last for a long time when using single crystal diamond, but it can be easily worn out in materials like cemented carbide. On the other hand, in applications requiring very small edge radii, FIB process should be preferred, however creating nanometer scale edge radii in tungsten carbide and similar materials seems to be unfeasible, because of the accelerated wear of the tool at the initial stages of the machining. Although, high resolution and high accuracy can be considered as the main advantages of the FIB process, however, a very low material removal rate is a major limiting factor for FIB, which limits this fabrication process being used only for fabricating micro cutting tools with diameters less than 100  $\mu\text{m}$  [95].

### 5.3. Laser beam machining

In the application of laser for fabricating micro tools, several distinct aspects such as laser parameters (laser power, repetition rate,

pulse duration, spot size, etc.), surface integrity, kerf, re-solidified material and graphitization (for the case of diamond-based materials) should be carefully investigated. The laser processing of PCD, tungsten carbide and related composite materials has been studied by Harrison et al. [149] using Nd:YAG Q-switched diode pumped solid state lasers (DPSSL) at different laser repetition rates (10–50 kHz) and pulse width (47–156 ns) using fundamental wavelength of 1064 nm. The cutting mechanism is determined as reactive fusion cutting commonly known as melt, burn, and blow. Li et al. [150] studied the micro machining of PCD using a femtosecond pulsed Nd:YAG laser. They studied the effect of different irradiation parameters on the characteristics of ablated microstructure. Their findings revealed that, low intensity lasers are capable of ablating grain boundaries without damaging diamond grits.

A femtosecond pulsed laser has been used as an efficient processing method for micro tool fabrication from binder less polycrystalline diamond (BLPCD) by Ogawa et al. [151]. A direct conversion sintering method is used to synthesize BLPCD from graphite at ultra-high pressure and temperature without any binder materials [152]. BLPCD has superior mechanical properties when compared to the conventional PCD. Since BLPCD has no conductive binder, EDM-based techniques cannot be used for its processing. The findings of Ogawa et al. [151] revealed that, a circularly polarized femtosecond pulse laser is the most proper choice for successful machining of BLPCD. The use of this laser made it possible to obtain an average surface roughness of 0.022  $\mu\text{m}$  with an MRR of 0.004  $\text{mm}^3/\text{s}$ . They claimed that almost no graphitization has been observed at the surface. A Q-switched Nd:YAG laser (1064 nm, 100 ns, 70  $\mu\text{m}$  spot size) has been used by Everson and Molian [153] in the two-dimensional fabrication of micro tools in a fine-grain PCD. They achieved an MRR of 0.02  $\text{mm}^3/\text{min}$ , kerf (cutting width) of 27  $\mu\text{m}$ , and 3  $\mu\text{m}$  top surface edge radius. When a laser beam interacts with PCD material, the diamond can be transformed into amorphous carbon and graphite. Stress break up of diamond into fine particles may also be observed, which is attributed to several factors such as thermal stresses and the phase transition of diamond and cobalt. An IR YVO4 laser (1 -1.064 mm) was used by Suzuki et al. [154] to fabricate single crystalline diamond (SCD) micro milling tools having three dimensional cutting edges (Fig. 21(a)). Fabricated milling tools are presented in the Fig. 21(b).

Butler et al. [155] exploited ND:YAG Q-switched pulsed laser system along with the indexing rotary stage and fabricated rotary solid grinding wheel made of polycrystalline diamond (Fig. 22). 36 staggered rows of the grinding tool were laser ablated by setting the rotary stage at 10° and with the help of Mastercam X that controls the laser path. Laser parameters used in this fabrication were output power of 100 W, pulse frequency of 50 kHz, lasing wavelength of 1064 nm and focal spot diameter of 40  $\mu\text{m}$  [155].

Eberle et al. [156] demonstrated the laser technique to shape single cubo-octahedral shape diamond grains for engineering grinding tools (EGT) application. Fig. 23 shows the unmodified and modified diamond grain with the help of laser machining. For this purpose, an Nd:YVO<sub>4</sub> diode pumped MOPA laser system with pulse duration of 10 ps is used. As can be seen from Fig. 23, both clearance and rake angle are fabricated in a single diamond grain which reduces the volume of the grain to 50%. Eberle et al. [157] also fabricated drill bit of 150  $\mu\text{m}$  diameter using picosecond laser where the chisel and cutting face are completed in one step. However, this process comes with discretization error such as steps which are quite noticeable from the Fig. 24. Finer Z steps size and objectives with higher numerical aperture could be a solution to get rid of this problem.

With the downscaling of tool size, conventional machining no longer offers economical solution for fabrication of micro tools, especially with the cases when the hardness of cutting materials becomes a hindering factor. Thermal machining has the advantages over conventional mechanical machining in terms of no cutting force generation.

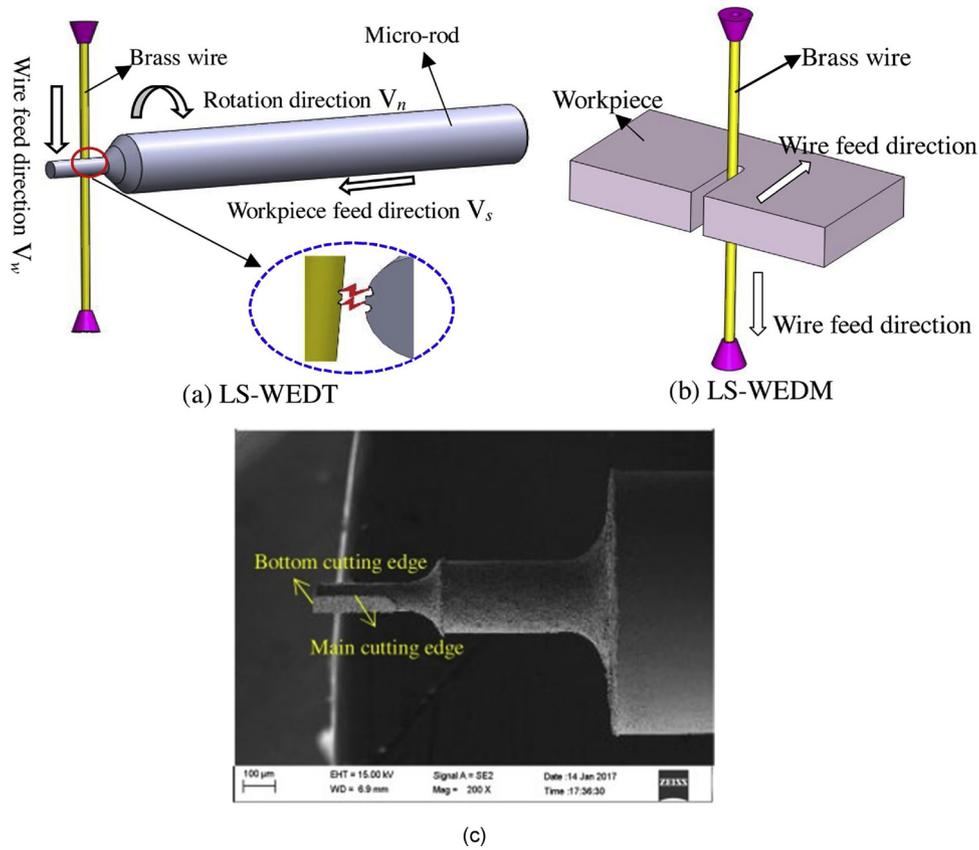


Fig. 17. The schematic diagram of (a) LS-WEDT method and (b)LS-WEDM (c) Fabricated D shaped tool [126].

5.4. Mechanical machining

The most predominant mechanical method of micro tool fabrication is the grinding process, which is widely accepted in the industry, however, on some occasions the grinding process is not considered precise enough to fabricate some micro tools with small diameters and complex geometries [11]. This mainly arises from the fact that in the grinding process, there is a direct mechanical contact between grinding wheel and cutting tool. The induced forces exerted to the cutting tool will result in tool deflections which reduces the grinding precision and may result in tool breakage [110]. These deflections together with grinding wheel wear and heat generation will result in some variations in the dimension of the produced micro end mills. The variability in the diameter of 30 up-sharp tools (0.8 mm nominal diameter) selected from same batch are shown by Oliaei [7] as depicted in Fig. 25 where tool diameters are measured using Keyence VHX-1000 digital microscope (600x magnification). It is worth mentioning that the actual diameter of the micro end mills is generally smaller than the nominal diameter in

order to compensate for possible runout in the tool holder-spindle system. However, there exists a size variation due to the grinding process. Another important issue when using grinding for micro tool fabrication is subsurface damages caused by grinding, which lowers the strength of the end mills fabricated by this method [110]. This issue has also been emphasized by Aoki and Takahashi [158], where they used grinding process to fabricate 25  $\mu\text{m}$  diameter simple oblique-cut mill (SOC mill) from tungsten carbide.

It is shown by Schaller et al. [159] that up to 50% of the micro cutting tools (50  $\mu\text{m}$  diameter, back angle approximately  $6^\circ$ , tip clearance of approximately  $6^\circ$ , and radial clearance of 5–10  $\mu\text{m}$ ) made up of tungsten carbide (ISO-K10) with a grain size of 1–2  $\mu\text{m}$ , were broken during grinding using WINTER diamond grinding wheels (resin-bonded, grade D126/D54/D15). This quite high scrap rate has a significant influence on the cost of micro end mills produced by grinding process. Therefore, as it has been suggested by Huo et al. [11] taking into consideration the probability of micro tool edge fracture and other grinding defects such as large heat affected zone and grinding burns,

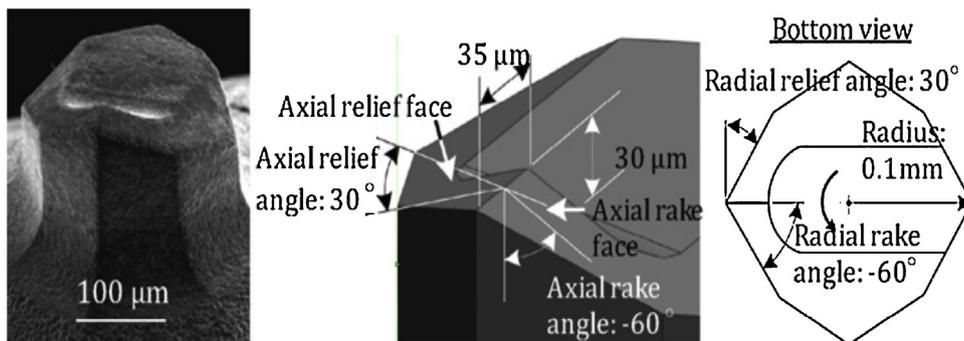
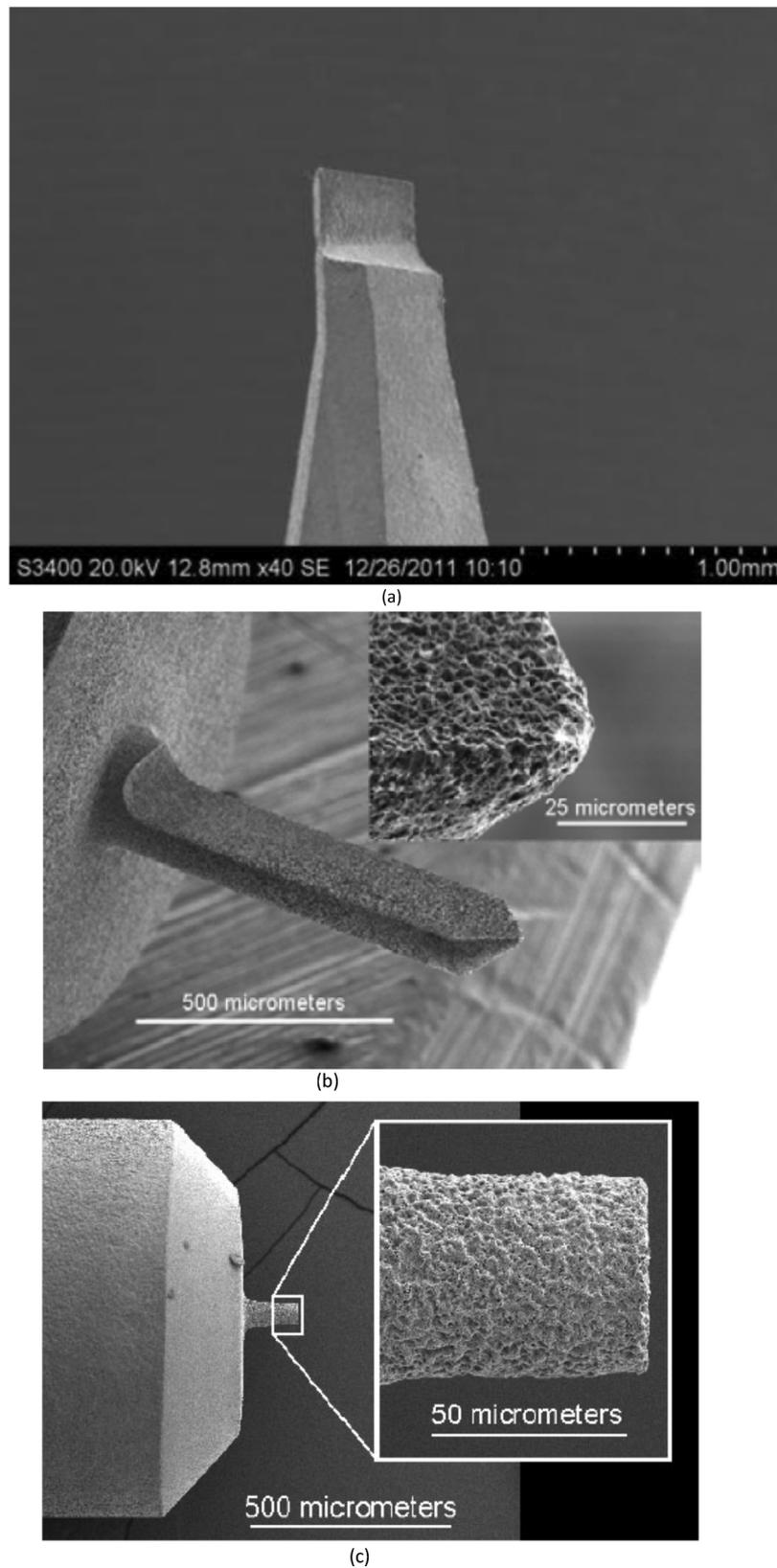


Fig. 18. Custom designed single edge PCD micro end mill by Nakamoto et al. [127].



**Fig. 19.** (a) A quadrilateral PCD micro milling tool designed and fabricated by Gao et al. [129]. (b) A conical tipped PCD micro tool [128] (c) A 50  $\mu\text{m}$  diameter cylindrical PCD micro end mill [128].

reliable micro tool supplier should be carefully selected. It is highly recommended to select carbide micro tools with finer grain size and to use microscopes with high magnifications to inspect the cutting edge geometry. The reason for the selection of smaller grain size is the

increased fracture toughness at finer grain sizes.

Due to the problems arising from mechanical contact during micro tool fabrication, the major concern is to reduce machining forces [160]. In an attempt to reduce grinding forces Onikura et al. [160] efficiently

**Table 3**  
Summary of tool fabrication using EDM techniques.

Type of EDM	Fabricated Micro-tool Material	Dimension of the tool	Application	Remarks
WEDG	Tungsten carbide	Cylindrical & semi cylindrical tool	Micro-ECM with ultrasonic vibration to create micro holes	Semi-cylindrical micro-tool offers higher machining rate as well as precision [130]
Wire EDM	Ultra-fine WC	21 by 21 microns square electrode array	Batch micro-holes on nebulizer	upward batch micro EDM provides better machining time than downward one due to better debris removal [131]
Micro-WEDM plus WEDG	WC	100 microns		Proposed surface roughness prediction model for the fabricated tool [132]
Micro EDM with sacrificial block, rotating disk, guided running wire	99.9% W (Ø0.2–0.5 mm)	High aspect ratio micro tools	Surface Engraving on Al alloy	Rotating disk offers best performance [133]
Micro-EDM with RC & transistor type isopulse generator	Tungsten	20–40 microns		Transistor type along with servo control offers 24 times material removal compared to RC type [134]
Micro-EDM with inchworm feeding system	Red copper	25 microns	micro holes and micro structures on stainless steel & single crystalline silicon	[135] tool aspect ratio of 20 can be achieved due to high accuracy of tool feeding as well as quick response for gap maintenance
Micro-EDM	Tungsten, cemented tungsten, cemented tungsten carbide made of super fine particles (SWC)	2.8–4 microns		SWC with 2.8 micron diameter was achieved [136]
tangential feed WEDG	Tungsten	27 microns electrodes	Array of Micro holes fabrication	Electrode fabrication accuracy less than 2 micron and hole fabrication accuracy $\pm 1.1 \mu\text{m}$ [137]
Twin-wire EDM system, combining TrC and RC electro-discharge pulse generators	WC	0.02 mm micro-electrodes		Machining time can be reduced upto 6 times of conventional machining [138]
WEDG	Tungsten	fabricated tool electrodes: cylindrical, conical, spherical, and bolt-shaped(below 60 micron diameter	EDM micro-grooving on stainless steel	high voltage and a small condenser capacitance is recommended to reduce tool wear [139]
WEDG	cemented carbide	6 microns tool	Micro-hole of 6.7 $\mu\text{m}$ diameter a	Higher feed rate can cause tool breakage [140]
WEDG	Tungsten carbide	31 micron tool	Micro-slot and micro thin-walled structure on Al alloy	Burr formation, can be prevented by minimum the axial engagement and the feed [141]
$\mu$ -WEDM	P type silicon wafer	High aspect ratio Silicon micro electrode 5 mm long 120 $\mu\text{m}$ by 120 $\mu\text{m}$ electrode		5–8 $\mu\text{m}$ recast layer removal by etching results in machined surface without cracks and electrode shape remains same [142].
WEDG	WC, Titanium	series-pattern micro-disk with thickness of 10 $\mu\text{m}$	Micro-slit with the width of less than 10 $\mu\text{m}$ .	Grain size of tool material affect the minimum thickness of fabricate tool due to internal stress state [143].
Turning- $\mu$ EDM' hybrid process and the 'moving-electrode-block- $\mu$ EDM' process	Brass and CuW	Ø: 70 mm, length: 3 mm	high-aspect-ratio micro-holes	Vibration-assisted micro-EDM was found to provide higher-aspect-ratio micro-holes compared to those without vibration [144]
Reverse electrical discharge machining	WC rod	Multiple-tipped micro electrodes. 35 $\mu\text{m}$ in diameter	Array of microholes	Micro-ECM is used for array of micro holes fabrication which suffers literally very low tool wear [120]
wire-EDM	WC	Multiple electrodes cross-section of 100 m and are 5 mm long.	Micro-slots	[145]

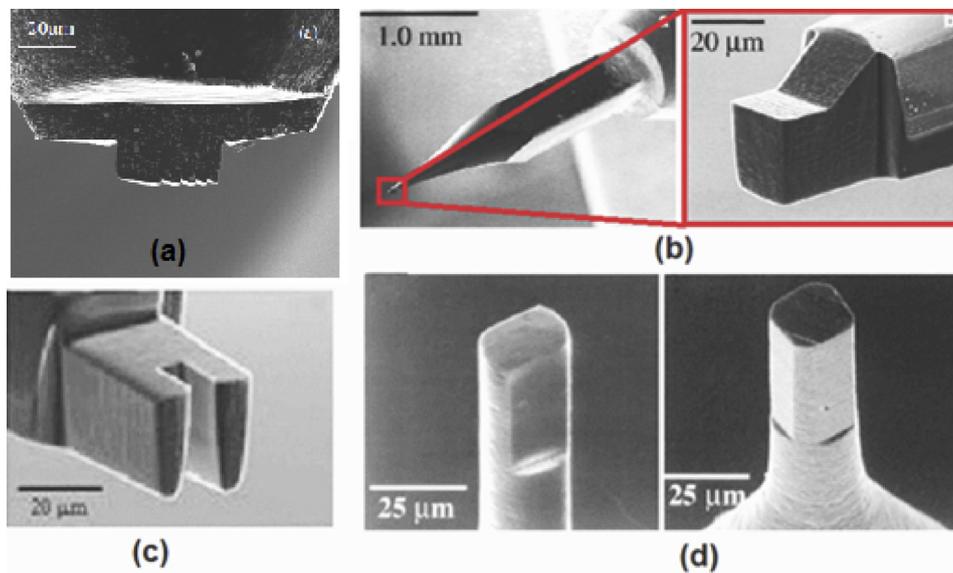
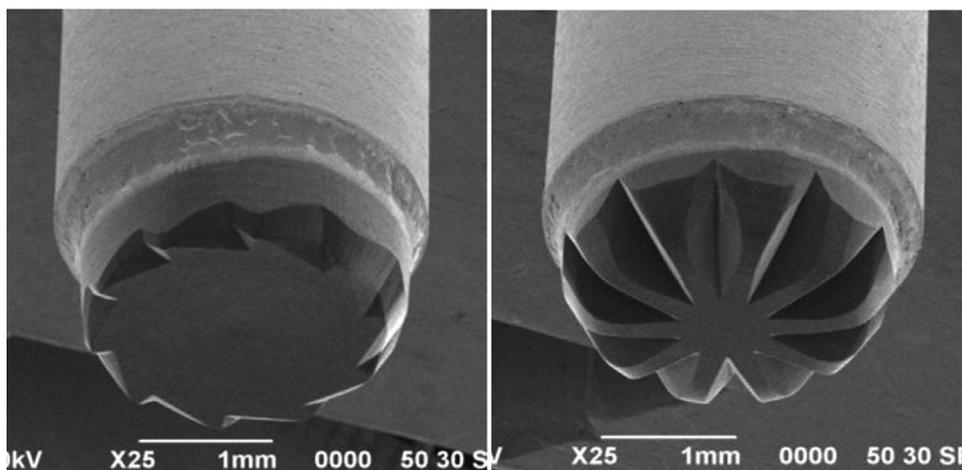
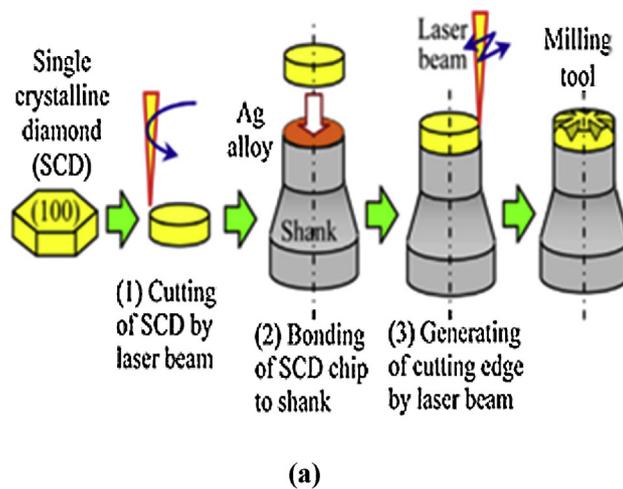


Fig. 20. Examples of micro tools fabricated by FIB process: (a) Xu et al. [77], (b) Wu et al. [146], (with the kind permission from Springer) (c) Picard et al. [148], (with the kind permission from Elsevier) (d) Adams et al. [95]. (With the kind permission from Elsevier).



(b)

Fig. 21. (a) Micro fabrication process for SCD milling tools, (b) SEM images of micro milling tool fabricated by Laser [154]. (With the kind permission from Elsevier).

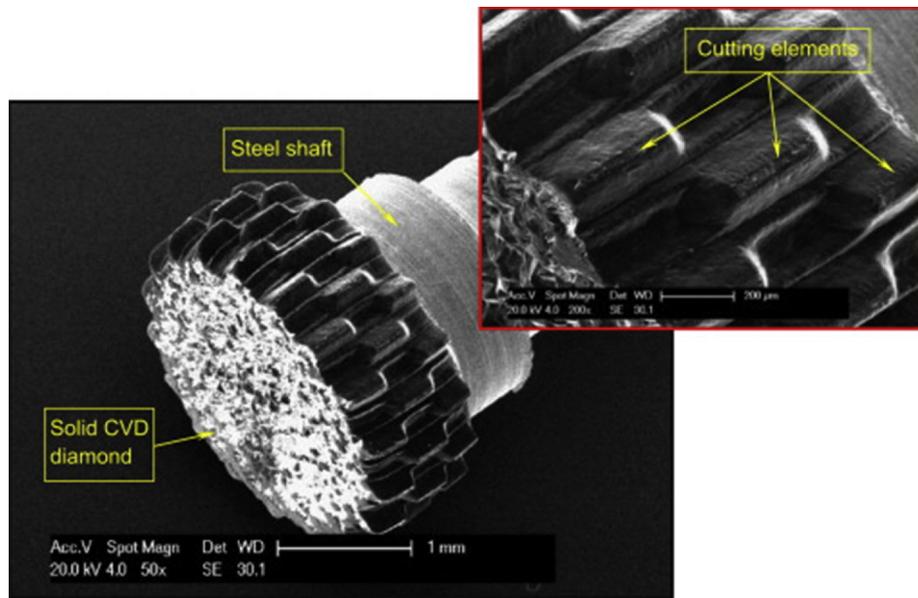


Fig. 22. Unused laser ablated solid diamond micro-grinding tool [155]. (with the kind permission from Elsevier).

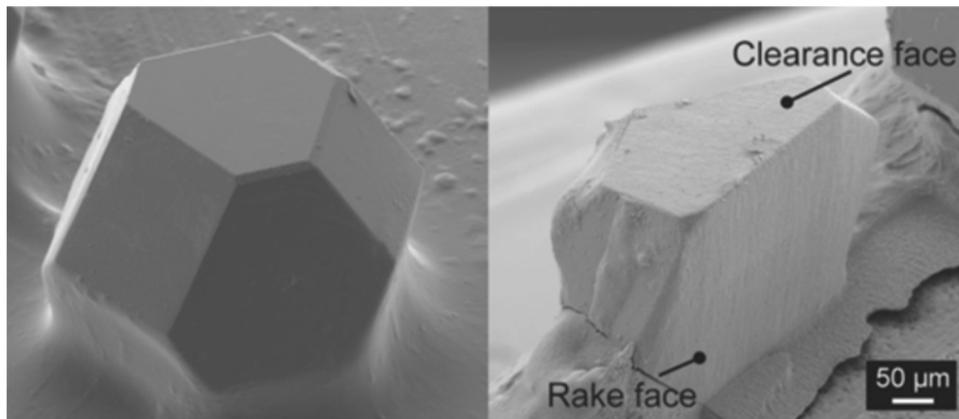


Fig. 23. Diamond grain shaped by laser for EGT applications [156] (with the kind permission from Springer).

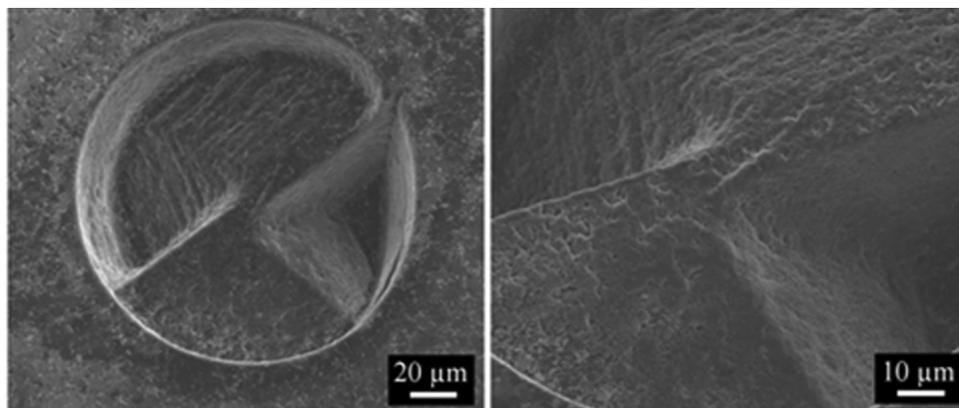


Fig. 24. Prospective drill bits and close up view [157] (with the kind permission from iopscience).

used ultrasonic vibration grinding (75 kHz-0.5  $\mu\text{m}$ ), to fabricate micro cutting tools with diameters less than 100  $\mu\text{m}$  and aspect ratios in the range of 3 to 18. They came into a conclusion that by applying ultrasonic vibrations, it is possible to achieve a 10–20% reduction in the diameter of micro tools and to increase aspect ratio about 50%. These improvements were mainly due to the reduced grinding forces upon applying ultrasonic vibrations. A grinding system equipped with super-

fine abrasive wheels is developed by Ohmori et al. [161] and is used to fabricate ultra-fine micro cutting tools with various geometries as depicted in Fig. 26. Profilometer with resolution of 0.1  $\mu\text{m}$  installed on the machine assists in measuring tool diameter during machining process without taking off the tool from the machine. Therefore, tool with initial diameter of few hundred micrometers can be reduced to final tool with several micrometers of diameter.

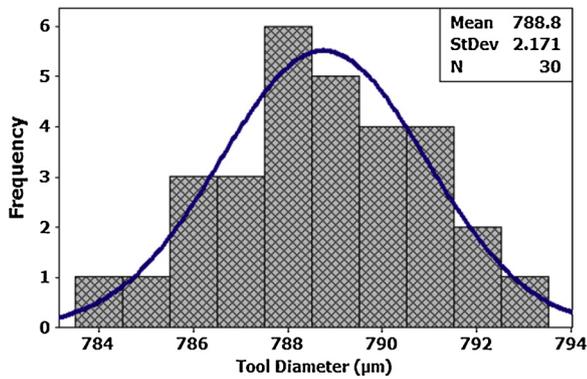


Fig. 25. The measured diameter of 30 up-sharp micro end mills [7].

Aurich et al. [162] made use of the process kinematics of grinding and fabricated customized end geometry micro-end mills. 10 µm and 20 µm tool made of tungsten are fabricated using a desktop 3-axis tool grinding machine having two grinding spindles (pre grinding or fine) as shown in the Fig. 27. The details of the fabricated tools can be seen in Fig. 28. Small cutting edge radius and specific geometry tools facilitate the easy chip formation as well as low cutting force. This fabrication process also has the potential to fabricate tools with different helix angle as well as other shapes like dovetail profile or ball end mills. Liang et al. [163] have used a six axis CNC grinding machine to produce micro conical surface ball-end mills (CSBM) with 500 µm diameter and normal rake and relief angle of 10° and 20°, respectively. In their study, the kinematic principle of the six axis CNC grinding machine has been used to realize micro ball end mills with a diameter error of about 0.26%. CSBMs are used to produce micro dimples on hardened die steel H13. When machining with CSBMs, more stable radial milling forces, stable micro dimple roundness error and improved wear resistance have been observed compared to spiral blade ball-end mills (SBBM). These improvements reveal that by modifying some features of the conventional micro end mills, their performance can be improved significantly.

5.5. Hybrid and multi-process fabrication techniques

There are some limitations associated with traditional machining in terms of micro scale fabrication of tools. The tool life span has been reduced significantly due to the thermal stresses and deformations, and degenerative layer on the fabricated tools associated with this process. Therefore, some hybrid techniques have been proposed to fabricate micro tool. Fabrication of miniature grinding tool from diamond for precision grinding of micro-structure was proposed by Chen et al. [164]. WEDG along with micro-EDM was used to fabricate tungsten tool substrate of 100-20µm external diameter and then Ni(binder), Diamond (cutting edge) were co-deposited on the substrate using

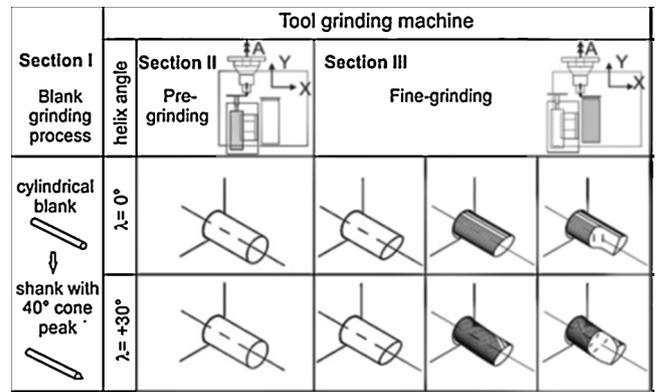


Fig. 27. Schematic representation of the tool fabrication process [162] (with the kind permission from Elsevier).

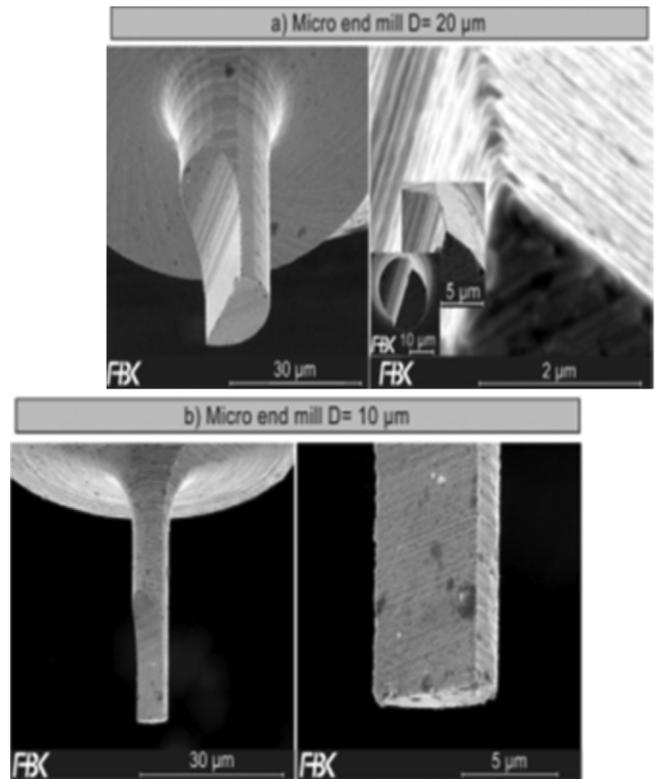


Fig. 28. Micro end mill D = 10 µm and D = 20 µm [162]. (with the kind permission from Elsevier).

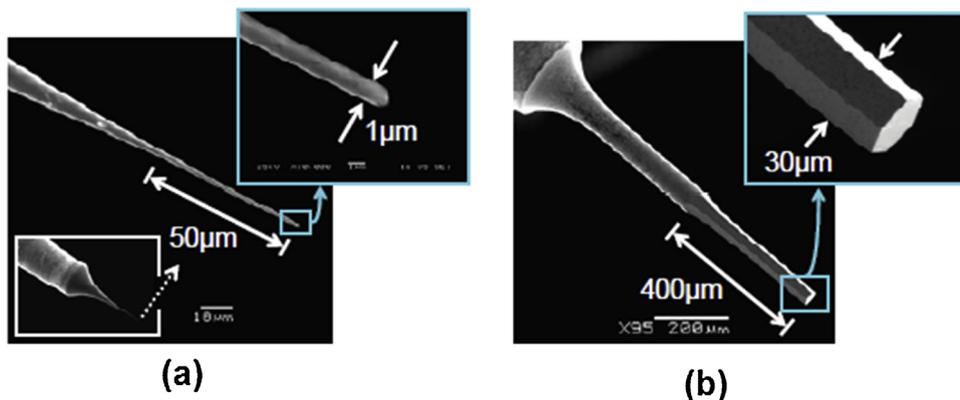


Fig. 26. Micro end mills fabricated by grinding process [161] : (a) Ultra-fine micro end mill, (b) Hexagonal micro-tool. (with the kind permission from Elsevier).

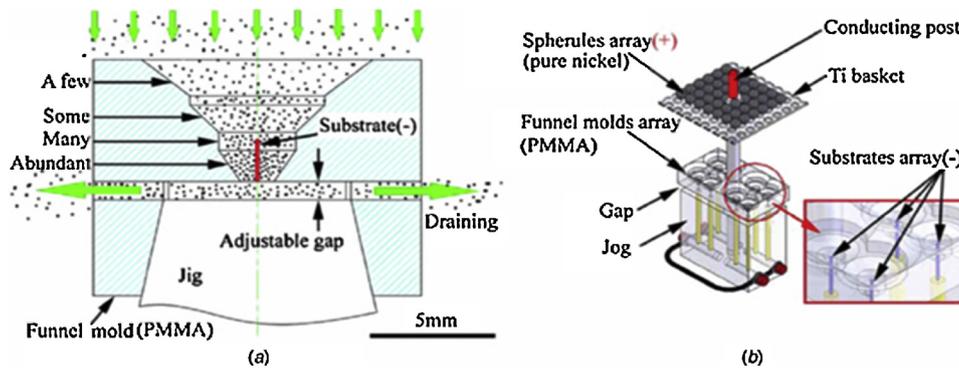


Fig. 29. (a) Miniature funnel mould (b) Array of mould [164] (with the kind permission from iopscience).

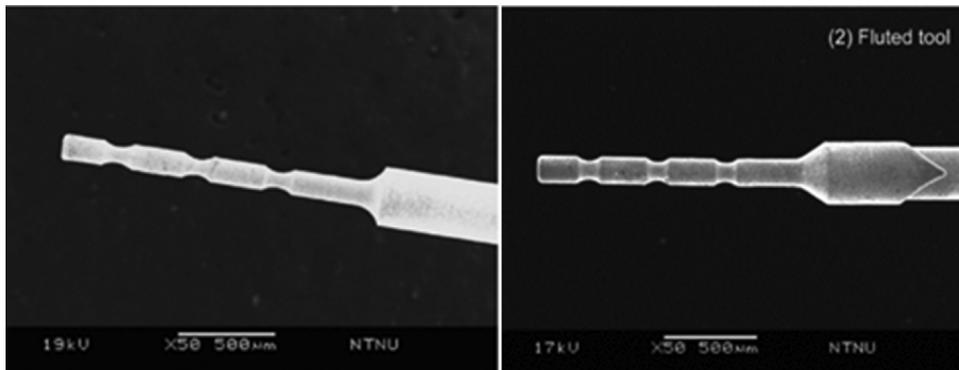


Fig. 30. (a) Tungsten substrate after wire EDG & micro EDM (b) micro tool after co-deposition [164]. (with the kind permission from iopscience).

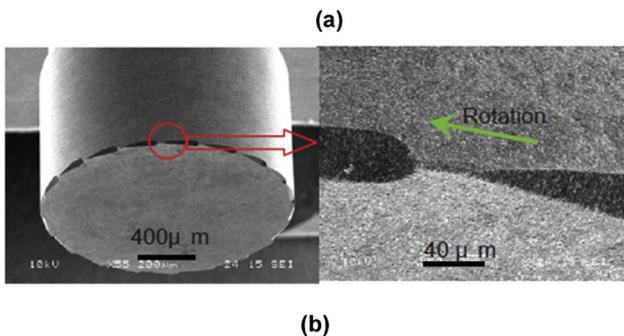
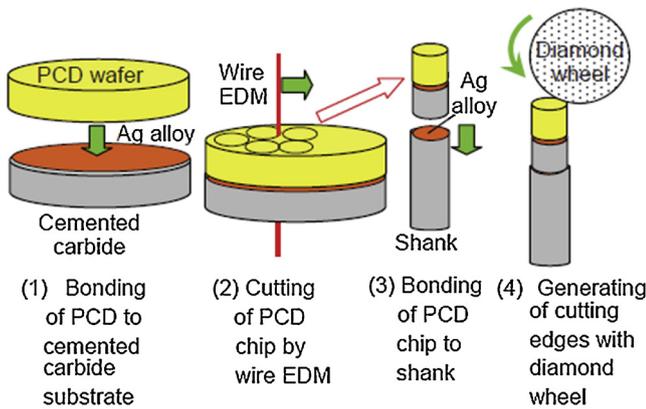


Fig. 31. (a) The process of fabricating micro-milling tool from PCD (b) SEM image of multi-teeth PCD micro-milling tool and its cutting edges [165] (with the kind permission from Elsevier).

electroform technique (Fig. 29). In order to facilitate better deposition of diamond grain, Chen et al. [164] also designed miniature funnel mould. The substrate is placed in the funnel mould which also works as a cathode. Inner tapered hole of funnel helps deposition of increased amount of diamond as it flows from top to down. As a result, probability of diamond deposition on the substrate increases. Moreover, this funnel has the added advantage of separating the unnecessary current from the high current density region which helps reducing effect of point on the cathode. Application of such array of funnel can facilitate the fabrication of several different micro tools with increased efficiency.

Fabricated tool after combined WEDG and micro-EDM plus co-deposition are presented in the Fig.30 [164]. Suzuki et al. [165] developed a micro end mill from PCD for ductile mode machining of ceramic micro aspheric molds and dies. In their study, combined WEDM and diamond grinding technique is used to fabricate micro end mills. WEDM helps to fabricate the cylindrical plain tool from PCD wafer. A multi-tooth PCD milling tool with twenty cutting edges which are obtained by grinding and polishing using diamond wheels and loose abrasives on a PCD rod having the grain size of 0.5 μm being produced as depicted in Fig. 31. Table 4 provides summary of multi-process techniques for tool fabrication.

## 6. Summary

Application of miniaturized products and parts in different industries clearly is pushing the manufacturers towards conducting research in the field of micro fabrication and to adopt newer technologies. This growing field is demanding the change of machine tool technology, metrology, fabrication, cutting tool and coating technologies, since factors such as cutting edge radius, tool run out, material homogeneity at microscopic scale and microscopic defects which are quite negligible at macro-scale are gaining crucial importance in micro-scale. Taking these issues into account this review paper discusses the challenges faced in the micro cutting tool technology which is a major

**Table 4**  
Summary of tool fabrication using hybrid & Multi-process techniques.

Type of process combination	Fabricated Micro-tool Material	Dimension of the tool	Application	Remarks
BEDG process & micro Turning Micro Turning micro EDM hybrid process	PCD insert CuW, Brass	11 $\mu\text{m}$ in diameter 45-19.3 $\mu\text{m}$	Micro holes, 3D micro-features Micro holes machining	[166] [144]
LIGA & micro -EDM	WC-Co	Below 200 $\mu\text{m}$	Micro –mechanical component and micro processing tool	[167]
Vibration assisted micro EDM	Ag-W	50 $\mu\text{m}$ by 50 $\mu\text{m}$ square shaft		Significant reduction of machining time, perpendicular vibration results in shorter machining time than the parallel vibration [168]
WEDM and ECM	tungsten	0.3 $\mu\text{m}$ diameter	1 $\mu\text{m}$ diameter Holes drilled in brass	0.5 $\mu\text{m}$ diameter holes in silicon is smallest hole reported ever [169]

requirement for realizing micro-features and to manufacture micro parts.

Tailoring micro cutting tools based on the requirements of micro-features which should be machined (geometry, required tolerances, aspect ratio, surface quality, etc.), workpiece material properties (hardness, ductility, chemical affinity, thermal conductivity, etc.) and characteristics of the fabrication technique which should be used for micro tool fabrication (precision, material removal rate, minimum achievable edge radius, surface integrity, etc.) seem to be the main requirement for today's micro cutting tool technology. This is basically demanding a thorough understanding of the challenges in the design phase (from selection of appropriate cutting tool material to the use of different analysis tools), fabrication phase (Process capabilities and limitations) and application phase (precise clamping, run out and deflection compensation, etc.).

This review paper clearly demonstrated the lack of a systematic approach for designing micro cutting tools. Therefore, before making decision about fabrication technique, micro tool design aspects need to be considered carefully in the design phase in order to deal with tool wear, stiffness, strength, tool run out and the interaction between micro cutting tool and workpiece material. As proposed by different researchers, different part of the micro tool such as, rake angle, edge number, under neck length, diameter can be designed to optimize all these criteria. To do so, the development of analytical and numerical models capable of prediction tool wear, breakage and stiffness in conjunction with micromachining process models is essential. Furthermore, there is a need for a database of material properties such as fracture toughness, elastic modulus, thermal conductivity, thermal expansion, etc. for different tool materials based on grain size, binder and their processing information. Apart from tool geometry design, researchers also reported on the potential of tool coating in order to achieve improved tool life and better tool performances. However, conventional coating technology may not be successfully applied for micro scale tool coating due to the fact that microscale defect which was not an issue for macroscale tool can be detrimental for microscale tool performance. According to the literature, coating technology such as CVD, hot filament CVD reactive closed field unbalanced magnetron sputtering ion plating, combined sputtering and arc ion plating (hybrid coating system) are successfully exploited for microscale tool coating, however general guidelines for the selection of appropriate coating type based on workpiece material properties have not established yet. This is demanding for more researches about the effect of coating on the performance of micro cutting tools during machining of different engineering materials. Additionally, there are many publications in the literature without reporting coating specifications. Therefore, the research community should be encouraged to provide the coating specifications to make it possible to establish a general guideline for the selection of suitable coating based on the requirements of micro-machining task.

It can be seen that, while grinding is the most extensively used process for micro tool fabrication in the industry, the research community has been well benefited from non-traditional machining processes for this purpose. Among non-traditional methods, EDM-based techniques seem to be the most widely used processes of micro tool fabrication due to its versatile nature as long as hardness concerns. The presence of recast layer, over-burn, larger cutting edge radius and tool wear can be named as the limitations of EDM-based techniques which need further investigations. Comparing FIB and EDM-based techniques, it can be found that FIB is noticeably more costly and slower than EDM-based techniques, however it is capable of producing very sharp edges. The very sharp edge (small edge radius) generated by FIB in materials such as WC and PCD can be easily chipped at the initial stage of the cutting process or it can be rounded and transformed into larger radii with the continuation of micro machining operations. Therefore, there is a need for using stronger materials wherever sharp edges are a significant requirement. On the other hand, laser fabrication of micro tools

can offer complicated tool shape generation using picosecond laser pulse, nevertheless laser itself can be directly applicable to micro-structure generation without any tool concern, and therefore not much research efforts are directed to this direction. Moreover, the further advancement in the mechanical micromachining requires facilitating the manufacturing of tailored micro-cutting tools based on the requirements of particular machining operations. The available cutting tool geometries should be optimized in terms of rigidity, deflection and material removal rate. This may indeed results in micro-end mills with complex geometries, which may not be realized using existing machine tool technologies. Therefore, machine tools having more simultaneously operated CNC controlled axis seems to be a major requirement for realizing newly designed micro end mills. More emphasis should be given to the design and manufacturing of micro tools with dimensions less than 100  $\mu\text{m}$  with very sharp cutting edges in order to achieve smaller feature sizes and finer details and to extend the capabilities of micromachining beyond its present state. More and more hybrid and multi-processing manufacturing technologies combining more than two individual processes could be another possible future direction of research as it is certainly could shorten tool fabrication time while achieving tools with smaller diameters. On top of these, wherever possible, on-machine fabrication of micro tools should be adopted to eliminate clamping errors and issues arising from tool runout. This is demanding some new developments in the field of spindle technologies, as tool fabrication normally requires smaller rotational speed than what is used for micromachining operation.

## References

- [1] Liu X, et al. The mechanics of machining at the microscale: assessment of the current state of the science. *J Manuf Sci Eng* 2004;126(4):666–78.
- [2] Chae J, Park S, Freiheit T. Investigation of micro-cutting operations. *Int J Mach Tools Manuf* 2006;46(3-4):313–32.
- [3] Lai X, et al. Modelling and analysis of micro scale milling considering size effect, micro cutter edge radius and minimum chip thickness. *Int J Mach Tools Manuf* 2008;48(1):1–14.
- [4] Wang Y, et al. Analyzing the performance of self-developed cermet micro end mills in machining of TC4 alloy micro-grooves. *Procedia CIRP* 2018;71:424–8.
- [5] Okazaki Y, Mishima N, Ashida K. Microfactory—concept, history, and developments. *J Manuf Sci Eng* 2004;126(4):837–44.
- [6] Malekian M, Park SS, Jun MB. Tool wear monitoring of micro-milling operations. *J Mater Process Technol* 2009;209(10):4903–14.
- [7] Oliaei SNB. Design and fabrication of micro end mills for the machining of difficult-to-cut materials. Bilkent University; 2016.
- [8] Brinksmeier E, Riemer O, Stern R. Machining of precision parts and micro-structures. Initiatives of precision engineering at the beginning of a millennium. Springer; 2002. p. 3–11.
- [9] Asad A, et al. Tool-based micro-machining. *J Mater Process Technol* 2007;192:204–11.
- [10] Weck M, Fischer S, Vos M. Fabrication of microcomponents using ultraprecision machine tools. *Nanotechnology* 1997;8(3):145.
- [11] Mativenga PT, Aramcharoen A, Huo D. Micro tooling design and manufacturing. Micro-cutting: fundamentals and applications. 2013. p. 45–61.
- [12] Aramcharoen A, et al. Evaluation and selection of hard coatings for micro milling of hardened tool steel. *Int J Mach Tools Manuf* 2008;48(14):1578–84.
- [13] Huo D, et al. Modeling the influence of tool deflection on cutting force and surface generation in micro-milling. *Micromachines* 2017;8(6):188.
- [14] Dornfeld D, Min S, Takeuchi Y. Recent advances in mechanical micromachining. *CIRP Ann-Manuf Technol* 2006;55(2):745–68.
- [15] Aurich JC, Reichenbach IG, Schüler GM. Manufacture and application of ultra-small micro end mills. *CIRP Ann-Manuf Technol* 2012;61(1):83–6.
- [16] Davim JP. Modern mechanical engineering. Springer; 2014.
- [17] Oliaei S, Karpat Y. Experimental investigations on micro milling of Stavax stainless steel. *Procedia CIRP* 2014;14:377–82.
- [18] Oliaei SNB, Karpat Y. Influence of tool wear on machining forces and tool deflections during micro milling. *Int J Adv Manuf Technol* 2016;84(9-12):1963–80.
- [19] Vollertsen F. Categories of size effects. *Prod Eng* 2008;2(4):377.
- [20] Abouridouane M, Klocke F, Lung D. Microstructure-based 3D FE modeling for micro cutting ferritic-pearlitic carbon steels. ASME 2014 International Manufacturing Science and Engineering Conference Collocated With the JSME 2014 International Conference on Materials and Processing and the 42nd North American Manufacturing Research Conference 2014.
- [21] Moronuki N, Liang Y, Furukawa Y. Experiments on the effect of material properties on microcutting processes. *Precis Eng* 1994;16(2):124–31.
- [22] Takács M, Verő B. Material structural aspects of micro-scale chip removal. *Materials science forum*. Trans Tech Publ.; 2003.
- [23] Weule H, Hünttrup V, Tritschler H. Micro-cutting of steel to meet new requirements in miniaturization. *CIRP Ann-Manuf Technol* 2001;50(1):61–4.
- [24] Uriarte L, et al. Error budget and stiffness chain assessment in a micromilling machine equipped with tools less than 0.3 mm in diameter. *Precis Eng* 2007;31(1):1–12.
- [25] Tansel I, et al. Micro-end-milling—II. Extending tool life with a smart workpiece holder (SWH). *Int J Mach Tools Manuf* 1998;38(12):1437–48.
- [26] Tansel I, et al. Tool wear estimation in micro-machining.: part I: tool usage–cutting force relationship. *Int J Mach Tools Manuf* 2000;40(4):599–608.
- [27] Tansel I, et al. Tool wear estimation in micro-machining: part II: neural-network-based periodic inspector for non-metals. *Int J Mach Tools Manuf* 2000;40(4):609–20.
- [28] Altan T, Lilly B, Yen Y. Manufacturing of dies and molds. *CIRP Ann Manuf Technol* 2001;50(2):404–22.
- [29] Kim BH, Park BJ, Chu CN. Fabrication of multiple electrodes by reverse EDM and their application in micro ECM. *J Micromech Microeng* 2006;16(4):843.
- [30] Kim BH, et al. Micro electrochemical milling. *J Micromech Microeng* 2004;15(1):124.
- [31] Wu Z-z, et al. Vibration-assisted micro-ECM combined with polishing to machine 3D microcavities by using an electrolyte with suspended B4C particles. *J Mater Process Technol* 2018;255:275–84.
- [32] Rathod V, Doloi B, Bhattacharyya B. Fabrication of microgrooves with varied cross-sections by electrochemical micromachining. *Int J Adv Manuf Technol* 2017;92(1-4):505–18.
- [33] Ghoshal B, Bhattacharyya B. Micro electrochemical sinking and milling method for generation of micro features. *Proc Inst Mech Eng Part B J Eng Manuf* 2013;227(11):1651–63.
- [34] Liu Y, et al. Development of microelectrodes for electrochemical micromachining. *Int J Adv Manuf Technol* 2011;55(1-4):195–203.
- [35] Liu Y, Zhu D, Zhu L. Micro electrochemical milling of complex structures by using in situ fabricated cylindrical electrode. *Int J Adv Manuf Technol* 2012;60(9-12):977–84.
- [36] Fleischer J, et al. Design and manufacturing of micro milling tools. *Microsyst Technol* 2008;14(9-11):1771–5.
- [37] Uriarte L, et al. Comparison between microfabrication technologies for metal tooling. *Proc. Inst. Mech. Eng. Part C: J. Mech. Eng. Sci.* 2006;220(11):1665–76.
- [38] Maloney KJ, et al. Multifunctional heat exchangers derived from three-dimensional micro-lattice structures. *Int J Heat Mass Transf* 2012;55(9-10):2486–93.
- [39] Terry SC, Jerman JH, Angell JB. A gas chromatographic air analyzer fabricated on a silicon wafer. *IEEE Trans Electron Devices* 1979;26(12):1880–6.
- [40] Castillo P, Lozano R, Dzul AE. Modelling and control of mini-flying machines. *Physica-Verlag*; 2006.
- [41] Fonda P, et al. A study on the optimal fabrication method for micro-scale gyroscopes using a hybrid process consisting of electric discharge machining, chemical etching or micro-mechanical milling. *CIRP Ann-Manuf Technol* 2013;62(1):183–6.
- [42] Rossetti A, Pavesi G, Ardizzon G. A new two stage miniature pump: design, experimental characterization and numerical analyses. *Sens Actuators A Phys* 2010;164(1-2):74–87.
- [43] Cox D, et al. Performance evaluation of a miniaturized machining center for precision manufacturing. ASME 2004 International Mechanical Engineering Congress and Exposition 2004.
- [44] Tansel I, et al. Micro-end-milling—I. Wear and breakage. *Int J Mach Tools Manuf* 1998;38(12):1419–36.
- [45] Liu Q, et al. Effect of milling modes on surface integrity of KDP crystal processed by micro ball-end milling. *Procedia CIRP* 2018;71(1):260–6.
- [46] Golshan A, et al. Ultraprecision machining of silicon wafer by micromilling process. *Procedia Eng* 2017;184:192–6.
- [47] Suzuki H, et al. Development of micro milling tool made of single crystalline diamond for ceramic cutting. *CIRP Ann-Manuf Technol* 2013;62(1):59–62.
- [48] Cheng X, et al. Design and development of PCD micro straight edge end mills for micro/nano machining of hard and brittle materials. *J Mech Sci Technol* 2010;24(11):2261–8.
- [49] Cheng X, et al. Design and development of a micro polycrystalline diamond ball end mill for micro/nano freeform machining of hard and brittle materials. *J Micromech Microeng* 2009;19(11):115022.
- [50] Zhan Z, et al. Precision milling of tungsten carbide with micro PCD milling tool. *Int J Adv Manuf Technol* 2015;77(9-12):2095–103.
- [51] Karpat Y, Oliaei SNB. Influence of cutting edge micro geometry on polycrystalline diamond micro milling of silicon. 14th International Conference on High Speed Machining (HSM 2018) 2018.
- [52] Wada R, et al. Wear characteristics of single crystal diamond tool. *CIRP Ann-Manuf Technol* 1980;29(1):47–52.
- [53] Sumiya H, Harano K, Murakami D. Application of nano-polycrystalline diamond to cutting tools. *SEI Tech Rev* 2012;75:18.
- [54] Ding X, et al. Fabrication of a micro-size diamond tool using a focused ion beam. *J Micromechanics Microengineering* 2008;18(7):075017.
- [55] Zak Fang Z. Sintering of advanced materials: fundamental and processes. Cambridge, UK: Woodhead Publishing Limited; 2010.
- [56] Tillmann W. Trends and market perspectives for diamond tools in the construction industry. *Int J Refract Metals Hard Mater* 2000;18(6):301–6.
- [57] Yan J, Watanabe K, Aoyama T. Micro-electrical discharge machining of polycrystalline diamond using rotary cupronickel electrode. *CIRP Ann-Manuf Technol* 2014;63(1):209–12.
- [58] Oliaei SNB, Karpat Y. Fabrication of PCD mechanical planarization tools by using  $\mu$ -wire electrical discharge machining. *Procedia CIRP* 2016;42:311–6.
- [59] Shabouk S, Nakamoto T. Micro machining of single crystal diamond by utilization of tool wear during cutting process of ferrous material. *J Micromechatron*

- 2002;2(1):13–26.
- [60] Fu L, Guo Q. Development of an ultra-small micro drill bit for packaging substrates. *Circ World* 2010;36(3):23–7.
- [61] Lacalle L, et al. *Advanced cutting tools. Machining of hard materials*. London: Springer; 2011.
- [62] Torres C, et al. Analyzing the performance of diamond-coated micro end mills. *Int J Mach Tools Manuf* 2009;49(7-8):599–612.
- [63] Jackson MJ, Robinson GM, Ahmed W. Micromachining selected metals using diamond coated cutting tools. *Int J Nanomanuf* 2006;1(2):304–17.
- [64] Baharudin BHT, Dimou N, Hon K. Tool wear behaviour of micro-tools in high speed CNC machining. *Proceedings of the 34th International MATADOR Conference* 2004.
- [65] Rahman M, Kumar AS, Prakash J. Micro milling of pure copper. *J Mater Process Technol* 2001;116(1):39–43.
- [66] Takacs M, Verö B, Meszaros I. Micromilling of metallic materials. *J Mater Process Technol* 2003;138(1-3):152–5.
- [67] Yang S, et al. Microtool coatings using magnetron sputtering. *Mater Technol* 2011;26(1):20–4.
- [68] Krebs E, et al. High-quality cutting edge preparation of micromilling tools using wet abrasive jet machining process. *Prod Eng* 2018;12(1):45–51.
- [69] Steffens H-D, et al. Reduction of droplet emission in random arc technology. *Surf Coat Technol* 1991;46(1):65–74.
- [70] Wang H, et al. The corrosion behaviour of macroparticle defects in arc bond-sputtered CrN/NbN superlattice coatings. *Surf Coat Technol* 2000;126(2-3):279–87.
- [71] Heaney PJ, et al. Diamond coatings for micro end mills: enabling the dry machining of aluminum at the micro-scale. *Diam Relat Mater* 2008;17(3):223–33.
- [72] Hei H, et al. Preparation and performance of chemical vapor deposition diamond coatings synthesized onto the cemented carbide micro-end mills with a SiC interlayer. *Surf Coat Technol* 2015;261:272–7.
- [73] Kim M, et al. Cutting performance of nanocomposite Cr–C–N, Cr–Si–N and Cr–Si–C–N coated tools for micro end-milling operation. *Curr Appl Phys* 2009;9(2):e201–4.
- [74] Bian R, et al. Experimental investigation on ductile mode micro-milling of ZrO<sub>2</sub> ceramics with diamond-coated end mills. *Micromachines* 2018;9(3):127.
- [75] Romanus H, et al. Micromilling of sintered ZrO<sub>2</sub> ceramic via cBN and diamond coated tools. *Procedia CIRP* 2014;14:371–6.
- [76] Wu Y, et al. Experimental study of rectangular groove texture in the surface of photovoltaic silicon with diamond coated micro-milling tools. *Mater Sci Semicond Process* 2018;86:23–35.
- [77] Xu Z, et al. Fabrication of micro DOE using micro tools shaped with focused ion beam. *Opt Express* 2010;18(8):8025–32.
- [78] De Oliveira FB, et al. Size effect and minimum chip thickness in micromilling. *Int J Mach Tools Manuf* 2015;89:39–54.
- [79] Saedon J, et al. Prediction and optimization of tool life in micromilling AISI D2 (~62 HRC) hardened steel. *Procedia Eng* 2012;41:1674–83.
- [80] Biermann D, Steiner M, Krebs E. Investigation of different hard coatings for micromilling of austenitic stainless steel. *Procedia CIRP* 2013;7:246–51.
- [81] Sadiq MA, et al. Experimental study of micromilling selective laser melted Inconel 718 superalloy. *Procedia Manuf* 2018;26:983–92.
- [82] Câmara MA, et al. Determination of the critical undeformed chip thickness in micromilling by means of the acoustic emission signal. *Precis Eng* 2016;46:377–82.
- [83] Krebs E, Kersting P. Improving the cutting conditions in the five-axis micromilling of hardened high-speed steel by applying a suitable tool inclination. *Procedia CIRP* 2014;14:366–70.
- [84] Filiz S, et al. Micromilling of microbarbs for medical implants. *Int J Mach Tools Manuf* 2008;48(3-4):459–72.
- [85] Foy K, et al. Effect of tilt angle on cutting regime transition in glass micromilling. *Int J Mach Tools Manuf* 2009;49(3-4):315–24.
- [86] Arif M, Rahman M, San WY. Ultraprecision ductile mode machining of glass by micromilling process. *J Manuf Process* 2011;13(1):50–9.
- [87] Komatsu T, et al. Effect of crystal grain size in stainless steel on cutting process in micromilling. *Procedia CIRP* 2012;1:150–5.
- [88] Swain N, et al. An experimental investigation on the machining characteristics of Nimonic 75 using uncoated and TiAlN coated tungsten carbide micro-end mills. *CIRP J Manuf Sci Technol* 2017;16:34–42.
- [89] Uhlmann E, Schauer K. Dynamic load and strain analysis for the optimization of micro end mills. *CIRP Ann-Manuf Technol* 2005;54(1):75–8.
- [90] Zaman M, et al. A three-dimensional analytical cutting force model for micro end milling operation. *Int J Mach Tools Manuf* 2006;46(3-4):353–66.
- [91] Uhlmann E, Piltz S, Schauer K. Micro milling of sintered tungsten–copper composite materials. *J Mater Process Technol* 2005;167(2-3):402–7.
- [92] Mougo AL, de Oliveira Campos F, Araujo AC. Mechanistic study on micromilling of the super duplex stainless steel UNS S32750. *J Manuf Process* 2018;34:31–9.
- [93] Mittal RK, et al. Characterization of anti-abrasion and anti-friction coatings on micromachining response in high speed micromilling of Ti-6Al-4V. *J Manuf Process* 2018;34:303–12.
- [94] Özel T, et al. Experiments and finite element simulations on micro-milling of Ti–6Al–4V alloy with uncoated and cBN coated micro-tools. *CIRP Ann-Manuf Technol* 2011;60(1):85–8.
- [95] Adams DP, Vasile MJ, Krishnan A. Microgrooving and microthreading tools for fabricating curvilinear features. *Precis Eng* 2000;24(4):347–56.
- [96] Ziberov M, et al. Effect of cutting fluid on micromilling of Ti-6Al-4V titanium alloy. *Procedia Manuf* 2016;5:332–47.
- [97] Mittal RK, Kulkarni SS, Singh R. Characterization of lubrication sensitivity on dynamic stability in high-speed micromilling of Ti–6Al–4V via a novel numerical scheme. *Int J Mech Sci* 2018;142:51–65.
- [98] Mittal RK, Kulkarni SS, Singh RK. Multiple degree of freedom rotordynamics based stability modeling in high-speed micromilling of Ti-6Al-4V. *Procedia Manuf* 2018;26:607–16.
- [99] Mittal RK, Kulkarni SS, Singh RK. Effect of lubrication on machining response and dynamic instability in high-speed micromilling of Ti-6Al-4V. *J Manuf Process* 2017;28:413–21.
- [100] Wang Z, et al. Built-up-edge effects on surface deterioration in micromilling processes. *J Manuf Process* 2016;24:321–7.
- [101] Singh KK, Singh R, Kartik V. Comparative study of chatter detection methods for high-speed micromilling of Ti6Al4V. *Procedia Manuf* 2015;1:593–606.
- [102] Singh KK, Kartik V, Singh R. Modeling dynamic stability in high-speed micromilling of Ti–6Al–4V via velocity and chip load dependent cutting coefficients. *Int J Mach Tools Manuf* 2015;96:56–66.
- [103] Yadav AK, et al. FE modeling of burr size in high-speed micro-milling of Ti6Al4V. *Precis Eng* 2017;49:287–92.
- [104] Kumar M, Dotson K, Melkote SN. An experimental technique to detect tool–workpiece contact in micromilling. *J Manuf Process* 2010;12(2):99–105.
- [105] Rodríguez P, Labarga J. A new model for the prediction of cutting forces in micro-end-milling operations. *J Mater Process Technol* 2013;213(2):261–8.
- [106] Dib M, Duduch J, Jasinevicius R. Minimum chip thickness determination by means of cutting force signal in micro endmilling. *Precis Eng* 2018;51:244–62.
- [107] Li P, et al. Design of micro square endmills for hard milling applications. *Int J Adv Manuf Technol* 2011;57(9-12):859–70.
- [108] Fang F, et al. Tool geometry study in micromachining. *J Micromech Microeng* 2003;13(5):726.
- [109] Reichenbach IG, et al. Micromachining of PMMA—manufacturing of burr-free structures with single-edge ultra-small micro end mills. *Int J Adv Manuf Technol* 2018;96(9-12):3665–77.
- [110] Yan J, et al. Fabrication of micro end mills by wire EDM and some micro cutting tests. *J Micromech Microeng* 2009;19(2):025004.
- [111] Fleischer J, et al. Geometry optimization of micro milling tools. *Fourth International Conference on Multi-Material Micro Manufacture*. 2008.
- [112] Oliaei SNB, Karpat Y. Built-up edge effects on process outputs of titanium alloy micro milling. *Precis Eng* 2017;49:305–15.
- [113] Ravi N, Huang H. Fabrication of symmetrical section microfeatures using the electro-discharge machining block electrode method. *J Micromech Microeng* 2002;12(6):905.
- [114] Perveen A, San WY, Rahman M. Fabrication of different geometry cutting tools and their effect on the vertical micro-grinding of BK7 glass. *Int J Adv Manuf Technol* 2012;61(1-4):101–15.
- [115] Perveen A, Wong Y, Rahman M. Characterisation and online monitoring of wear behaviour of on-machine fabricated PCD micro-tool while vertical micro-grinding of BK7 glass. *Int J Abras Technol* 2011;4(4):304–24.
- [116] Masuzawa T, et al. Wire electro-discharge grinding for micro-machining. *CIRP Ann-Manuf Technol* 1985;34(1):431–4.
- [117] Fleischer J, et al. New applications for micro-EDM. *J Mater Process Technol* 2004;149(1-3):246–9.
- [118] Morgan CJ, Vallance RR, Marsh ER. Micro-machining and micro-grinding with tools fabricated by micro electro-discharge machining. *Int J Nanomanuf* 2006;1(2):242–58.
- [119] Sheu D-Y. High-speed micro electrode tool fabrication by a twin-wire EDM system. *J Micromech Microengineering* 2008;18(10):105014.
- [120] Yamazaki M, et al. EDM of micro-rods by self-drilled holes. *J Mater Process Technol* 2004;149(1-3):134–8.
- [121] Masaki T, et al. Study on shaping spherical polycrystalline diamond tool by micro-electro-discharge machining and micro-grinding with the tool. *Int J Surf Sci Eng* 2007;1(4):344–59.
- [122] Oliaei SNB, Özdemir C, Karpat Y. On-machine fabrication of PCD and WC micro end mills using micro electro discharge machining. *Int J Mechatron Manuf Syst* 2014;7(4-6):246–64.
- [123] Cheng X, et al. Tool fabrication system for micro/nano milling—function analysis and design of a six-axis Wire EDM machine. *Int J Adv Manuf Technol* 2010;46(1-4):179–89.
- [124] Cheng X, et al. Fabrication accuracy analysis of micromilling tools with complicated geometries by wire EDM. *J Mech Sci Technol* 2014;28(6):2329–35.
- [125] Oliaei S, Karpat Y. Polycrystalline diamond end mill cutting edge design to improve ductile-mode machining of silicon. *Precis Eng* 2018;51:403–14.
- [126] Sun Y, Gong Y. Experimental study on the microelectrodes fabrication using low speed wire electrical discharge turning (LS-WEDT) combined with multiple cutting strategy. *J Mater Process Technol* 2017;250:121–31.
- [127] Nakamoto K, et al. A study on the quality of micro-machined surfaces on tungsten carbide generated by PCD micro end-milling. *CIRP Ann-Manuf Technol* 2012;61(1):567–70.
- [128] Morgan CJ, Vallance RR, Marsh ER. Micro machining glass with polycrystalline diamond tools shaped by micro electro discharge machining. *J Micromech Microeng* 2004;14(12):1687.
- [129] Gao C, et al. Research on WEDM process optimization for PCD micro milling tool. *Procedia CIRP* 2013;6:209–14.
- [130] Yu ZY, Masuzawa T, Fujino M. Micro-EDM for three-dimensional cavities - development of uniform wear method. *CIRP Annals* 1998;47(1):169–72.
- [131] Shun-Tong C. Fabrication of high-density micro holes by upward batch micro EDM. *J Micromech Microeng* 2008;18(8):085002.
- [132] Spieser A, Ivanov A. Recent developments and research challenges in electro-chemical micromachining ( $\mu$ ECM). *Int J Adv Manuf Technol* 2013;69(1):563–81.

- [133] Lim HS, et al. A study on the machining of high-aspect ratio micro-structures using micro-EDM. *J Mater Process Technol* 2003;140(1):318–25.
- [134] Han F, Wachi S, Kunieda M. Improvement of machining characteristics of micro-EDM using transistor type isopulse generator and servo feed control. *Precis Eng* 2004;28(4):378–85.
- [135] Li Y, et al. Micro electro discharge machine with an inchworm type of micro feed mechanism. *Precis Eng* 2002;26(1):7–14.
- [136] Han F, et al. Experimental attempts of sub-micrometer order size machining using micro-EDM. *Precis Eng* 2006;30(2):123–31.
- [137] Zhang L, Tong H, Li Y. Precision machining of micro tool electrodes in micro EDM for drilling array micro holes. *Precis Eng* 2015;39:100–6.
- [138] Dong-Yea S. High-speed micro electrode tool fabrication by a twin-wire EDM system. *J Micromech Microeng* 2008;18(10). 105014.
- [139] Yan J, et al. Fabricating microgrooves with varied cross-sections by electro-discharge machining. *Int J Adv Manuf Technol* 2010;50(9):991–1002.
- [140] Egashira K, Mizutani K. Micro-drilling of monocrystalline silicon using a cutting tool. *Precis Eng* 2002;26(3):263–8.
- [141] Chern G-L, et al. Study on burr formation in micro-machining using micro-tools fabricated by micro-EDM. *Precis Eng* 2007;31(2):122–9.
- [142] Rakwal D, et al. Fabrication of compliant high aspect ratio silicon microelectrode arrays using micro-wire electrical discharge machining. *Microsyst Technol* 2009;15(5):789–97.
- [143] Kuo C-L, Huang J-D. Fabrication of series-pattern micro-disk electrode and its application in machining micro-slit of less than 10  $\mu\text{m}$ . *Int J Mach Tools Manuf* 2004;44(5):545–53.
- [144] Jahan MP, et al. On-machine fabrication of high-aspect-ratio micro-electrodes and application in vibration-assisted micro-electrodischarge drilling of tungsten carbide. *Proc Inst Mech Eng Part B J Eng Manuf* 2010;224(5):795–814.
- [145] Weng F-T, Her M-G. Study of the batch production of Micro parts using the EDM process. *Int J Adv Manuf Technol* 2002;19(4):266–70.
- [146] Wu W, et al. Microtool fabrication by focused ion beam technology. *Handbook of manufacturing engineering and technology*. 2013. p. 1–33.
- [147] Vasile MJ, et al. Micrometer-scale machining: tool fabrication and initial results. *Precis Eng* 1996;19(2-3):180–6.
- [148] Picard YN, et al. Focused ion beam-shaped microtools for ultra-precision machining of cylindrical components. *Precis Eng* 2003;27(1):59–69.
- [149] Harrison PM, Henry M, Brownell M. Laser processing of polycrystalline diamond, tungsten carbide, and a related composite material. *J Laser Appl* 2006;18(2):117–26.
- [150] Li ZQ, Wu Q, Wang J. Ultrashort pulsed laser micromachining of polycrystalline diamond. *Advanced materials research*. Trans Tech Publ; 2012.
- [151] Ogawa Y, et al. A study on machining of binder-less polycrystalline diamond by femtosecond pulsed laser for fabrication of micro milling tools. *CIRP Annals* 2016;65(1):245–8.
- [152] Harano K, Satoh T, Sumiya H. Cutting performance of nano-polycrystalline diamond. *Diam Relat Mater* 2012;24:78–82.
- [153] Everson C, Molian P. Fabrication of polycrystalline diamond microtool using a Q-switched Nd:YAG laser. *Int J Adv Manuf Technol* 2009;45(5):521.
- [154] Suzuki H, et al. Development of micro milling tool made of single crystalline diamond for ceramic cutting. *CIRP Annals* 2013;62(1):59–62.
- [155] Butler-Smith PW, et al. Micro/nanometric investigations of the effects of laser ablation in the generation of micro-tools from solid CVD diamond structures. *J Mater Process Technol* 2013;213(2):194–200.
- [156] Eberle G, Dold C, Wegener K. Laser fabrication of diamond micro-cutting tool-related geometries using a high-numerical aperture micro-scanning system. *Int J Adv Manuf Technol* 2015;81(5):1117–25.
- [157] Eberle G, Dold C, Wegener K. Picosecond laser fabrication of micro cutting tool geometries on polycrystalline diamond composites using a high-numerical aperture micro scanning system. *SPIE LASE* 2015.
- [158] Aoki I, Takahashi T. Micropattern fabrication by a specially designed microtool. *Micromachining and Microfabrication Process Technology V*. International Society for Optics and Photonics; 1999.
- [159] Schaller T, et al. Microstructure grooves with a width of less than 50  $\mu\text{m}$  cut with ground hard metal micro end mills. *Precis Eng* 1999;23(4):229–35.
- [160] Onikura H, et al. Fabrication of Micro carbide tools by ultrasonic vibration grinding. *CIRP Annals* 2000;49(1):257–60.
- [161] Ohmori H, et al. Microscopic grinding effects on fabrication of ultra-fine Micro tools. *CIRP Annals* 2007;56(1):569–72.
- [162] Aurich JC, Reichenbach IG, Schüler GM. Manufacture and application of ultra-small micro end mills. *CIRP Annals* 2012;61(1):83–6.
- [163] Liang Z, et al. Design and fabrication of a new micro ball-end mill with conical flank face. *Int J Adv Manuf Technol* 2018:1–12.
- [164] Shun-Tong C, Yun-Cheng L, Ching-Chang L. Fabrication of a miniature diamond grinding tool using a hybrid process of micro-EDM and co-deposition. *J Micromechanics Microengineering* 2008;18(5):055005.
- [165] Suzuki H, et al. Precision cutting of aspherical ceramic molds with Micro pcd milling tool. *CIRP Annals* 2007;56(1):131–4.
- [166] Rahman M, et al. A multiprocess machine tool for compound micromachining. *Int J Mach Tools Manuf* 2010;50(4):344–56.
- [167] Takahata K, Shibaie N, Guckel H. High-aspect-ratio WC-Co microstructure produced by the combination of LIGA and micro-EDM. *Microsyst Technol* 2000;6(5):175–8.
- [168] Endo T, Tsujimoto T, Mitsui K. Study of vibration-assisted micro-EDM—the effect of vibration on machining time and stability of discharge. *Precis Eng* 2008;32(4):269–77.
- [169] Egashira K, Morita Y, Hattori Y. Electrical discharge machining of submicron holes using ultrasmall-diameter electrodes. *Precis Eng* 2010;34(1):139–44.