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# Current trends and future of sequential micro-machining processes on a single machine tool

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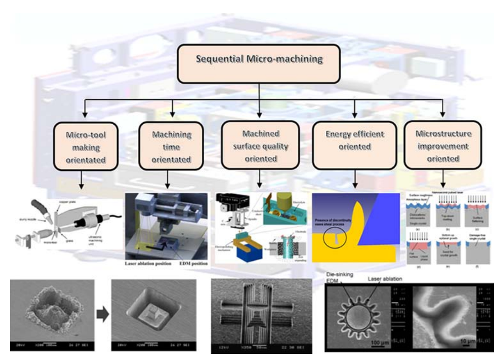
## ABSTRACT

A sequential micro-machining process chain is described as the machining strategy whereby two or more micro-machining techniques are implemented in sequence on same or different machine tools. This is in contrast to hybrid micro-machining where two standalone machining technologies are integrated together. A recent surge of interest is geared towards building sequential micro-machining capabilities on a single machine tool to avoid realignment errors. One of the major advantages of performing sequential micro-machining on a single machine tool is that it suppresses repositioning errors so enabling much higher levels of accuracy (and thereby tighter tolerances), reduced rejection of machined components, and lower production time; all of these would be otherwise unachievable. Thus, multifunctional micro-machining centres are attracting global interest. Clearly, the necessity of developing reconfigurable, precise and flexible manufacturing is a key driver to this trend. This review aims to provide a critical insight into the recent trends and new classification of sequential micro-machining processes with a special focus on evaluation of such capabilities built on a single machine tool and further potentials. The machining capabilities, advantages and opportunities in the area of sequential micro-machining techniques are evaluated thoroughly and the directions for future work are highlighted.

## GRAPHICAL ABSTRACT




## 1. Introduction

There are ever-progressing demands of miniaturized/micro-products/systems and components, e.g. micro-electro-mechanical systems (MEMS), nano-electro-mechanical systems (NEMS), micro-reactors, fuel cells, fuel pumps and micro-medical components that are nowadays commonly utilised in automobile, aircraft, telecommunication and information technology, home appliances, medical-devices and medical implants [1]. Several techniques exist for precision manufacturing of micro-components. These techniques can be divided into lithography-

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**Nomenclature**

| | |
|---|---|
| DVEE | diameter variation between the entrance and exit |
| ECM | electro-chemical machining |
| ECDM | electro-chemical discharge machining |
| EMM or ECMM | electrochemical micro-machining |
| EDM | electric discharge machining |
| EDMM | electric discharge micro-machining |
| LIGA | German acronym for lithography, electroplating and moulding, plating |
| MEMS | micro-electro-mechanical systems |
| MRR | material removal rate |
| MUSM | micro-ultrasonic machining |
| NEMS | nano-electro-mechanical systems |
| Nd:YAG | neodymium-doped yttrium aluminium garnet |
| PCD | poly-crystalline diamond |
| PTFE | polytetrafluoroethylene |
| SDM | surface defect machining |
| SEM | scanning electron microscope |
| SPDT | single point diamond turning |
| TRL | technology readiness level |
| μ-LAM | micro-laser assisted machining |
| USM | ultrasonic machining |
| USMM | ultrasonic micro-machining |
| WEDG | wire electrical discharge grinding |
| WEDM | wire electric discharge machining |

based and non-lithography-based micro-manufacturing techniques. Lithography-based micro-manufacturing techniques comprise methods like chemical-etching, photolithography, LIGA (German acronym for Lithographie Galvanformung und Abformung which means lithography, electroplating, moulding and plating). Non-lithography-based manufacturing includes methods such as mechanical micro-machining, electro-physical and chemical machining i.e. electric discharge machining (EDM), electrochemical machining (ECM), laser machining, and micro-moulding etc. [2]. Lithography-based micro-manufacturing techniques are important to semiconductor industries or MEMS/NEMS and are utilised for mass production, mainly sensors and actuators made from silicon or a limited range of metals. Non-lithography-based manufacturing processes have the capability to create 3D complex shapes, better relative tolerances with smooth surfaces in all directions and can be applied almost universally to a wide range of materials. Although for very small absolute tolerances and 2D shapes, lithography is the best approach, non-lithography processes are suited to bridge the gap between the macro and nano/micro-machining domains [3] and are therefore scientifically important.

Various machine tools have been designed and built to do the job of precision micro-machining but overcoming the stringent requirements of tighter tolerances, high positioning accuracies, and controlled modulations of machined surface texture, low-cost-modular-multi-featured part manufacturing requires further innovations in manufacturing research. As a response to these necessities, multifunctional machine tools have been developed to perform several sequential micro-machining processes on a single machine tool for agile and cost-efficient manufacturing of the micro-components [4]. This process chain is referred to here as sequential micro-machining and it should not be confused with the term hybrid micro-machining. An illustrative example of the differences between the two terms is given by considering micro-laser assisted machining (μ-LAM) and surface defect machining (SDM) [5]. Both μ-LAM and SDM approaches make use of a laser beam during or before mechanical micro-machining. However, the former uses the laser in real-time during the cutting process to facilitate softening of the substrate and hence the name hybrid micro-machining while the later uses the laser beam to create pre-manufactured surface defects to ease the shearing of the substrate prior to mechanical cutting making – thus making it a sequential micro-machining operation.

So defined, hybrid micro-machining processes are based on simultaneous and controlled interactions between two or more machining mechanisms and/or energy sources/tools having a significant effect on the process performance. The phrase “simultaneous and controlled interactions” means that the processes/energy sources should interact in the same processing zone and at the same time [6]. However, for sequential micro-machining processes, two or more micro-machining techniques are implemented “in-sequence” and may involve one or multiple machine tools. Recently, authors have characterized the machining capability, advantages, drawbacks, possible future efforts

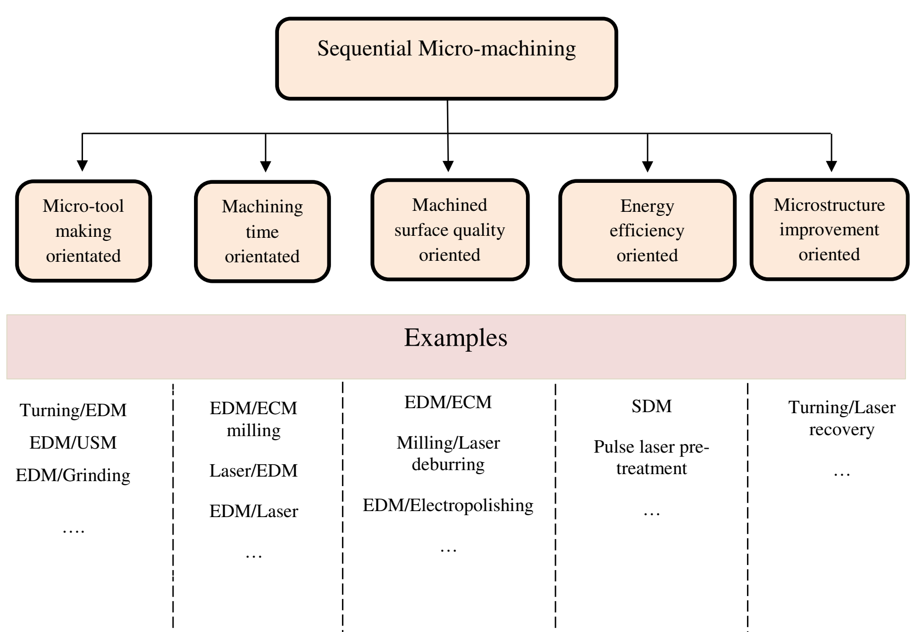


**Fig. 1.** Classification of sequential micro-machining.