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ORIGINAL ARTICLE

Micro-electrode fabrication processes for micro-EDM drilling and milling: a state-of-the-art review

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Abstract These days, miniaturized products have a lot of applications in biotechnology, information technology, environmental and medical industries, electric devices, miniaturized machines, and so on. Micro-electrical discharge machining (micro-EDM) is one the most efficient technologies among the nonconventional machining technologies for producing micro-components. Micro-EDM is able to machine tough die materials which cannot be machined by micro-milling. The micro-EDM method has the capability to machine electrical conductive materials with various hardness, strength, and temperature-resistant and complex shapes with accurate dimensions and fine surface roughness. Moreover, it is widely used to produce micro-scale components and structures such as micro-mold, micro-die, micro-probes, micro-tools, fuel nozzles, photo-masks, thin sheet materials, and complex 3D shapes with high accuracy. This paper presents a state-of-the-art review of micro-EDM process as well as the various kinds of micro-electrode and workpiece materials and dielectrics that have been used by previous researchers. In addition, this paper extensively describes and compares various micro-electrode and micro-tool fabrication processes in order to produce precise micro-products. This work is very helpful for the micro-EDM manufacturers and users to select suitable material, dielectric and fabrication processes in researches, and industry applications.

Keywords Micro-EDM · Micro-electrode fabrication · High aspect ratio · Measurement · Micro-drilling · Micro-milling · Dielectric

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1 Introduction

Micro-machining is utilized to produce miniaturized parts and products with less than 1-mm dimensions (between 1 and 999 μm) [1]. Recently, the demands for micro-machining are augmented because of the increasing requirement for lighter weight and miniaturization of products [2] in biotechnology, information technology, environmental and medical industries, electric devices, machines, and so on [3, 4]. Many studies about micro-structure and component fabrication have been done [5, 6]. Actually, micro-machining processes are categorized into conventional, nonconventional, and hybrid material removal processes. Conventional material removal processes remove the material by physical contact between cutting tools and material [7, 8] which are classified into micro-drilling, micro-milling, micro-turning, and micro-grinding. They can be utilized to machine most materials (ferrous and non-ferrous metals, semiconductors, and plastics) with various shapes such as flat surfaces, arbitrary curvature, long shaft, and so on [9, 10]. Nonconventional material removal processes remove the material by alternative forms of energy which include spark, vibration, light and electrolysis energy in addition to the mechanical energy (which is based on erosion mechanism), energy beams (ion beams, laser beams, or electron beams), etc. [8, 11–13]. These processes are categorized into electrical discharge machining (EDM), wire electrical discharge machining (WEDM), ultrasonic machining

(USM), electrochemical machining (ECM), abrasive jet machining (AJM), laser beam machining (LBM), cover plate laser beam machining (c-LBM) [14], laser-induced plasma micro-machining (LIPMM) [15], focused ion beam (FIB) system [16], gas cluster ion beam irradiation system, and so on. Hybrid machining process is nonconventional, and conventional material removal methods are combined for the production of high-precision microstructures [4, 17]. Hybrid material removal process can produce the micro-components with almost all material kinds (semiconductors, plastics, and metal) and various shapes (long shaft, arbitrary curvatures, and flat surface); these are required for the moving parts and guide structures [18–21]. The hybrid machine which includes micro-milling, micro-turning, micro-EDM, micro-WEDM, wire electrical discharge grinding (WEDG), and on-machine measurement equipment is shown in Fig. 1.

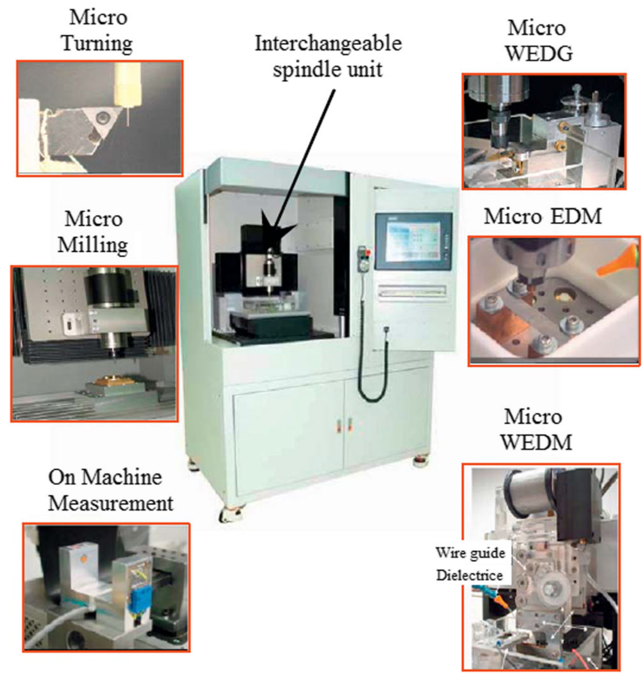

Fig. 1 Hybrid machine for multi-processes of micro-machining [4]

2 Micro-EDM

2.1 Definition of micro-EDM

EDM is a nonconventional machining method in which materials are removed by a series of sparks which happen between the electrical conductive workpiece and the electrode inside dielectric fluid relying on thermal energy (melting and partly vaporizing workpiece) [22–34]. The EDM method has the capability to machine electrical conductive materials with various hardness, strength, and temperature-resistant and complex shapes with accurate dimensions and fine surface roughness [30–32, 34–39]. EDM can also be used for machining of semi-conductive material [40] such as single crystal silicon carbide (Sic) [41–43]. EDM comes with the major problem of low material removal rate (MRR) compared with the milling, ECM, and so on [24]. So, it is the suitable for small batches of parts [44, 45].

The EDM processes can be classified into die-sinking EDM, EDM drilling, EDM milling, WEDM, powder mixed EDM (PMEDM), and dry EDM. WEDM has the capability to cut and produce complex 3D structures by programing wire electrode movement path as the wire is connected to the downer and upper guides [46]. Die-sinking EDM can fabricate different structures by copying the electrode shape to the workpiece [46]. In this method, several electrodes are needed to fabricate the desired workpiece shape for each step of machining (roughing, semi-finishing, and finishing) which causes to increase the machining time and cost [47]. EDM drilling and EDM milling are similar to die-sinking EDM, but they used electrodes with simple shape. Among the EDM processes, EDM milling can produce grooves, pockets shapes, and 3D cavities on the workpiece by using a simple electrode [46]. The PMEDM mechanism is completely different from the conventional EDM. In this process, an appropriate powder material is mixed into the EDM dielectric fluid [48]. In dry EDM, high-pressure gas or air is used instead of dielectric fluid. High-pressure gas is supplied through a thin-walled pipe electrode and removes the debris from the gap as well as cools the inter electrode gap [48, 49].

Micro-EDM is similar to EDM except that only the electrode discharge energy, size, and axis movement resolution are at the micron range in micro-EDM [7]. Micro-EDM is widely used to produce micro-scale components and structures such as micro-mold, micro-die, micro-probes, micro-tools, fuel nozzles, photo-masks, and complex 3D shapes with high accuracy [4–6, 26, 50–53]. Also, it can be used to machine highly accurate slope surface, curved surface, and thin sheet materials which are difficult to machine [1, 7, 54–56]. There is not any tool deformation, vibration errors, mechanical stress, and chatter in EDM and micro-EDM processes because of the absence of direct contact and insignificant force between the electrode and workpiece [7, 55, 57–59]. Therefore, long and thin electrode can be utilized in micro-EDM process for manufacturing micro-products and molds [4–6]. Moreover, the special advantages of micro-EDM are that it can produce micro-holes with free burr even after heat treatment processes [26]. Also, micro-EDM is one of the most efficient means for machining of materials which are hard to machine like tungsten carbide (WC) [60, 61].

2.1.1 Electrode material for micro-EDM

The micro-EDM is a thermal process and removes the material by melting and partly vaporizing workpiece. So, the