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Non-traditional machining: a review on methods employed in advanced materials treatment

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Abstract. This article guides the reader through the latest publications about non-traditional machining processes, also revealing those which present hybrid methods, developed for promoting bigger efficiency and economic advantage in non-conventional machining execution. There is, also, an attention to micro machining, a micrometer scale application in dimensions, but with big prospections in modern industry. International articles published since 2014 to 2019 in knowledge bases of Science Direct, CAPES, MDPI, SAGE and IEEExplore referring to methods and new technologies developed in this field are evaluated. The studies expansion in this segment are necessary, since engineering materials or micro machining applications are not well finished by conventional methods and advanced methods can be slow, expensive or even poorly researched, since there are no articles that study absolutely all processes. The optimization techniques, however, give a new vision to maximum utilization possible of the presented techniques.

Keywords: Non-traditional machining. Advanced machining. Micro machining. Non-conventional machining. Hybrid methods. Material removal rate.

1 Introduction

With increasing technological development and the development of state-of-the-art industries, the evolution of the materials used in engineering increasingly requires an evolution in the methods of treatment of these materials (SHUKLA; SINGH, 2017). Therefore, traditional machining loses its place for advanced machining, which corresponds to a set of more efficient methods capable of machining high-cost materials such as ceramics, composites and metal alloys, more economically for the aerospace, electronic, automotive (BAI ANISH ROY, 2019) and biomedical (SAHU; ANDHARE, 2019) industries, for manufacturing tools, molds and so on. Installing the apparatus required to perform these procedures, however, remains a problem.

Among the research articles which review the theme, ten of them were selected for evaluate how the review articles already published about the theme address the topic.

The ten evaluated review articles with their respective authors, years of publication, methods in focus, analysis, comments and respective research bases where the articles were hosted are listed on Table 1. The development of this work follows with the section "Methodology", that explains the carried out research, the "Background Theory", that discourses about the theme of the paper, and the section "Results", where the evaluation of the research articles is categorized into: new experiments, abrasive material, modeling and optimization and applications, according to the categories found in Kumar e Hiremath (2016).

At last, sections "Discussion", which carries out an analyze about the aforementioned works, "Conclusion", which makes relevant remarks referring to the still necessary efforts to the large application of these procedures, and "References", where all the consulted materials for the conception of this review article are exhibited. The importance of this work lives in the union of information about the last published articles about several non-traditional machining methods and about the accomplished efforts in lead to assign more and more efficiency to these procedures execution.

AUTHORS	COUNTRY	YEAR	BASE	JOURNAL	FOCUSED METHOD	ANALYSIS	COMMENT
(CHAVOSHI; LUO, 2015)	United Kingdom	2015	Science Direct	Precision Engineering	several	They have focused on non-traditional machining processes that have micrometric scale application.	Most methods are still in the research phase, in laboratories. Still far from industrial application.
(GOUD; SHARMA; JAWALKAR, 2016)	India	2016	Science Direct	Precision Engineering	ECDM (Electrochemical Discharge Machining)	They conducted a review on the concept of Electrochemical Machining and discussed probable ways to promote enhancement in material removal rate.	The authors state that, according to literature, the material removal mechanism concept in Electrochemical Machining is still not well understood and remains as a research topic, without inclinations to make it a method of industrial application.
(KUMAR; HIREMATH, 2016)	India	2016	Science Direct	Procedia Technology	AFM (Abrasive Flow Machining)	The article presents schematic diagrams of all the new processes developed and studied.	There were a big number of hybrid process considered in an attempt to achieve bigger efficiency in material removal.
(MANJAIAH; NARENDRANATH; BASAVARAJAPPA, 2014)	India	2014	Science Direct	Transactions of Nonferrous Metals Society of China	EDM – WEDM (Wire Electro discharge Machining)	EDM (Electro discharge Machining) and Wire-EDM methods are considered as the more suitable for machining of shape memory alloys, with dimension accuracy.	The authors highlight the fact of there are not many studies on the electric parameters involved in machining.
(MISHRA; YADAVA, 2015)	India	2015	Science Direct	Optics and Lasers in Engineering	LBMM (Laser Beam Micro Machining)	The emergent technology of Laser Beam is presented, short and ultrashort, in submicrometric applications, in which causes little or even no side effects.	It is necessary more computational models and simulations using the FEM (Finite Element Method) method applied in LBMM study.

Table 1 continued from previous page

AUTHORS	COUNTRY	YEAR	BASE	JOURNAL	FOCUSED METHOD	ANALYSIS	COMMENT
(MOLITORIS et al., 2016)	Slovakia	2016	Science Direct	Procedia Engineering	WJ (Water Jet) with slurry injection	Process needs lower pressure to demonstrate the same efficiency of AWIJ (Abrasive Water Ice Jet).	The method presents long commutation times and big abrasive wear.
(RAJURKAR et al., 2017)	USA	2017	Science Direct	Procedia Manufacturing	EDM (Electro discharge machining) – ECM (Electrochemical machining) – USM (Ultrasonic machining) and AFM (Abrasive flow machining) at macro, micro and nano scales	It was presented a study of sustainability issues of four processes (EDM, ECM, USM and AFM).	The three scales (macro, micro and nano) are considered.
(RAO; KALYANKAR, 2014)	India	2014	CAPES	International Journal of Advanced Manufacturing Technology	several	A review concerning to the most industrially employed methods was performed and the selected papers were classified into groups that correspond to this widely used methods.	There are much less works accomplished on micro machining and nano finishing.
(WANG et al., 2018)	China	2018	Science Direct	Ceramics International	RUM (Rotary Ultrasonic Machining)	The material removal mechanism and cutting force modeling of fragile materials were presented.	The method induces undesirable damage in the material.
(YANG et al., 2016)	USA/ China	2016	CAPES	Surface Engineering	Electropolishing	General aspects, some theories and important process parameters are enumerated. Highlight to application in medical field.	It's necessary a deeper study, particularly in relation to used electrolyte to enable the method get more security and applicability.

Then its objective is present in a concise way an evaluation about the total of researched articles to guide the reader by the published works in the last five years.

Accordingly to El-Hofy (2005), machining is any process that promotes material removal with definition of a specific shape with precision dimension and surface finish quality restrictions, so that some modeling procedures requires additional efforts to guarantee this dimensional and superficial precision. In traditional machining, material removal techniques are based on cut and abrasion actions, the tool being harder than the workpiece to be laboured. The new materials used in engineering, however, exhibit thermal, chemical and mechanical peculiar properties that would make it impossible to submit to traditional methods. Appears then a class of processes, in which tools are presented with less hardness than the workpiece, being applied on these advanced materials treatment called non-traditional, unconventional or advanced machining.

In order to adapt the machining process to these new materials, several advanced methods have been developed, being classified in unique-action methods and hybrid methods (EL-HOFY, 2005). Among a universe of unique-action methods it can be distinguished three big groups, they are: mechanical, thermal, chemical and electrochemical. In the first group it is possible to exemplify with Ultrasonic, Water Jet, Abrasive Water Jet and Ice Jet Machining. In the second group, Eletro discharge, Electro Beam, Laser Beam, Ion Beam and Plasma Beam Machining. In the third group, Chemical Milling, Photochemical and Electrochemical Machining (EL-HOFY, 2005).

Within this range of possibilities of pure methods, there are those derived of the association of, at least, two unique-action processes. They are called hybrid processes, where a predominant factor in the auxiliary method could promote an improvement in machining efficiency performed by the base method. The study of these more complex processes generally focus on controlling specific machining factors. Intersections of pure methods to create hybrid methods can be exemplified by: fusion between Grinding and Electrochemical Machining to generate Electrochemical Grinding; fusion between Ultrasonic Machining and Electro discharge Machining to generate Electro discharge Machining Ultrasonically Assisted (EL-HOFY, 2005); and others. It is also possible to have pure and hybrid processes which are less-cited, such as the case of Cryogenic Machining, Burnishing, Abrasive Flow Machining (AFM) and its derivative like Electrochemical Abrasive Flow Machining (ECAFM) and Centrifugal Force Assisted Abrasive Flow Machining (CFAAFM) as cited in Kumar e Hiremath (2016), and so on.

2 Materials and Methods

The chosen set of bases was that whose scope contemplates the Mechanical Engineering, an area which includes the topics referring to machining processes, whether traditional or non-traditional. Scientific articles were searched in knowledge bases Science Direct, CAPES, MDPI, SAGE and IEEExplore, in descending order of results, that review or research the subject in question.

Firstly a general search was made to evaluate the subject coverage. Then, the advanced search restriction was started by the variety of terms that could express the search object. After acquiring a serie of papers, a keyword scan promotes a final adjustment to the formula applied in advanced international articles searches from 2014 to 2019.

In this review are assessed articles related to methods developed on non-traditional machining field, applied on advanced materials manufacturing, as ceramics, shape memory alloys, carbon fiber reinforced plastic (CRFP) and so on. The logical expression used on search on the base Science Direct was: "machining", in field "Find articles with this words" and ["surface" AND ("phenomena" OR "finishing" OR "roughness" OR "waviness" OR "quality" OR "integrity" OR "properties")] OR "surface-structuring" OR ["process" AND ("parameters" OR "optimization") AND "machining"] OR "finishing" OR "polishing" in field "Title, abstract and keyword". On base CAPES title should contain [("advanced"OR OR "nontraditional"OR "non-conventional") AND "machining"] and the subject, ["material removal rate"]. On base MDPI were searched articles by the formula [Abstract advanced machining] AND [All non traditional machining] AND [All material removal rate] AND [All micro machining], which approach the subject. In SAGE base were searched articles with the expression "advanced machining"which are also related to the subject. In IEEExplore base, title should contain "manufacturing" and the abstract, "material removal rate". The base with the largest number of articles displayed in the search was Science Direct, followed by CAPES, MDPI, SAGE and, finally, IEEExplore. Numbers of search, waste and appropriate justifications are shown on Table 2. At the end of search on bases, were selected 76 articles, 10 reviews e 66 researches. After selection, considering the involved methods and the approach used on researches, the articles contemplated in this review were revealed.

In category "New experiments", it was investigated in Zhou et al. (2015) the improvement of the surface integrity of the material after machined by the process of magnetic abrasion with ultrasonic vibration application, which adds to the method 40% more efficiency. The most important variables on magnetic abrasive finishing process were chosen in Jiao2015 and simulations were done by plotting graphs to determine the better polishment trajectory to be executed on the machining. Characteristics of the white layer in two distinct processes, on Laser cutting and on Electro discharge cutting, were compared in Fu et al. (2016). In category "Abrasive Material", a new technology on water jet, IAWJ (Ice Abrasive Water Jet), with expected efficiency between pure method WJ (Water Jet) and AWJ (Abrasive Water Jet), was developed in Jerman et al. (2016). This variation of the method uses ice particles instead of mineral abrasives. In category "Modeling and Optimization", an optimization study applying orthogonal array and analysis of variance in order to obtain better results on material removal and surface roughness in nickel-titanium alloy $Ti_{50}Ni_{40}Cu_{10}$ were carried out in Manjaiah, Narendranath e Akbari (2014). Nano-EDM (Nano Electro discharge Machining) method was studied in Zhang et al. (2014) to machining at nanometric scale, where it is necessary larger researches to overcome the incompleteness of the theories. In category "Applications", the influence of an external heat source, an oxyacetylene solder, in abrasive water jet machining process was studied in Patel e Tandon (2015). The focus of the procedure success lies in the thermal softening caused in hard-to-work materials, allowing them plastic deformation and consequent ease in material removal. A study concerning to diffractive optical elements (DOEs) machining with femtosecond laser was performed in Chabrol et al. (2016). Its purpose is to favour the rapid prototyping development using these materials.

3 Results

According to the division found in Kumar e Hiremath (2016), this article presents its results divided into 4 categories: new experiments, abrasive material, modeling and optimization and applications. The metric used in articles selection is: articles which review or research non-traditional machining methods, which make comparisons between methods, which carry out new experiments with studies of improvement or applications of optimization techniques or which study hybrid methods, innovative, whose results presents itself more efficient and accurate than those presented by a unique method.

3.1 New Experiments

The effects of ultrasonic machining actuation allied to magnetic abrasive finishing in the finalization of titanium workpieces were studied in Zhou et al. (2015). The principle of magnetic abrasive finishing is based on the alignment of abrasive material with the magnetic field imposed by the pole (Nd-Fe-B, for greater magnetic force) forming an abrasive brush, that rotates according to the pole. This material is composed of both ferromagnetic particles (steel), ensuring alignment with the field, and by abrasive particles (alumina or silicon carbide), ensuring necessary toughness in cutting of high hardness materials, immersed in lubricant SR-9911.

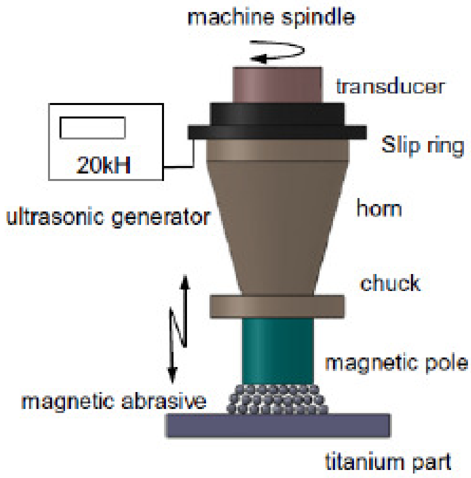

Figure 1: Schematization of the tool used in ultrasonic assisted magnetic abrasive finishing process.
Source: Zhou et al. (2015). Note: The distance between the pole and the workpiece about to be machined is adjusted to about 1-2 mm. Rotational speed is 1200 r/min. The area about to be finished has 2500 mm^2. 5ml of lubricant oil are used. 10g of magnetic abrasive particles with 350μm in dimension are used.

The joining of these two components ensures to abrasive brush flexibility, self adaptability and so on, facilitating internal machining of tubes, machining of more complex shapes and small parts, not reached by traditional methods. According to the authors, it is possible to remove milling layer with its residual tex-

Table 2: List of numbers referring to search on bases, waste and appropriate justifications.

BASE	NUMBER OF RESEARCHED ARTICLES	NUMBER OF REMOVED ARTICLES	JUSTIFICATION
Science Direct	162	113	Some articles talk about conventional machining processes.
CAPES	57	38	Some articles were found in the previous base.
MDPI	31	27	Some articles are not related to the subject in question.
SAGE	17	13	Some articles are not related to the subject in question.
IEEExplore	3	3	They do not refer exactly to an advanced machining method.

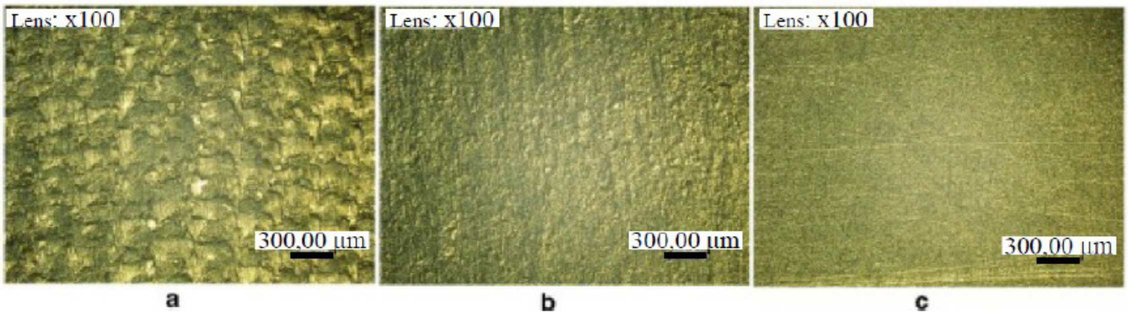

Figure 2: a – Surface of a titanium workpiece after milling. b – Surface of a titanium workpiece after magnetic abrasive finishing. c – Surface of a titanium workpiece after ultrasonic vibration assisted magnetic abrasive finishing.
Source: Adapted from Zhou et al. (2015).

tures and microcracks with this technique. Structure employed in the approached process and a comparison between the surfaces of titanium workpieces after milling, after magnetic abrasive finishing and after ultrasonic vibration assisted magnetic abrasive finishing are showed in Figures 1 and 2 respectively.

The Magnetic Abrasive Finishing (MAF) method was presented in Jiao et al. (2015). The principle of the technology employed in the procedure in question is: insertion of magnetic abrasive particles and lubricant in the space between the magnetic pole of the "tool" and the workpiece. These particles are magnetized and as a consequence of their alignment they will form a kind of abrasive brush that, with the rotation of the magnetic pole, will have their movement relative to workpiece as a promoter of the finishing. The magnetic abrasive finishing is a high-precision polishing process with advantages of using less machining force, self-adaptability, complex shape machining and better cutting edge control. The conventional trajectory, with only linear movement of the tool, and the trajectory experienced, with revolution movement of the tool, are showed in Figure 3.

For the experiment accomplishment a prototype was developed that allows a distinguished movement of the workpiece. The equipment is illustrated in Figure 4. As a result it concludes that the better trajectory planning promotes better surface finishing, which was already known and executed in traditional machining centres programming also in relation to the reduction of working time. The evaluated parameters are: surface roughness, material removal, cross-section format and 3D micromorphology in the polished area of four workpieces used in the experiment.

A comparative study of the properties of the white layer (recast layer) was brought by Fu et al. (2016). The white layer is formed by rapid re-solidification of the melted material in cutting area due to the intense heat flow received. The two machining methods to be evaluated are Laser cutting and Electro discharge (EDM), that have presented a good performance in machining and both are the best procedures for Nitinol alloys cutting application (a kind of SMA – Shape Memory Alloy), material that also has features of superelasticity and biocompatibility. The main factors evaluated in this study were: surface roughness, topography, microstructure, grain orientation, nanohardness and elementary contamination. As a result, the highest white layer

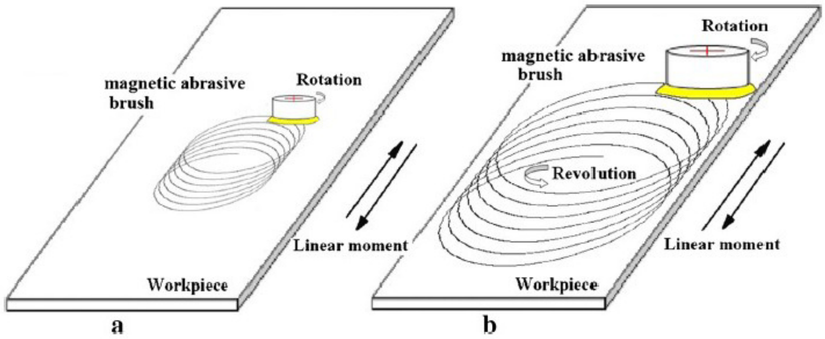

Figure 3: a – Conventional trajectory of magnetic finishing; b – Enhanced trajectory.
Source: Jiao et al. (2015). Note: The machined workpiece is stainless steel SUS304 with dimensions 100x100x2 mm. For magnetic abrasive particles suspension was used water-based lubricant; 2.8mg of steel particles with 30μm; 0.7mg of KMX powder with 5μm. The distance from the magnetic pole to the workpiece is 0.5mm. Pole rotational speed is 438r/min.

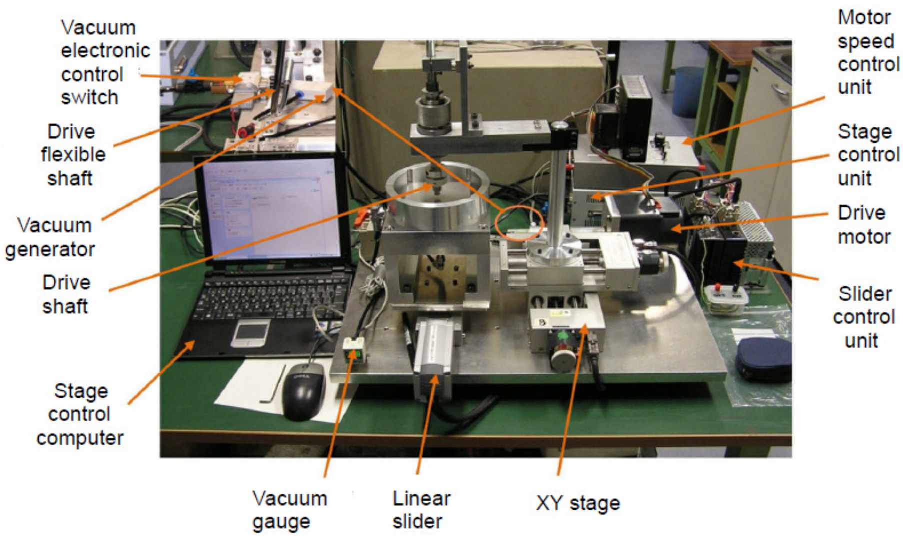

Figure 4: Prototype developed to carry out the enhancement tests of trajectory in magnetic abrasive polishing.
Source: Jiao et al. (2015).

roughness was obtained in Laser cutting due to the columnar pattern imposed by the beam flow, and it was uniformly distributed, without failures or new phases, and the nanohardness of white layer samples in material cut by laser is lower than in bulk material, although both techniques present white layers with smaller grains, of the order of submicrons, in relation to the rest of the material.

3.1.1 Abrasive Material

Concerning to water jet machining (WJM), it was shown in onlineJerman2016 a study about a new technology that uses ice particles in place of mineral abrasive employed in AWJ (Abrasive Water Jet). The attention given to this "group" of methods is due to its versatility and emergent application in industry. The custom machine used in IAWJM (Ice Abrasive Water Jet Machining) where this measurements are performed is shown in Figure 5.

In the cited article the study is done by the thermal aspect, where temperature is measured at different points of the jet in normal operation and when the water under high pressure is cooled. Three temperatures are chosen in the collimation tube to verify the influence of the water cooling on jet formation. It was concluded that there is not big changes in water temperature

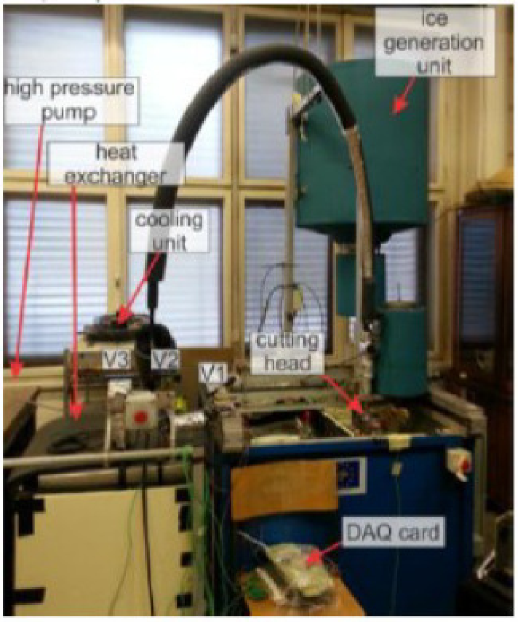

Figure 5: Water jet machine adapted to tests of IAWJ.
Source: Jerman et al. (2016).

during its passage through the water nozzle.

3.1.2 Modeling and Optimization

An optimization study to obtain better results referring to material removal rate and surface roughness of the machined material was presented in Manjaiah, Narendranath e Akbari (2014). For the analysis of the effects of the parameters in both aforementioned results is used a combination of orthogonal array and variance analysis. The highlighted machining procedure is WEDM (Wire Electrodischarge Machining), the appropriate procedure for the treatment of materials such as $Ti_{50}Ni_{40}Cu_{10}$ alloy, used in the experiment. In a larger scope, nickel-titanium alloys have unique characteristics among several materials like pseudoelasticity and shape memory and are widely employed in automotive, aerospace and biomedical industries. Experiments were carried out to validate values obtained by Taguchi L18 optimization method (Technique based on orthogonal arrays that allows the simultaneous study of several factors involved in the process). The observed error was measured around 6%, leading to the conclusion that the numbers originated from the optimization techniques are closely related to the reality of the experiments.

The application of Electrochemical machining in nanoscale was studied by Zhang et al. (2014). The computational modeling employed uses hybrid methods of MDSM (Molecular Dynamics Simulation Model) and TTM (Two Temperatures Model) for unique discharge process aiming to study the nano-EDM method by the thermal aspect. The association of these two methods suits better to the nanoscale investigation about dynamic effect of the material, that it is beyond of the traditional methods possibilities such as the Finite Elements Method, for example. Stresses in the material are analyzed during melting, cooling and solidifying. Before melting a thermal compressive stress higher than 3GPa is provoked. After melting this compression is relieved and a tensile stress appears. During cooling of the melted material was observed a stress higher than 3GPa which comes up and lead to the material disintegration.

3.1.3 Applications

It was performed by Patel e Tandon (2015) a study about a derivative process from Abrasive Water Jet Machining method, in which is used an oxyacetylene gas welding as a heat source external to the system. The new process, Thermally Enhanced Abrasive Water Jet Machining (TEAWJM), explores the thermal effect in the material which occurs with temperature increasing, what can facilitate hard-to-machine materials manipulation, since high temperatures imposition to machining enables occurrences of plastic deformation in cutting area, enhancing material removal and cutting depth in this area. Experiment data concerning to these parameters are collected in tests with the materials: Inconel 718 (Nickel, chromium, molybdenum and niobium alloy, mostly), Titanium Ti_6Al_4V and Mild Steel MS-A36 (carbon steel). These data points that Mild Steel is not well machined by the technique in question when its application requires bigger precision, because it presented microcracks in surface. The Inconel and Titanium Ti_6Al_4V are well machined by the technique, being very resistant to pressure and heat without big damages in their structures. Then it was obtained, as efficiency evaluation parameters of the procedure, increase of material removal rate and machining time reduction.

It was studied by Chabrol et al. (2016) machining by femtosecond laser of a specific type of material, which shows diffractive optical characteristics (DOE) such as fused silica and quartz, for example.

AUTHORS	COUNTRY	CLASSIFICATION	YEAR	FOCUSED METHOD	BASE	JOURNAL	COMMENT
(BAI ANISH ROY, 2019)	China/ UK	Enhancement	2019	Ultrasonically assisted turning (UAT)	Science Direct	Journal of Materials Processing Tech.	Improvement of the machining of SiC-reinforced metal-matrix composite by Ultrassonically assisted turning.
(SAHU; ANDHARE, 2019)	India	Optimization	2019	Turning	Science Direct	Journal of Computational Design and Engineering	Optimization study of some parameters involved in machining of Ti-6Al-4V.
(KUMAR; HIREMATH, 2016a)	India	Enhancement/ Application	2016	micro AJM	Science Direct	Procedia CIRP	Improvement of hole machining. Reduction of conicity.
(KUMAR; HIREMATH, 2016b)	India	Optimization	2016	micro AJM (Micro Abrasive Jet Machining)	Science Direct	Procedia Technology	The microabrasive machining technique has wide industrial applications and is used for making holes, ducts and others on fragile materials. There is an investigation of the optimal machining parameters, as well as is used a Gray Relational Analysis (GRA) to optimize material removal rate parameters and radial overcut. The set Taguchi L9 is used for project the experiments.
(AICH et al., 2014)	India	Modeling/ Optimization	2014	AWJM (Abrasive Water Jet Machining)	Science Direct	Procedia Materials Science	The process is appropriate for several cuts of crystalline materials, however there are not studies about amorphous materials. The borosilicate glass is studied in this article. A model is done. The optimal condition of control parametrization is researched by Particle swarm optimization.
(ARIF; KAUTEK, 2014)	Austria	New experiments	2014	Pulsed Laser	CAPES	Applied Surface Science	Removal of impurities in the material.

Table 3 continued from previous page

AUTHORS	COUNTRY	CLASSIFICATION	YEAR	FOCUSED METHOD	BASE	JOURNAL	COMMENT
(KUMAR; YOGANATH; KRISHNA, 2018)	India	New experiments (Parameters investigation)	2018	Cryogenic	Science Direct	Materials Today: Proceedings	Cryogenic Machining was presented as an economical, green and alternative way to machine hardened alloys. Machinability factors such as tool life, surface roughness and power consumption are studied.
(AYYAPPAN; SIVAKUMAR; KALAIMATHI, 2015)	India	New experiments	2017	ECM	SAGE	Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science	In this study, a tool with low frequency of vibration and assisted by a magnetic flux was used as an efficient hybrid technique in ECM for improving material removal rate and surface roughness of 20MnCr5 alloy steel.
(BRECHER et al., 2016)	Germany	Simulation	2016	general	Science Direct	CIRP Journal of Manufacturing Science and Technology	The precision loss in multitechnology machining centres is studied. A simulated analysis was done.
(CHABROL et al., 2016)	France	New experiments/ Application	2016	Laser	CAPES	Applied Surface Science	The laser machining of Diffractive Optical Elements (DOE) is approached.
(CHE et al., 2016)	China	Enhancement	2016	EDM	Science Direct	Journal of Materials Processing Technology	The Electro discharge method and the attempt of enhancement of its efficiency with the Ultrasonic vibration of the electrode is addressed.
(CHEN et al., 2016)	China	New experiments (Parameters investigation)	2016	Micro ECM	Science Direct	Procedia CIRP	For material removal rate and precision evaluation, changes in machining parameters such as voltage, electrolyte flow, frequency of pulse generator and so on are investigated.

Table 3 continued from previous page

AUTHORS	COUNTRY	CLASSIFICATION	YEAR	FOCUSED METHOD	BASE	JOURNAL	COMMENT
(EL-HOFY et al., 2018)	UK/ Egypt	New experiments	2018	AWJM	Science Direct	Procedia CIRP	The author presented an experimental study and a statistical analysis about CFRP (Carbon fiber reinforced plastic) laminates cutting by AWJM method, which are widely used in aerospace, automotive and marine industries.
(FERNÁNDEZ-VALDIVIELSO et al., 2016)	Spain	New experiments	2015	Turning of Inconel 718	SAGE	Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science	An indirect way of looking for common features in a group of tools that have the best performance in Inconel 718 machining has been presented.
(FEUCHT et al., 2014)	Germany/ Japan	New experiments (New technique)	2014	Ultrasonic	Science Direct	Procedia CIRP,	Integration of ultrasonic systems in machining centres.
(FU et al., 2016)	USA/ China	New experiments (Comparative study)/ Application	2016	LC (Laser Cutting) x EDM	Science Direct	Procedia CIRP	Potential differences between white layers formed after quick material resolidification in the surface affected by heat in each process, laser or electro discharge, were studied. All this relative to Nitinol machining, a shape memory alloy.
(GENG et al., 2017)	China	New experiments (New technique)/ Application	2017	UERV	Science Direct	Ultrasonics	Employment of a new technique UERV (Ultrasonic Elliptical Vibration-assisted Reaming) in the confection of screw holes.

Table 3 continued from previous page

AUTHORS	COUNTRY	CLASSIFICATION	YEAR	FOCUSED METHOD	BASE	JOURNAL	COMMENT
(GNANAVELBABU et al., 2018)	India	New experiments (Parameters investigation)	2018	AWJM	Science Direct	Materials Today: Proceedings	Metal matrix composites (MMC) are difficult to machine by conventional methods due to tool wear and cutting temperature. AWJM is a process which overcomes these issues, being efficient for these materials. In this article, an experimental study using AWJM to machine AA6061-B4C- CNT with parameters investigation was performed. Boron carbide was used as reinforcement and Carbon Nanotube (CNT) as solid lubricant.
(GOSWAMI; CHAKRABORTY, 2016)	India	Optimization	2017	ECDM (Electrochemical Discharge Machining)	CAPES	Opsearch	A multi-objective optimization study about the ECDM processes using Bird Mating Optimizer (BMO) was performed. The technique is a two single-action process combination. The hybrid process improves productivity, accuracy and surface quality.
(GOUD; SHARMA, 2016)	India	Simulation	2016	ECDM (Electrochemical Discharge Machining)	SAGE	Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science	Materials such as glass and ceramic have nowadays more industrial applications due to their characteristics: wear resistance, high compressive strength, chemical inertia, etc. Glass, polymer and silicon have become very popular in micro electromechanical systems. In this paper, a model based on Finite Elements was made to simulate the material removal in Electrochemical Discharge Machining Drilling.

Table 3 continued from previous page

AUTHORS	COUNTRY	CLASSIFICATION	YEAR	FOCUSED METHOD	BASE	JOURNAL	COMMENT
(GUPTA et al., 2014)	India	New experiments (Parameters investigation)	2014	AWJM	CAPES	Procedia Materials Science	AWJM and the influence of certain parameters in the process, such as water pressure, transverse velocity of the nozzle and abrasive flow rate were studied. Variance analysis was used for this.
(HAN et al., 2018a)	China	New experiments	2018	ECM	Science Direct	Procedia CIRP	Experiments with a "new" pulsed source in which there is an effort to reduce polarization voltage influence on ECM accuracy, the most appropriate method for high heat resistance and hardness conductors, have been performed.
(HAN et al., 2018b)	China	New experiments	2018	EDM	Science Direct	Journal of Materials Processing Technology	A solution to the white layer problem was studied.
(JANCZEWSKI et al., 2016)	Poland	New experiments (Parameters investigation)	2016	Burnishing	Science Direct	Tribology international	Ball burnishing was applied to specimens of low density high molecular mass polyethylene (LDPE) after milled. Burnishing decreases the wear rate by 58%.
(JAWAHIR et al., 2016)	USA	Overview	2016	Cryogenic	Science Direct	CIRP Annals	This article presents an overview of cryogenic machining processes which are emerging as better to environment, safer and less toxic processes with superior quality products.
(JERMAN et al., 2016)	Slovenia	Abrasive material	2016	IAWJM	Science Direct	Procedia Engineering	Technology development to reduce productivity differences between the AWJ and WJ cut. It is a cleaner and more efficient technology that would use ice instead of mineral abrasive.

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AUTHORS	COUNTRY	CLASSIFICATION	YEAR	FOCUSED METHOD	BASE	JOURNAL	COMMENT
(JI et al., 2014)	China	New experiments (Parameters investigation)	2014	EDM	CAPES	PloS ONE	It is the appropriate process for machining engineering ceramics. Relationships between material resistivity and process parameters such as material removal rate, surface roughness and wear ratio of the electrodes were investigated.
(JIAO et al., 2015)	China/ Japan	New experiments	2015	MAF (Magnetic Abrasive Finishing)	CAPES	International Journal of Advanced Manufacturing Technology	The experiments aim to increase the integrity and homogeneity of the surface.
(KAYNAK; GHARIBI, 2018)	Turkey	New experiments (Parameters investigation)	2018	Cryogenic	MDPI	Journal of Manufacturing and Materials Processing	Cryogenic coolants (Liquid nitrogen and Carbon dioxide) are studied and their performances compared to tool wear.
(KOVAČEVIĆ et al., 2014)	Serbia	Optimization	2014	general	Science Direct	Expert Systems with Application	Development of a software prototype that uses meta-heuristics algorithms to solve multi-objective optimization problems.
(KOZAK; ZYBURA-SKRABALAK, 2016)	Poland	New experiments	2016	ECM	Science Direct	Procedia CIRP	The ECM process is characterized and a mathematical model to simulate its evolution is developed.
(PAL; CHOUDHURY, 2015)	India	New experiments (New technique)	2016	AWJM	CAPES	International Journal of Advanced Manufacturing Technology	A new tool fabrication strategy based on AWJM has been proposed to manufacture large-area texturing tools for EDM.
(PAL; CHOUDHURY, 2014)	India	New experiments/ Application	2014	AWJM	Science Direct	Procedia Materials Science	Machining of blind pockets in Ti_6Al_4V alloy by AWJM method. During the tests, parameters such as pressure and particles size are changed.

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AUTHORS	COUNTRY	CLASSIFICATION	YEAR	FOCUSED METHOD	BASE	JOURNAL	COMMENT
(LIANG et al., 2016)	China	Optimization	2016	WJ grinding	CAPES	International Journal of Intelligent Manufacturing	An optimization study using orthogonal-experiment-design-based adaptive neural fuzzy inference system (ANFIS) was performed to obtain optimal grinding performance to bearing rings.
(LIN et al., 2018)	Taiwan	New experiments (New technique)	2018	Hybrid method of EDM and AJM	Science Direct	Procedia CIRP	The machining efficiency is evaluated, the optimization calculations are performed and the influence of parameters is investigated in a method that combines EDM and AJM (Abrasive Jet Machining) in the treatment of steel SKD 61.
(LIU; GUO, 2015)	USA	New experiments/ Application	2015	WEDM	Science Direct	Procedia Manufacturing	Machining of a shape memory alloy – Nitinol – by wire EDM. A comparison is made with the traditional mechanical cut.
(MANJAIAH; NARENDRANATH; AKBARI, 2014)	India/ Malaysia	Optimization	2014	WEDM	Science Direct	Procedia CIRP	The optimization is evaluated by the Taguchi technique.
(MAUROTTO; SCENINI; KRAEMER, 2018)	United Kingdom	New experiments (Parameters investigation)	2018	Laser Assisted Machining	MDPI	Journal of Manufacturing and Materials Processing	The using of a laser irradiation to improve machinability of hard-to-cut alloys has been studied. The machined type was 316L stainless steel.
(MCGEOUGH, 2016)	United Kingdom	Abrasive material/ Application	2016	WJM	Science Direct	Procedia CIRP	Other substances are investigated to compose the cutting jet in slaughterhouses.

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AUTHORS	COUNTRY	CLASSIFICATION	YEAR	FOCUSED METHOD	BASE	JOURNAL	COMMENT
(MENG; ZENG; ZHU, 2017)	China	New experiments	2017	WECM (Wire Electro-chemical Machi-ning)	CAPES	Electrochimica Acta	A flexible and effective method for making micrometal components in complex shapes and with many advantages over thermomechanical processing. Changes in voltage pulse wave form and electrolyte composition to increase the efficiency and machining stability were evaluated.
(MISHRA et al., 2014)	India	Simulation	2014	MAF	CAPES	Journal of Manufacturing Processes	The Abrasive Magnetic Finishing is a type of surface finishing process that promotes material removal by abrasive particles in the presence of a magnetic field. Surface temperature is investigated because temperature is a key parameter in the finishing mechanism and in integrity of the workpiece surface. A Finite Element analysis was performed on the magnetic field distribution and temperature at the machining interface.
(MORKAVUK et al., 2018)	Turkey	New experiments	2018	Cryogenic	Science Direct	Composites Part B	The way how cryogenic cutting fluids can improve machining performance of Carbon fiber reinforced plastics (CFRPs) has been studied.
(NEUENSCHWANDER et al., 2014)	Switzerland	Optimization	2014	Ultrashort pulsed Laser	CAPES	Physics Procedia	Characteristics, parameters and its optimal values for method efficiency are discussed.
(OSSWALD et al., 2018)	Germany	New experiments (Parameters investigation)	2018	Hand Scraping	MDPI	Journal of Manufacturing and Materials Processing	The process was studied and its characteristics were analyzed to contribute to a future implementation of an Automated Scraping.

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AUTHORS	COUNTRY	CLASSIFICATION	YEAR	FOCUSED METHOD	BASE	JOURNAL	COMMENT
(PARMAR; JAMES, 2018)	USA	New experiments (New technique)	2018	Laser Beam Micro machining	MDPI	Journal of Manufacturing and Materials Processing	The possibility of machining smart ceramic materials by a Liquid Assisted-Laser Beam Micro machining method was studied. Studies are performed to compare the Laser Beam Machining process in the air and in a liquid medium.
(PATEL; TANDON, 2015)	India	Enhancement	2015	TEAJM	CAPES	CIRP Journal of Manufacturing Science and Technology	The effect of the temperature on AJM is studied. The thermally enhanced process presents increasing in material removal rate, reducing machining time and energy consumption.
(PATEL et al., 2017)	USA/ Mexico	Enhancement	2017	ECM	Science Direct	Procedia Manufacturing	Enhancement electrochemical machining by combination of pulsed current and ultrasonic wave.
(PAUL; HIREMATH, 2016a)	India	Overview	2016	ECDM	Science Direct	Procedia Technology	Theoretical study, experimental investigation and control strategies for the hybrid process of ECDM.
(PAUL; HIREMATH, 2016b)	India	Electrolyte	2016	ECDM	Science Direct	Procedia Technology	Use of mixed electrolyte (NaOH and KOH) in the ECDM process aiming to evaluate improvements in the machining rate.
(PRAMANIK et al., 2015)	Australia	Application	2015	EDM	Science Direct	The Nonferrous Metals Society of China	Material removal rate, cutting width, surface finishing and wear of the electrode wire were studied in wire-EDM machining of 6061 aluminum alloy.
(RAO; RAI; BALIC, 2017)	India/ Slovenia	Optimization	2017	WEDM/ LC/ ECM/ FIB micro milling	CAPES	Engineering Applications of Artificial Intelligence	Four processes to optimization were considered in this work: wire-EDM, laser, ECM e FIB (Focused Ion Beam) micro-milling.

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AUTHORS	COUNTRY	CLASSIFICATION	YEAR	FOCUSED METHOD	BASE	JOURNAL	COMMENT
(SACHIN; NARENDRANATH; CHAKRADHAR, 2018)	India	New experiments	2018	Diamond Burnishing	Science Direct	Materials Today: Proceedings	Surface integrity characteristics such as microhardness and residual stresses were studied after diamond burnishing of 17-4 PH Stainless Steel under three different environments: Cryogenic, Dry and Minimum quantity lubrication (MQL).
(SANCHEZ et al., 2017)	Brazil	New experiments (New technique)	2017	Hot Burnishing aided by infrared radiation	Science Direct	Procedia CIRP	Based on the fact that burnishing occurs by plastic deformation, a technique to heat the workpiece with less costs and space was studied in this paper. The machining characteristics such as surface roughness and circularity, however, have not been improved with the use of infrared radiation.
(SHARMA; MOHANTY; PARDASANI, 2018)	India	New experiments (New technique)	2018	Cryogenic EDM	Science Direct	Materials Today: Proceedings	A thermo-numerical model based on Finite Element Method to predict two process parameters: Material removal rate (MRR) and Tool wear rate (TWR) was studied. The model aim to enhance productivity in Cryogenically treated EDM.
(SHUKLA; SINGH, 2017)	India	Optimization	2017	AWJM	CAPES	Swarm and Evolutionary Computation	Process experimental investigation following the Taguchi methodology. Seven advanced optimization methods are used to compare experiment data and simulation results. The aim is verify the efficiency of this tools.

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AUTHORS	COUNTRY	CLASSIFICATION	YEAR	FOCUSED METHOD	BASE	JOURNAL	COMMENT
(SIHAG; KALA; PANDEY, 2015)	India	New experiments/ Simulation/ Application	2015	MAF	CAPES	Procedia CIRP	There is a conception of a new surface machining method that combines chemical oxidation and abrasion assisted by a magnetic field to the faster processing of tungsten, which if it is processed by individual machining assisted by a magnetic field, abrasive flow machining or chemical mechanical finishing, the process would be slower. A variance analysis was performed to evaluate the influence of each factor. The experiment was planned using Taguchi L9. A regression model was made to predict percentage variation of the surface roughness as a function of the factors changes.
(SINGH; DVIVEDI, 2016)	India	New experiments/ Application	2017	EDM	Science Direct	Materials Today: Proceedings	Several effects of the parameters during Electro discharge Machining were studied. This is the most suitable method to manufacturing dies with complex shapes.
(SRIKANTH; RAO, 2015)	India	Optimization	2015	AJM	Science Direct	Materials Today: Proceedings	Study of the influence of machining parameters in AJM process applied in the ceramics cover treatment. The abrasive particles used was Al2O3.
(SRIKANTH; SREENIVASARAO, 2014)	India	Optimization	2014	AJM	Science Direct	Procedia Materials Science	The optimization is evaluated using the Taguchi technique.
(TANG et al., 2018)	China	New experiments (Parameters investigation)	2018	Cryogenic burnishing	Science Direct	Surface and Coatings Technology	The effect of cryogenic burnishing on the Ti-6Al-4V titanium alloy corrosion film formation mechanism was investigated.

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AUTHORS	COUNTRY	CLASSIFICATION	YEAR	FOCUSED METHOD	BASE	JOURNAL	COMMENT
(UCHIYAMA; HASEGAWA, 2018)	Japan	Optimization	2018	ECM	Science Direct	Procedia CIRP	An optimization study is carried out on the design of the tool and the machining conditions of short curved holes by the ECM method.
(WANG et al., 2017)	China	New experiments (New technique)	2018	ECM	SAGE	Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science	The authors sought to find a suitable method for making holes by electrochemical machining.
(XU et al., 2017)	China	New experiments	2017	ECM/ ultrasonic	Science Direct	Precision Engineering	Micro Machining and electrode vibration technique. Their influences in several parameters are investigated.
(XU et al., 2018)	China/ USA	New experiments (New technique)	2018	ECDM	Science Direct	Journal of Materials Processing Technology	ECDM method is characterized as a promising technology for micro machining and the advantages of a new drilling method in comparison with an old method by gravity, principally about repeatability are investigated.
(ZHANG et al., 2014)	China	Simulation	2014	Nano-EDM	CAPES	Applied Surface Science	Unsolved problem: incompleteness of the theories of the process that prevents its more advanced development. A computational simulation was performed to study nano-EDM mechanism from a thermal point of view.
(ZHOU et al., 2015)	China	New experiments (New technique)	2015	UMAF	CAPES	International Journal of Advanced Manufacturing Technology	Experimental verification of UMAF (Ultrasonic Magnetic Abrasive Finishing) efficiency.

Aiming to make the prototype of these materials more efficient and agile, ultrashort pulsed laser is used to overcome materials reflectivity, employing in its cut a laser whose energy is lower than material band gap, making it transparent and allowing its treatment in less time and with lower cost.

4 Discussion

According to what can be observed in the "Focused Method"column of the table where all the research articles are listed (Table 3), there are groups of methods that appear more frequently, they are water jet, electro discharge, magnetic finishing and machining laser-cut groups of methods. The articles presented in the "Results"section can be accurately classified, two by two, into these groups.

An approach to Laser Cutting was performed in Chabrol et al. (2016) and Fu et al. (2016). In the first one, a study is realized referring to reduction of the period of the laser beam to facilitate diffractive materials machining, such as BK7 (a type of optical glass with characteristics inferior to fused silica), allowing the treatment of a binary phase grating of this material with dimensions 20x1x8 micrometres could happen in 4 hours, which took a couple of days before. It was obtained 27% of efficiency, ratified by the theoretical calculation. Secondly, however, there is a comparison on the Electro discharge method in machining of Nitinol alloys. The result obtained with laser is: white layer evenly distributed, bigger roughness and lower hardness in nanoscale in comparison with entire workpiece. A possible explanation is the difference between cooling and hardening rates and oxides formation in EDM method.

An approach to abrasive water jet machining was performed in Patel e Tandon (2015) and Jerman et al. (2016). In the first one a thermal improvement in the technique is tried, that when maintained at its optimum point facilitates the cut due to the plastic deformation of the part. With the Inconel 718, there is an increase in the rate of material removal as long as the temperature and pressure increase as well. The same is true for mild steel. On the other hand, in Jerman et al. (2016), the use of a different abrasive in the process, the ice, was tested, and the hypothesis of large temperature variation at the exit of the water nozzle was discarded. The use of ice finds applications in food and medical areas, because the low temperature prevents the growth of bacteria.

A study on Magnetic Abrasive Finishing was performed in Jiao et al. (2015) and Zhou et al. (2015). In the first, there is only one change in the trajectory of the abrasive brush, which varies from linear to circular, increasing the operation area of the tool. With the progressive increase of the radius of trajectory there is a reduction in the maximum height difference in the polishing area compared to the original method. For a radius of 4 mm, the maximum height difference is 1.2 μm, which accounts for a reduction of 52% in relation to the linear polishing trajectory. For a radius of 5 mm, the height difference is 1 μm and the reduction is 60%. For a radius of 6 mm, the height difference is 0.8 μm and the reduction is 68%. The mathematical software Graph is used for better trajectory planning, by plotting graphs based on the lateral and central regions of the polished area, where there is greater density of intersections of the various circumferences performed by the tool. In the second one is tested a improvement of the technique, the use of ultrasonic vibration, which reduces tensions, promotes flexibility for the abrasive brush and allows micrometric cutting, increasing the efficiency of the method. The quality of the final surface of the workpiece is evident with microcracks and roughness reductions.

Finally, a study about Electro discharge Machining was performed in Manjaiah, Narendranath e Akbari (2014) and Zhang et al. (2014). The first one focuses on the machining of shape memory alloy wires and uses the Taguchi optimization technique. The values resulting from the theoretical calculus show error of 3.22% for material removal rate and 5.73% for surface finishing, in which the maximum acceptable is 10%. The second one studies the process mechanism applied to micro machining and uses computational simulation to predict results. Existing discrepancies are due to the use of only a little portion of the real electrode, to reduce computational costs. In the experiment, the formation of the white layer occurs when the temperature of the melted region drops to about 700K, when the homogeneous solidification is processed. Another detail related to this layer formation is the quenching effect provoked by the dielectric at a lower temperature, which was not taken into account in the experiment.

Hybrid methods tend to appear as an attempt to reach bigger efficiency in the execution of the base method, both in relation to a better surface finishing and lower tool wear. In this sense, studies of Laser irradiation application in pure methods of Milling and Hot burnishing, respectively, are accomplished in Maurotto, Scenini e Kraemer (2018) and Sanchez et al. (2017).

In the first one, in which there is a laser incidence at the same time of the material removal, the surface melting by the laser has led a formation of a fast solidification layer resulting in removal of cold-worked effect and softening of the surface layers. In the second one, the heat provided by irradiation may have been the reason why the hybrid method was no more efficient than the pure method. According to the authors there was an excessive plastic deformation with the increase of the force, preventing a better performance of the method in question when compared to the traditional method.

The group of processes which contains the methods of machining by Material Addiction, however, it was not contemplated in this article. This group is divided in techniques based on use of liquids (Stereolithography - SLA, for example), powder (Selective laser sintering - SLS, for example) and solids (Solid foil polymerization, for example).

5 Conclusions

This review article contemplates international papers published from 2014 to 2019 in Science Direct, CAPES, MDPI and SAGE knowledge bases concerning to non-conventional machining methods. Based on technological development alleged in several selected papers, in the fact of these articles privilege certain methods and in the necessary structure to these advanced processes accomplishment, further studies are needed to promote cost-benefit comparisons and extend these technologies to the industrial sector. Among the analyzed articles, temperature control during the process seems to be a key point that influences both the plastic deformation of the surface (related to recast layer, quenching effect and others) and the less wear of the tool used. The methods influenced by the ultrasonic vibration presented good results in the surface finishing of their workpieces with less damages. As mentioned above, this work does not include non-traditional machining processes by material addiction, only machining processes by material removal, being this subject a suggestion to future works.

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