

HYBRID MICRO-MACHINING PROCESSES WITH ULTRASONIC ASSISTANCE: A REVIEW

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ABSTRACT: The paper deals with the main nonconventional hybrid micro-machining processes with ultrasonic assistance, starting from basic nonconventional technologies. In introduction, some hybrid processes were presented, like vibration, laser, fluid, magnetic and external electric fields, or carbon nanofibre assisted micro-machining. The study details the means of ultrasonic vibrations were applied, i.e., by vibrating the tool, workpiece or working fluid, and also the effect on output (technological) process parameters, mainly the machinability and removal rate for specific machined material. A comparison was made between the results obtained using classic electrical discharge machining (EDM) and ultrasonically aided EDM (EDM+US). In this case, the surface roughness, the machining rate, and the volumetric relative wear were studied. Finally, the advantages and disadvantages were exposed, and some solutions of output technological parameters for further improvement.

KEYWORDS: Hybrid micro-machining, ultrasonic assistance, vibration, hybrid ultrasonic machining.

1. INTRODUCTION

Nowadays the major developments are made at a submicron level machining and big challenges for engineers is to find solutions, to fabricate components at lower dimensions. The micro-fabrication is a very important player in the battle of manufacturing, and many studies have approached micro-electronics devices.

The micro-parts can be found in industrial domains as electronics, optics, biomedicine, aerospace, energy, and automotive. It includes various products for micro-electromechanical systems (MEMS), systems for micro-analysis, micro-volume reactors and others.

It can be observed that is a large area for micro-fabrication, and the increasing of micro-parts influence creates the requirement to machine advanced materials, and hence major difficulties. Some examples of materials that can be micro-machined, with low machinability by classic technologies, are carbides, W, and Ni superalloys, Au, Ag, ceramics, composites etc. [1].

In this paper, major trends are presented concerning the advanced machining processes which can have impact in 4.0 manufacturing. The hybridization of conventional and nonconventional machining processes follows the improvement of the performances, to find more productive and efficient technologies. The principle of hybrid processes is to augment the advantages of single processes and minimize their potential with withdrawals [2]. These can be classified in: (a) assisted and (b) mixed hybrid micro-machining processes.

In case (a), the main machining process is super imposed with the contribution of one or more types of external energy provided by ultrasonic vibration, laser, different fluids, magnetic field etc. [1].

In case (b), the capacity of producing complex parts is increased, because each individual micro-process involved contributes at the same time to the removal mechanism. These are the effects of the synergy of the components involved within the technological system. So, the output technological parameters are increased as removal rate, and also the quality of the surface, in a relatively short production time [1].

A **nomenclator** of the abbreviations for specific terms used in this paper is presented below:

AMP - Advanced Machining Processes; AJM - Abrasive Jet Machining; WJM - Water Jet Machining; AWJM - Abrasive Water Jet Machining; AFM - Abrasive Flow Machining; CIRP - Collège International pour la Recherche en Productique; CHM - Chemical Machining; ET - Energy type; ES - Energy Source; ECM - Electrochemical Machining; EDM - Electrical Discharge Machining; WEDM - Wire Electrical Discharge Machining; EBM - Electron Beam Machining; HAZ - Heat-Affected Zone; HMP - Heat Machining Processes; IJM - Ice Jet Machining; IBM - Ion Beam Machining; LBM/LBMM - Laser Beam Machining/Micro-Machining; LAM - Laser Assisted Machining; M, C, EC, T - Mechanical, Chemical, Electrochemical, Thermal; MEMS - Micro-Electromechanical Systems; MRR - Material Removal Rate; PAM - Plasma Beam Machining; TBC - Thermal Barrier Coating; USM - Ultrasonic Machining.

2. CLASSIFICATION OF SIMPLE AND HYBRID MICRO-MACHINING PROCESSES

In today's world, for the implementation of the 4.0 Production, an important factor is the hybridization of manufacturing processes.

As it is presented in the introduction, the hybrid machining means the mixture of processes in parts production aiming at efficiency and improving the technologies that are used in the present.

ET	NMP	Tool	Transfer medium	Material removal mechanism
M	USM	Sonotrode	Abrasive slurry	Erosion or abrasion
	AJM	Abrasive jet	Air	
	WJM	Water jet	Air	
	AWJM	Water-abrasive jet	Air	
	IJM	Ice particles jet	Air	
	AFM	Abrasive suspension	Suspension	
C	CHM	Mask	Etchant	Chemical dissolution
EC	ECM	Electrode	Electrolyte	Anode dissolution
T	EDM	Electrode	Dielectric	Melting and vaporization
	EBM	Electron beam	Vacuum	
	IBM	Ion beam	Atmosphere	
	LBM	Laser beam	Air	
	PAM	Plasma jet	Plasma	

In table 1, the individual nonconventional machining processes are classified by the energy type (ET) directly used in removal mechanism, the energy source, tool, transfer medium state, and material removal mechanism, that can be combined to get a hybrid process. The synergy created by hybrid manufacturing is based on "1+1=3" principle.

The plentiful discussions within the working group of *Collège International pour la Recherche en Productique (CIRP)*, on hybrid manufacturing processes subject generated its definition: "Hybrid manufacturing process are based on the simultaneous and controlled interaction of process mechanisms and/or energy sources/tools having a significant effect on the process performance" [2,3].

From this point of view, the hybrid micromachining processes can be categorized based on the following issues [5,9]:

a) Type (A): Combination of two of several processes. In this case, the removal mechanism occurs due to the concurrent action of the involved processes under controlled way.

The material removal mechanism is the effectively obtained from the individual processes.

b) Type (B): More energy sources aiding in the mechanism of material removal, and thus augmenting machining performance.

c) Type (C): Several tools that can simultaneously machine two or more surfaces.

In figure 1, the hybrid assisted micro-machining processes are presented that will be described in this paper.

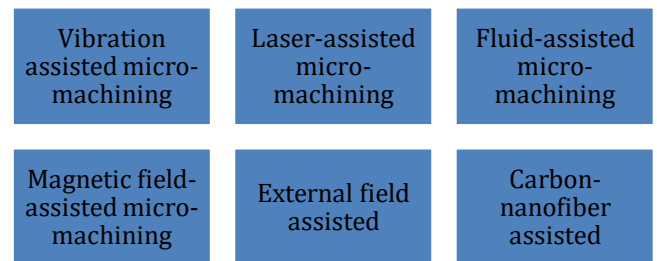


Figure 1. Hybrid assisted micro-machining processes

2.1 Vibration aiding micro-machining

In this case, the vibrations are applied to the elements of technological system: tool, workpiece or working fluid. The tool durability and the surface finish can be improved by vibration assisted micro-cutting, but the superficial cracks are caused by cycling mechanical action of the tool.

Also, the machining performance for non-cutting processes can be better using vibrations. In micro-EDM process, a spectacular increase of material removal rate and flushing efficiency, are obtained using ultrasonic vibrations. In this hybrid process, reduced thermally influenced zone can be achieved and so low thermal stress. The work fluid vibration can help in appropriate circulation of removed particles, and it leads to a good productivity, surface finish and accuracy. Some examples of processes that can be improved applying the vibrations in the working fluid are micro-EDM, and micro-ECM [4,5,6,10].

2.1.1 Vibrations applied to tool in hybrid micro-machining

In vibration assisted micro-machining processes, the tool vibrations are generated using a piezoelectric transducer, a booster, and a horn. The piezoelectric effect converts the electric impulse into mechanical vibrations with ultrasonic frequency. Then, along the ultrasonic chain, the tool vibration is amplified by the booster and the horn. A lot of studies have been done

on machining rate, surface roughness and integrity of superficial layer, volumetric relative wear, micro-holes aspect ratio, the involved forces, using the vibrations applied to the tool [5,7,8].

Some researchers studied the EDM hybrid process, by applying ultrasonic vibrations to the workpiece or dielectric fluid.

The investigations fulfilled using ultrasonic vibration applied on the tool and wire electrode in EDM, are presented in the next paragraph.

As can be seen in figure 2, Kremer et al. used a cross vibrating system actuated by a transducer, comprising one end connected to the EDM working head and another other end to the tool-electrode. Comparing this process with the non-vibration tool EDM, it could be observed that the tool vibration improved process performance [23].

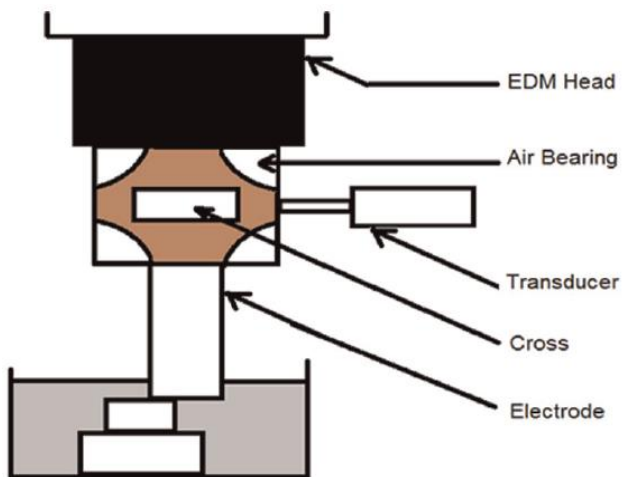


Figure 2. Ultrasonic vibrating EDM [11,23]

In ultrasonic vibration-assisted WEDM, Lipchanskii had some experiments explaining the phenomenology of performance improvement of hybrid process [33]. A device developed by Guo et al., comprising a transducer, and a wire holder actuated by an ultrasonic generator assembled on a WEDM machine are presented in figure 3.

The ultrasonic parameters were 12 μm amplitude, 35 kHz frequency. Thus, the results indicated that ultrasonic vibration increased the WEDM removal rate by 30% and reduced the roughness of the surface in a visible way [24].

In order to drill micro-holes with high aspect ratio by micro-EDM, Yu et al. used a combined ultrasonic vibration with planetary movement of the tool-electrode. Therefore, this hybrid technology improved material removal rate [25].

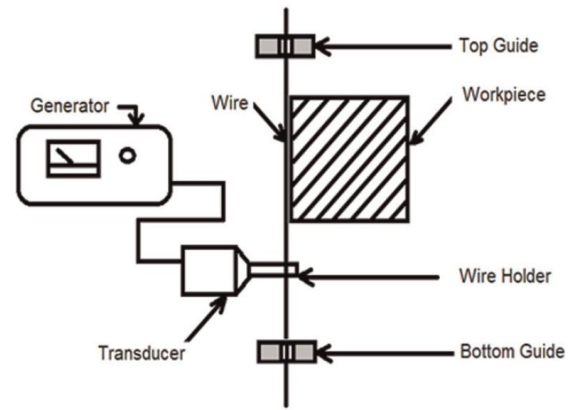


Figure 3. Ultrasonic-aided WEDM set-up [11,24]

2.1.2 Vibrations applied to workpiece in hybrid micro-machining

The transducers can be with piezoelectric or magnetostrictive effect. Murthi and Philip fabricated a magnetostrictive transducer, functioning at resonance frequency of 22 kHz with an amplitude of 3 mm.

The experimental results obtained by ultrasonic assistance are very relevant concerning EDM technological performances when machining holes and cavities. The sparking stability is also improved, due to the ultrasonic field forces.

Gao and Liu developed a technological system for micro-EDM ultrasonically aided by presented in figure 4 [12]. In this case, it can be observed that the workpiece is assembled on a piezoelectric transducer that provides the ultrasonic vibrations.

The results showed that applying ultrasonic vibrations to the machined sample, the efficiency of the process grows eight times comparing to classic micro EDM [14, 33].

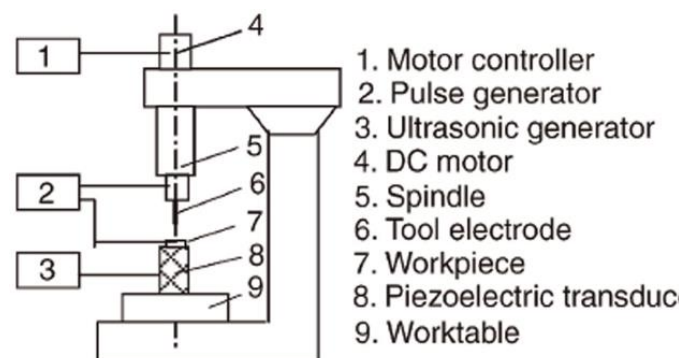


Figure 4. Ultrasonic-aided micro EDM [11,12]

In figure 5, a system made by Hoang and Yang is presented. They did their experiment using a piezoelectric effect at micro-WEDM, using the method of workpiece ultrasonic vibration [11, 13].

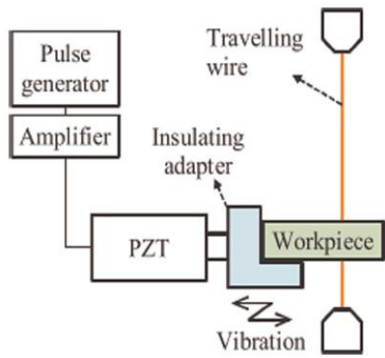


Figure 5. Ultrasonic-aided micro WEDM [11,13]

The experiments reported that when the vibration is applied to the machined sample the removal rate is 1.5 increased in comparison to wire vibration and 2.5 times increased than in classic WEDM.

A greater surface of the workpiece is used for dielectric flow and remove the molten material in when workpiece is vibrated, thus increasing the WEDM efficiency when comparing to wire vibration [11,13].

2.1.3 Vibrations applied to dielectric fluid in hybrid micro-machining

The concept of applying ultrasonic vibration to the work liquid for micro-EDM is presented in figure 6. The frequency used in this case was 43 kHz, and the purpose was to increase by ultrasonic cavitation the kinetic energy of removed particles in the working tank (ultrasonic tub). The machining rate and the surface quality were improved using this concept [11,14].

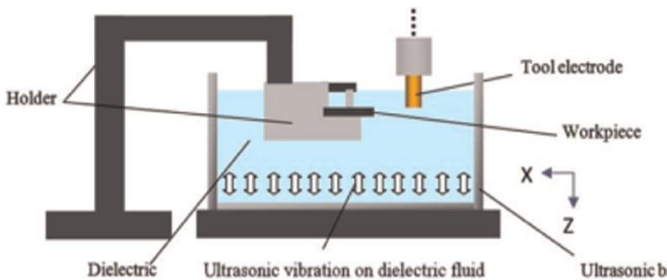


Figure 6. Ultrasonic bath in micro EDM [11,25]

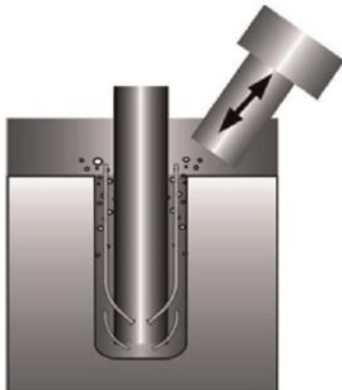


Figure 7. Ultrasonic sonotrode in micro EDM [11,14]

Schubert et al. reported the results obtained by immersing the end of an ultrasonic chain in the dielectric (figure 7). The main objective was to increase the productivity of the process through aligning the axis of the ultrasonic chain with the working gap, increasing the ultrasonic pressure within [11,15].

Another study related to immersed ultrasonic chain in dielectric was made by Ghiculescu et al. They conceived an equipment for ultrasonic assistance of WEDM that increased the output technological parameters like machining rate and surface roughness, based on ultrasonically induced cavitation in a hopper filled with dielectric fluid. In this case, the relative position workpiece – tool-electrode was kept constant, aiming at precision of WEDM [11,16].

Using the same method, Ichikawa and Natsu applied ultrasonic vibration to the work fluid, and reported a considerable increase of the removal rate at micro-EDM [11,35].

The use of the three methods of ultrasonic assistance, described above is presented in figure 8, for the main variants of EDM.

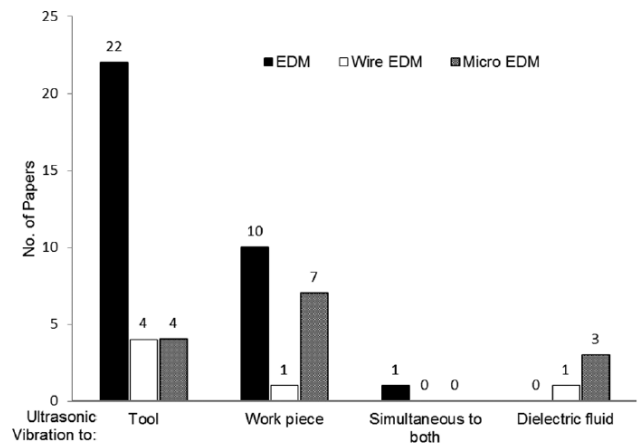


Figure 8. Papers in ultrasonic assistance of EDM, differentiated on specific methods [11]

All these methods have aspects that can be improved. Considering the information presented in 2.1, it can be summed up: the ultrasonic vibration applied to the workpiece enhances the dielectric circulation, and flushing efficiency, obtaining a higher material removal than using the vibration of the wire; the vibration of the workpiece requires larger piezoelectric ultrasonic device, so the vibration of the tool assures low cost and energy consumption; the dielectric fluid creates pressure variation within the gap, and improved evacuation of the debris [11].

Ultrasonic machining is a very efficient method of materials processing nowadays technological competition. It gives some relative advantages [22]: the process is clean, unfailling, steady, and reasonably priced; it uses no consumables; ultrasonic is reliable

in the welding processes, ensuring stable quality; the energy consumption is one of the lowest in comparison with other processes; preparation of fabrication cycle is relative short using computer aiding; tooling has high durability without or little maintenance.

2.2 Laser aiding micro-machining

Laser beam micro-machining (LBMM), represents an important technology for industries like micro-optics, micro-biology, micro-electronics, micro-chemistry etc. The purpose of LBMM technology is to generate surfaces with superior precision and closer dimensional tolerances. This technology can be combined with other separate micro-machining processes, aiming at increase production economical performances assuring also high-quality needs. Another objective of the laser-assisted micro-machining is better surface quality, and roughness [5,17,18].

2.2.1 Laser beam aiding water jet micro-machining

In this process, the basic material is thermally softened by laser and easier removed by high-pressure waterjet. Before hydraulically removal, the material state is changed is melting and vaporization by laser. Since the waterjet reduces the temperature for material removal, this also requires less thermal energy that permits the laser speed feed increasing for a high material removal. This combination has the disadvantage of thermal shock, laser heating and waterjet removal workpiece material, producing micro-cracks. This can be ameliorated by an appropriate pressure of the waterjet, so the effect of this thermal shock is reduced to minimum on machined material. A hybrid cutting head by laser assisted waterjet is presented in figure 9.

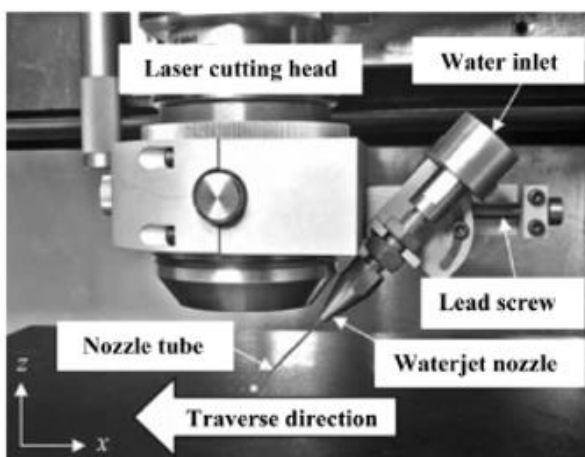


Figure 9. The hybrid head of laser-assisted waterjet machining [17,26]

The system comprises a waterjet nozzle and a laser beam within the hybrid head [5,17,19,36,37].

2.2.2 Laser beam aiding electrochemical jet micro-Machinimng

In case of this process, the main objective is to achieve a better localization, which can lead to a better precision. So, the laser is used to accurately direct and assist the electrochemical process. The laser component augments the speed of electrochemical reactions by its additional thermal energy and the localization of the desired area to be dissolved. But the major material removal process remains electrochemical dissolution in this hybrid micro-machining technological system. In figure 10, it can be seen that the process of material removal occurs in the axial direction instead of the lateral direction. In this way the dimensional precision is improved. Another advantage of using laser beam, is that it helps in the depasivation of oxide layer from the sample surface [5,17]. The experiments realized by the researchers showed that the surface roughness can be improved for holes or cavities [38,39,40].

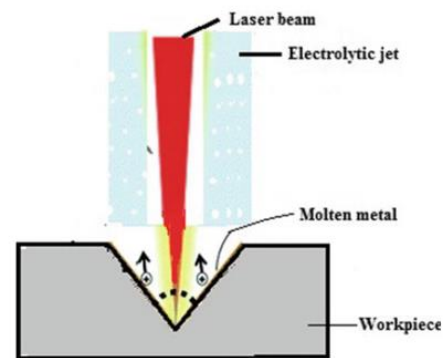


Figure 10. The hybrid micromachining scheme of laser assisted electrochemical jet [5]

2.3 Fluid aiding micro-machining

This hybrid assisted micro-machining involves the using of different forms of fluids like: water, gas, chemical agents, or other special fluids on the machined surface aiming at technological performances augmentation.

2.3.1 Chemical aiding micro-machining

A good example for this technology is the usage of methanol fluid in micro-drilling by laser beam, which can generate micro-holes surfaces with better leveling. This could be explained by lower boiling temperature of the solvent, which assures a higher rate of cooling and hence surface quality.

The classic USM has low-rate removal and surface quality but the combination with the action of low concentration hydrofluoric acid containing abrasive grains can eliminate the withdrawals mentioned above. Chemical-assisted USM at micro and macro-drilling processes can also lead to a strong decrease of the machining forces [5,17].

2.3.2 Gas aiding micro-machining

The fabrication of the aero-engine components, especially cooling holes, using laser micro-drilling, involves techniques like percussion or trepanation to get sharp angles of the generated surface. These parts can be made from Nimonic263, a super-alloy that is often covered by plasma spraying with ceramic *thermal barrier coatings* (TBC). This aims at protection of very high temperatures. A problem to be solved is the delamination of the TBC during functioning. To eliminate this issue, an additional gas jet was applied under a certain angle in order to control the flow of the melt trajectories (figure 11), [5,17].

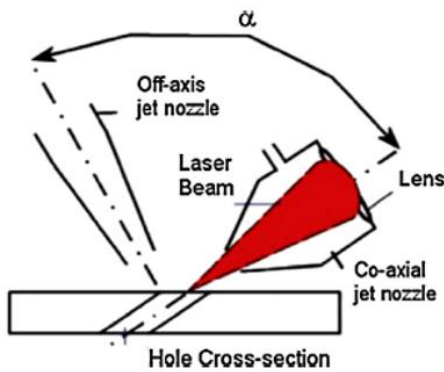


Figure 11. The scheme of secondary gas jet assistance of laser micro-drilling [17,27]

2.3.3 Water aiding micro-machining

Holes can be performed by ablation with higher efficiency, about two times faster, and with less nonconformities like taper, and micro-cracks, when covering the machined surface with thin water layer on machined surface.

In figure 12, is a schematic diagram of water-assisted laser ablation technological system [5,17].

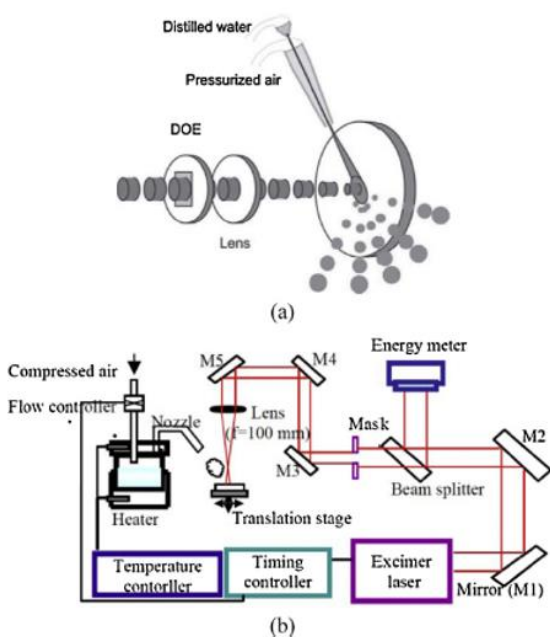


Figure 12. The scheme of hybrid technological system of water-assisted laser ablation [17,28,29]

2.4 Magnetic field aiding micro-machining

Magnetic field assisted works as a boost of the initial machining process by the aiding of magnetic field. The objective is to obtain higher removal rate and better quality of machined surface [20].

a) Magnetic field aiding EDM (MAEDM)

A magnetic force oriented perpendicular to the charged particles trajectory is exerted when the magnetic field is introduced. In this way, the removed particles in the working gap are actuated by a dual force, magnetic and a centrifugal one, to assure a better evacuation [20].

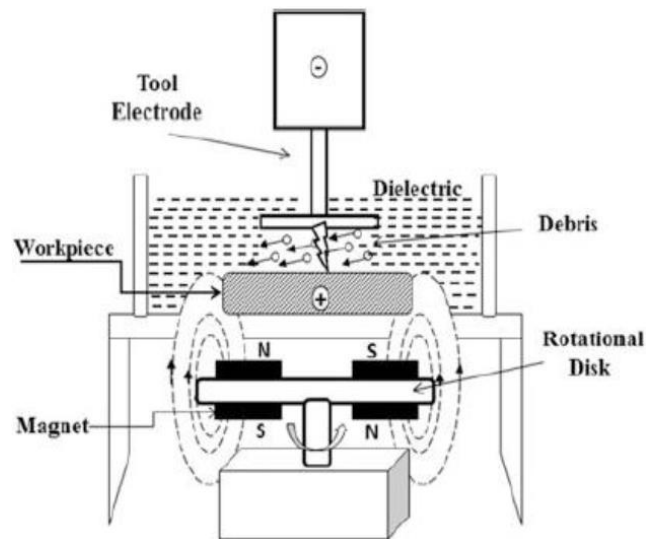


Figure 13. A technological system of magnetic field aiding EDM process [20]

b) Magnetic field aiding abrasive flow machining (MAAFM)

Magnetic field is used at assistance of abrasive flow machining. The aiding of a magnetic field brings the ways of restricting the cutting forces and therefore the output technological performances as better quality of machined surface. This process can produce a surface roughness, Ra of 8-10 nm [20].

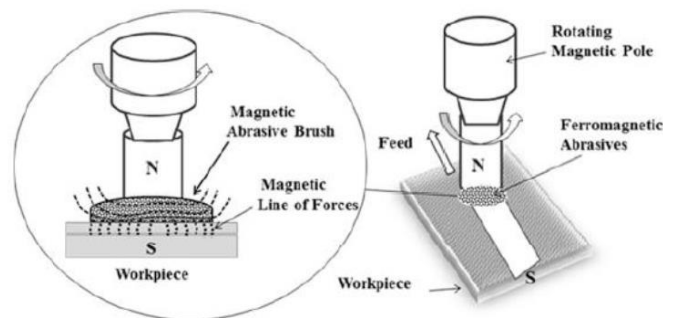


Figure 14. The scheme of finishing by magnetic field assistance of abrasive flow machining [20]

c. Vibration and magnetic field aiding micro-machining

When a magnetic field and an ultrasonic vibration are applied at the same time, in micro-machining process, the efficiency, the surface roughness of the process, can be improved. Figure 15 presents the scheme of technological system of vibration and magnetic field aiding micro-electrochemical machining. The components of this system are a magnetic applicator, ultrasonic generator, a pulse-generator, pump, flow meter, and filter.

The polishing process can be also enhanced by aiding a sort of magnetostrictive polisher, like in figure 16 [17,21].

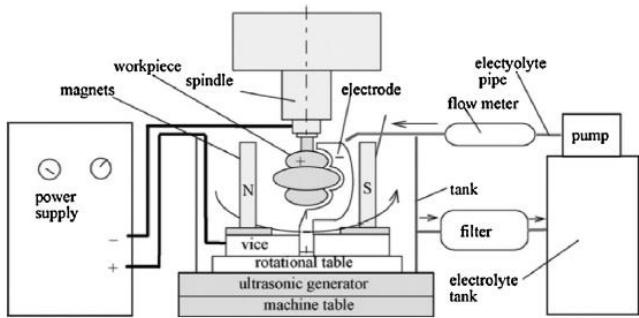


Figure 15. The scheme of technological system of vibration and magnetic field aiding micro-electrochemical machining [17,21]

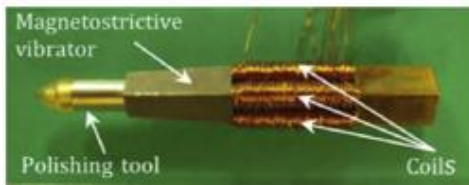


Figure 16. 4-Coil magnetostrictive vibrating polisher [17,30]

2.5 External electric field aiding micro-machining

An electric field aiding micro-machining can be used in LBM process to remove particles and avoid redeposition on machined surface. In figure 17, is a schematic of the experimental technological system using an external electric field for aiding laser micro-machining (a), and the device that provides the external electric field (b).

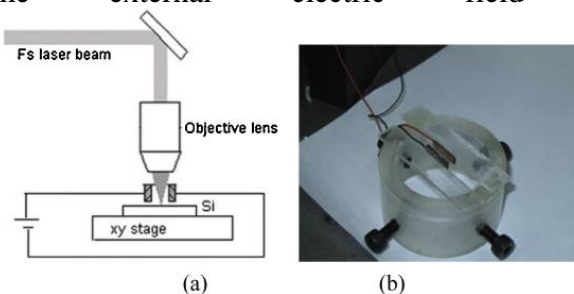


Figure 17. (a) Scheme of the technological system for external electric field applied at laser micro-machining. (b) External electric field device applicator [17, 31]

In figure 18, can be observed the difference between manufacturing silicon parts with femtosecond laser without and with external electric field.

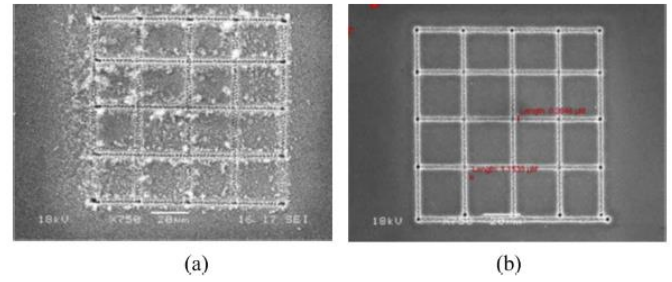


Figure 18. Silicon micro-machining by fs laser: (a) usual and (b) with the aiding of external electric field [17,31]

2.6 Carbon nanofiber aiding micro-machining

In figure 19, is a scheme of the process occurring at classic EDM and carbon nanofiber aiding micro-EDM. Carbon nanofiber has an excellent electrical conductivity, and wherefore is introduced in dielectric fluid to increase its conductivity and the sparking gap between the active surfaces of tool-electrode and workpiece. Consequently, increased working gap helps at evacuation of particles during the micro-machining process.

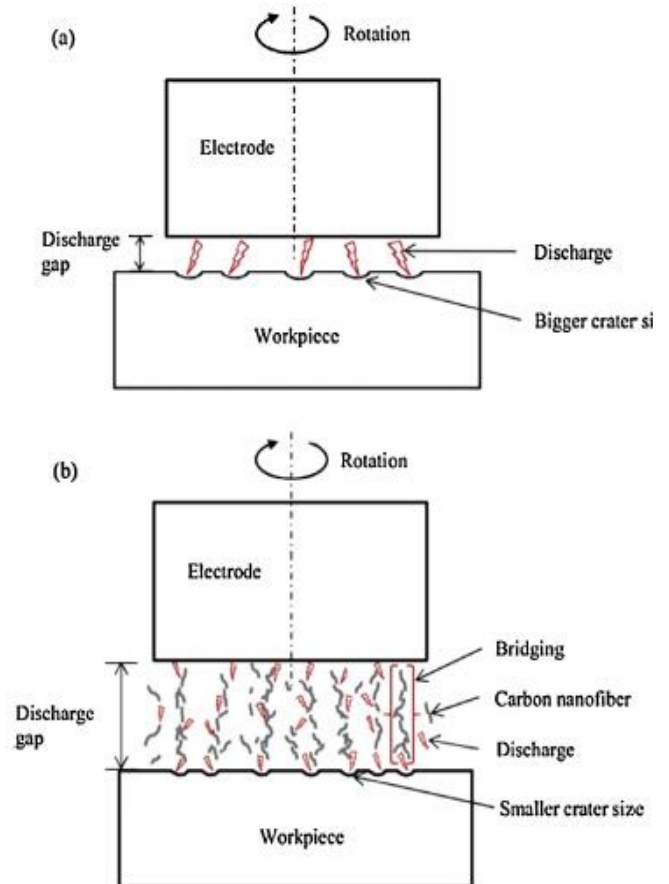


Figure 19. Scheme of the process in case of (a) classic EDM and (b) carbon nanofiber aiding micro-EDM [17,32]

3. CONCLUSIONS

A review concerning the hybrid machining processes is provided, with an essential component, the ultrasonic vibrations.

Hybrid micro-machining processes are in the phase of development and in the context of 4.0 industry, it is a big challenge to improve or discover other performant technologies, as response to progressively increased resistance characteristics of advanced materials and intricate machined surfaces. These technologies are beneficial and efficient in production of complex parts in the peak industries.

The ultrasonic vibrations applied to the most used nonconventional technology, EDM pointed out an increase of the main output technological parameters, i.e. productivity, precision and quality of machined surface, especially in case of working modes with low energy discharges and narrow working gap. The ultrasonic vibration was applied in three variants to: the tool, workpiece, and dielectric liquid. In case, of microEDM, the ultrasonic vibration applied to workpiece and working liquid seems to become dominant trends due to the difficulties to vibrate and assemble very small-scale (micrometric) tool within ultrasonic chains.

Laser assisted process by fluids, chemical agents, magnetic and electric fields is another major research direction, providing solutions to improve the performances of classic LBM, through efficiency of material removal mechanism. These are other technologies that have more and more enhanced area of utilization.

There is a growing trend of using nonconventional hybrid processes in the manufacture of ultraminiaturized parts with complex geometry, proved by the increased number of articles published in recent years in the literature on this topic.

4. ACKNOWLEDGEMENT

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