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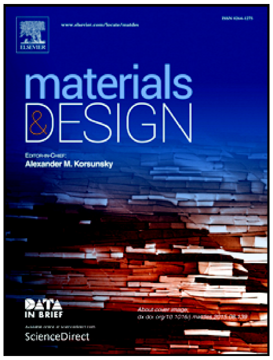

Current trends and future of sequential micro-machining processes on a single machine tool

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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 and registration errors between processes. 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.

Keywords: Sequential micro-machining; Multifunctional machine tool; Micro-components

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

1. Introduction

There are ever-progressing demands of miniaturised/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-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-multifeatured part manufacturing requires further innovations in manufacturing research. As a response to these necessities, multifunctional machine tools have been developed to perform several sequential 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 characterised the machining capability, advantages, drawbacks, possible future efforts and developments in the area of hybrid micro-machining processes under two major categories namely, assisted and combined techniques [7] that has served as a valuable guideline to draw upon the stark differences between hybrid and sequential micro-machining articulated in this work.

Micro-components might have to satisfy some predefined requirements including geometric complexity, geometric tolerances, surface integrity (surface roughness, microstructure, grains sizes and orientation, surface hardness and residual stresses), micro-component life, cost, machining time and production size. Usually, fulfilling such requirements cannot merely be accomplished by a single micro-machining process. It requires an entire micro-machining process chain to fabricate a micro-component capable of satisfying these requirements. In other words, better quality and efficiency are achievable with a properly defined micro-machining process chain encompassing sequential micro-machining processes on a single machine tool enabling continuous modifications and optimisations of the micro-components.

Inspired by the lack of consolidated literature in this area, this paper aims to provide a new classification and then to summarise the current developments and recent trends in sequential micro-machining processes. Therefore, this study is expected to be of use as a possible research guideline for further work in this area. It may be noted here that while the above brief introduction highlights some of the possible combinations of the micro-machining processes, there are a range of other processes that can be implemented in sequence in general. However, the main purpose of this review is to analyse the possibility of integrating some of these sequential micro-machining operations on a single machine tool and in order to provide a step advance in the currently available machine tools. In the next section, definition and classification of the sequential micro-machining processes are provided. On a note that micro-machining processes described in this work refer to mask-less direct material removal processes, a comprehensive review of the sequential micro-machining research efforts are summarised. Alongside identifying future research trends in sequential micro-machining processes, a concise view on future research directions are concluded in the final section.

2. Definition and classification

As noted earlier, sequential micro-machining incorporates at least two different micro-machining processes in sequence on one or multiple machine tools rather than integrating the two standalone machining technologies together. Hence, no simultaneous interaction between two or more machining mechanisms occurs during the fabrication cycle. A modern trend in micro-machining technology is gearing towards building capabilities on a “single machine tool” to perform sequential micro-machining operations. Based on the purpose with which sequential micro-machining techniques are executed, they can broadly be classified into five major categories, depicted in Fig. 1. Sequential micro-machining processes such as Turning/EDM [8, 9], Block-EDM/EDM [10], EDM/Grinding [11] and EDM/USM [12] are motivated primarily for customised tool making followed by carrying out the mainstream machining process to avoid realignment and clamping errors. It may also be noted that ECM/EDM [13], Laser/EDM [14-16] and EDM/Laser [17] can be integrated with the purpose of enhancing material removal rate (MRR) whilst EDM/ECM milling [18-20], Milling/Laser deburring [21], and EDM/Electropolishing [22] are considered as roughing/finishing sequential micro-machining processes to improve machined surface finish and form accuracy. Energy efficient and microstructure improvement oriented sequential micro-machining processes i.e. SDM [23-25] and single point diamond turning (SPDT)/laser recovery [26], respectively, are also proposed in this paper. However, it may be noted that up until now SDM and SPDT/laser recovery have been performed on different machine tools. Nonetheless, there is a great potential to integrate them on a single machine tool. Hence, they are also introduced and characterized in this paper. Basically, SDM [23-25] and pulse laser pre-treatment [27] are among energy efficient machining processes utilising laser ablation/turning to reduce the energy consumption as well as to improve the quality of surface finish. Similarly, turning/laser recovery [26] may be adopted to improve the crystal structure of the machined surface of workpiece post-machining by the diamond cutting tool.

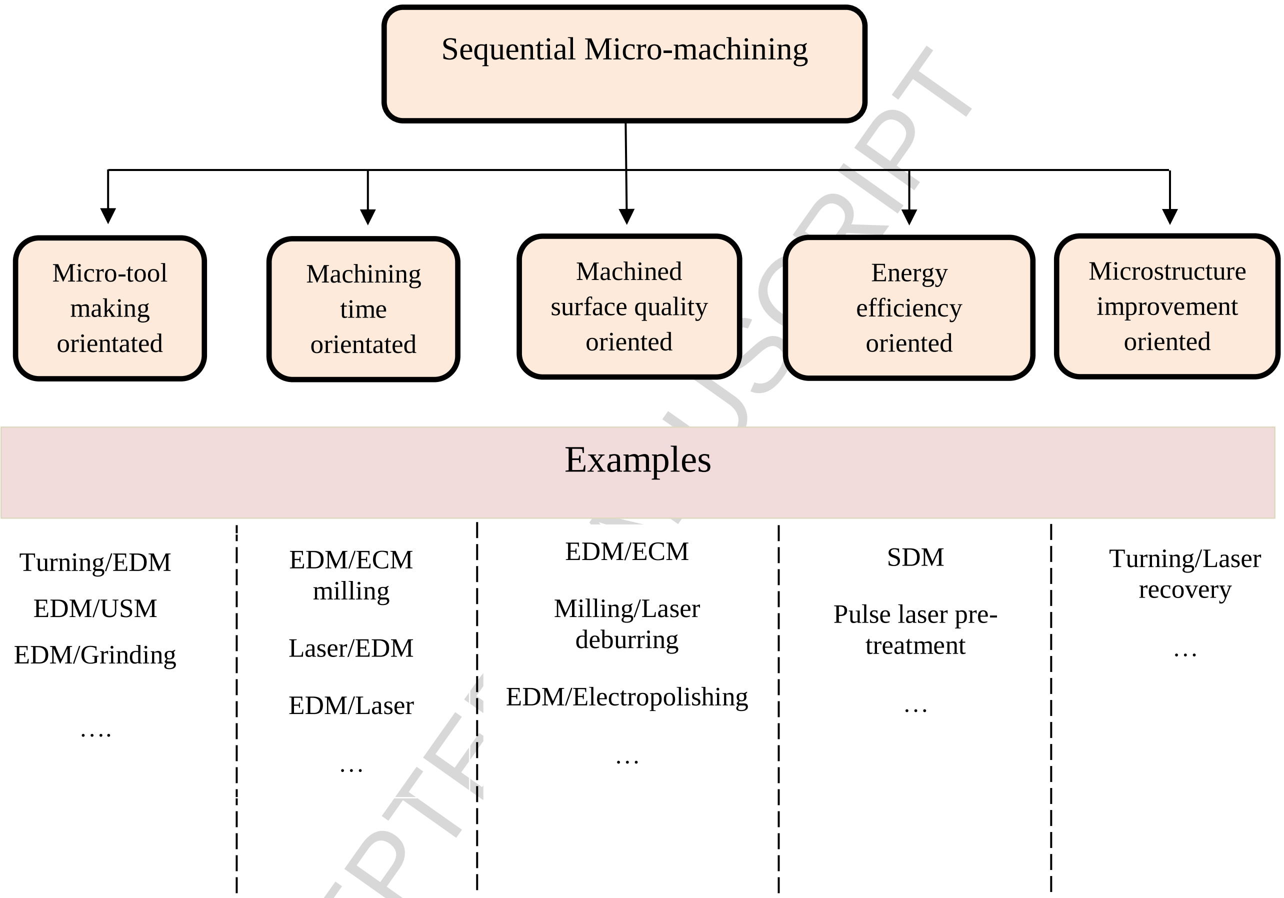


Fig 1. Classification of sequential micro-machining

3. Micro-tool making orientated processes

3.1. Micro-turning plus micro-EDM

Micro-EDM has started to emerge as a standalone technology due to its popularity in micro-machining especially for fabricating extremely fine-featured micro end mills [28].

Nevertheless, the process inherently has some drawbacks, such as a high electrode wear rate and low MRR. To alleviate this critical shortcoming, the electrode requires either to be replaced by a new one or to use a longer electrode allowing compensation of the worn height of the electrode. However, a better solution would be in-situ fabrication of the electrode.

Replacing the microelectrode during machining is not advisable as it may compromise the accuracy during repositioning. Machining with longer electrodes introduces deflection due to low stiffness. On-machine fabrication of the tool would be a good solution to avoid such issues. Aside from this, dielectric fluid is also suggested to play an important role in influencing the process performance [29]. Fig. 2 illustrates the concept of turning/EDM sequential micro-machining. In this process, fabrication of stainless-steel was accomplished by a sequential micro-machining approach using an electrode which was first fabricated using a micro-turning process and was subsequently used to drill micro-holes using the micro-EDM process.

Fabrication of variable hole sizes requires different sizes of electrodes and this is easily achievable from micro-turning. Hence, this sequence significantly reduces the electrode preparation time, in comparison with the conventional sacrificial electrode fabrication method. Aside from this, this sequence eliminates the problems of positioning errors and deflection of the electrode. There is however a caveat that the micro-turning process cannot normally be used for producing large micro-shafts (longer than 1 mm) and may need other fixtures or manufacturing solutions. This issue is identified as a primary drawback of turning/EDM sequential micro-machining techniques. Other examples are shown in Fig. 3 and Fig. 4. Fig 3 shows a 22 µm brass shaft fabricated by a micro-turning process and used for EDM. The figure highlights wear of the electrode induced at the tip of the electrode after boring about 10 holes in stainless steel plate. Fig. 4 demonstrates an example of a micro-scale machining artefact successfully machined by turning/EDM sequential micro-machining [8, 9].

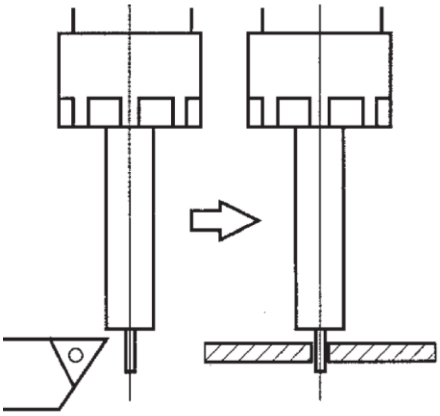


Fig 2. Turning/EDM sequential micro-machining concept [8, 9]

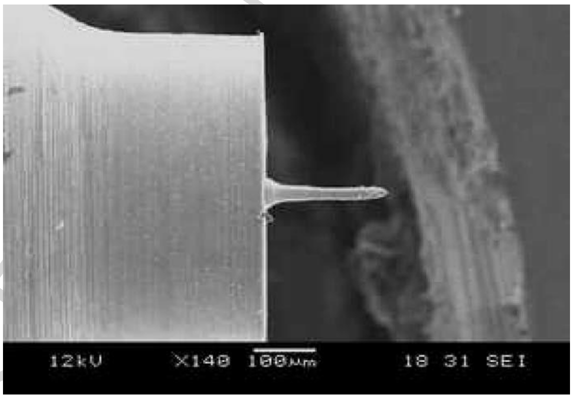


Fig. 3. A 22 µm brass electrode manufactured by micro-turning and utilised for machining 10 micro-holes on stainless steel plate [8]

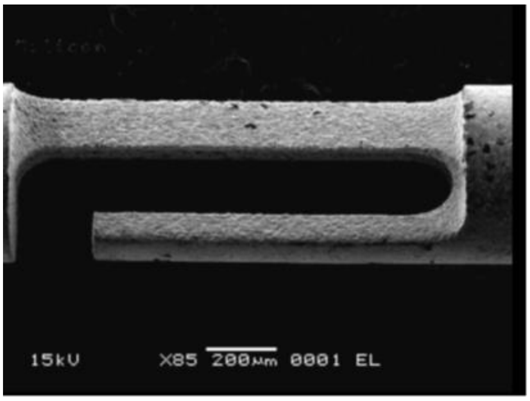
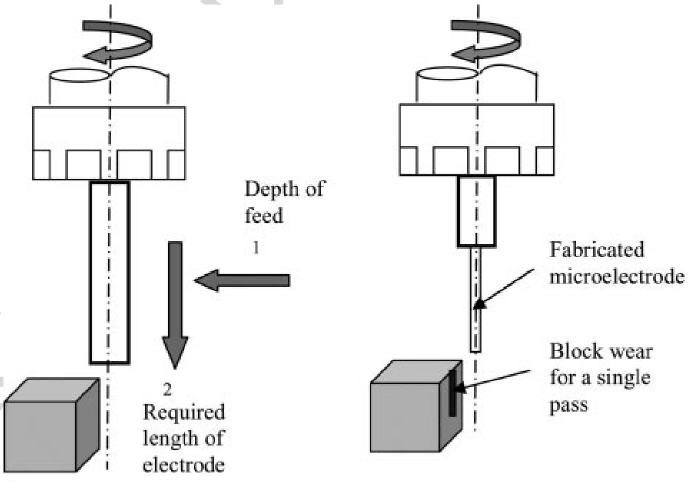


Fig. 4. A steel micro-scale machining artefact fabricated by turning/EDM sequential machining [30]

3.2. Block-micro-EDM plus micro-EDM

Fabrication of high-aspect-ratio micro-holes via micro-EDM can be accomplished by using a very long electrode (usually many times longer than the workpiece thickness). As mentioned in the previous section, fabrication of a large micro-shaft by using the micro-turning process would be problematic. Thus, researchers have employed a free-force technique called block-μEDM process to manufacture high aspect ratio micro-electrodes. Fig. 5 shows a schematic diagram demonstrating the concept of block-μEDM technique. A high wear resistant material like tungsten carbide (WC) is utilised for fabricating the block material. Any commercial grade electrode suits the purpose. During the μEDM process, the block and cylindrical rod are utilised as the cutting electrode and workpiece, respectively. The micro-electrode to be machined is fed against the conductive block of WC. A controlled electric spark is applied during the process. Flushing action of the dielectric during the process aids carrying away the eroded material.

The major drawback of the block-μEDM process is undesirable tapering of the micro-electrode. To avoid this problem, a modified block-μEDM process has been developed that makes use of a scanning movement of the electrode along with the downward movement. The scanning movement refers to a ‘back and forth’ movement along a specific direction. Fig. 6a and Fig. 6b are SEM images of the tungsten (W) electrodes manufactured using stationary and moving block-µEDM processes. It has been found that the moving block-µEDM process creates less tapered micro-electrodes; hence, better dimensional accuracy in the fabrication process can be achieved. Conversely, the sacrificial electrode method takes much more time than the micro-turning process (10-20 minutes compared with 2 minutes for micro-turning) [10, 11]. Fig. 7 shows an SEM image of a micro-pyramid of steel fabricated using the micro-EDM milling process with the on-machine block-µEDM fabricated electrode. Each step is machined layer by layer to 7 µm in width and 7 µm in depth using an electrode with a diameter of 15 µm and electrical parameters of 80V and 30pF capacitance and the whole process takes only about 150 minutes to finish the fabrication [11].



(a) (b)

Fig. 5. Concept of block-µEDM process (a) at the beginning of the process and (b) the fabricated micro-electrode [10]

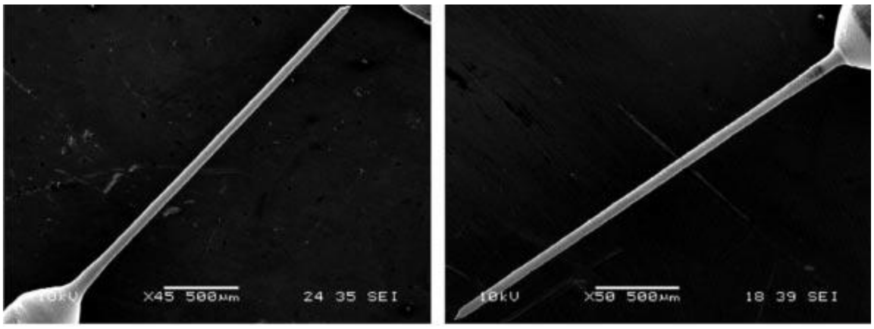


Fig. 6. W micro-electrode, (a) with a diameter of 60 µm and a length of 3 mm (aspect ratio=50) fabricated by the stationary block-µEDM process and (b) with a diameter of 40 µm, and a length of 3 mm (aspect ratio=75) fabricated by the block-µEDM process with a moving electrode [10]

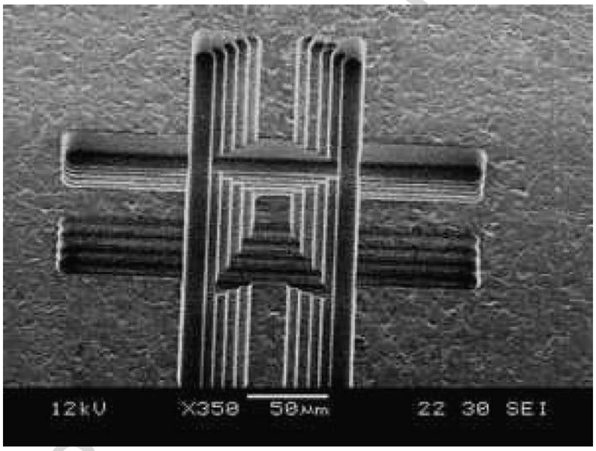


Fig. 7. Micro-pyramid (25 µm×25 µm×35 µm at the top, step size 7 µm) machined on steel by micro-EDM milling with the on-machine block-µEDM fabricated electrode [11]

3.3. Micro-EDM plus micro-grinding

In this method, a micro-grinding tool is firstly fabricated on-machine with a two-step process of block-µ-EDM and scanning micro-EDM for the sake of ensuring a polished flat surface. A sacrificial tungsten block with high wear resistance is utilised to fabricate the tool. The polycrystalline diamond (PCD) tool is set to positive polarity and the tungsten block is set to negative polarity. Once a voltage is applied between the PCD rod and tungsten block, an intermittent spark occurs in the gap between the two which causes the surface of the block and the rod to melt, leading to the removal of the material from both the electrodes. The removed material is carried away from the cutting zone via side flushing. Changing the capacitance and voltage can influence the surface generation process. The fabricated PCD tool in the micro-EDM phase is then utilised to micro-grind the glass material on the same machine without removing the tool from collet (and losing registration). Fig. 8 shows the setup of micro-grinding with micro-EDM (used to fabricate the PCD tool). Fig. 9 displays the machining features in the form of characters “N” and M” in BK7 using micro-grinding process with the on-machine produced PCD tool. A smooth and clear surface is visible in the slots. The measured surface roughness on the slots is around 12 nm [9, 11].

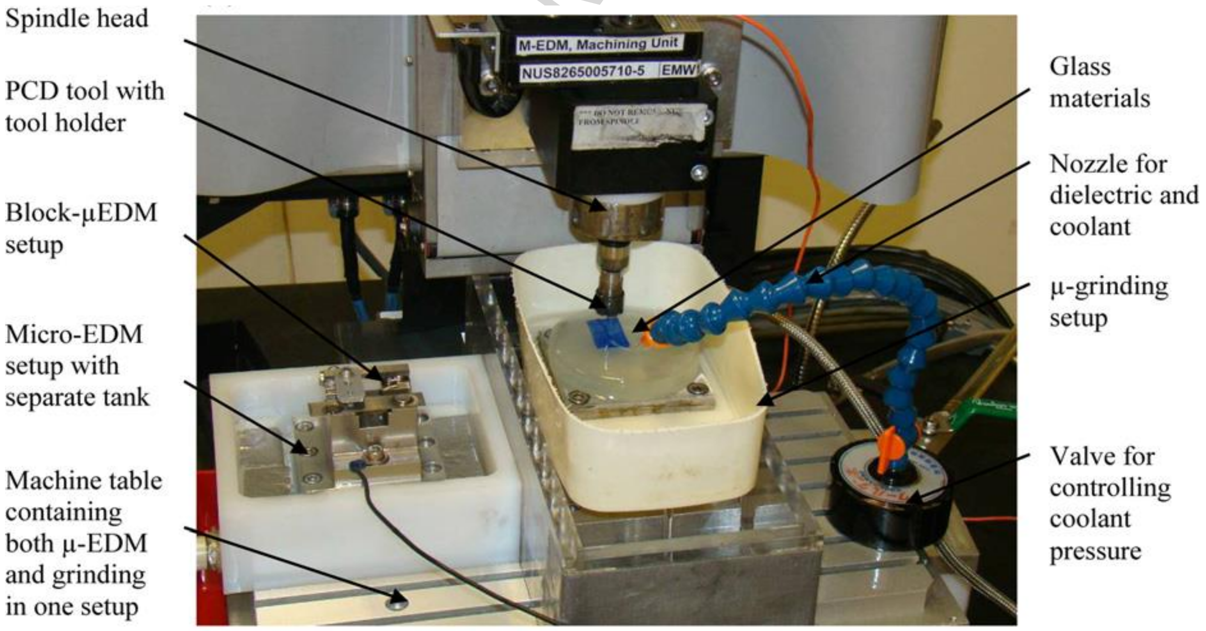


Fig. 8. Set-up of micro-EDM and micro-grinding on the same machine [11]

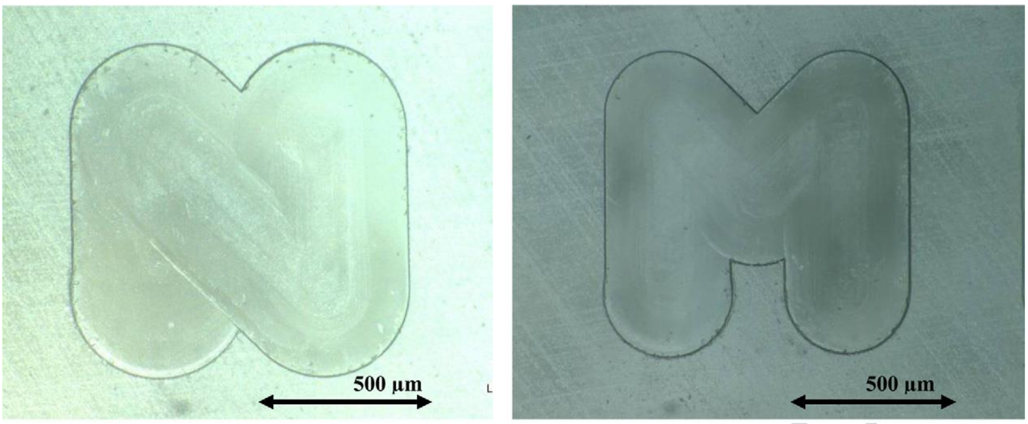


Fig. 9. "N" and "M" shapes produced on BK7 glass by micro-EDM plus micro-grinding [11]

3.4. Micro-EDM plus micro-USM

In this technique, a circular tungsten carbide micro-tool is first fabricated using the micro-EDM process. The newly fabricated tool is then used to drill micro-holes in non-conductive materials using the micro-USM (MUSM) process. In this process, the micro-tool is retained in the same fixture thus tool eccentricity issues are avoided. As shown in Fig. 10, the experimental equipment required for this sequential process consists of an EDM machine, a four-axis control system and an ultrasonic machining unit. The four-axis control system is fixed onto the EDM worktable. Motor '*X'* moves the borosilicate glass or copper plate in forward and backward directions, while motor '*Y'* provides upward and downward movements to the workpiece. The micro tool is clamped into a horizontal chuck rotated by the motor '*C*' and directed left and right by the motor '*Z*'. The micro-machining process is performed horizontally easing clearing of debris originating from the micro-holes during micro-USM. The ultrasonic machining unit (frequency, 30 kHz) consists of an electronic generator, a transducer and horn-tool combination equipment. The tool is a cylindrical rod fastened on the horn tip. A small piece of borosilicate glass is chemically glued onto a small rectangular plate attached to the tool tip, as shown in Fig. 11. To evaluate the proposed sequential process, a WC rod is shaped into a micro-tool using a copper plate as an electrode, followed by MUSM of the borosilicate glass. As shown in Fig. 12, a micro-hole with acceptable form and integrity can be fabricated using this sequential micro-machining process [12]. It has also been established that diameter variation between the entrance and exit (DVEE) is influenced by the concentration of slurry, ultrasonic vibration amplitude or rotational speed of the micro-tool. Threshold values of these parameters can be determined at which DVEE is minimum. Furthermore, smaller particle sizes or micro-tool feed rates produced better DVEE. Moreover, experiments have shown that the influence of rotational speed on roundness is similar to the rotational speed effect on the DVEE. Hence, for better roundness of the micro-holes, good control of rotational speed is critically important. As for the surface roughness, a finer quality of machined finish can be obtained when smaller abrasive particle sizes are used. It should be noted here that the noise produced by the ultrasonic frequency generation system could be a significant concern in terms of noise pollution in some environments.

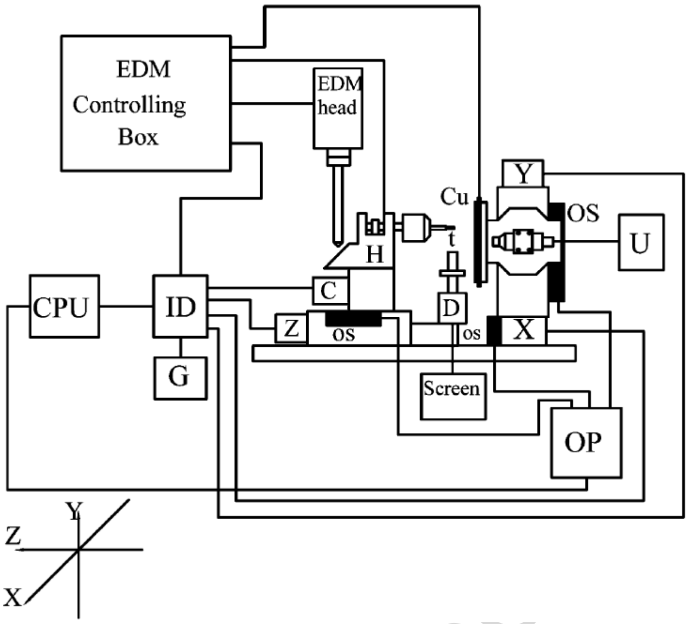


Fig. 10. The arrangement of MEDM and MUSM apparatus: U, ultrasonic vibration equipment; OS, optical scale; OP, optical scale counter; X, Y and Z, motors for x-, y- and z axes movement; Cu (copper plate), EDM electrode; H, rotating chuck holder; t, micro-tool; D, computer controlled display; C, motor for c-axis rotation; ID, interface circuit and motor driver; G, function generator; CPU, computer [12]

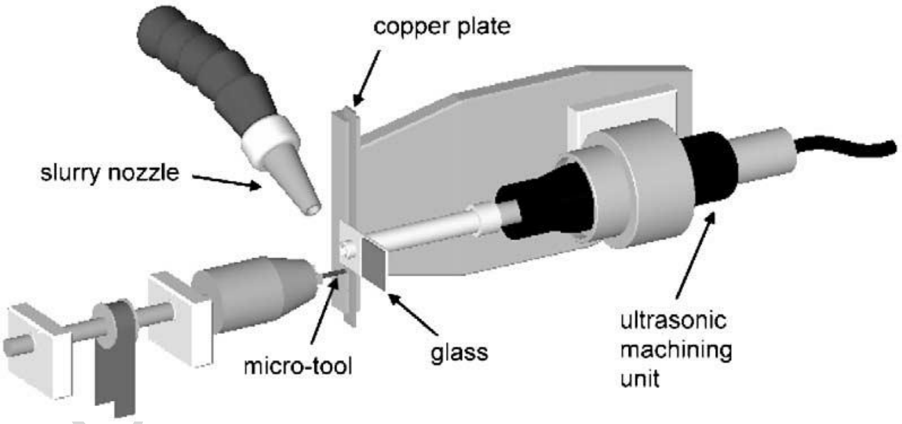
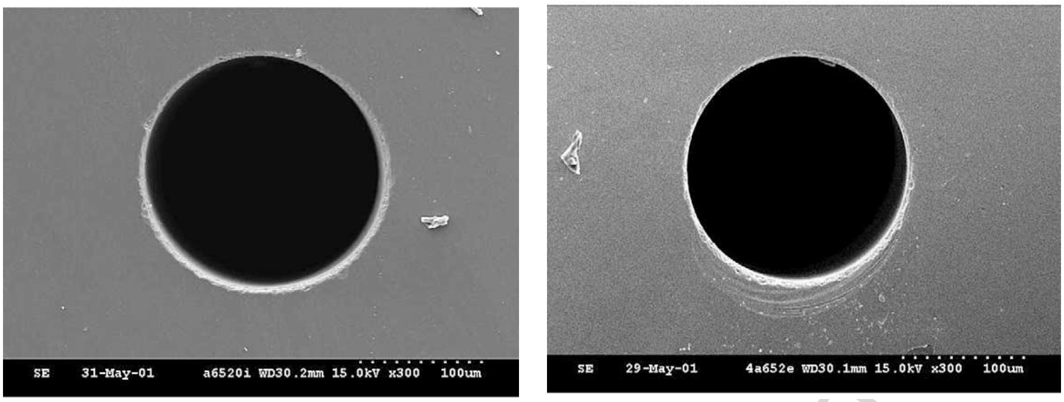


Fig. 11. A detailed diagram of experimental apparatus used in the MUSM process [12]



(a) The entrance of the micro-hole (b) The exit of the micro-hole

Fig. 12. Micro-hole fabricated on borosilicate glass by micro-EDM/USM (a) The entrance of the micro-hole (b) The exit of the micro-hole [12]

4. Machining time orientated processes

4.1. Micro-ECM plus micro-EDM

Sequential micro-ECM followed by a micro-EDM process on a single machine tool can be performed with the primary aim of reducing machining time. A prototype of this sort of machine tool is shown in Fig. 13 which was designed and tested at the Institute of Production Engineering at the Cracow University of Technology to examine the process capabilities. Fig. 14 compares the machining time while adopting this sequential micro-machining approach and it has been shown that the application of electrochemical followed by electric-discharge micro-machining (EC/EDMM) in sequence permits a nearly 50% reduction in machining time compared with performing the same task by electric-discharge micro-machining (EDMM) alone. Furthermore, the mean edge radii of cavities machined with the EC/EDMM sequence are found to be considerably more precise than that obtained from the electrochemical micro-machining (ECMM) alone (is virtually the same as the one achieved during EDMM), as demonstrated in Fig. 15. In the EC/EDMM process sequence, when the parameters of the EDM phase are appropriately chosen, the influence of tool wear on the cavity shape is insignificant [13].

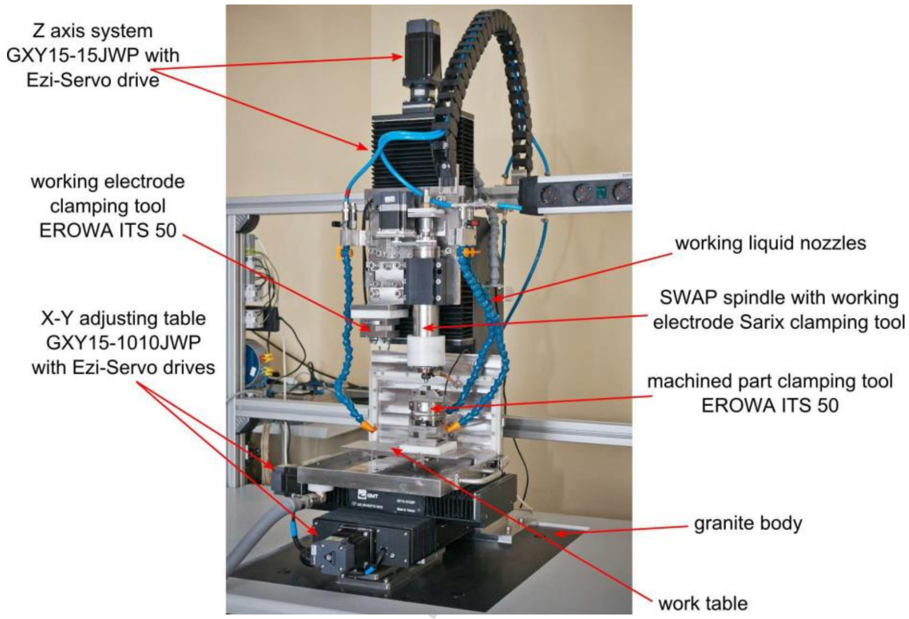


Fig. 13. Photo of the machine prototype for EC/ED micro-machining [13]

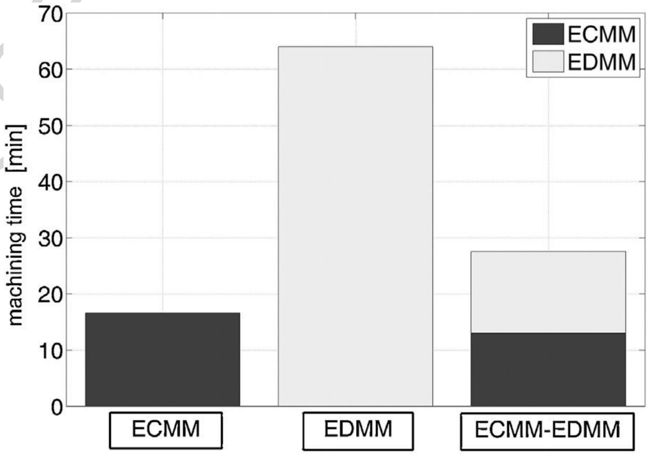


Fig. 14. Comparison of machining time [13]

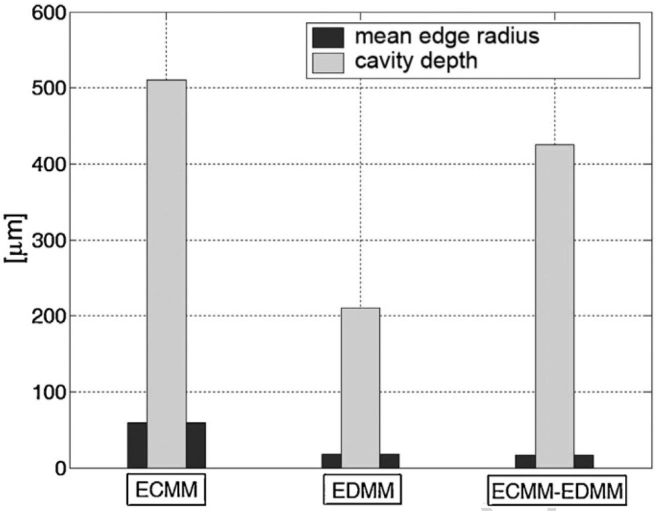


Fig. 15. Comparison of mean edge radius and cavity depth [13]

Fig. 16 demonstrates groove milling by the ECMM and EC/EDMM processes. Edge roundness is considered as a critical problem in 3D-ECMM machined components. Such a problem can be chiefly attributed to irregular electric field distribution, yet it is additionally linked to the fundamental principle of ECMM. When the cylindrical electrode tool is applied, the dissolution time decreases with distance from its axis in a direction that is perpendicular to the electrode movement. Inaccuracy on the interior edges of the parts can be caused by high localisation of the electrochemical dissolution. Fig. 16 shows that milling with the 3D-EC/EDMM sequence can diminish this ECMM drawback [13]. In a general sense, one can state that carrying out ECMM and EDMM treatment on the same machine tool allows for an essential reduction of the disadvantages and enhances the advantages of both methods. The examples of EC/EDMM sequence application presented above indicate numerous benefits resulting from the proposed concept mentioned earlier. These include a decrease in the total machining time (in relation to EDMM) and enhanced accuracy (in relation to ECMM). One of the technical problems for such a process sequence is the changeover of working fluid (electrolyte to dielectric and the reverse). Hence, special care should be taken while designing this system. On the other hand, the final phase in this sequential micro-machining process is micro-EDM which is a thermal process and can engender micro-cracks and recast layer. Thus, it cannot be a complete sequential process. More importantly, cost-effectiveness is a crucial aspect that needs to be considered when fabricating micro-components by this machine prototype and sequential process, requiring post-micro-machining finishing processes.

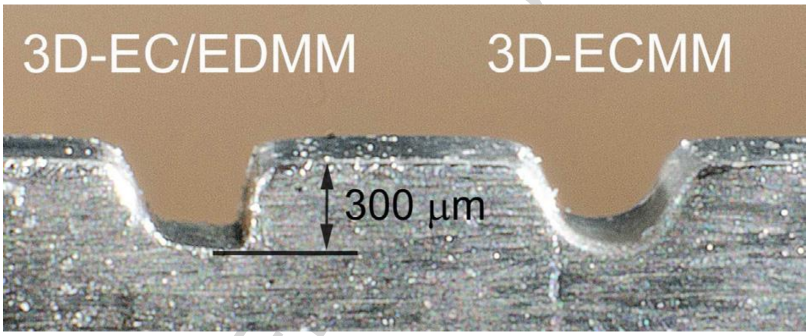


Fig. 16. Micro-grooves fabricated on SAE 304 grade stainless steel by ECMM and by a sequence of EC/EDMM [13]

4.2. Laser micro-ablation plus micro-EDM

In this technique, pilot micro-scale artefacts are first subjected to a roughing cut by a pulsed laser beam and then finished precisely using micro-EDM [14-16]. The main concept of this sequential process is presented in Fig. 17. Firstly, a nanosecond pulsed laser is utilised in order to achieve higher material removal rate using higher ablation power so that the process doesn’t cause any tool wear, albeit care must be taken to avoid overheating of the lens through which the laser passes. Micro-EDM achieves relatively low MRR but it is a reliable process, and is utilised sequentially to carry out the final finishing operation and to remove the metallurgically deformed recast layer left by the laser. Thus, this sequential technique can reduce the overall process time whilst retaining the shape accuracy. Compared with EDM, laser machining time is barely significant; hence, the two dominant parameters for enhancing the machining efficiency are (a) minimisation of the time interval and (ii) decrease of the machining time in EDM that is supported by laser pre-machining.

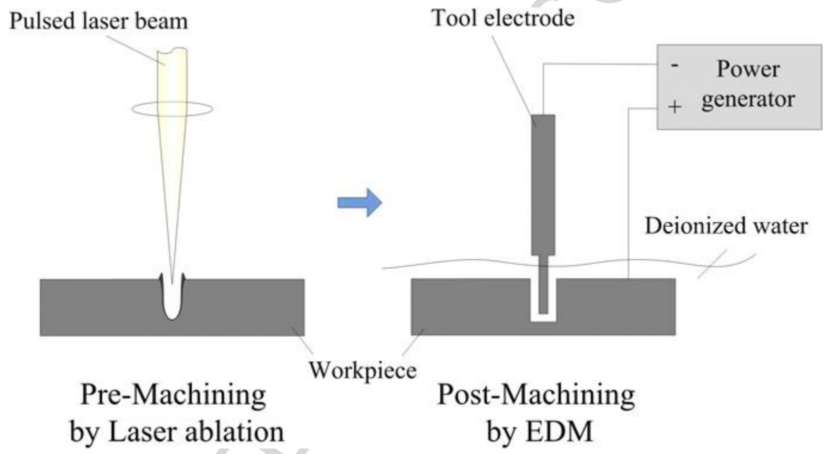


Fig.17. Concept of laser ablation/EDM [14]

Fig. 18 shows an experimental system that was developed for carrying out this sequential micro-machining technique. In this process, deionised water is utilised as the dielectric fluid. Although the machining gap in micro-EDM turns out to be smaller when using kerosene in contrast to deionised water, a higher machining efficiency can be achieved by increasing the feed rate. This sequential process is demonstrated to achieve cost reduction by 42% [15] and the drilling time reduced by up to 90%. Micro-grooves of up to 75 µm width and 100 µm depth can easily and flexibly be fabricated using this sequential technique and the overall process time decreases by as much as 75%. Fig. 19 provides additional evidence in the form of an SEM image of a micro-pyramid fabricated on SAE 304 grade stainless steel through this sequential machining method. The machining time for fabricating this micro-scale artefact is around 13 minutes. The decrease of total machining time is 65% compared with the case of conventional micro-EDM [14]. The drawback of this sequential process is that after laser pre-machining, the workpiece needs to be repositioned for carrying out the EDM operation. This may naturally induce unintentional realignment and repositioning errors and there exists an opportunity to develop and eliminate this undesirable drawback.

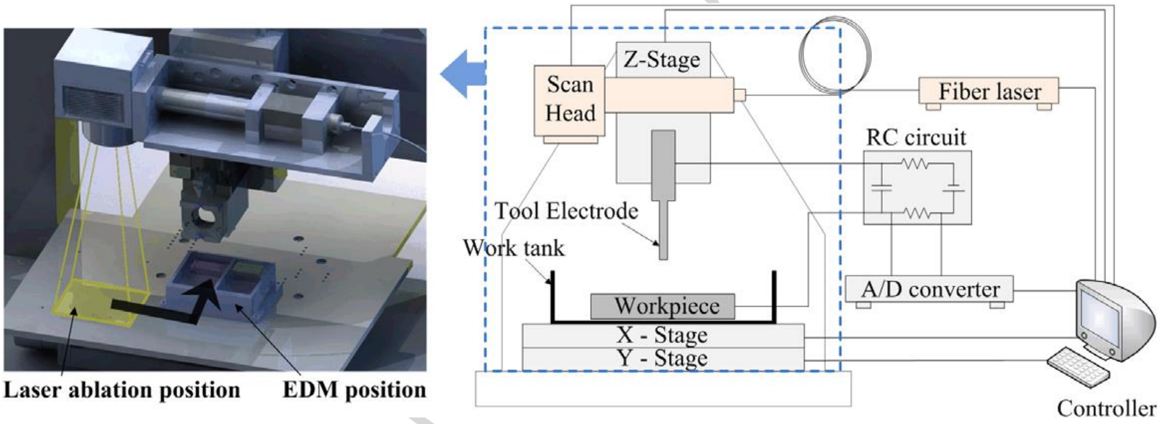


Fig. 18. Laser micro-ablation/EDM set-up [14]

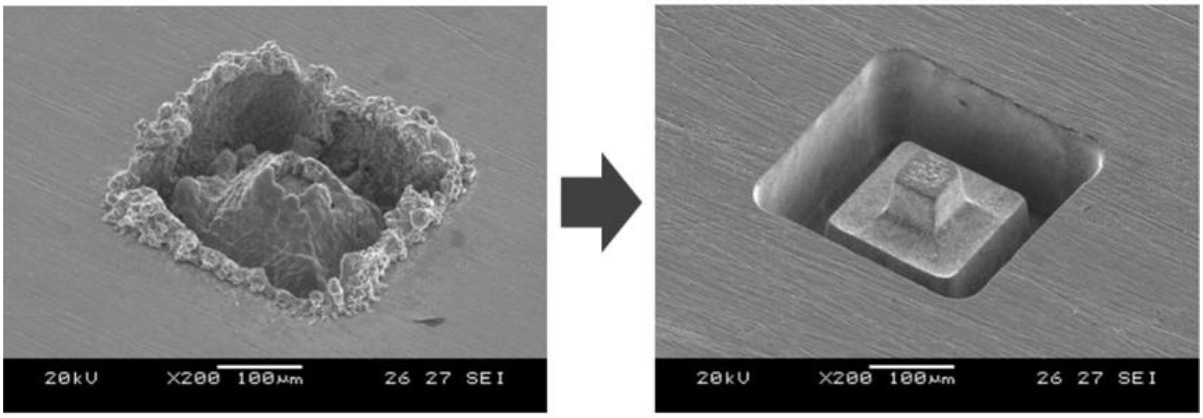


Fig. 19. Micro-scale artefact fabricated on SS304 by sequential laser ablation and EDM [14]

4.3. Micro-EDM plus laser micro-ablation

A die-sinking-EDM-head and a picosecond laser can be integrated on a five-axis machining centre to fabricate micro-scale artefacts. Fig. 20 shows configuration of an EDM/Laser ablation machine tool. This sequential method provides the advantage of reduction in machining time e.g. by eroding the larger micro artefacts with a die-sinking electrode and subsequently ablating the fine details with the laser. The workpiece can be positioned using an *x*-*y*-table and two attached goniometer axes. An objective lens focusses the laser to exhibit a pulse diameter of 7 µm directly onto the workpiece. Both the objective and the EDM-head are assembled with independent *z*-axes. For hardened steels, laser ablation rates vary with the roughness of the surface e.g. laser ablation rates are 1×10^{-5} mm^3/s at a surface roughness of R_a = 0.15 µm whilst the ablation rate can be raised up to 6.2×10^{-3} mm^3/s (depending on the electrode diameter) at a surface roughness of R_a = 0.4 µm for EDM. Thus, ablation by die-sinking EDM can be improved by a factor of 600. By pre-structuring the inner part of the gear wheel with a 200 µm electrode and finishing the tooth-geometry by laser ablation (see Fig. 21), machining time was reduced by 53% [17]. The main problem for this sequential process stems from the dissimilar machining depths due to undefined ablation of the laser. The machining depths of EDM and laser ablation must be carefully synchronised; hence, further investigations are needed to overcome this limitation.

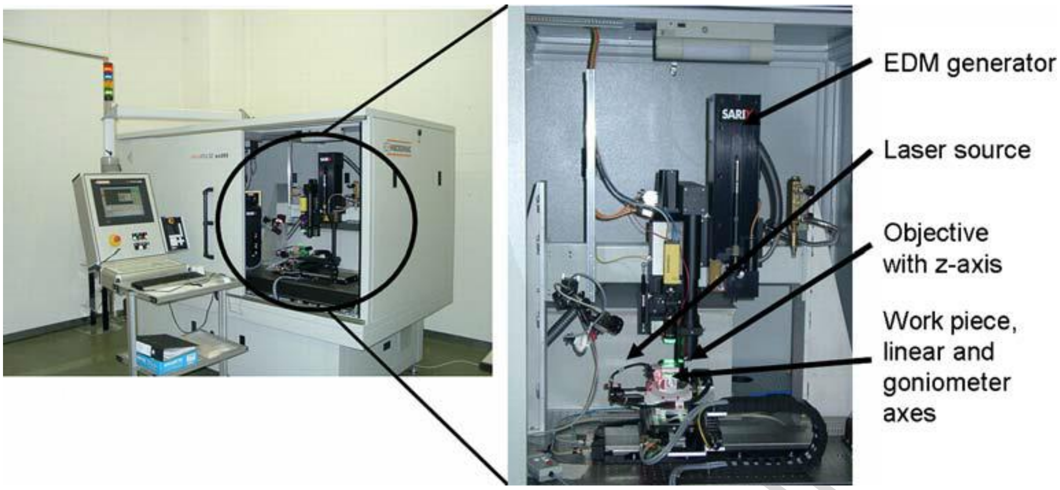


Fig. 20. Machine tool to perform sequential EDM/Laser ablation [17]

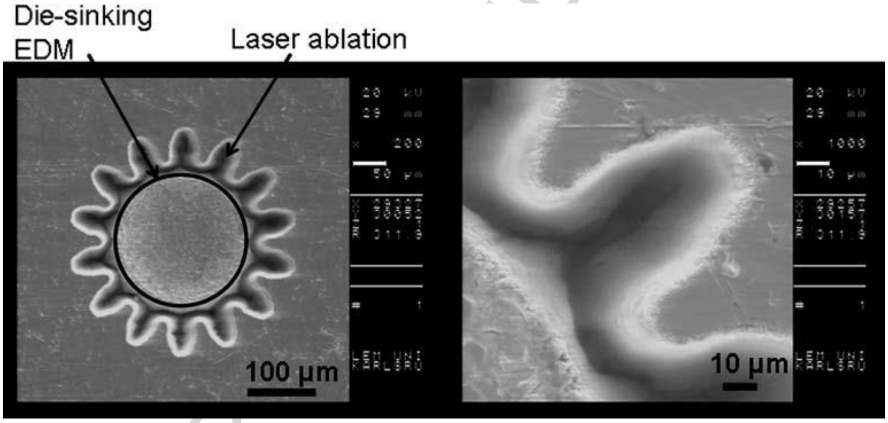


Fig. 21. Hardened steel gear wheel machined by micro-EDM and laser ablation [17]

5. Machined surface quality enhancement oriented processes

5.1. Block-micro-EDM plus Micro-EDM plus micro-ECM

One of the drawbacks of micro-EDM is that it can deteriorate the machined surface due to it being a thermal process involving significant heat transfer which causes metallurgical transformations of the machined surface. The same becomes evident from the visual inspection of the recast layer and micro-cracks generated on the cut surface that could lead to compromised mechanical properties. Furthermore, wear of the electrode requires frequent replacement, thereby bringing reduction in the machining efficiency. In contrast to this, μECM does not produce cracks or the recast layer on the machined surface, and there is no electrode wear in this process. Nonetheless, the stray corrosion during μECM of metallic materials could lead to unsatisfactory part shape in addition to the low accuracy control of workpiece size. To address this shortcoming, a nanosecond short pulse power supply has been adopted to shorten the chemical reaction time by several microseconds. However, accuracy of control of shape and size of micro-parts fabricated by ECM are still low. Additionally, MRR is very low in micro-ECM owing to low energy, pulse-on time and numerous short-circuits, which impede the efficient exploitation of micro-ECM for bulk machining of 3D metallic micro-components. Researchers have attempted to improve precision and accuracy of μECM parts and surface quality of μEDM workpieces to enhance machining efficacy. Advancing these efforts, an application of μEDM and μECM in a sequential process has been proposed (Fig. 22). This process can be implemented by μEDM shaping and μECM finishing in sequence on a single machine tool with the same electrode using different dielectric media (i.e. EDM oil and ECM electrolyte). To avoid realignment and clamping errors, the electrode tool can be fabricated online by a block-EDM process. This sequential micro-machining technique is a three-phase process, namely micro-tool making, roughing and finishing. Fig. 23 illustrates the system configuration of the μEDM and μECM machine tool. Fig. 24 shows SEM images of the five-pointed star machined by micro-EDM and sequential processes. As is evident, the burrs, bumps, micro-pores and craters on the surface machined by the micro-EDM process are successfully removed by micro-ECM finishing, and shape and size of the micro-part is controlled precisely [18-20]. The average machined surface roughness (Ra) of the SS304 surface fabricated by micro-EDM was improved from 0.707 µm Ra to 0.143 µm Ra while using µECM finishing [20]. It should also be noted that the process parameters of the µECM phase should be accurately specified in order to avoid low-accuracy micro-machining. This sequential micro-machining process can be regarded as a successful process since the combination of tool making, main process and finally the polishing process can reduce realignment errors in the first phase and improve machined surface quality in the final phase.

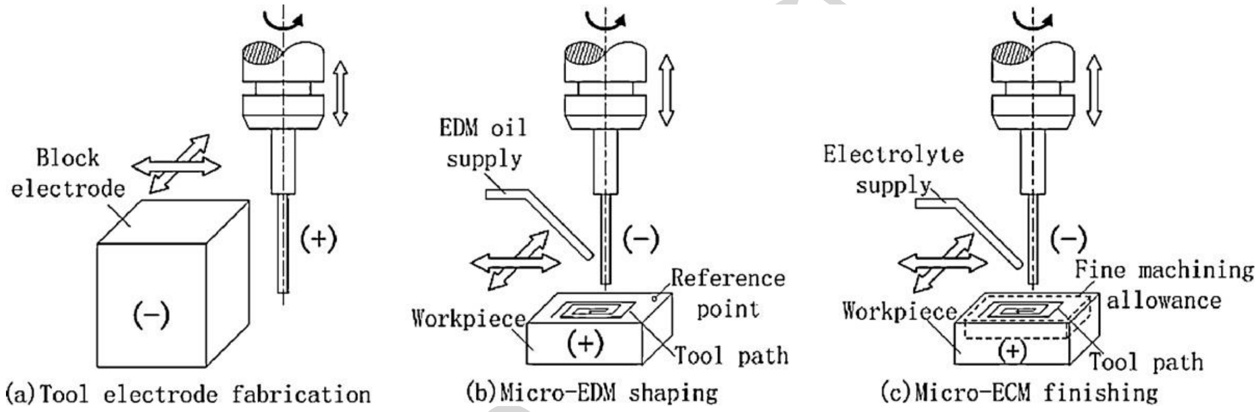


Fig. 22. Concept of block-EDM/ EDM/ ECM sequential machining process [20]

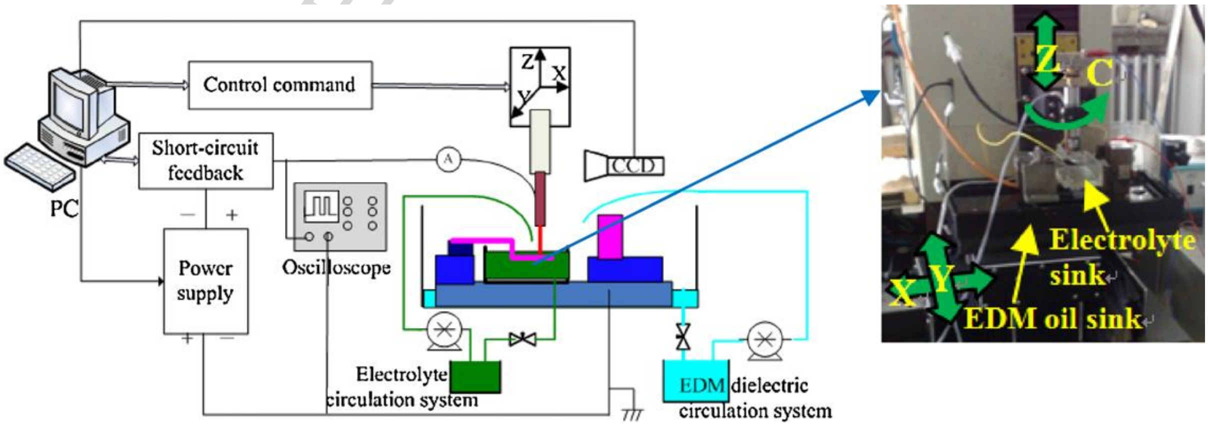
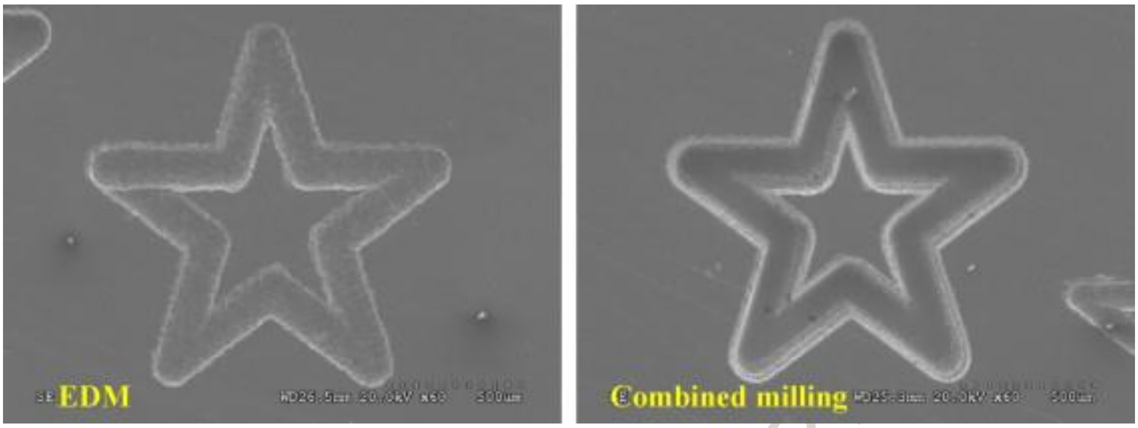


Fig. 23. Schematic diagram and experimental set-up of micro-EDM and micro-ECM machine tool [20]



(a) (b)

Fig. 24. SEM image of the five-pointed star fabricated by (a) micro-EDM milling (b) sequential micro-EDM and ECM milling [20]

5.2. Micro-milling plus laser deburring

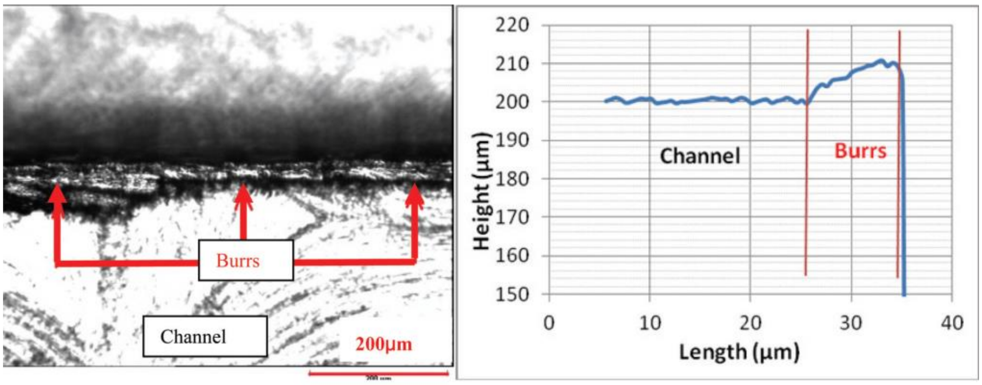
Micro-milling is an efficient technique for fabrication of micro-channels required primarily by NEMS/MEMS as well as for drug-delivery in biomedical applications. Nonetheless, this process would lead to the formation of burrs on the edge or boundaries of the machined surfaces which can influence the flow within the machined tracks e.g. laminar flow can turn into turbulent flow within the micro-fluidic devices. Consequently, a deburring process is required after the micro-milling process. The primary aim of the post-processing method is to carry out deburring with a laser. Laser deburring can be carried out by applying a neodymium-doped yttrium aluminium garnet (Nd:YAG) laser to eliminate the burrs created during the micro-milling process. A crucial parameter in laser machining is the energy density (F). F is obtained by applying the Beer's law:

$$F = F_0 e^{-\alpha I_f} \tag{1}$$

where F_0, α, and I_f are the ablation threshold, optical penetration depth, and ablation rate, respectively. The ablation threshold and optical penetration depth are workpiece-dependent parameters. The ablation rate can be considered equivalent to the protruding volume of the material above a reference surface to be removed per pulse. Hence, the energy density can be derived using equation (1). The power of the laser system to be utilised in laser deburring can be obtained as:

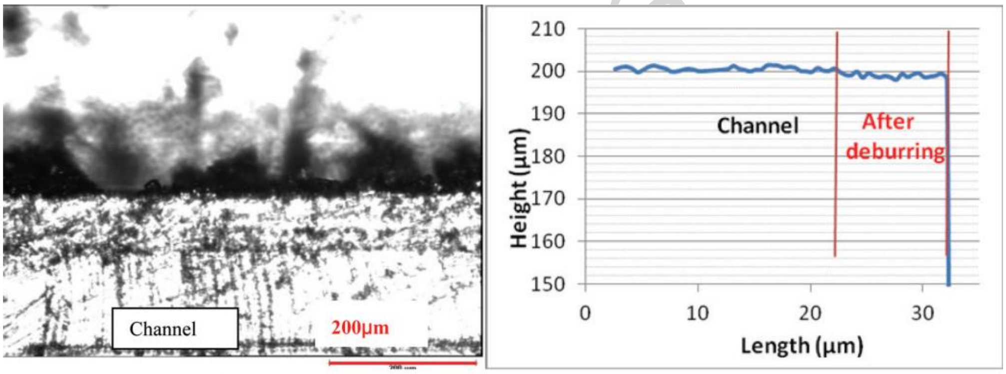
$$P = F \times F_r \times A \tag{2}$$

where P, F, Fr, and A are the laser power, energy density, laser frequency, and area of the laser spot, respectively. The profile of the burr left on the top surface of the micro-fluidic mould channel after the micro-milling process is illustrated in Fig. 25a and Fig 25b. It is evident that the burrs exhibited an average width of around 10 μm and are spread along the channel edge. The height of the burr varies from 8 to 10 μm. It can also be observed from Fig. 26a that the burrs produced in the micro-milling process were removed in their entirety by the laser deburring process. The quality of the micro-fluidic mould channel was improved significantly and control on flow is now more reliable. Fig. 26b shows profile of the cross-section on the edge [21]. Whilst this method seems promising, care must be taken to control the surface oxidation and cracking problems as well as melt depth that may be triggered inappropriately due to improper execution of the laser deburring process.



(a) (b)

Fig. 25. Burrs left on the edge of the NAK80 microfluidic channels (a) SEM image of the burrs observed on the edge of the channel and (b) the profile of the channel [21]



(a) (b)

Fig. 26. Edge of the NAK80 microfluidic channel after laser deburring (a) the burrs removed from the edge and (b) profile of the channel post-deburring [21]

5.3. Micro-WEDM plus micro-EDM plus electropolishing

In this sequential technique, a micro-tool of tungsten carbide is fabricated by a wire electric-discharge grinding (WEDG) process as a prerequisite to drilling micro-holes on the workpiece by a micro-EDM process. As shown in Fig. 27, the tool electrode lengths of both "A" and "B" are 1.5 mm. Area-A is utilised for fabricating micro-holes by micro-EDM whilst Area-B is used for finishing those micro-holes by electropolishing. The surface quality and shape accuracy of the tool deteriorates during the micro-EDM drilling as a result of electrode wear. Thus, the new surface "B" is used to perform electropolishing by adding the electrolyte medium into the tank. The EDM machine is coupled with the electropolishing mechanism as shown in Fig. 28. This sequential process eliminates the necessity of unmounting the electrode thereby avoiding tool eccentricity. Fig. 29 depicts configuration of the micro-EDM and electropolishing system with built-in WEDG. The WEDG mechanism is fixed on the EDM worktable. The four-axis control system is fixed onto the EDM machine head on which the linear guide can be moved in the forward/backward and left/right directions by motors *Y* and *X*, respectively. The micro-tool is clamped onto a vertical chuck and can be rotated by a motor *C*, and it can be moved up and down by the EDM main spin motor *Z*. The electropolishing system is made up of a conductive sheet, a power supply and a polytetrafluoroethylene (PTFE) tank. During the operation, the workpiece is fixed at the centre of the electropolishing mechanism.

This sequential technique is a multi-phase process i.e. straight deep micro-holes are drilled by micro-EDM in the initial phases and finishing is done by the electropolishing process in the final phase. The machined surface roughness R_{max} in a high nickel alloy workpiece was reduced from 2.11 μm before electropolishing to 0.69 μm after electropolishing, signifying the importance of this sequential micro-machining process in fabricating micro-holes with precise shape and smooth surface. The polishing phase takes about 5 minutes [22].

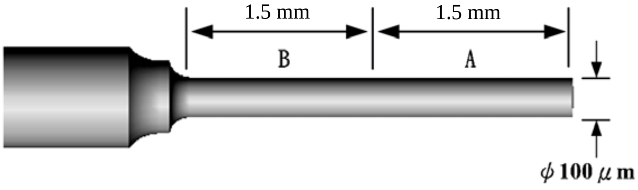


Fig. 27. The model of a tungsten carbide tool rod [22]

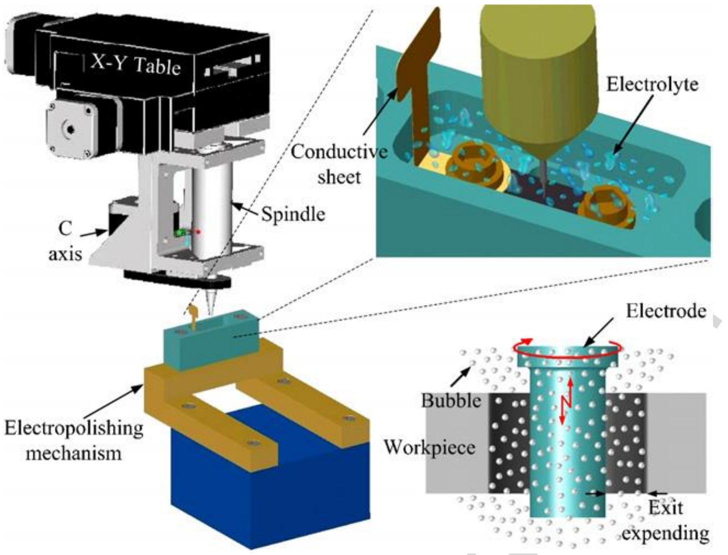


Fig. 28. Schematic diagram of electropolishing after micro-EDM [22]

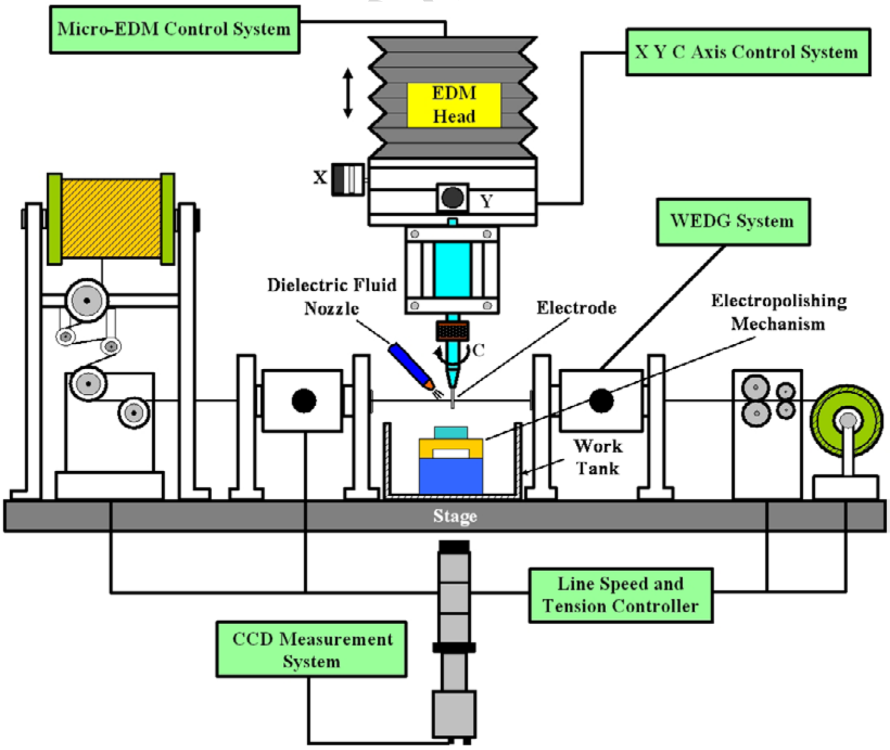
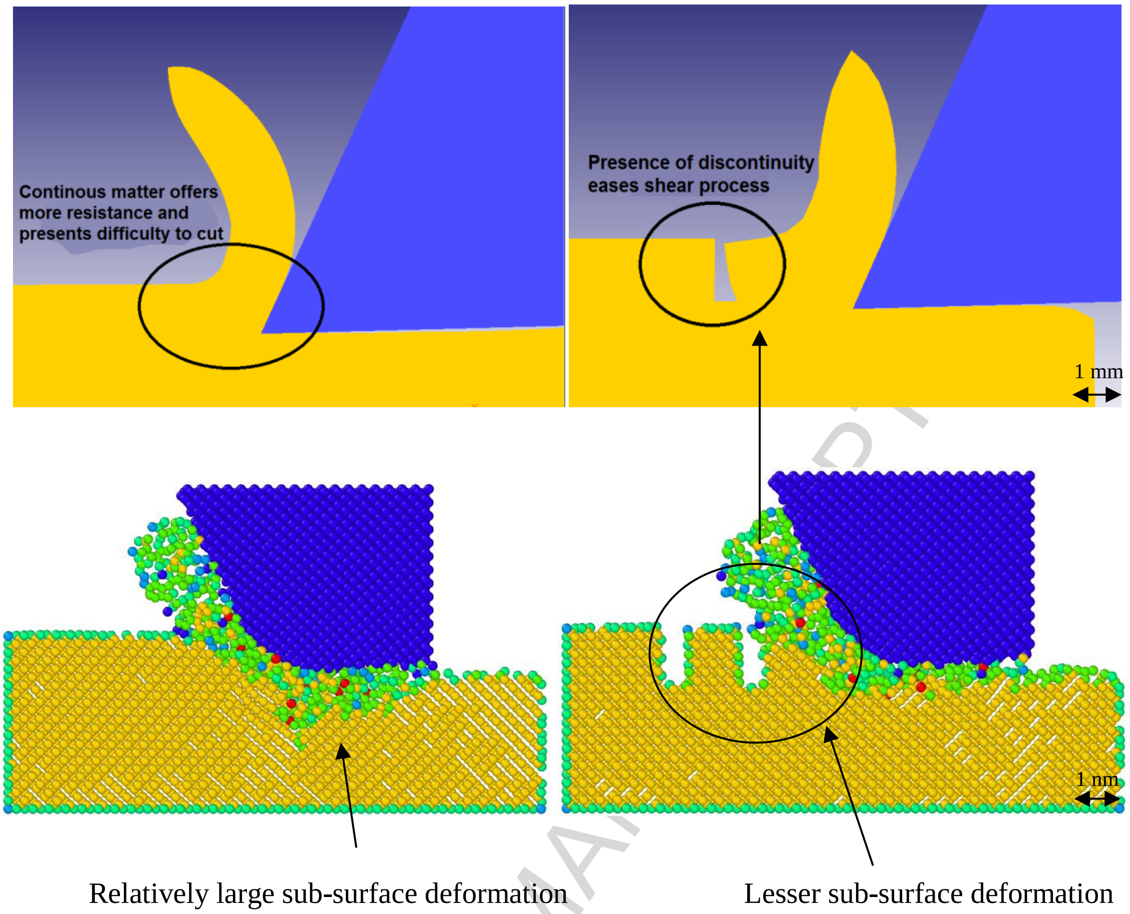


Fig. 29. System arrangement of the micro-EDM and electropolishing system with built-in WEDG [22]

6. Energy efficient sequential micro-machining

In this category of machining processes, surface defects at depths less than the uncut chip thickness are generated on top of the workpiece surface by mechanical means /laser ablation prior to carrying out the routine cutting process. It has been shown that this sequence of operation results in reduction of specific cutting energy more than the energy consumed in manufacturing the surface defects [5, 23-25, 27] by the means of laser. This promising machining technique have been so far conducted for macro-machining on separate machine tools. However, it can be miniaturized and integrated on a single machine tool. This method is beneficial for micro-machining of difficult-to-cut materials such as hard steels and silicon carbide and its developers believe that the method is versatile enough and can be applied universally across a range of other materials. Besides lowering the machining energy, SDM also provides an additional advantage of reduced sub-surface deformation as shown in Fig. 30. Adoption of this sequential micro-machining process enables ease of material removal by shearing the material at reduced input energy. Also, due to the large proportion of stress concentration in the cutting zone – rather than the sub-surface – it enables a reduction in the associated residual stresses on the machined surface.



(a) (b)

Fig. 30. Schematic diagram indicating the differences between the mode of deformation during (a) conventional machining and (b) SDM obtained from the FEA simulation of hard steel and MD simulation of silicon carbide respectively [24]

It is assumed that the shape of the surface defects (Fig. 31) plays a significant role in governing the mechanism of deformation in the cutting zone of the workpiece. The geometry and spacing of surface defects eventually dictates the shear plane angle and the achievable reduction in the machining energy. Compared with mechanical processes, the advantage of laser ablation is that any sub-surface deformation triggered by laser heating can be reduced during the heat treatment process; therefore, the proposed method is potentially superior due to the subsequent thermal annealing [24] especially during machining hard steels i.e. in a hard turning process.

Depending on the density of surface defects, it is possible to realise significant improvement in the machinability of difficult-to-machine materials and obtain reduced side flow and a better machined surface with less metallurgical transformation on the finished component. Using a traditional turret lathe and a CBN tool, the machined surface roughness R_a on an AISI 4340 workpiece was reduced from 47 nm to 30 nm using this sequential micro-machining method [23]. It may be noted that originally SDM [24] was not performed for micro-machining on a single machine tool, however, there is a great potential to integrate a laser source and micro-turning machine on a single machine tool, similar to the approach of a pulse laser pre-treated machining process [27].

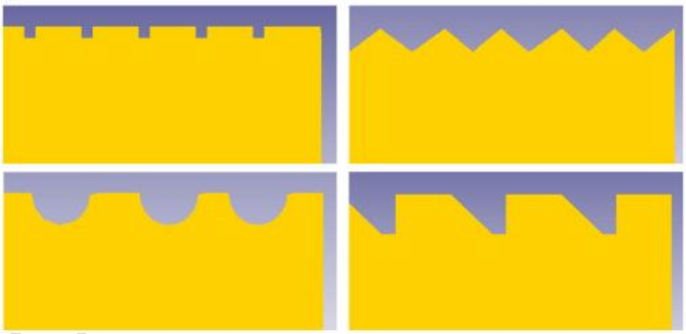


Fig. 31. Examples of the various surface defects [23]

7. Microstructure improvement oriented sequential micro-machining processes

This is an emerging technique which can be employed to achieve atomic-level subsurface integrity and nanometric surface roughness. Micro-turning/laser recovery is a good example of this group of sequential micro-machining processes. The method was first proposed by

Yan and Kobayashi [26] to recover machining-induced surface damage on single-crystal silicon left by diamond machining. The proposed laser recovery mechanism is schematically shown in Fig. 32. Diamond machining leaves an amorphous layer on the machined silicon surface. Amorphous silicon has a remarkably higher laser absorption rate than crystalline silicon i.e. there is sufficient absorption of laser radiation in the near-surface layer to form a liquid thin film (b). The liquid layer has a much higher absorption rate, thus becomes increasing its thickness through positive feedback, limited by the attenuation from increased absorption (c). The top-down melted liquid phase finally extends below the dislocations/microcracks (d). After the laser pulse, environmental cooling results in bottom-up epitaxial growth from the defect-free bulk region, which serves as a seed for crystal growth (e). In this way, a perfect single-crystal structure identical to the bulk region can be obtained (f) eliminating the necessity of chemical etching, which is environmentally unfriendly. Moreover, due to the surface tension effect of the liquid layer during silicon melting, an initial rough surface may become smooth after crystal regrowth (b)-(f). Therefore, improvement in both surface quality and subsurface integrity may be realised at the same time. This process involves no material removal, no emission and no pollution, thus provides an effective new approach for ultraprecision manufacturing. Note that Yan and Kobayashi [26] utilised this technique on isolated machine tools, however, the method, similarly to SDM, is readily adoptable for integration on a single machine tool.

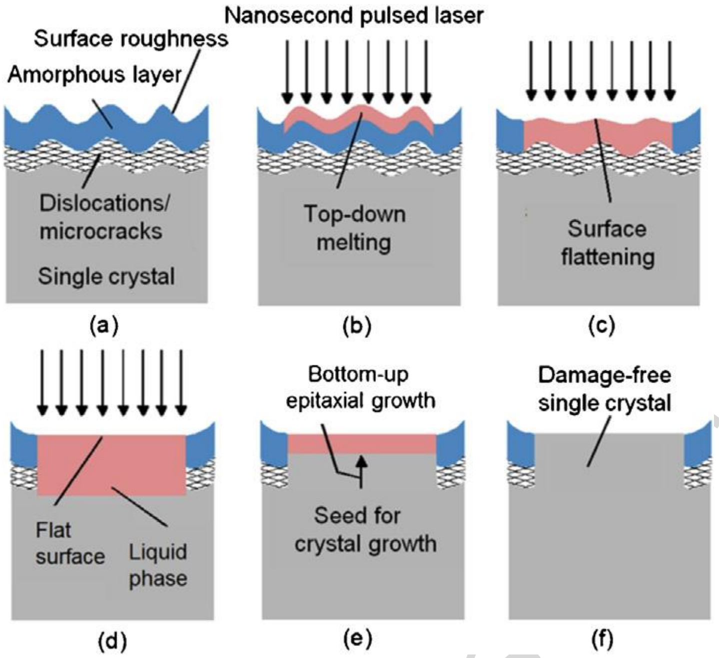


Fig. 32. Schematic diagram of proposed laser recovery mechanism [26]

8. Discussion and outlook to the future developmental work

Increasing demands on precision, complexity, surface quality and process reliability in the machining of micro-parts are present challenges in different branches of micro-machining industries. Sequential micro-machining is found to be a suitable choice to satisfy these increasing demands as it can integrate two or more micro-machining techniques to enhance advantages and diminish potential shortcomings observed in individual machining techniques. Nonetheless, very few studies are done in this area. Given the fact that the subject of this review is underdeveloped and the papers on this topic are rather scarce, Table 1 presents an overview of various studies that were conducted to date and reviewed in this paper, while highlighting the major characteristics and concerns of these processes.

Table 1. Overview of the studies made in the area of sequential micro-machining

Category	Sequential micro-machining process	Work material	Primary characteristic	Primary concern
Micro-tool making orientated	Turning/EDM	Turning of CuW and brass/EDM of steel [8, 9]	Avoiding clamping error, improvement of machining accuracy, drilling varying hole sizes, reduction in the electrode preparation time	Inability to fabricate large micro-shafts/electrodes (longer than 1 mm) using micro-turning, inability to fabricate high-aspect-ratio micro-holes
	Block-EDM/EDM	Block-EDM of CuW and W/EDM of steel [10]	Avoiding clamping error, improvement of machining accuracy, drilling varying hole sizes, reduction in the electrode preparation time, ability to fabricate high-aspect-ratio micro-holes	Tapered micro-electrodes and micro-holes, taking much more time in comparison with micro-turning
	EDM/Grinding	EDM of PCD/Grinding of lithosil, BK7 and N-SF14 glass [11]	Avoiding clamping error, improvement of machining accuracy, reduction in the electrode preparation time, achieved average surface roughness (Ra) for BK7 is 12 nm	Has only been used to fabricate the grinding wheel rather than to machine the workpiece
	EDM/USM	EDM of tungsten carbide/USM of borosilicate glass [12]	Avoiding tool eccentricity and clamping error, improvement of machining accuracy, reduction in the electrode preparation time	Process parameters should be determined carefully. The noise produced by the ultrasonic frequency generating system could be a major concern
Machining time orientated	ECM/EDM sinking and milling	SS304 [13]	Double decrease in the machining time in comparison with EDMM, accuracy increase in comparison with ECMM	Exchange of working fluid, rapid wear of the electrode, requiring post-micro-machining processes, cost-effectiveness
	Laser/EDM	2% nickel-2% chromium	Reduction in drilling time by a maximum of	Repositioning errors, heat damaged surface layer

		case hardened steel [15], SS304 [14], 18CrNi8 steel [16]	90% [15], reduction in milling time by 75% [14]	
	EDM/Laser	Hardened steels [17]	Reduction in machining time by 53%	Dissimilar machining depths due to undefined ablation of the laser
Machined surface quality enhancement oriented	EDM/ECM milling	SS304 [15, 18, 20]	Avoiding clamping error, improvement of machining accuracy, reduction in the electrode preparation time, achieved surface roughness (Ra) are 0.143 µm and 0.52 µm	Exchange of working fluid, process parameters should be determined carefully,
	Milling/Laser deburring	NAK80 [21]	Better surface finish, achieved surface roughness (Ra) is 0.417 µm	Surface oxidation, cracking and melt depth problems due to improper laser deburring
	WEDG/EDM/ Electropolishing	High nickel alloy [22]	Avoiding the eccentricity problems and clamping error, achieved surface roughness (Rmax) is 0.69 µm	
Energy efficient oriented	Laser surface defects followed by Hard turning using a CBN tool	AISI 4340 steel [23-25]	Suitable for the difficult-to-cut materials, reduced sub-surface deformation, achieved reduction in the specific cutting energy as well as an improved machined surface roughness (Ra) of 30 nm	Miniaturization and integration on a single machine tool
Microstructure Improvement oriented	SPDT/ Laser recovery	Silicon [26]	Improved the crystalline structure of the machined surface without influencing the surface roughness	Miniaturization and integration on a single machine tool

Recently, a spin out (Loxham Precision) of Cranfield University, UK has developed a commercial machine tool capable of executing hybrid and sequential micro-machining processes. 6-Axis µMill[1] is the machine representing a unique combination of micro-milling and diamond turning capabilities on the same machine tool – with in addition on-machine improved metrology for workpiece inspection without unloading of the part. This machine tool is purpose built specifically for manufacturing small micro-components required in watch, optics, medical and print head devices sectors. Also, further research supported by the Research councils of the UK is underway at University of Strathclyde, UK to integrate and build a machine capable of performing micro-turning/milling/grinding and laser micro-machining[2].

Amongst the research studies on sequential micro-machining, four sequential micro-machining processes appear to be effective for fabricating complex micro-parts, particularly if the micro-tool making process is included in these techniques. Table 2 summarises these processes that could be considered effective processes for manufacturing 3D micro-scale artefacts.

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[1] http://www.loxhamprecision.com

[2] http://ukmanufacturing2015.eng.cam.ac.uk/proceedings/Day2_Session4XLuo_sent.pdf

Table 2. Effective sequential micro-machining techniques for fabrication of 3D complex micro-parts

Sequential micro-machining process	**Feasible material**	**Geometric complexity**
Micro-EDM plus micro-ECM	Conductive materials	3D
Laser micro-ablation plus micro-EDM	Conductive materials	3D
Micro-EDM plus laser micro-ablation	Conductive materials	3D

Despite these developments, there are certain research challenges associated with sequential micro-machining and the outlook towards them is summarised as follows:

1. Micro-EDM process is found to be an important process to be included in the sequential micro-machining processes. Laser machining and ECM are other popular processes that are considered by scholars in sequential micro-machining. These processes have remained important due to their proven capability of machining intricate features with reasonable dimensional accuracy, surface quality and MRR. Nevertheless, these processes have some drawbacks, which can be overcome by integration of alternative processes. It is evident that the current research lacks application of other micro-machining techniques for sequential micro-machining processes, since the studies have been dominated by three micro-machining techniques: EDM, laser machining and ECM. Consequently, there is an urgent need to establish novel sequential micro-machining techniques using other mechanical, chemical, electrochemical and thermal micro-machining processes to be able to meet

stringent requirements of flexible and reconfigurable manufacturing of 3D micro-components.

2. Owing to the great capability of electrochemical micro-machining (EMM or ECMM) to fabricate different shapes and sizes of micro-tools, this process can be utilized in upcoming sequential micro-machining processes as a tool-making process, followed by the main micro-electrochemical discharge machining (ECDM), micro-EDM, EMM, etc. on a single machine tool. Likewise, SDM and SPDT/laser recovery processes have great potentials for integration on a single machine tool.
3. Another important issue is that the development of sequential micro-machining processes should be done to possess the capability of machining both conductive and non-conductive materials. Furthermore, most researchers have integrated only two micro-machining processes; hence, another interesting research area might be the integration of three or more micro-machining techniques in order to enhance the capabilities of sequential micro-machining processes. Similarly, assisted and combined hybrid micro-machining techniques, which are tremendously advantageous to achieve higher machining efficiency [7], can be used in sequential ways to increase process capabilities associated with surface integrity, MRR, tool life and form accuracy. This opens promising pathways to design novel machine tools. It should be mentioned here that all processing parameters of each individual techniques in sequential processes should be selected carefully for the sake of achieving the best micro-machining performance.
4. According to the insights achieved and the problems confronted, a successful sequential micro-machining process can be assumed as follows:

Micro-tool making + Main material removal processes + Enhancement fine finishing processes.

For enhancement phase, laser micro-processing such as laser polishing/deburring and laser recovery appears to be very promising in improving the surface integrity of micro-components. Also, for the main process, a laser can be used to generate defects on the workpiece surface to perform SDM. Note that laser micro-processing is a non-contact and high speed process. It is particularly suited for difficult--to-machine materials.

5. To date, most studies are of experimental nature. Work is needed on modelling and simulation of the micro-machining sequential technologies for material characterisation at the atomic scale. The emerging field of multiscale modelling would probably play an important role in the characterisation and explanation of various phenomenological scientific effects in such processes to gain detailed analysis with high fidelity. In addition, research could apply experimentation to develop empirical models of phenomena occurring in sequential processes. Another field is to use appropriate physics to generate custom computer-based modelling and simulation tools or to liaise with established software vendors to provide them. Such computational tools can reduce the cost and time associated with extensive experimentation of sequential micro-machining processes.
6. In order to perform fully automated sequential micro-machining, in-process or at least on-machine metrology is essential to characterise, control, and improve the machining accuracy. Accordingly, suitable sensors should be deployed in sequential micro-machining. In particular, a sensor is needed to interface metrology systems to small-scale micro-components. Ideally, this sensor would be non-contact, have high resolution and high bandwidth. This would enable high-speed, high-precision dynamic measurements of micro-components and systems. Moreover, significant efforts are needed in developing sequential micro-machining process models,

controllers and control algorithms to utilise these models to improve process stability issues and vibrations and in turn the overall process and, ultimately, the product.

7. New multi-axis machine tools are required to be developed for sequential micro-machining processes so as to implement numerous tasks in miscellaneous directions according to the optimised tool path algorithm. Machine tool accuracy is another factor, which needs to be considered and developed in order to fabricate high quality micro-components by sequential micro-machining processes.
8. Finally, nearly all the studies performed on sequential micro-machining are at most at TRL 5 level and these are yet to be integrated in commercially realised process chains. Therefore, research on economic aspects of sequential micro-machining has to be carried out to bring this technology into general practice in industry.

9. Concluding remarks

Moving the micro-part among different stand-alone machine tools increases the lead time and introduces machining errors due to repositioning and realignment of the workpiece. To solve issues like this, micro-machining processes can be integrated on a single machine tool – the better the integration, the better is the outcome of micro-machining. This integration in sequence rather than hybridisation is referred to as “sequential micro-machining” in this paper. So defined, sequential micro-machining processes include performing two or more micro-machining techniques in sequence on a single machine tool to increase machining efficiency and achieve a high quality micro-component. The review of the research trends in sequential micro-machining suggests that the literature in this field is rather scarce. Micro-EDM is found to be a dominant technique, which has been utilised in most of the sequential micro-machining studies. Laser machining and ECM are two other popular methods used by researchers in sequential micro-machining processes. Other micro-machining techniques, including assisted and combined hybrid micro-machining processes, are yet to be used in sequential micro-machining to enhance the capabilities of these processes. Moreover, extant literature has shown several examples of integration of only two micro-machining processes on a single machine tool. Three or more micro-machining techniques could be applied in a sequential micro-machining process to achieve a successful sequential micro-machining process. This paper reviews these techniques and provide some directions for future work. Based on this, it can be asserted that sequential micro-machining processes are just now being developed; therefore, numerous other research areas such as modelling and simulation tools, in-process and on-machine metrology of sequential processes, specific multi-axis machine tools for sequential processes, machine tool accuracy and economic aspects of sequential micro-machining processes should be targeted for future investigations.

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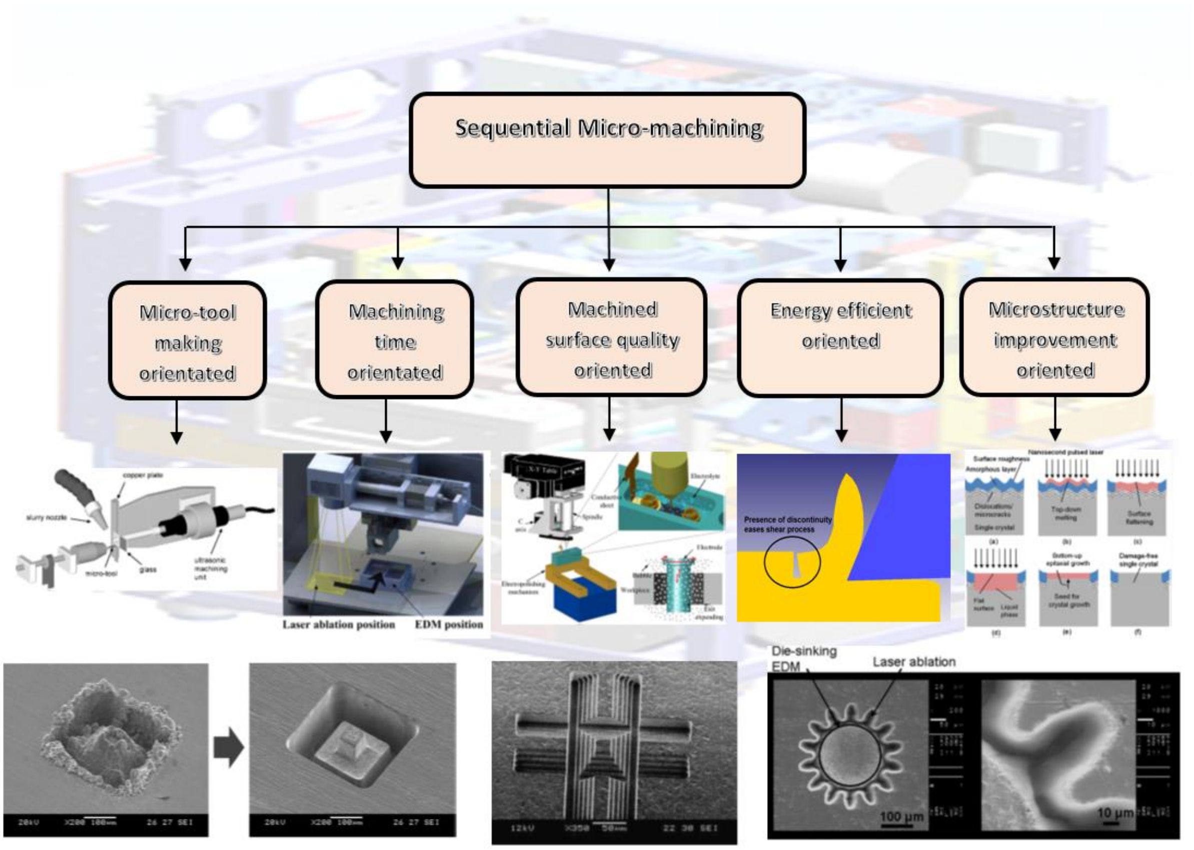
Graphical Abstract



Highlights

- A new area of sequential micro-machining process chain is reviewed.
- This review offers a novel classification of sequential micro-machining techniques.
- Sequential micro-machining on a single machine tool is gaining global interest.
- While the use of laser and µECM seems ubiquitous, µEDM needs better integration.
- The challenges, opportunities and future research directions are identified.