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A review of sequential micro-machining: State of art approach

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ABSTRACT

In the recent years, a sequential micromachining is attracting attention of researchers as it is most promising structured approach to combine and utilize advantages of different types of micromachining techniques which improves the productivity in manufacture of high precision micro features of most advanced components. Sequential micromachining is a most effective recent approach to fabricate micro features of sophisticated parts to minimize drawbacks of individual machining techniques if they were used individually. In general, this technique combines the individual micro machining techniques in a logical sequence stages to machine faster with rough cuts in the former and achieve final sizes and tolerances in the later stage. It is the opposite of hybrid micro machining in which two techniques are combined together. Sequential micromachining can be done on different machine tools or preferably on the same machine tool for better work settling accuracy, low production time and hence less rejection. Thus, it is leading to manufacture of multifunction machine centers to perform sequential micromachining on the same machine. Eventually its necessities this manufacture to be more flexible and dynamic to accommodate the future requirements in a better way. The main aim of this review paper is to give latest developments in the field of sequential micromachining processes, especially done with same machine tools and their usefulness in terms of advantages, productivity, and applications. It also gives emphasis on capabilities of future possible combinations of various techniques with high potential in this domain.

Selection and peer-review under responsibility of the scientific committee of the 2nd International Conference and Exposition on Advances in Mechanical Engineering.

1. Introduction

In recent years, the micro-machining has become more popular amongst research as micro-products like micro batteries, micro sensors etc. have become inevitable in daily life [3] in sectors where it needs micro-level accuracy and precision like optical fields, optical waveguides devices, fiber-optic connector, micro-lens array [4] renewable energy, automotive, and biomedical instruments [3]. Rashef et al. [5] found the reason behind this is that the devices and tools are getting smaller and smaller also complex day-by-day with an increase in demand to deliver micro-level to nano-level precision with appreciable surface finish. Saeed et al. [6] found that there have been many micro machining techniques available but shortcomings associated with these needed to develop multifunctional machine tool to perform many cost-effective sequential processes on single machine tool. A sequential micromachining basically is a chain of two or more techniques to implement in a sequence [7] aiming at exploiting the advantages of both the processes to improve product quality [5] and reducing the disadvantages, realignment error, reducing handle time which finally improves overall machining efficiency [7]. Sequential micromachining aims to exploit the advantages of individual techniques to improve upon surface roughness, the machining rate, accuracy, and to reduce tool wear rate [8]. Sequential micromachining is broadly classified into five major categories based on purpose of operation shown in Fig. 1. Eventually-one can add future combinations hereafter in the list.

The idea to write this review is to present the attempt made by researchers to understand the methodologies of individual machining processes to develop sequential possible combinations. It also aims to present the work to develop a multifunctional machine tool to execute two or more dissimilar machining processes to reduce power and time to great extent [9]. Golam et al. [10] reported that many processes which are not perfect for machining certain types of materials can be machined with micro EDM, but they are mostly suitable at last stage for high level finish. So, these processes perform better if combined in sequence with

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Nomenclature

ANN	Artificial Neural Network [1]	PCD	Polycrystalline Diamond
μEDM	Micro Electro-Discharge Machining [1]	ECM	Electro- Chemical Machining [2]
WEDM	Wire Electrical Discharge Machining	WECM	Wire Electro- Chemical Machining
LBMM	Laser Beam Micro Machining	ECDM	Electro- Chemical Discharge Machining
OMM	On-Machine Measurement	MIMO	Multi-Input Multi-Output

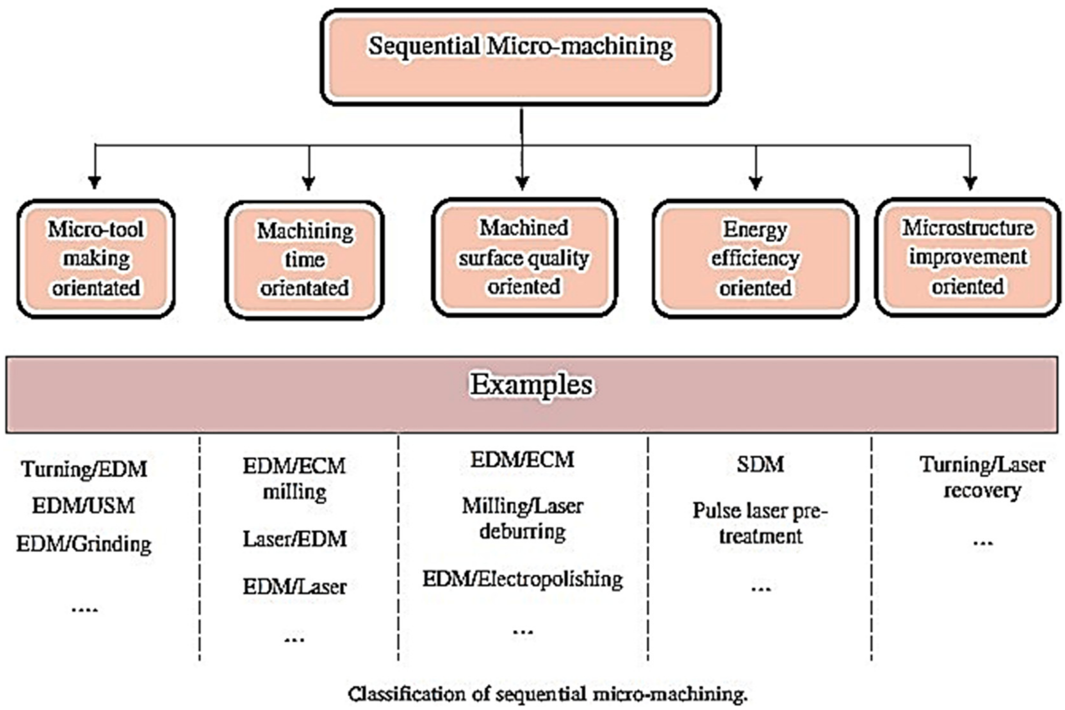

Fig. 1. Classification of sequential micromachining [4].

micro EDM than using that process singly. With sequential micromachining tool wear drawback of μEDM can be addressed better. In wire EDM process high heat generated by electrical discharge melts and vaporizes small material from surface of work piece without touching the electrode tool to work piece and hence no stresses developed. Sarat Kumar et al. [11] reported that using EDM taper part with varying cross sections can be machinated just by inclining wire electrode with guides. Combining electrochemical micromachining and electro discharge micromachining in sequence minimizes drawbacks of both the methods, improves surface quality and decreases machining time [12], also this sequential combination on single machine tool gives effective 3D-surfaces with more accuracy.

Skoczypiec et al. [13] reported that electro-chemical electro-discharge machining sequential prototype is developed on single machine tool; gives possibilities of selection of same kind of function units simplifying the constructions while designing the machine tool. However, integrating them together because technological difficulties related to process realization and hence complex design. Gross et al. [14] found that conventional machining processes fall short in manufacture of dies demanding more accuracy, with increased complexity of geometric structuring and maximum material removal rate. To overcome this difficulty sequential combination of laser machining with small time pulse and micro-milling is used. The requirements of die design are a decisive factor to select the priority between two processes and areas of allocation on the die surface. Sequential micromachining technique based on laser beam micro-machining with micro electro discharge machining LBMM - μEDM, have been attempted by researchers to utilize the benefits of both methods [15–17]. Saeed et al. [6] reported that the LBMM has an ability of fast material removal rate at the cost of producing heat affected zones causing inaccuracy in the product feature, also causes machined surfaces to be tapered. Lasers were sequentially used at μEDM and lasers were sequentially used at μECM to create micro-holes in Hastelloy X. Micro holes formed by continuous laser treatment with μEDM improve response compared to individual μEDM outputs. The new sequential laser approach μEDM is more efficient than sequential laser applications using μECM [18]. Xiaolong et al. [19] reported that drilling micro-holes in combination with EDM-ECM is performed sequentially on the same machine tool and found that the processing efficiency is improved by 9.2 times compared to micro-ECM alone, also the ECM completely eliminates the surface defects generated in EDM.

2. Sequential micromachining combinations

This section aims to provide various sequential micromachining combinations which have been tried in literature. The combinations are categorized as two or more techniques applied on separate machine tool or combined on single machine tool. Uniqueness of individual machining process, their advantages, disadvantage, input energy availability and output requirements of high level of precision of finished work are some of the criteria to choose the processes in sequence. Generally, it is targeted to remove maximum material with first technique and later selected which is capable of giving high surface finish qualities.

2.1. Sequential micromachining on different machine tools

2.1.1. Laser beam micromachining (LBMM) and micro electro-discharge machining (μEDM) based sequential micromachining technique LBMM-μEDM

Sequential micromachining combination LBMM-μEDM utilizes the benefits of both methods, i.e., LBMM and μEDM [8]. Mir Akmam et al. [16] performed experiment on stainless steel SS304 to investigate LBMM the laser input parameter effects like laser power, scanning speed, and pulse frequency on the performance of μEDM. The experiment for 1-D machining, (drilling micro-holes) conducted where it is understood that input parameters of laser, speed of scanning, have significant effect on μEDM output performance. Problem may arise if it is operated on two different machine tools, where there will be repositioning error, requires great amount of downtime or settling time. To address this issue, the authors proposed a new Sequential LBMM and μEDM combination. First pilot holes were machined partially with LBMM machine tool where material removal was at faster rate. Later these rough pilot holes were operated subsequently on micro-EDM machine to obtain final shape gives optical image as seen in Fig. 2 (b). For carrying out this fine machining tungsten tool was used with μEDM. For achieving position accuracy on - machine measurement unit (OMM) was used seen in Fig. 2 (a). It uses high resolution digital camera mounted on optical microscope. Tungsten tool of μEDM was placed directly above centre of pilot LBMM hole for micromachining within acceptable accuracy (theoretically, it is within 2 μm) given in Fig. 2 (b) [16]. 20-W power was utilized for LBMM micro-drilling, also 200 mm focal length and 1060 wavelength pulsed laser utilized [15] It was confirmed with this study that LBMM μEDM sequential micro-machining technique reduced tool wear, the machining time, and instability in contrast with the pure μEDM process with no compromise in quality of drilled holes [16]. Combined sequentially micro EDM with grinding to make grind tool from polycrystalline diamond (PCD). Micro-EDM sharpened tool seen in Fig. 3 can be used to machine precise structure like V- groove [5,10].

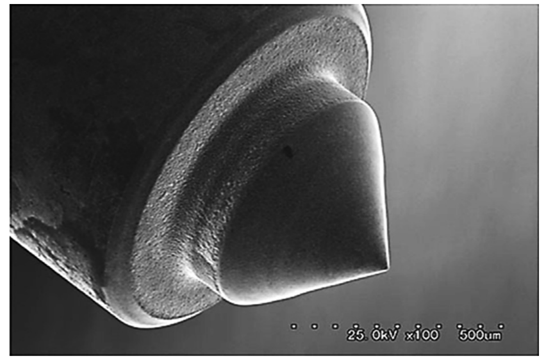

Fig. 3. Micro-EDM sharpened tool [5].

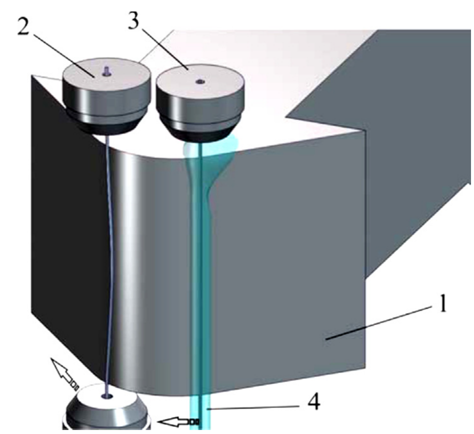

Fig. 4. Hyperbolic Lens Pole [4].

2.1.2. Electro-discharge and electro-chemical machining

Oleksandr et al. [20] attempted to manufacture parts of magnetic optics pole tip. It offers combination of electro-discharge and electro-chemical machining of magnetic optics. The pole tip working surface was 43 mm height with hyperbolic profile can be seen in Fig. 4. The method uses multi-pass wire EDM-ECM

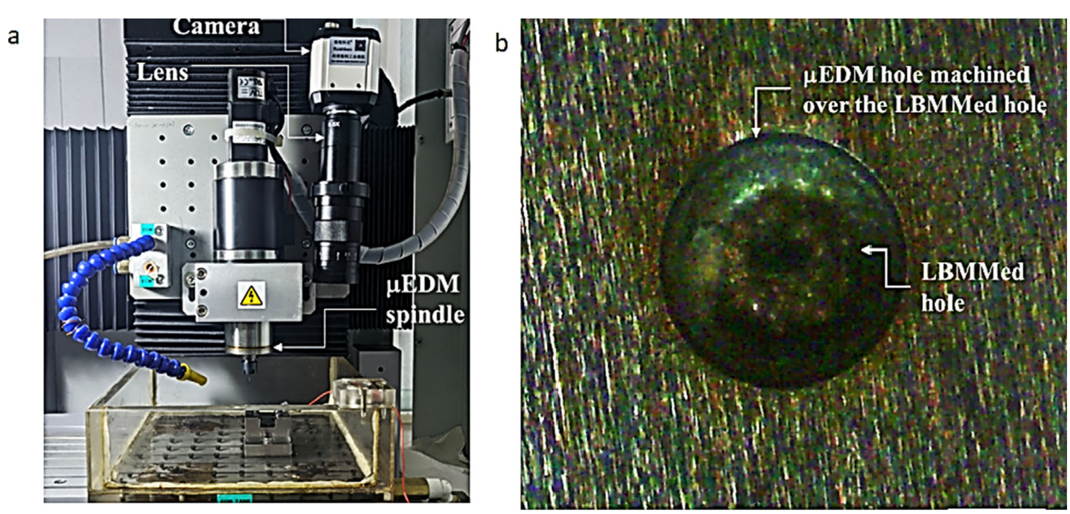

Fig. 2. (a) EDM with OMM system camera (b) Micro-EDM tool centering method effectiveness on pre-machined LBMM hole [16].

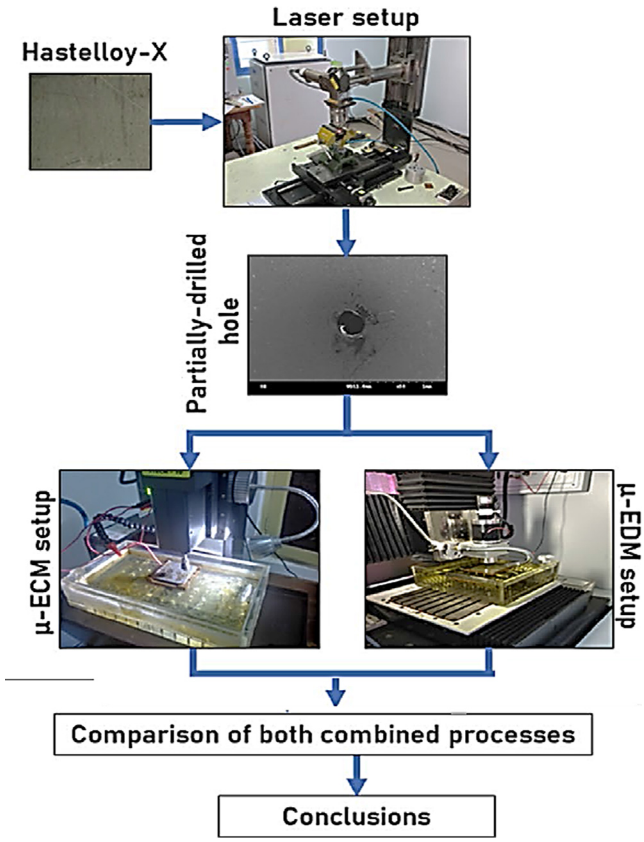

Fig. 5. Schematic work diagram Laser- µEDM, Laser- ECM [18].

method. 1-hyperbolic surface of lenses pole; 2- first WEDM pass; 3 - second wire ECM pass; 4 – electro-lite jet [4,20].

Oleksandr et al. [20] investigated parts made with multi-pass wire EDM. Use of linear motors for drives, granite guides, gas lubrication. Support guarantees minimal displacement error. The wire rewind path is designed using a smoothing compensator, along with a V-shaped guide to minimize wire electrode vibration. Results of tests shown were stable operation of parts for controlling the ion beam with submicron resolution precision.

2.1.3. Laser- µEDM sequential arrangement

Sivaprasad et al. [18] used lasers sequentially at µEDM and separately used sequentially at µECM to create micro-holes in Hastelloy X. Fig. 5 shows the sequential arrangement of the machining. Micro-holes formed by continuous laser treatment with µEDM improve response compared to individual µEDM outputs. The new sequential laser approach µEDM is more efficient than sequential laser applications using µECM.

2.2. Sequential micromachining on same machine tools

2.2.1. Sequential technique of micro-electrochemical discharge and micro-electro chemical machining

Raju et al. [21] performed sequential micro-machining µECDM drilling and µECM finishing to improve circularity in holes, machining time, taper angle of hole and circularity shown in Fig. 6.

The cost effective and compact sequential micromachining of µECDM drilling and µECM finishing process setup has been developed, operations were carried out on same workstation with single machine tool without changing tool and work piece positions. Fig. 7 demonstrates the improvement of quality of machined hole is found with sequential combination of µECDM drilling and µECM finishing. The hole taper also was reduced to zero degrees after the implementation of µECM process. Further, the circularity of 0.75 increased to 0.98.

2.2.2. Wire electro discharge machining and wire electro chemical machining (µWEDM - µWECM)

Performing sequentially micro-wire EDM (µWEDM) with micro-wire ECM (µWECM) was attempted as shown in Fig. 8. Here µWEDM was performed on wire-cut EDM and µWECM on newly designed setup. Titanium alloy (Ti6Al4V) specimen was used to cut micro groves [22].

For µWEDM, the optimal process parameters for microgroove generation with the least observed width overlap were pulse-on time 4 µs, servo voltage 10 V, µWECM processing voltage 8 V, processing time 30 s, and duty-ratio 60 % ware obtained. As shown in Fig. 9 (a), the generated microgroove has a rough wall due to the formation of a re-melt layer in the heat-affected zone. Fig. 9 (b) shows the results of a sequential processing approach with µWEDM followed by the µWECM process. The walls of the micro-grooves look relatively uniform, improving surface quality and dimensional stability [22].

2.3. Application of machine learning techniques to quantify the process characteristics

2.3.1. ANN for sequential Laser beam micro-machining (LBMM) and micro-electro discharge machining (µ-EDM)

Wazed et al. [15] implemented sequential combination of laser beam micro-machining (LBMM) and micro-electro discharge

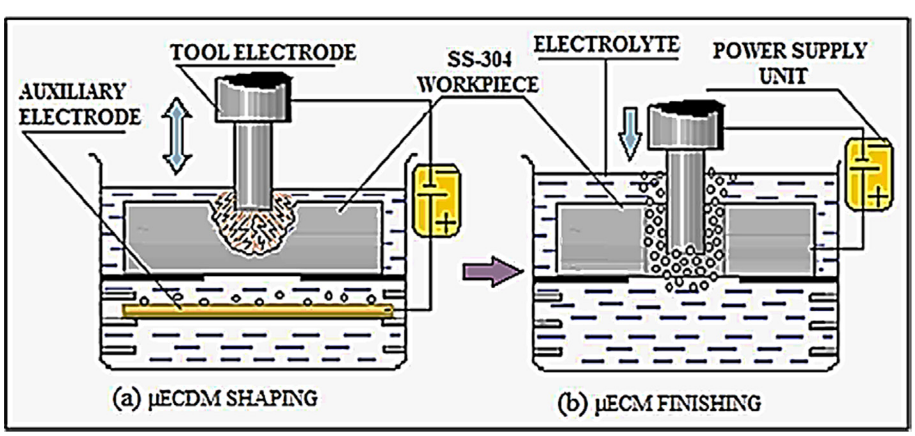

Fig. 6. Sequential micro-machining µECDM drilling and µECM finishing [21].

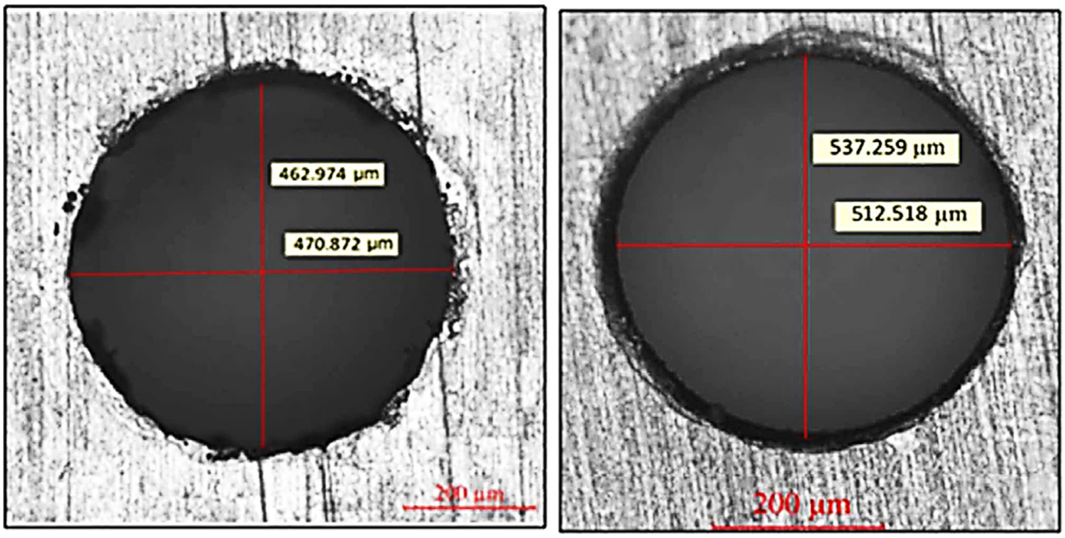

Fig. 7. Micro hole images: drilled by µECDM and Finished by SMM [21].

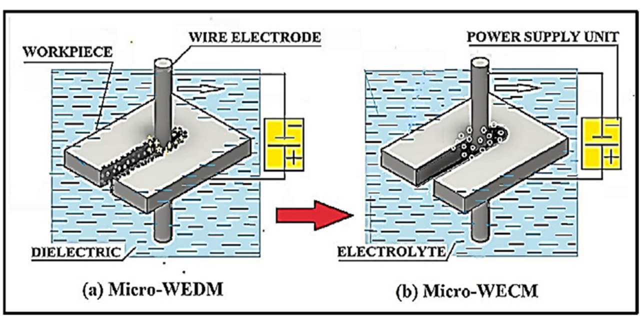

Fig. 8. Sequential µWEDM and µWECM [22].

machining (µEDM) for micro drilling purpose. A guide hole was created using LBMM initially and later same hole was used for fine machining, seen in Fig. 10. Used combination results in more improvement in stability of process, more machine efficiency, also processes fast ensuring good quality hole.

It is found for a sequential process that there exist structural co-relations among input parameters and output parameters. To study these, analytical models which predict their inter-relationships need to be developed. Here for this purpose dual stage method multi-input multi-output based on artificial neural network (ANN) was used. Fig. 11 shows ANN model applied in two stages. The experiment outputs were compared with predicted responses. A model's overall accuracy was found affected by accuracy of the first stage. Fig. 12 demonstrates comparison of experiment values of outputs of laser beam machining with predicted values from stage-1. It shows models accuracy is depending on first stage accuracy.

3. Future sequential combinations

Although in the literature some sequential micromachining process combinations have been developed with certain features, it provides ample opportunity for future research on many possible combinations. Micro-milling and laser micro-structuring can be combined, which may reduce net machining time. Another sequential combination EDM-Electro-polishing can be targeted for tighter tolerances to use EDM for maximum material removal and policing for achieving final dimensions. Also, the use of machine learning based micromachining combinations to predict and quantify the input output relations of process variables could give fair ideas to understand the combinations better, and to make the machining effective and faster.

For all these areas, process mechanisms, simulation methods, ultra-precision machine tools for sequential micromachining, pro-

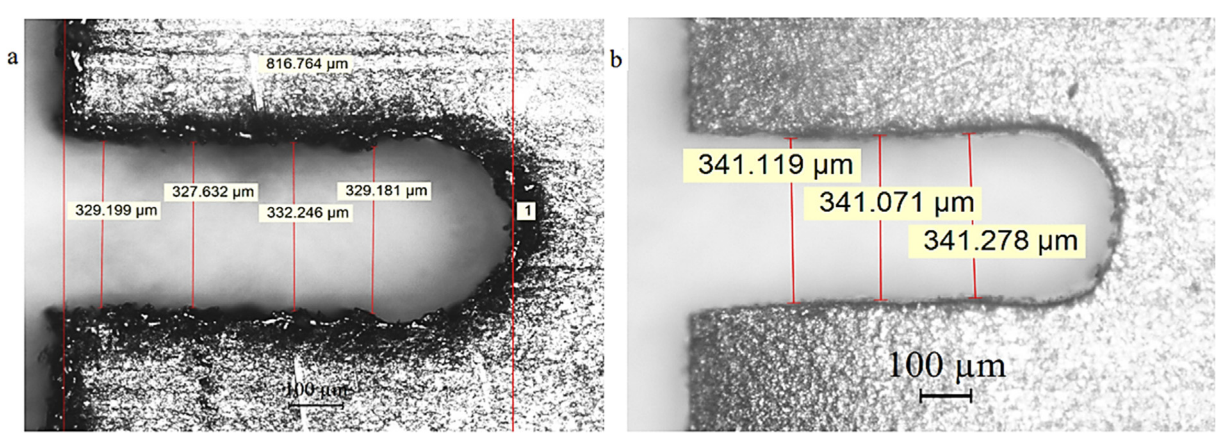

Fig. 9. Optical image (a) µ-WEDM shaping and (b) µ-WECM finish [22].

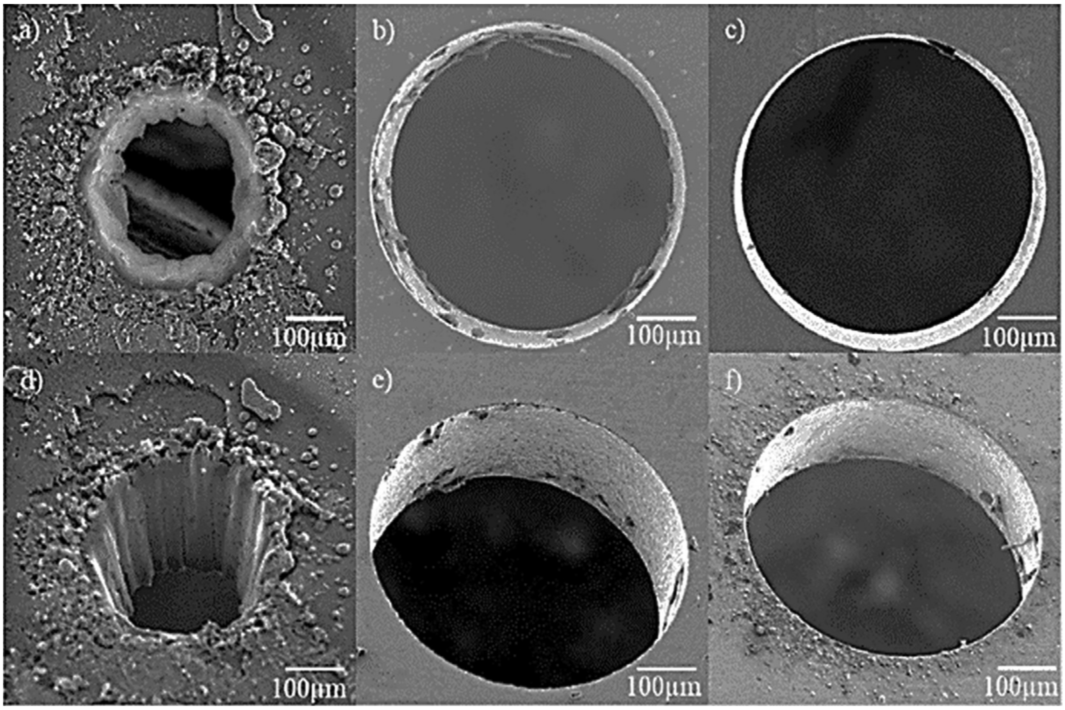

Fig. 10. Morphological, performance compare of LBMM hole (a-d), LBMM μEDM hole (b-e), and μEDM hole (c-f) [15].

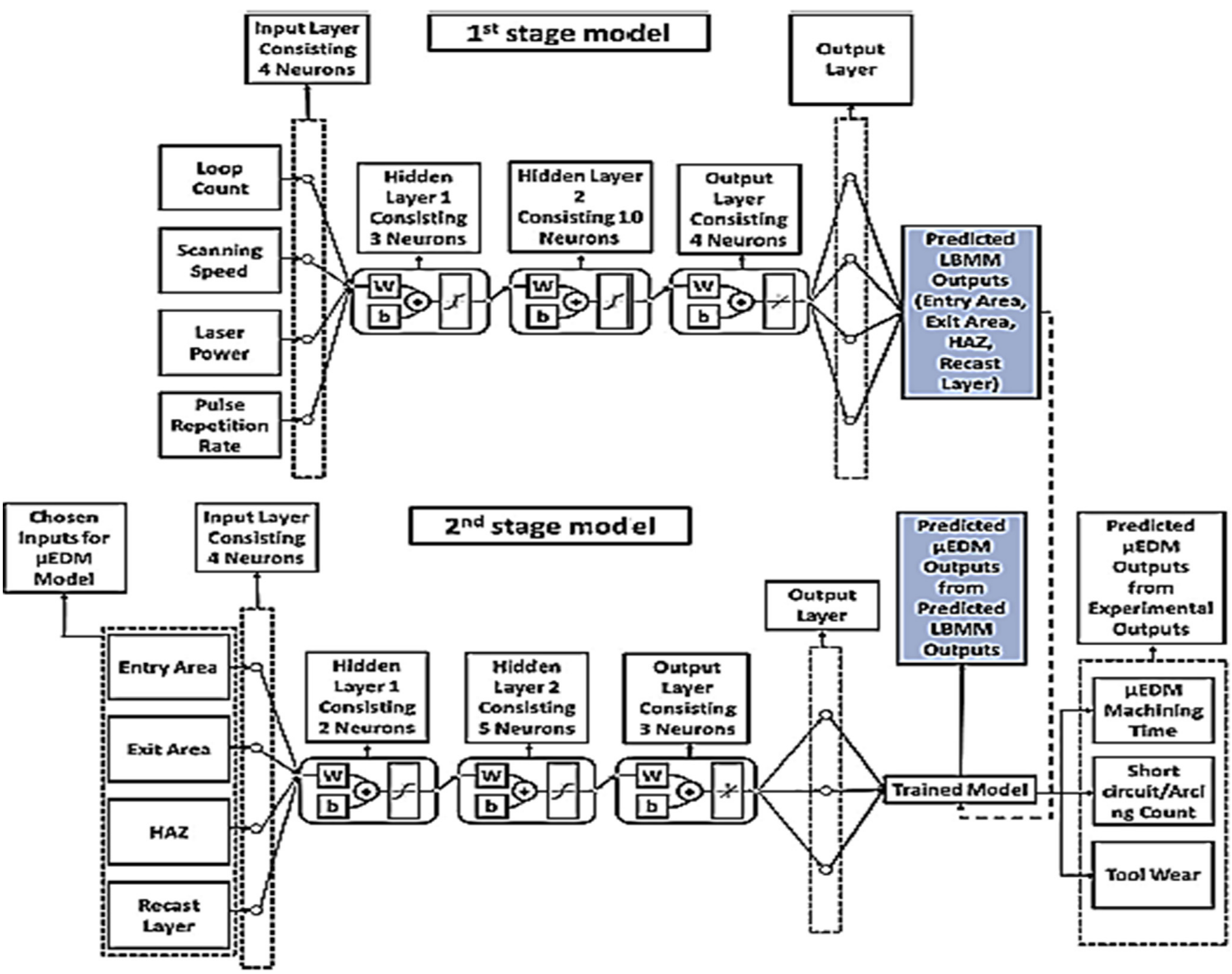

Fig. 11. Multi input multi-output (MIMO) ANN [15].

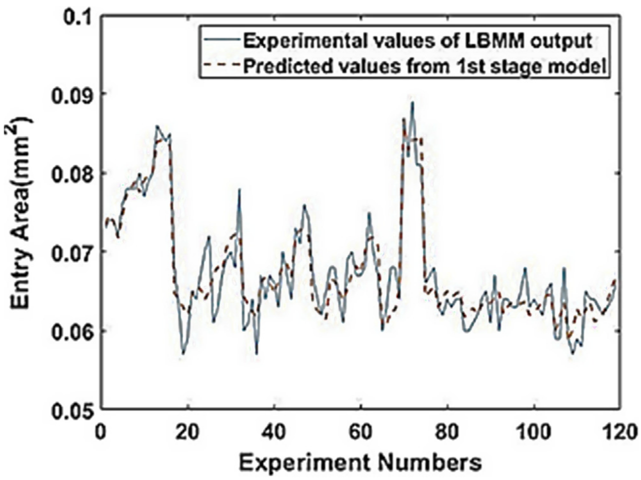

Fig. 12. First stage prediction accuracy [15].

cess monitoring, economics, and industrial implementations need to be studied.

4. Conclusions

After reviewing of literature research trends were found rare for sequential micro-machining. Most of the researchers have carried out the sequential combinations with micro-EDM in general. Laser micromachining and ECM are two other common methods used by researchers. Sequential micro-machining process can be implemented to improve process capability in terms of surface roughness, tool life, and geometric accuracy. Sequential micro-machining processes have great potential for fabricating 3D complex micro-components with high accuracy and surface quality. In most cases, it is found that up to two micromachining processes are integrated into one machine tool. Three or more micromachining techniques can be applied sequentially to the micromachining process to make it more effective. An introduction of machine learn based sequential combinations for micro grinding-μEDM, μECM-μEDM, etc. can be investigated in future.

CRediT authorship contribution statement

Nanaji Kshirsagar: Software, Validation, Investigation, Writing – original draft, Writing – review & editing. **R.M. Tayade:** Conceptualization, Methodology, Formal analysis, Supervision.

Data availability

No data was used for the research described in the article.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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