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A review on process capabilities of electrochemical micromachining and its hybrid variants

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ABSTRACT

Electrochemical micromachining (micro-ECM) is an unconventional micromachining technology that has capability to fabricate high aspect ratio micro-holes, micro-cavities, micro-channels and grooves on conductive and difficult-to-cut materials. Both academia and industry have the consensus that it offers promising machining performance especially in terms of high surface finish, no tool wear and absence of thermally induced defects. Furthermore in order to machine novel materials with extreme properties, novel hybrid electrochemical micromachining technologies are under development. With these hybrid micro-ECM technologies, capabilities of micro-ECM can be expanded by combining it with other processes. To fully exploit the potential as well as improve micro-ECM technology and related hybrid processes, a wide spectrum of multidisciplinary knowledge is needed. The present review systematically discusses process capabilities and research developments of electrochemical micromachining and its hybrid variants considering knowledge of both basic and applied research fields. After few introductory review articles in prior state of the art, this review fills an important gap in research literature by presenting first time an extended literature source with a wide coverage of recent research developments in electrochemical micromachining technology and its hybrid variants. This paper outlines the research and engineering developments in electrochemical micromachining technology and its hybrid variants, review of the related concepts, aspects of tooling, advanced process capabilities and process energy sources. It also provides new sights into technological understanding of micro-ECM technology which will be helpful in future engineering developments of this technology.

1. Introduction

The trend of product miniaturization alongwith advent of novel materials with extreme properties has posed a challenge for machining industry [1]. The demand for fabrication of micrometer scale features on variety of materials with stringent requirements on tolerances [2], shape control and metallurgical constraints has focused research on expanding the capabilities of existing micromachining technologies and development of novel hybrid micromachining technologies. This includes development of miniaturized machine tools, exploring advanced process capabilities, fabrication of high aspect ratios, knowledge of process-material interaction, effects of scaling on material processing, etc. [3]. The key applications in different sectors demanding developments in micromachining are cooling holes in gas-micro turbines, fuel injection nozzles, MEMS, components of wrist watches, MEMS, biochips, opto-electronic components, nuclear reactor components, inkjet nozzles, printed circuit boards, microfluidic channels, surgical micro-tools, micro-dies, implants, etc. In micromachining domain, the application of mechanical micromachining processes such as micro-milling, micro-turning etc. is limited by the hardness of workpiece material and issues such as tool failure, excessive tool wear, chatter and limited surface quality. Among non-conventional micromachining technologies, micro-EDM is a commercialized technology which has capability to machine micro-dimensional features on conductive materials irrespective of hardness. It suffers from the problems with surface integrity owing to the thermally induced defects. Process repeatability and capability is very low for features smaller than 100 μm. Laser beams wins when it comes to micromachining in non-conductive materials which are beyond the capability of electrical micromachining techniques. Also, laser beam micromachining is an electrodeless machining so no tool design and fabrication is required. The use of green fiber lasers of ultrashort pulse durations has made the micromachining process easy

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to monitor. However, laser beam machining (LBM) and electron beam machining (EBM) are less effective for drilling in thick workpiece materials due to the limited working range of lasers. Laser beam micromachining suffers from heat affected zone, spatter and micro cracking. Use of femtosecond pulse lasers has shown very less thermally induced defects but it is very slow and cost intensive process and not suitable for mass production. Another commercialized technology, laser micro-jet has offered possibilities in clean processing of materials with reduced thermal defects. However, the technology is limited in aspect ratio and precision is limited by hydraulic jump of water-jet especially in drilling configuration.

Table 1 shows comparison of four commercially available micromachining technologies. It is important to note that micro-ECM offers promising capability to fabricate high aspect ratio features without thermal defects and high surface finish can be achieved. In micro-ECM process, localized material removal is achieved by controlled anodic dissolution of workpiece. Since, the material removal occurs at atomic level, high surface finishes can be obtained. Micro-ECM technology has been foreseen as a promising technology in future. Its process capabilities and material processing window is expected to be expanded by hybridizing electrochemical process energy with other process energies. To enable the development of micro-ECM technology and its hybrid variants, a wide knowledge spectrum is required.

In this paper, we fill an important literature gap in the existing state of the art focusing extensively on updated developments in electrochemical micromachining technology and its hybrid variants considering a wide knowledge spectrum. Development of hybrid process needs knowledge of parent process and hence this review is intended to combine knowledge of electrochemical micromachining as well as micro-ECM based hybrid micromachining technologies in single manuscript. Some of the introductory review articles on electrochemical micromachining are available in Refs. [4–7] which only deal with the early basic knowledge in this field. References [4] [5], reported very early introduction about localized ECM processes and were several years ago. In the work of Bhattacharya et al. [6], basics of electrochemical micromachining as well as comparison between ECM and micro-ECM were presented after reviewing 60 publications. Recent developments and several aspects were not included in the review and since then the technology has already advanced by leaps and bounds. Landolt et al. [7] reviewed fundamental chemical aspects of electrochemical micromachining including mass transport effects. They also discussed several aspects of oxide film laser lithography and fabrication of two or multi-level structures. In the work of Sen et al. [8], a review on ECM drilling was presented focusing mainly on the hole quality aspects and discussion on effect of process parameters on hole quality was presented. Several aspects such as tooling, importance of interelectrode gap, process energy sources, selection of electrolytes for machining specific material, etc. were not covered comprehensively. A recent conference review article [9] in related field gave a shallow coverage of ECM technology without detailing processes and was merely a collection of literature on EDM and ECM. In the work of Leese et al. [10], an overview was presented considering mainly the process parameters. In our review article we present an extended review article by considering upto-date knowledge of basic and applied research fields targeting both academia and industrial audience. The paper covers comprehensively and systematically the research developments in electrochemical micromachining technology and its hybrid micromachining variants. It covers wide knowledge spectrum including almost all aspects such as fundamentals of material removal mechanism, process material interaction, electrochemical micromachining process configurations, electrolyte and tooling aspects, process energy sources and process capabilities. The review also covers electrochemical micromachining based hybrid processes. Both assisted and combined processes are discussed vividly. Fig. 1 depicts the scope of this review paper. Several aspects are cross-connected and are discussed in detail in each subsection. The paper also deduces current and future research trends in this technology.

Table 1
Comparison of four commercially established micromachining technologies.

	Micro-EDM	Micro-ECM	Laser micro-jet	Laser ablation
High aspect ratio features	✓	✓	✓	x
Micromachining on nonconductive materials	x	x	✓	✓
Micro tool design and fabrication	✓	✓	x	x
Independent of hardness	✓	✓	✓	✓
Thermally induced defects (HAZ, spatter)	✓	x	x	✓
Micro residual stresses on workpiece	✓	x	x	✓
High surface finish (nm)	x	✓	x	x
High MRR	✓	✓	x	x
Mass production	x	x	x	x

2. Micro-ECM technology

Micro-ECM is an unconventional micromachining technology which finds application in wide range of sectors such as aerospace [11], automotive [12], biomedical [13–17], micro-electronics [18], shaver heads [19] [20], etc. The principle of material removal is anodic dissolution of workpiece as in electrochemical machining. However, in micro-ECM the goal is to localize the material removal so as to control the shape precisely. Micro-ECM technology has several advantages over other localized material removal processes. Some of them are:

i. Independent of workpiece hardness.
ii. Complex shapes can be machined.
iii. It has no tool wear and high surface finish as dissolution occurs at atomic level.
iv. It can be precisely controlled in micromachining domain through use of ultrashort pulsed power.
v. It is a non-contact machining process so no machining forces involved and size effects don't come into picture.
vi. It can be easily hybridized with other processes to broaden process capabilities and material processing window.
vii. Material removal rates can be controlled from electrical parameters (Voltage, Current) and pulse characteristics (Pulse frequency, on time, duration, duty cycle).

The experimental studies conducted till date have shown direct and simultaneous involvement of several process parameters on the process performance of micro-ECM. These process parameters can be grouped into six broad categories and are represented in the form of fish-bone diagram in Fig. 2. For controlled and precise material removal in micro-ECM process, it is often required to set different machining parameters at their optimal levels. Furthermore, the surface roughness and material removal rate is influenced by pulse duration, applied voltage, pulse frequency, electrolyte concentration and tool feed rate. The general effect of different process parameters on the process performance characteristics during micro-ECM process is summarized in Table 2.

2.1. Fundamentals of material removal

The material removal in ECM is achieved through controlled anodic dissolution of workpiece. The workpiece is made as anode and the tool electrode is made as cathode. At the anode, the metallic workpiece (M) undergoes oxidation thereby releasing the electrons. The reaction is known as anodic reaction and is represented as [24]:

$$M \rightarrow M^{n+} + ne^{-} \ (\textit{Anodic dissolution}) \tag{1}$$

where n represents the number of electrons released during reaction. Besides anodic dissolution, oxygen evolution takes place when