

Review

# Wire Electrical Discharge Machining—A Review

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Received: 15 September 2020; Accepted: 23 October 2020; Published: 28 October 2020



**Abstract:** Wire electrical discharge machining has appeared mainly in response to the need for detachment with sufficiently high accuracy of parts of plate-type workpieces. The improvements introduced later allowed the extension of this machining technology to obtain more complex ruled surfaces with increasingly high requirements regarding the quality of the machined surfaces and the productivity of the wire electrical discharge machining process. Therefore, it was normal for researchers to be interested in developing more and more in-depth investigations into the various aspects of wire electrical discharge machining. These studies focused first on improving the machining equipment, wire electrodes, and the devices used to position the clamping of a wire electrode and workpiece. A second objective pursued was determining the most suitable conditions for developing the machining process for certain proper situations. As output parameters, the machining productivity, the accuracy, and roughness of the machined surfaces, the wear of the wire electrode, and the changes generated in the surface layer obtained by machining were taken into account. There is a large number of scientific papers that have addressed issues related to wire electrical discharge machining. The authors aimed to reveal the aspects that characterize the process, phenomena, performances, and evolution trends specific to the wire electrical discharge machining processes, as they result from scientific works published mainly in the last two decades.

**Keywords:** wire electrical discharge machining; phenomena; actual state; equipment improvement; wire tool electrode; process optimization; evolution trends

## 1. Introduction

The wire electrical discharge machining (WEDM) is currently one of the most well known and applied electrothermal machining processes by which the material removal from the workpiece occurs due to non-stationary electrical discharges developed between the traveling wire tool electrode and the workpiece. The resulting waste is removed from the working gap due to the circulation of a dielectric fluid. The wire tool electrode must unwind on one coil wheel and wrap on another coil wheel to reduce or even avoid the influence of material loss due to electrical discharges that also contribute to the removal of material from the wire tool electrode. In the working gap, the traveling wire electrode has a rectilinear shape due to its low rigidity and the presence of a tension force and suitable guiding subsystems. If initially only ruled surfaces were obtained by WEDM, now there has been a certain diversification of the machining processes included in the general group of WEDM machining techniques, since it is possible to obtain other various categories of surfaces [1–4].

As another limitation of use in industrial practice, at least the classic version of WEDM did not allow the machining of blind holes or cavities. To some extent, this limitation is currently being eliminated using the WEDM milling process.

Research on WEDM has expanded widely in recent decades due to the involvement of many researchers and research structures, and an impressive number of scientific papers addressing topics or related to such a subject were published.

Through this paper's content, in connection with the best information they had access to, the authors tried to provide an image of the current state of scientific and technical knowledge about WEDM and the future development directions. The paper includes a characterization and evaluation of the main current achievements in the field of a WEDM process. The steps that led to the emergence and the promotion of the WEDM process were considered in more detail. A systematic presentation of the main ways of approaching and optimizing the different aspects specific to the WEDM process was made, in accordance with the authors' opinions on these aspects. A brief statistical analysis of the papers published to date has been used to highlight the interest of researchers to investigate issues related to the WEDM process.

## 2. Essential Aspects of the WEDM Processes

In the initially promoted version, the WEDM process involved the use of a traveling wire electrode ( $v_{TE} = 0.1\text{--}10$  m/min) vertically positioned and supported in the machining zone on two guide subsystems. There was movement between the wire tool electrode and the plate-type workpiece ( $2\text{--}6$  mm/min) in a horizontal coordinate system. The working gap usually has values of  $0.02\text{--}0.05$  mm. As the other conditions for carrying out a process of electrical discharge machining were also fulfilled, from the plate-type workpiece, it was possible to gradually separate a part characterized by simpler or more complex contours. In this version, it was possible only to obtain ruled surfaces in which the right line generatrix remained permanently parallel to the vertical direction.

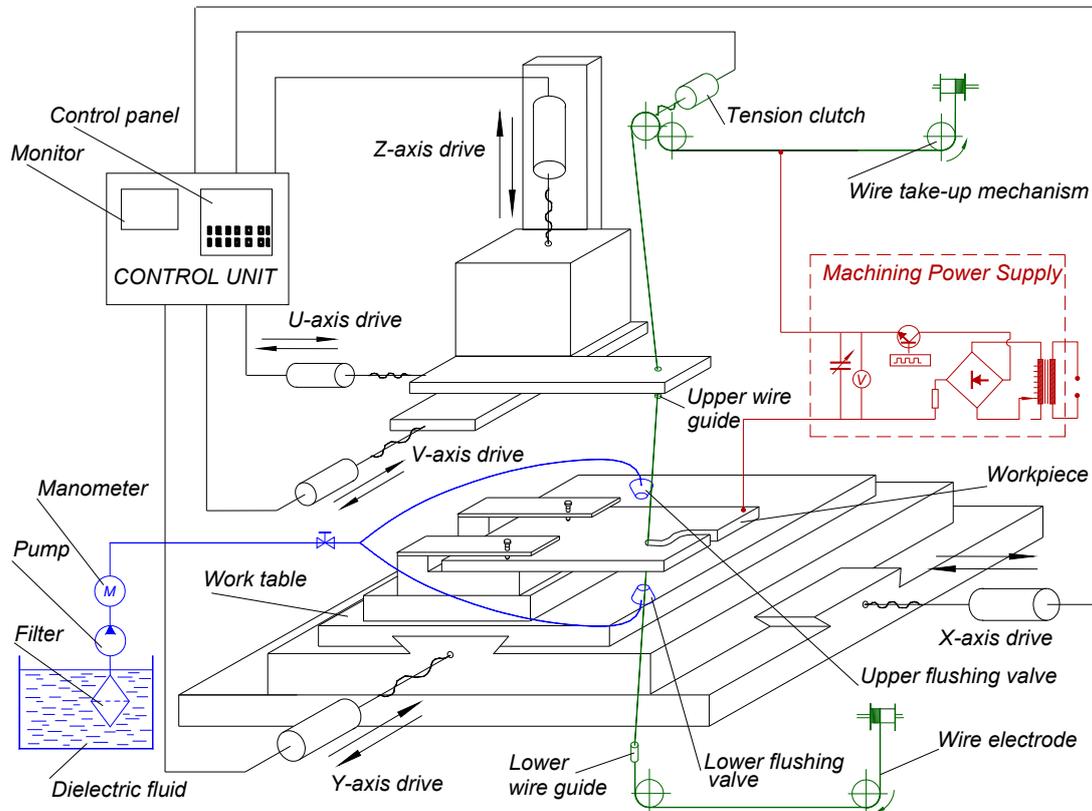
The wire tool electrode's upper guide support can achieve a controlled movement, also in the horizontal plane (Figure 1). Thus, for example, this allows the approach of machining some conical surfaces. The addition of other possibilities for moving the wire electrode and the workpiece has significantly increased WEDM process versatility [5–7].

The diameter of the wire electrode was  $0.01\text{--}0.3$  mm. It must first be flexible enough to take the form of guide rollers or coin wheels on which it is stored. A second necessary condition that the wire electrode material must meet is that it has a high tensile and bending strength. The wire had to be as long as possible ( $7\text{--}12$  km), to allow machining without the interruption of the contours, themselves of long length, and in workpieces whose thickness has increased over the years [3,8].

As a working fluid, deionized water is usually preferred since it has high fluidity and allows, as such, the relatively simple removal of particles detached by the electroerosive process by the action of gravity. A less convenient aspect is the possible development of an electrolysis process. The electrolysis could generate microexplosions by igniting hydrogen from bubbles formed due to the electrolysis process, with undesirable consequences on the wire's integrity, but also on the quality of the machined surface. For this reason, other liquids usable for processing by wire EDM have been investigated and promoted [4,9,10].

The speed of movement of the wire along its axis must be high enough to avoid affecting the precision of processing by possible thinning of the wire due to electrical erosion, which also affects the wire electrode. For a long time, the traveling speed was about  $1.5\text{--}80$  mm/min. WEDM processes use very high speeds of traveling movement in high-speed WEDM processes [11,12]. It is necessary to exert a tension on the wire under the action of forces of about  $0.04\text{--}0.7$  daN, to ensure its rectilinearity in the machining zone.

The main benefits of WEDM are the following: efficient production capabilities, production reliability, difficulties or even impossibility to obtain surfaces by other machining methods, low costs, stress-free and burr-free cutting, tight tolerances and excellent finishes, CNC (Computer Numerical Control) downloadable program files [1,2,13,14].



**Figure 1.** Schematic representation of the machining zone and the machining equipment in the case of the wire electrical discharge machining (WEDM) process.

### 3. Evolution of WEDM

The first proposals for the use of electric discharges for cutting metallic workpieces were formulated by Tilghman (“Cutting metal by electricity”), towards the end of the 19th century (1889). A fuller outline of a field that would refer to electrical discharge machining took place once with the patent application elaborated by Boris and Natalia Lazarenko (1943). They aimed to develop a method of machining the electroconductive materials. Almost two decades later, real electrical discharge machines were to be built and used.

Gradually, these machines became more and more complex. They were equipped with subsystems for machining process optimization and benefited greatly from the emergence and development of numerical control subsystems.

Some of the moments considered decisive for developing the equipment currently used for WEDM were highlighted in Figure 2. These moments were mentioned according to the information identified in the consulted literature [3,15–29].



Figure 2. Evolution of knowledge about WEDM processes and equipment.

#### 4. WEDM Equipment

The WEDM mechanical system involves the CNC controlled worktable (X–Y) on which the workpiece is clamped and an electrode wire driving mechanism for continuous motion through the workpiece with a mechanical tension between a pair of wire guides (Figure 1). According to the workpiece's height, the lower wire guide is stationary, and the upper guide could be repositioned along the Z axis. The mechanism involves moving the upper guide in Cartesian coordinates (U–V) by driven servo motors to obtain tapered surfaces.

The spark generator enables various forms of electric pulses. It allows the variation of electrical parameters to adapt the sparks to the working conditions to generate a series of electrical discharges between the workpiece and the continuous wire electrode.

If how the dielectric fluid reaches the working zone is taken into account, the following categories of WEDM processes can be highlighted [6]:

1. *Submerged type WEDM*, when the wire electrode and the workpiece are immersed in the dielectric fluid;
2. *Non-submerged (co-axial flushing) type WEDM*, when the dielectric fluid reaches the space around the wire electrode in the machining zone from the top and the bottom nozzles;
3. *Dry and near dry WEDM*, when the dielectric liquid is replaced with a minimum amount of atmospheric gas or other gas. In this case, the ecological requirements are better fulfilled.

In recent decades, the development and improvement of numerical control subsystems have generated a strong impetus for designing and developing new WEDM equipment. Such equipment has made it possible to solve a broad set of problems required by the WEDM process in a short time. If the first software for the numerical control of WEDM equipment was quite complicated, it gradually came to simpler software, which allows the development of CNC programs even by specialists who do not have in-depth knowledge in this field [16].

## 5. Improvements in the WEDM Processes and Equipment

### 5.1. General Classification

A possible grouping of improvements applied to the WEDM process could consider:

- Improvements regarding the machining equipment and its operation;
- The emergence of hybrid machining processes, with the adaptation of machining equipment to the requirements of such processes;
- Improvements of the geometric wire shape and chemical compositions of the wire materials;
- The use of the WEDM process for new materials and including the improvement of the characteristics of the surfaces processed as a result of the application of WEDM;
- Identifying the optimal conditions for the development of the WEDM process.

These improvements will be briefly addressed below, with a separate chapter covering some key ways to optimize WEDM processes.

### 5.2. Improvements Regarding the Machining Equipment and Its Operation

**Improved solutions for the pulse generator.** The improvement of the WEDM process results acting on the characteristics of electric discharges characteristics was implicitly connected with some improved pulse generators or at least of the generators capable of ensuring the variation between certain limits of the machining pulse characteristics [30,31]. A particular objective of the research regarding the improvement of pulse generators was to ensure better environmental protection. This led to the effective shaping of “clean-cut” type generators [31]. Intending to eliminate the influence of stray capacitance in the pulse generator circuit and at the same time, the wear of the wire electrode connection brushes in the pulse generator circuit, methods aiming to use electrostatic induction feeding method were investigated [21].

**Subsystems for the estimation of workpiece height.** The use of WEDM in the case of a workpiece that presents components with different thicknesses highlighted an unstable process in the transition zone. The research developed to avoid or reduce such a negative effect aimed at using information during the processing process to assess the thickness of the workpiece thickness and change continuously. As such, the values of process input factors so that an optimal process occurs. The information regarding the spark frequency [20], the abnormal ratio defined by the proportion of abnormal sparks in a sampling period [32], variable gap error (considered as a combination of ionization-time and servo voltage) [33] were used. New subsystems were proposed to be part of the WEDM machining equipment.

**Near-Dry WEDM.** Near-Dry WEDM is a machining process involving a minimum amount of liquid with a mixture of gases to the working gap. This process's main advantages are a possible better quality of the resulting surface, more stable development of electric discharges, and a reduced negative impact on the environment. In recent decades, this latest argument has led to a real intensification of the research in near-dry WEDM [34,35].

**Use of an additional indexing axis of rotation.** Better knowledge of how the WEDM process was used to separate parts with different contours from the plate-type workpiece, suggested machining revolutionary surfaces. This led to the addition of an indexable rotation axis of the workpiece that allowed the development of effectively distinct WEDM grinding and turning processes, but also to the machining of slots in secured positions using an indexable positioning subsystem of the workpiece by its controlled rotation around an axis [7,36].

**Wire electrical discharge grinding.** The initial version of the wire electrical discharge grinding (WEDG) was proposed by Masuzawa in 1985 and applied to produce high accuracy microshafts repeatedly.

The WEDG process has certain similarities with the wire electrical discharge turning (WEDT) process. Both processes were used to remove material from a rotating axially workpiece against the wire's traveling electrode. In the opinion of some researchers, the difference among the two machining methods is the fact that WEDG is used, like the classic grinding, to obtain a lower roughness of the machined surfaces and sometimes a higher accuracy of these surfaces (a high accuracy also being accessible to some WEDT processes).

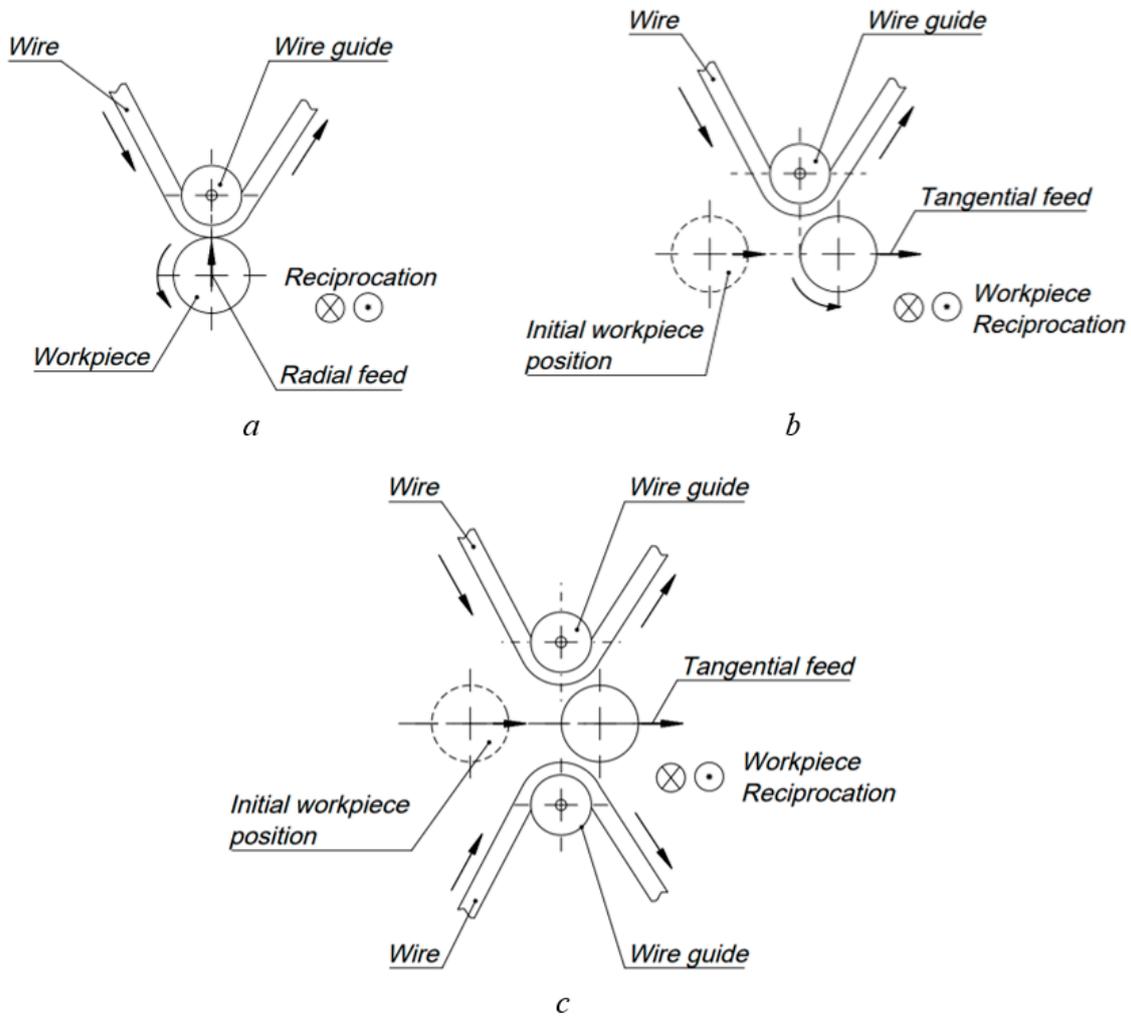
There are currently several machining processes that are known under the more general name of WEDG. The process called twin-wire WEDG allowed the simultaneous development of rough and finish machining, thus reducing two-thirds of the machining time (Figure 3a). Subsequently, there was a process which was promoted in which instead of the radial feed motion, a tangential feed motion was used. This method was called tangential feed WEDG (TF-WEDG) (Figure 3b) [17,26]. The method was reducing the effect of the workpiece positioning error in the conventional radial feed WEDG version (Figure 3a). The twin-mirroring-wire tangential feed electrical discharge grinding (TMTF-WEDG) (Figure 3c) was then promoted. It was considered as a combination of twin-wire WEDG with tangential feed WEDG [17]. Using a novel active supplying wire-electro discharge (AS-WEDG) device, a microelectrode of 40.3  $\mu\text{m}$  in average diameter and 49.6 in aspect ratio was obtained [37].

**WEDM milling.** Gotoh et al. [26] investigated a machining process developed by taking into account the wire electrical drilling process. It can be seen that a traveling wire electrode was used (Figure 4). The wire electrode is active and has a circular arc shape due to its winding on hemispherical wire support and on which there is placed a semicircular groove. This groove determines the diameter of the circular arc of the wire arrangement. The wire support still has the possibility of achieving a reciprocating rotation characterized by a certain angle. Using such a tool it becomes possible to apply three-dimensional machining, similar to a certain extent to those in traditional milling with a ball-end mill.

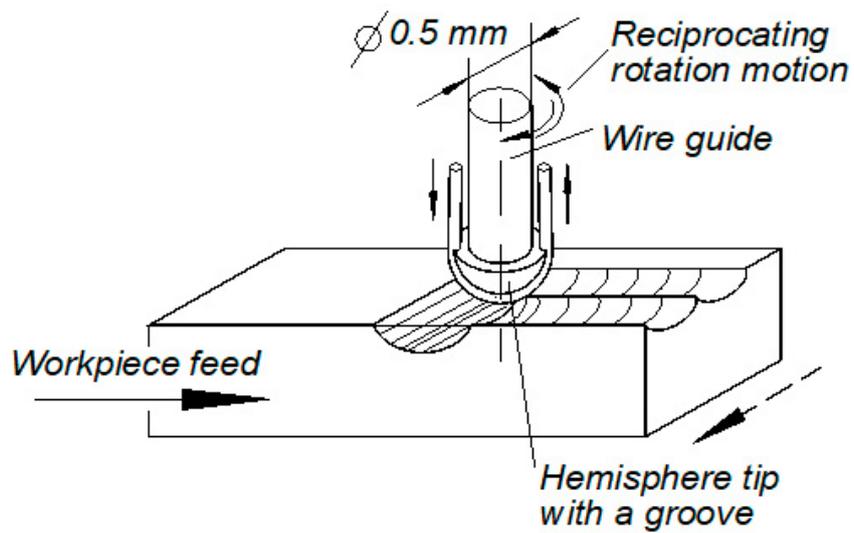
As there is currently milling equipment with multiple possibilities of moving a hemispherical milling cutter to the workpiece, especially for roughing or finishing complex surfaces of high precision, it is expected to be investigated in the future similar milling techniques with wire electrode. Such techniques could provide a considerable extension of the possibilities of using WEDM, taking into account that initially the WEDM process was used only to obtain ruled surfaces.

**Wire cutting of the twist drill cone flank.** A method based on the WEDM process was proposed starting from the conventional grinding wheel-sharpening process of the conical flank face or twist drills [38]. A wire-cutting and forming device was used after a preliminary simulation of the machining conditions using UG NX software.

**Wire cutting of the noncircular gears.** The high precision and the good quality of the surfaces made by WEDM led to the idea of cutting noncircular gear teeth in a single operation [39]. CAD/CAM software was used to determine the trajectory of the wire electrode relative to the workpiece.



**Figure 3.** Redrawn figure of the schematic representations of different WEDG processes: (a)—conventional WEDG; (b)—tangential feed WEDG; and (c)—twin-wire WEDG [17].



**Figure 4.** Redrawn figure of the wire electrical discharge (WED) milling (ref. [26]).

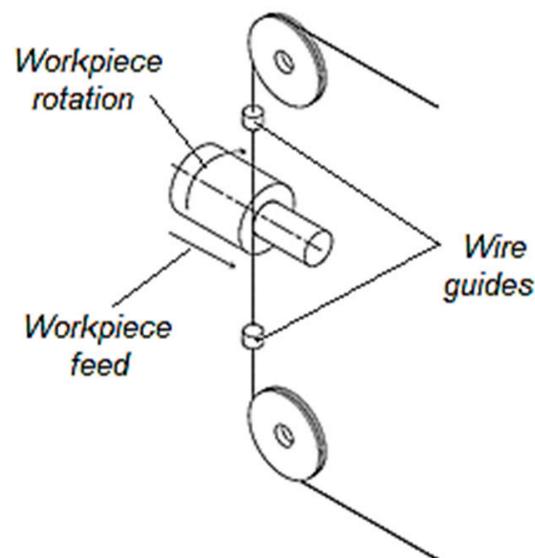
**Micro WEDM.** The micromachining concept was defined by considering the possibilities of obtaining parts with dimensions between 1 and 999  $\mu\text{m}$  [40]. It was appreciated that the versatility

proved by the WEDM applications led to the adaptation of this machining process, including for the micromachining processes [41].

In principle, micro WEDM does not generate additional problems than those generally known in WEDM. However, the maximum pulse energy must be limited to avoid breaking the wire.

Some characteristics of the micro-WEDM process can be considered the small values of the roughness of the processed surfaces ( $Ra < 0.1 \mu\text{m}$ ), machining accuracy ( $< \pm 0.2 \mu\text{m}$ ), the thickness of the white layer ( $< 2 \mu\text{m}$ ), and gap size ( $< 4 \mu\text{m}$ ). The WEDM of micro gears with modules of  $40 \mu\text{m}$ , a thickness of  $3.5 \text{ mm}$  and a  $30 \mu\text{m}$  width slot has been reported [42].

**WEDM turning.** Wire electrical discharge turning (WEDT) is considered an adaptation of the WEDM process that allows the machining of revolutionary surfaces of difficult-to-machine electroconductive materials. The existence of almost insignificant forces in size generated by the WEDM process ensured conditions for machining the parts with revolution surfaces characterized by a high aspect ratio. An illustration of a WEDT process can be seen in Figure 5. Over the last decade, studies have considered the effects of input factors on the values of output parameters (including roundness and the cylindricity of turned surfaces), optimizing the development of the WEDT process [36,43–45].



**Figure 5.** Redrawn figure of the of wire electrical discharge turning (WEDT) process (ref. [36]).

**Monitoring of the WEDM process.** Monitoring a process refers to a set of actions designed to identify changes in some characteristic sizes of the process, but without using the interruption of the process and the existing possibility of a rapid response to the stochastic events, to ensure process development in better conditions. In the case of the WEDM process, the sensors could collect information about the integrity of the wire electrode, working gap size, level of vibrations, mechanical stresses, discharge pulse characteristics, amount of heat released, temperatures reached in the machining zone, energy consumption, integrity of the machined surface, etc. [28,46–49]. Currently, such information can be obtained inclusively by taking images from the processing area.

It was considered that one of the first uses of monitoring subsystems in the field of nonconventional technologies was aimed at preventing the breakage of the wire tool electrode or even launching appropriate commands if such breakage of the wire electrode occurred [46].

**Fabricating micro-texture on the workpiece surface.** An interesting application of the WEDM process is the one that allows the generation of microtextures on the surfaces of different categories of cutting tools. Small width slots can be made into the workpiece by controlled short working strokes of the wire electrode or the workpiece [50]. Grooves with a depth of  $250 \mu\text{m}$  and width of  $100$  and  $200 \mu\text{m}$

were achieved by a WEDM process to process the cutting edges of a turning tool used to generate a micro square structure [51].

**Powder mixed WEDM.** One of the possibilities to improve the WEDM process's performance is the introduction in the dielectric liquid of some powder particles that modify, to a certain extent, the mechanism of material removal from the workpiece. Usually, the mixed powder particles in the dielectric are electrically charged and arranged in chain formation, which facilitates the earlier generation of electric discharges. These effects result in an increase in material removal rate and improved machined surface roughness in these surfaces' texture. Tungsten carbide, cobalt, boron carbide, silicon, silicon carbide, and aluminum can be used as powder materials [52–54]

**Combined electrical wire discharge-electrochemical machining in sequential use.** To obtain specific benefits, both the EDM process (machining accuracy) and ECM process (quality of the surface integrity), a successive machining by wire electrical erosion and, respectively, by wire electrochemical erosion on the same machining equipment, using the same wire tool electrode, have been identified and investigated [55]. Tap water was used as the dielectric liquid for WEDM, while aqueous sodium chloride solution was preferred for wire ECM.

### 5.3. Hybrid WEDM Processes

There are also improvements to the WEDM process which consider combining the WEDM process with other unconventional processes or by assisting the WEDM process with other conventional or unconventional processes.

It is worth mentioning that the WEDM process is assisted by vibrations in the sonic or ultrasonic field [19,56], wire electrochemical discharge machining [18,57,58], and abrasive wire electrical discharge machining [59].

A possible direction for the future development of the WEDM process could be determined by examining the possibilities of combining WEDM with aspects specific to one or more conventional or unconventional processing processes.

**Wire electrochemical discharge machining.** It is mainly applied to nonconductive brittle materials such as quartz glass or ceramics.

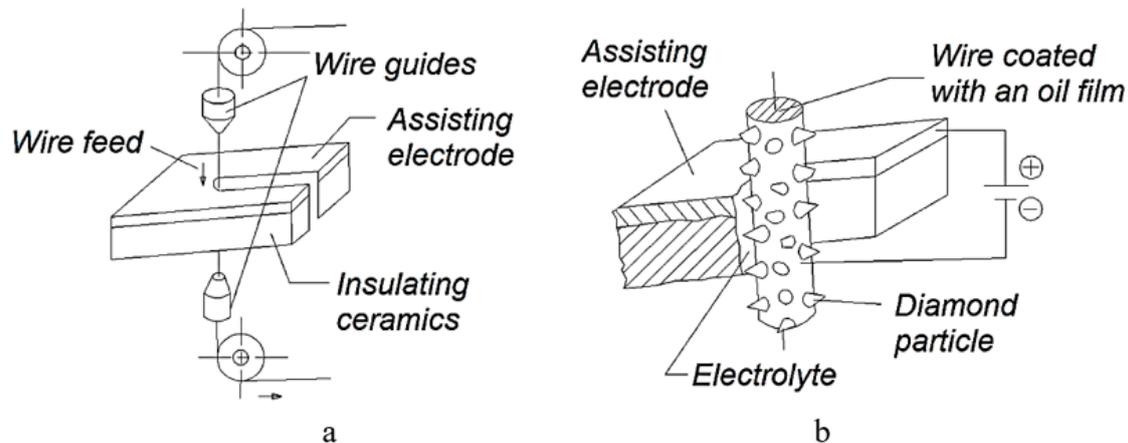
The machining process can occur either by immersing the machining area in the electrolyte or by introducing the electrolyte in the form of droplets [57,60]. The drops also contribute to a material removal of the products resulting from the process in the working gap. The tool electrode is connected to the cathode, using another additional electrode (Figure 6a), connected to the direct current source's anode, and located near the workpiece. It is necessary to ensure a certain pressure between the wire electrode and the workpiece. In essence, the electrolysis process contributes to the appearance of oxygen and hydrogen bubbles. The electric discharges passing through the hydrogen bubbles gradually remove material from the workpiece. The electrolyte may be, for example, an aqueous solution of sodium chloride.

In Figure 6b, an illustration of the electrochemical discharge-assisted diamond wire cutting can be observed. The diamond wire was obtained by bonding diamond particles onto the steel wire [61]. The process ensures a material removal rate higher than that of the case using the conventional diamond wire cutting process.

**High-speed WEDM (HSWEDM).** In principle, the high-speed WEDM (HSWEDM) process is a WEDM process in which high speeds of wire movement in both directions along its axis are used, much higher (10–12 m/s) than those in the case of ordinary WEDM processes (1.5–80 mm/min [12,63,64]).

It is estimated that the removal of material from the workpiece results from both electrical discharges and the anodic dissolution of the workpiece material, which would include this process in the category of hybrid processes. The HSWEDM ensures a 200–600% increase in the material cutting rate. The process involves using a new wire winding subsystem, hybrid electrolyte, and high-efficiency pulse generator.

**External magnetic field-assisted WEDM.** It was found that the presence of a magnetic field at the working zone contributes to an increase in the density and stability of the plasma channel, to the intensification of the debris removal from the workpiece surface, to an improvement of machining efficiency and quality [65,66]. The magnetic field's influence on the WEDM process was investigated when the magnetic field lines are perpendicular to the direction of the wire electrode's movement.



**Figure 6.** Redrawn figure concerning the assisting electrode use in the wire electrochemical discharge machining: (a)—simple version; and (b)—electrochemical discharge-assisted diamond wire cutting [61,62].

#### 5.4. Improvements Concerning the Wire Tool Electrode Material and Geometrical Characteristics

When selecting the wire electrode's material and dimensions, properties such as conductivity, tensile strength, elongation, melting point, straightness, flushability, cleanliness, geometric properties (diameter, shape, coating, and surface layer structure) are considered [3,14].

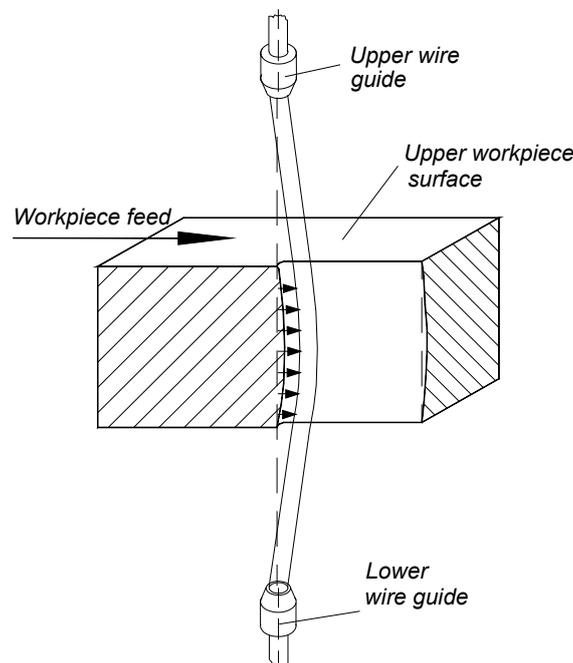
Trying to achieve high-speed and high-precision WEDM, Okada et al. used a piano wire coated with a thin wire of an electrically conductive brass layer [9].

Various versions of wire electrodes have also been proposed and to some extent, investigated and even used in practice. Thus, there were proposed wire electrodes with cross-sections that revealed the presence of a core coated with a single layer (for example, the brass core coated with a layer of copper alloy) or with two layers (a low boiling temperature will characterize the outer layer), with an oxide layer (to diminish the process of developing electrical discharges on the side of the wire electrode), with a layer formed by twisting thin wires of brass characterized by high mechanical strength and an external layer of zinc or zinc alloy). The possibilities of using electrodes with a cross-section different from the circular one (rectangular, square, trapezoidal section, with triangular channels or other shapes) and possibly obtained by twisting [3], as well as wire electrodes on which diamond particles were attached to outer surfaces [67].

The cryogenic treatment of the brass wire tool electrode (cooling to very low temperatures) was one of the researcher's solutions to improve the wire electrode's behavior. As a result of the application of a cryogenic treatment, the structure of the wire electrode material (brass) was refined, and the electrical conductivity of the material was improved, thus facilitating an increase in the material removal rate [25] and an improvement of the surface roughness [68]. Filiform electrodes made of brass [25,68,69] and zinc-coated diffused brass [68–71] were subjected to cryogenic treatments.

**Wire deflection and deviation from the prescribed path of the wire electrode.** Although the tension force acts on the wire electrode and it should ensure a rectilinear shape of its axis, the wire electrode does not behave like a rigid bar. Under the action of forces quite small in value generated by the electroerosive process, the dielectric liquid circulation in the working gap and feed motion along the established path, the electrode wire deforms, and its axis is no longer rectilinear in the machining zone (Figure 7) [72–74]. There is also a vibration of the tool electrode between the upper wire guide and lower wire guide, and this usually generates a larger kerf width in the middle zone of the workpiece.

Research methodologies and simulations of errors generated by the wire electrode's deflection and its vibration have been proposed [72,75–77].



**Figure 7.** Redrawn figure of the wire tool deflection in the work zone during the WEDM process [72].

Another error investigated by researchers refers to the deviation from the prescribed path in trajectories that include sharp angles or radii of small values. This error can be determined by the accuracy of the relative feed movement subsystems between the wire and workpiece, by the use of certain commands for the CNC subsystem, but also by the previously mentioned wire deflection [72,73,78], or plastic deformation of thin tips, to the diamagnetic or paramagnetic character of the workpiece [23].

Wire tension control subsystems were proposed and experimented with, improving the machined surface's quality and geometric accuracy [76,79].

#### 5.5. Improvements of the Usage Properties of the Parts Obtained by WEDM, Including by Using New Parts Materials

**Expanding the range of materials processed by WEDM.** As a result of the development of car manufacturing fields, increasingly diversified materials could be observed. A consequence of this fact has been the research efforts aimed at investigating the various materials' behavior during the WEDM process and, respectively, to optimize the machining of workpieces made of such materials.

Thus, it was found, first of all, that the use of WEDM for very different groups of electroconductive materials and some of the studies in this direction took into account:

- Various steels [68,78,80–82];
- Nickel–chromium-based alloys and superalloys type Inconel [30,83–91], nickel-based alloys [2];
- Aluminum alloys [92–94], tungsten [95,96], copper [97];
- Titanium and titanium alloys [30,98–103];
- Aerospace alloys [31,104];
- Shape memory alloys [105];
- Carbide type materials [34,106–108];
- Polycrystalline diamond [109];
- Semiconductor materials: silicon [110–113], germanium [114];
- Some categories of composite materials [44,106,115–127];

- Ceramics [27].

**Improving the use of properties of surfaces obtained by WEDM.** Mechanisms specific to the WEDM process lead to the generation of specific geometric characteristics of the processed surface and structural changes in the machined surface layer. Some of these consequences of using the WEDM process can determine the improvement in the part of the operating behavior.

Trauth et al. managed to optimize the surface's integrity previously obtained by the WEDM process using the surface finishing process machine hammer peening. In this way, an improvement of the fatigue strength of the workpiece material (Inconel718) was observed [128]. Improvement in mechanical properties and especially fatigue strength has also been noticed in the use of WEDM for the manufacture of highly loaded titanium parts for space applications [129]. In other situations, it was appreciated that the topography of the obtained surface has more convenient tribological characteristics, allowing to increase the load-carrying and the duration of use of the gears whose flanks were obtained by WEDM [130].

**WEDM of ceramics.** The concept of ceramics refers to a wide range of hard, brittle, heat-resistant, and corrosion-resistant materials, made by shaping and then firing a nonmetallic material. In principle, it is known that to be processed by WEDM, the materials must have a certain electrical conductivity. From this point of view, ceramics can be divided into the following categories:

- Conductive ceramics, characterized by electrical conductivity of at least 10–2 ohms.cm (titanium nitride TiN, titanium diboride TiN<sub>2</sub>) and which, with some small difficulties, can be processed by WEDM;
- Nonconductive ceramics: for such materials, a so-called assisting electrode method was considered. There must be at least a thin conductive layer on the workpiece's surface or immediately near this surface [131,132]. Under the action of high temperature developed by the electric discharges between the wire electrode and the conductive layer, cracks are developed, and this effect can contribute to the removal of material from the workpiece. The dielectric hydrocarbons can also be cracked. Some of the resulting conductive carbon compounds could adhere to the surface of the workpiece, ensuring a certain continuity of the conductive layer. Another WEDM way of non-conductive ceramics was based on an electrolyte in a hybrid WEDM process;
- Semiconductive ceramics, whose WEDM process can take into account the version applicable in the case of conductive ceramics (with lower machining performance) or the one usable in nonconductive ceramics.

In recent years, Zhang [27] appreciated that fluid machining is the main influencing factor of MRR and surface integrity quality when applying WEDM to ceramic nanocomposites. Smirnov et al. considered obtaining low asperities at the WEDM of ZrO<sub>2</sub>/TiN ceramic nanocomposites not to negatively affect the flexural strength of the parts [133].

## 6. Input Factors and Output Parameters for WEDM

The wire electrical discharge machining system (Figure 1), as any other system, was defined by *the input factors*, by *the output parameters* which measure the process performance, *the intermediate process factors* (parameters whose values are continuously changing during the process), and *the disturbing factors* or *system noise* [1,59,134].

Depending on the possibility of choosing their values, the input factors are classified into *adjustable factors* and *imposed factors*, which are, in general, those related to the workpiece or some devices of the WEDM machine. The WEDM process performance is decided by the values of *the following input factors*:

- *Characteristics of the wire electrode tool*: material, the chemical composition of wire electrode tool, resistivity, specific heat, thermal conductivity, melting temperature, latent heat of melting, vaporization temperature, latent heat of vaporization, specific mass, tensile strength, wire diameter, the shape of the wire (cross-section, structure), positioning accuracy of EF (angular positioning, coordinate error in the horizontal plane, etc.);

- *Characteristics of the workpiece*: thickness, material, chemical composition, electrical conductivity, specific heat, thermal conductivity, melting temperature, the accuracy of workpiece positioning, etc.;
- *Characteristics of the positioning-clamping device*: positioning-clamping accuracy, clamping force, etc.;
- *Characteristics of the dielectric circulation subsystem*: electrical conductivity of the dielectric liquid, chemical composition, impurities concentration, liquid viscosity, surface tension, specific heat, temperature, flow direction through the working gap, dielectric pressure, inlet flow, relative position of the electrodes pair to dielectric flow;
- *Characteristics of the electric pulses*: voltage pulses shape, frequency and filling factor, pulse on-time, pulse off-time, cycle time, discharge frequency, peak or average voltage, peak or average current, pulse energy, electrodes polarity;
- *Characteristics of the mechanical conditions*: stability of the wire electrode feed subsystem, sensitivity and reaction speed, the adjustment range of the wire electrode feed subsystem, running speed of wire electrode, axial tension of the wire electrode, distance between the guides of the wire electrode, the initial inclination of the wire electrode;
- *Characteristics of the process control and optimization subsystem*: possibilities for the monitoring, adaptation, and optimization of parameters.

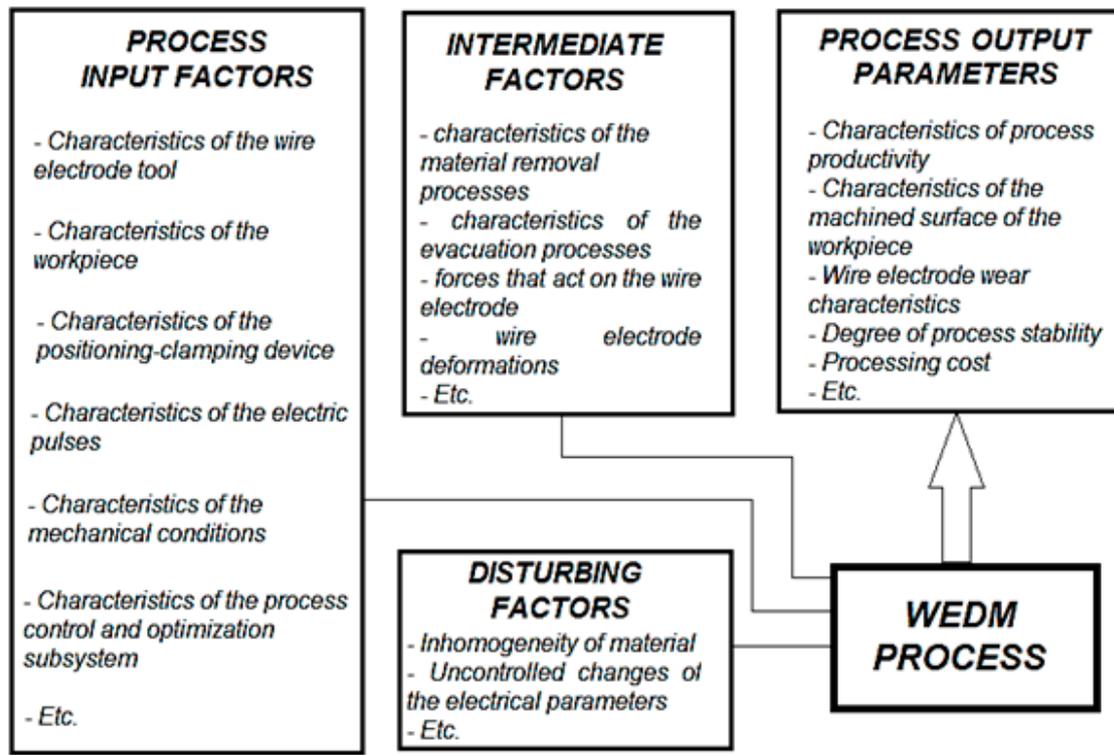
*Intermediate factors* or so-called *process-dependent* parameters are dependent on the characteristic of the fundamental phenomena in the working gap, and their values change during the process. The following intermediate parameters can be considered:

- *Characteristics of the material removal processes*: the working gap size (front and lateral), kerf width, technological gap shape (kerf size in the upper workpiece zone, at the of workpiece bottom, at mid-height of workpiece, convexity, taper angle), length of the free path of particles expelled from the crater, percentage of pulse energy received by the working environment, by the workpiece material, the volume of removed material from the wire electrode tool by a single discharge, average depth of the crater in the electrode tool surface and in the workpiece surface, local average density of spurious pulses, and short-circuited pulses, local, average current intensity;
- *Characteristics of the evacuation processes*: flow rate of solid waste and of gaseous waste from the gap, local density of erosive particles, average speed and pressure of shock waves, flow rate of erosive particles formation;
- *Forces that act on the wire electrode*: electrostatic forces, electromagnetic forces, hydrostatic forces, hydrodynamic forces, forces due to the pressure in the plasma column, forces due to the pressure of the gas bubble;
- *Wire electrode deformations*: dimensional deformation, vibration, position in the two directions, properties, structure.

The performance of the WEDM process is evaluated using *the following output parameters*:

- *Characteristics of process productivity*: productivity, cutting speed evaluated in mm/min or mm<sup>2</sup>/min, totally removed volume, the total length of the machined kerf;
- *Characteristics of the machined surface of the workpiece*: the physicochemical appearance of the machined surface (chemical composition, structure, properties), geometric appearance (dimensional accuracy, shape and position accuracy, maximum shape deviation, the roughness of rounding radii of the edges of the machined surfaces) [135];
- *Wire electrode wear characteristics*: wire electrode wear rate, relative volume wear, specific consumption of wire electrode;
- Degree of process stability;
- *Processing time*: total working time, specific working time;
- *Processing cost*: specific cost of used wire electrode, total specific machining cost.

The analysis of the presented system (Figure 8) suggests the complexity of the WEDM process and the fact that establishing the optimal processing conditions must be the result of analyzing the effects of as many factors as possible and the interactions between them.



**Figure 8.** Several factors and groups of factors highlighted when analyzing WEDM as a system.

Sometimes, highlighting the input factors in the WEDM process was done using Ishikawa diagrams and grouping the factors considering the dielectric medium, the wire tool, the machine, and the workpiece [2].

In extensive research to optimize the WEDM process, by reviewing 32 scientific articles, Alduroobi et al. [134] assessed the importance of the WEDM process input factors by considering the number of articles addressing these factors. They found that as input factors, 28 articles mentioned pulse input on-time, 24 papers—pulse off-time, 17 papers—current intensity, 16 papers—servo-voltage, 13 papers—wire speed, 10 papers—servo feed, 8 papers—wire tension, 8 papers—dielectric pressure, 3 papers—workpiece thickness, etc. At the same time, as process output parameters, they found that there were addressed problems related to surface roughness (in 22 papers), material removal rate (16 papers), machining speed (7 papers), machining accuracy (4 papers), kerf width (3 papers), white layer thickness (2 papers), machining time (2 papers), electrode wear rate (2 papers), surface waviness (1 paper), etc.

**Corner and wall thickness accuracy.** It was found that the WEDM process can ensure the accurate machining of the intersections of surfaces at sharp angles on the one hand, and on the other hand, of parts with quite low thicknesses. In the first case, the numerical control subsystem's characteristics can exert a significant influence on machining a low-value radius of connection of surface intersections.

## 7. Influence of Different Factors on the Values of the Parameters of Technological Interest in the Case of WEDM

Some aspects specific to the results obtained by the experimental research of the WEDM process were summarized in Table 1. From the synthetic diagrams included in the table, it was found that sometimes they showed the same variation trend of an output parameter when changing the values of an investigated input factor, as, at other times, there were pronounced differences between the

trends of variation. The explanations of the differences can be found essentially in the different domains of values related to the variation of the input factors, the different materials of the workpieces, electrodes, dielectric fluids, and the possible interactions of the input factors. Then, some simple general considerations resulted from the analysis of the information contained in Table 1 will be presented. In many situations, the explanations regarding the influence of the input factors, values on the sizes of the output parameters are entirely valid also for ram electrical discharge machining.

In principle, increasing the pulse time on-time will lead to an increase in the amount of energy corresponding to the electrical discharge in the machining process's productivity. When the discharge energy exceeds some values specific to the proper machining conditions, however, there is an increase in the amount of vapor of the electrodes' materials, the number of particles detached from the electrodes and found in the dielectric liquid, the intensification of the pyrolysis process that affects the properties of the dielectric liquid and as such, a possible reduction of processing productivity. The curves of variation of the machining process productivity to the pulse duration can therefore present a maximum point. In the cases of some diagrams included in Table 1, it can be noticed that the experimental studies have highlighted the existence of a maximum point, as sometimes they may correspond to the ascending zone or the descending zone of the curve.

Explanations similar to those presented above can be formulated in the case of the influence exerted by the intensity of the current in the electrical discharge and, to a certain extent, for how the gap voltage affects the productivity characteristics of the WEDM process. Thus, it was accepted that an increase in the voltage gap has, as a consequence, an increase in the intensity of the discharge current, and therefore of the energy corresponding to the electrical discharge. In fact, increasing the voltage gap leads to an increase in the number of electrically charged particles that break the working gap and increase the distance they are able to cover.

A decrease in the productivity of the process can usually be signaled in the case of the influence exerted by the increase in the duration  $T_{off}$  of the pause between the pulses, due to the decrease in the time interval in which the electric discharges act on the electrode materials.

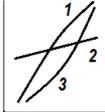
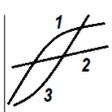
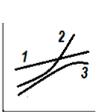
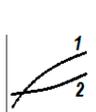
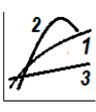
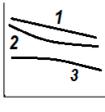
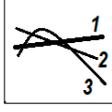
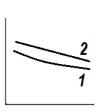
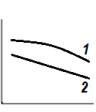
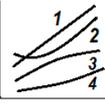
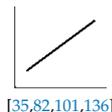
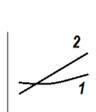
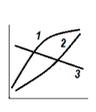
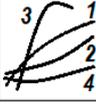
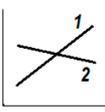
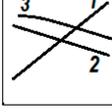
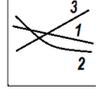
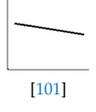
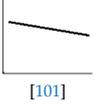
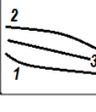
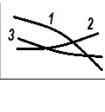
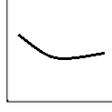
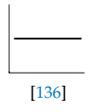
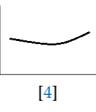
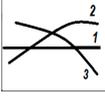
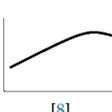
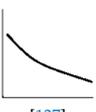
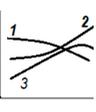
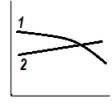
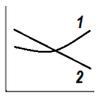
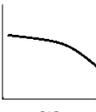
If the increase in flushing pressure of the dielectric fluid worsens the conditions for electrical discharges, we will see a decrease in WEDM process productivity. However, suppose by that increasing the flushing pressure, there is a faster evacuation of detached particles, a refresh of the working gap with clean and favorable dielectric fluid, and as such, there will be an increase in process productivity. The diagrams in Table 1 revealed somewhat contradictory and explicable aspects.

As mentioned above, at the plasma column's contact corresponding to an electric discharge with the electrodes' surfaces, a material removal process develops. It is desirable that the sampling of workpiece material be maximum or rigorously controlled. On the other hand, the material is taken from the wire electrode, causing its wear. The continuous displacement of the filiform electrode along its axis was reported to diminish the wear's influence on the machining accuracy.

However, the process of wearing the wire electrode cannot be avoided, but machining conditions that lead to the minimum wear of the wire electrode can be identified. Such conditions can be considered in the context of optimizing the WEDM process. Since the removal of material is largely similar to that of removing material from the workpiece, it was expected that the influences exerted by different input factors would be similar to those of the influence exerted by the same input factors on the productivity of the WEDM process. This was evidenced by the trends of the curves in column 6 (corresponding to the wear of the wire electrode) in Table 1 with those of the curves in column 2 (corresponding to the productivity of the WEDM process).

As there are many factors whose effects and interactions influence the values of technological interest parameters, but in the literature accessible to the authors of this review paper, no graphical representations corresponding to these influences were identified, thus Table 1 contains only synthetic graphical information on such aspects.

**Table 1.** Effects exerted by distinct input factors on the values of the output parameters in the case of WEDM.

| Input Factors      | Output Parameters   |   |   |   |  |   |
|--------------------|---|---|---|---|--|---|
|                    | Material Removal Rate   | Surface Roughness, $Ra$   | Dimensional Deviation   | Recast/White Layer Thickness  | Wire Tool Electrode Wear   | KerfWidth   |
| Pulse-on time      |  <ol style="list-style-type: none"> <li>[35,101,132,136–138]</li> <li>[116]</li> <li>[82,91]</li> </ol>  |  <ol style="list-style-type: none"> <li>[35,136]</li> <li>[101,116]</li> <li>[82]</li> </ol> |  <p>[84,101]</p>   |  <ol style="list-style-type: none"> <li>[136]</li> <li>[138]</li> <li>[101]</li> </ol>  |  <ol style="list-style-type: none"> <li>[137]</li> <li>[101]</li> </ol> |  <ol style="list-style-type: none"> <li>[99,136,137]</li> <li>[82]</li> <li>[101]</li> </ol>         |
| Pulse-off time     |  <ol style="list-style-type: none"> <li>[35,116];</li> <li>[82,91,101]</li> <li>[138]</li> </ol>         |  <ol style="list-style-type: none"> <li>[35]</li> <li>[101,116]</li> <li>[82]</li> </ol>     |  <ol style="list-style-type: none"> <li>[101]</li> <li>[84]</li> </ol>   |  <ol style="list-style-type: none"> <li>[138]</li> <li>[101]</li> </ol>                 |  <ol style="list-style-type: none"> <li>[137]</li> <li>[101]</li> </ol> |  <ol style="list-style-type: none"> <li>[99,138]</li> <li>[82]</li> <li>[101]</li> </ol>             |
| Dis-charge current |  <ol style="list-style-type: none"> <li>[35]</li> <li>[82]</li> <li>[138]</li> <li>[101,132]</li> </ol> |  <p>[35,82,101,136]</p>   |  <ol style="list-style-type: none"> <li>[101]</li> <li>[84]</li> </ol>  |  <ol style="list-style-type: none"> <li>[136]</li> <li>[138]</li> <li>[101]</li> </ol> |  <p>[101]</p>  |  <ol style="list-style-type: none"> <li>[136]</li> <li>[83]</li> <li>[82]</li> <li>[101]</li> </ol> |
| Gap voltage        |  <ol style="list-style-type: none"> <li>[35]</li> <li>[91,101,116]</li> </ol>                          |  <ol style="list-style-type: none"> <li>[35]</li> <li>[101,116]</li> <li>[139]</li> </ol>  |  <ol style="list-style-type: none"> <li>[101]</li> <li>[81]</li> <li>[84,140]</li> </ol> <p>(air pressure)</p> |  <p>[101]</p>   |  <p>[101]</p>   |  <ol style="list-style-type: none"> <li>[83]</li> <li>[139]</li> <li>[101]</li> </ol>              |
| Flushing pressure? |  <ol style="list-style-type: none"> <li>[35]</li> <li>[91]</li> <li>[4]</li> </ol>                     |  <p>[35,136]</p>   |  <p>[81]</p>   |  <p>[136]</p>   |  <p>[4]</p>   |  <p>[136]</p>  |
| Wire feed          |  <ol style="list-style-type: none"> <li>[91]</li> <li>[8]</li> <li>[132]</li> </ol>                    |  <p>[8]</p>  |  <p>[84]</p>   |  <p>[137]</p>   |  <p>[137]</p>   |  <ol style="list-style-type: none"> <li>[99,137]</li> <li>[83]</li> <li>[8]</li> </ol>             |
| Wire tension       |  <p>[8]</p>  |  <ol style="list-style-type: none"> <li>[8]</li> <li>[76]</li> </ol>                       |  <ol style="list-style-type: none"> <li>[81]</li> <li>[84]</li> </ol>  |  <p>[8]</p>   |  <p>[8]</p>   |  <p>[8]</p>  |

However, there are other factors whose effects on the output parameters in the case of the WEDM process can also be discussed.

Thus, *the polarities* corresponding to the two electrodes involved in the process exert, of course, a significant influence. For short pulse times, only a small number of ions can cross the entire working gap and transfer energy to the workpiece surface layer. As a consequence, such situations could lead to a lower machining productivity determining an electron character of the material removal from the workpiece. This would correspond to a connection of the workpiece to the positive pole of the power supply, following that when high productivity is pursued, the workpiece will be connected to the negative pole.

However, the effect of electrode polarity can be significantly modified by other process input factors, such as the tool electrode and workpiece materials, the chemical composition of the dielectric liquid, the values of electrical and mechanical machining input factors, which may favor or prevent the formation of a graphitizing film on the wire tool electrode, etc.

The existence of very high temperatures, which determines the melting and even vaporization of small quantities of the workpiece material and the wire electrode, will lead to the appearance of a heat-affected zone. The thickness of this zone, and the thickness of the white layer resulting in steels and cast iron by decarburization, are dependent on the energy of electric discharges, flushing conditions, etc. [101,136,138,141].

Deeper research into the influence of input factors in the WEDM process also allowed an assessment of the weights of the effects exerted by these factors [101,134].

To a lesser extent, the influence of some input factors in the WEDM process, such as wire diameter, spark gap or workpiece height, spark ignition intensity, workpiece cross-section, and pulse shape, on the values of the process output parameters was investigated [134,142]. There is also relatively little research on the influence of input factors in the WEDM process on output parameters such as the corner radius, wire offset, and acoustic emission signal [142].

## 8. Modeling and Optimizing the WEDM Process

The need to use some models appears especially when the problem of optimizing the process arises.

The empirical models (first-degree polynomial, second-degree polynomial, power type function, etc.), established using regression analysis, are well known and applied even for the WEDM process. The constants and exponents are present in the empirical models, but most often graphical representations made based on the models provide information about the intensity of the influence exerted by the input factors in the WEDM process or the interactions of these factors on the values of some output parameters [99,137].

Extensive research has been undertaken to outline and use more complex mathematical models, the matrix type, and the Taguchi method.

The methods used over time to model the WEDM process and its results can be highlighted as regression analysis and response surface methodology [99], the Taguchi method [134,143–145], and the least squares method [50].

As previously mentioned, using specialized software for processing experimental results, empirical mathematical models were identified for the output parameters of the WEDM process, with the inclusion of independent variables of a greater or lesser number of the input factors of the process. Most such empirical mathematical models are based on the use of first or second-degree polynomial functions and power functions, respectively. With software evolution, more complex empirical mathematical functions have been considered.

As examples of empirical mathematical models, we can mention those established by Ikram et al. [144] for the kerf width and the Ra roughness parameter. The respective models were in the form of a first degree polynomial with eight independent variables, which were the workpiece thickness, open voltage, pulse on-time, pulse off-time, servo voltage, wire feed velocity, wire voltage, and dielectric pressure. An example of the power function used as an empirical mathematical model

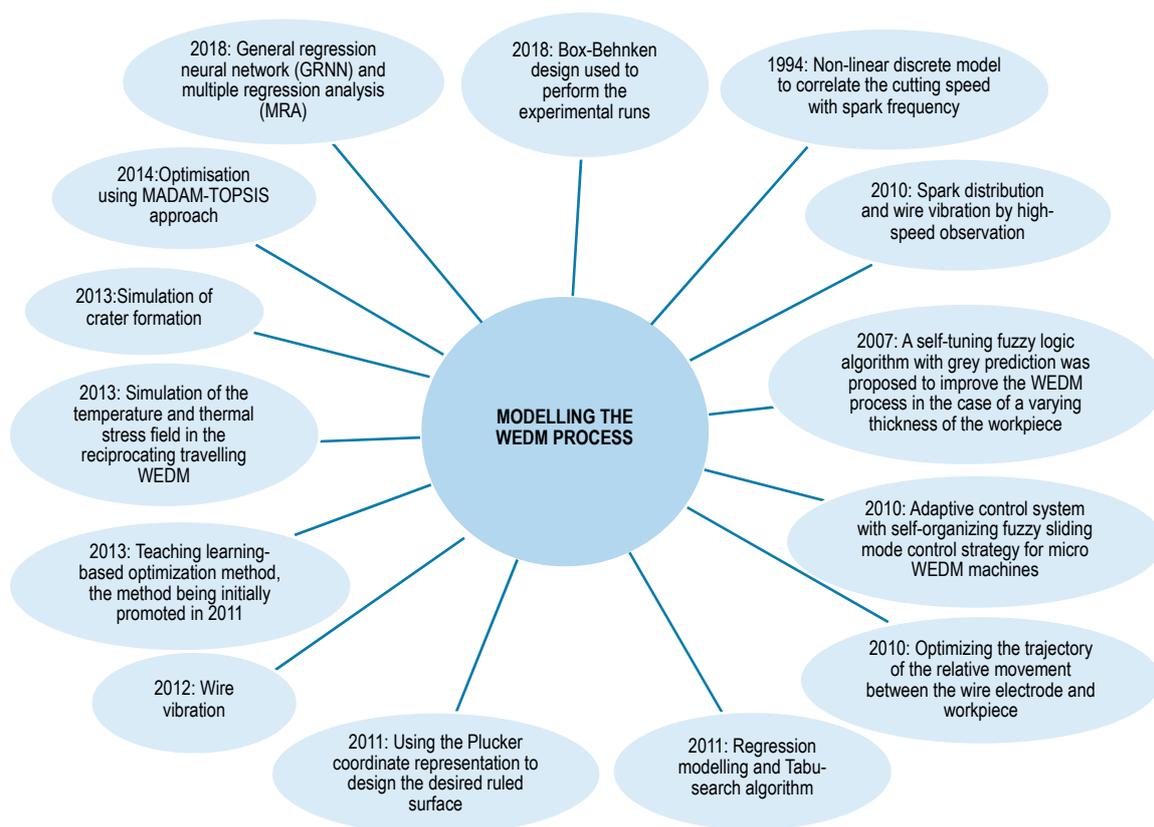
was recently proposed by Yang et al. [50] for the width of the slits used to generate micro-textures in a cemented carbide workpiece, taking into account as independent variables (input factors), the pulse on-time, pulse off-time and pulse current. Sometimes, researchers have also proposed more complex empirical mathematical models, which also consider the interactions between two or more input factors in the WEDM process.

Theoretical mathematical models are also important and are determined by taking into account the different input factors in the WEDM process. For example, theoretical models for the wire vibration during the WEDM process were highlighted by some researchers [42,74].

If the amplitude of the lateral vibration is taken into account, Chen et al. [76] considered that the kerf width could be expressed as a function of the radius of the cross-section through the wire electrode and the breakdown distance, i.e., the maximum distance between the wire electrode and the workpiece for which the electric discharge no longer occurs [76].

Straka et al. appreciated that the shape error of the real surface obtained by the WEDM process to the requested surface could be estimated by the sum of different dimensional deviations [78].

Some of the models proposed over time to characterize some of the specific aspects of the WEDM process can be seen in Figure 9. When developing the graphic representation from Figure 9, the information identified in the consulted literature [5,11,23,32,75,82,102,132,146–151] was taken into account.



**Figure 9.** Some of the proposed models for the WEDM process.

*Optimization* refers to identifying one or more solutions appreciated as the most convenient from several available solutions. Optimal solutions are sought in many areas of human activity, and it was normal, as such, to formulate *the problem of optimization in the WEDM process*.

Considering this process as a system, its optimization can be approached from several points of view. Thus, by optimizing the process, it can follow the identification of that combination of the input factors values that contributes to the maximization or minimization of an output parameter (monocriterial or monobjective optimization) or of many output parameters (multicriterial

or multiobjective optimization). In this sense, the problem of maximizing the cutting speed within the WEDM process (for example, in the case of the need to ensure high productivity), of minimizing the height of the machined surface asperities, and of maximizing the machining accuracy (in case of a high accuracy cutting) were all addressed.

A problem of interest for optimizing the WEDM process was the one in which it was necessary to identify the path of the relative movement between the wire and workpiece to ensure a high machining accuracy in the case of small width grooves in the workpiece. Such a problem has been addressed, for example, in the situation of the manufacture of graphite discs with thin circular grooves, the WEDM process was selected to be used [58].

To date, in the field of WEDM processes, researchers have addressed to a lesser extent monocriterial optimization problems [50], however, they have more frequently addressed multicriteria/multiobjective optimization problems, applied in this sense as different methods, such as:

- Taguchi method [81,84,89];
- Taguchi and analysis of variance [143,146];
- Taguchi and grey relational analysis [126,147];
- Box-Behnken design (considered a type of response surface methodology (RSM) designs) method, showing that it is possible to reduce the number of experiments aimed at optimizing the WEDM process [82,99];
- Grey-based response surface methodology [87];
- Grey relational analysis [148];
- Grey-fuzzy methodology [98];
- Response surface methodology;
- Response surface methodology coupled with grey relational analysis–Taguchi technique [152];
- Desirability function analysis (DFA) and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) methods [127,153];
- Genetic algorithms [47];
- Non-dominated sorting genetic algorithm approach and Pareto method [138];
- Artificial neural networks [154];
- Teaching learning-based optimization [36,155–157];
- Analysis of the fractal dimension of the surface obtained by WEDM [158], etc.

Analysis of variance (ANOVA) has been used relatively often to highlight the significance of the factors found concerning one or more of the objectives considered functions [150].

*The grey relational analysis* is based on evaluating the quantitative relationship between the two series' elements, one of the series, including the entities of the best quality. The grey relational analysis method is used when at least two output parameters of the WEDM process are considered. Each of the output parameters is associated with a certain distinguishing coefficient that highlights the importance of each output parameter in an overall assessment. The sum of the distinguishing coefficients is equal to 1. Most research has taken into account two [147] or at most three output parameters of the WEDM process. It may also be of interest to optimize the WEDM process using grey relational analysis, which considers even more than three process output parameters.

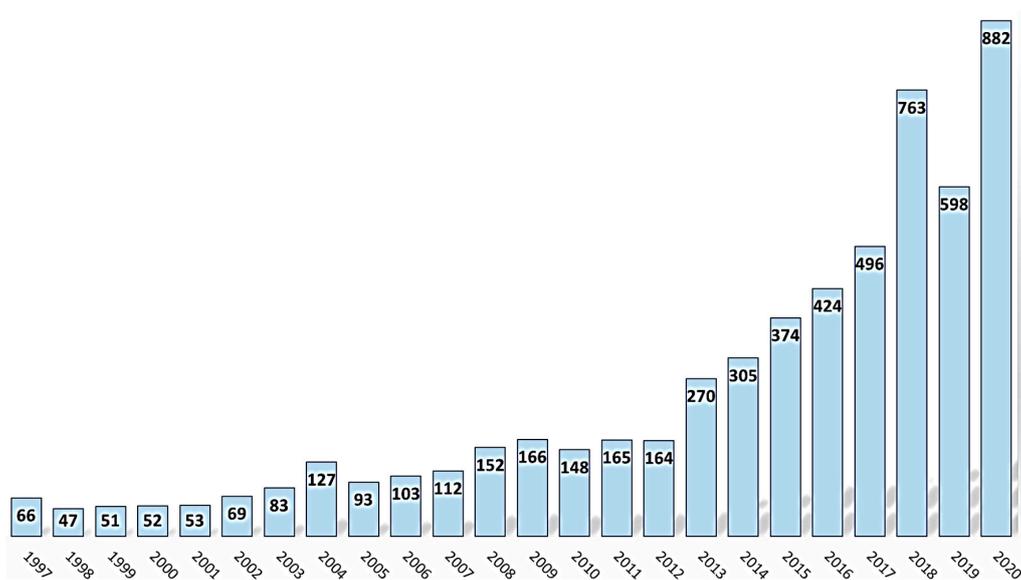
## 9. Evolution Trends of WEDM Processes

Over the last decade, many researchers have focused their research on optimizing the wire EDM process for machining specific materials such as superalloys (austenitic nickel–chromium-based, nickel-based, etc.), nickel alloys, titanium alloys, shape memory metallic materials such as nickel–titanium alloy, porous metallic materials, metal matrix composites with ceramic reinforcement, tungsten carbide, boron carbide, and silicon wafers. Their work was developed using various scientific tools such as response surface methodology, multiple regression analysis, neural artificial

networks, Taguchi method, analysis of variance (ANOVA), grey wolf optimizer, fuzzy method, maximum deviation method, particle swarm optimization, Monte-Carlo simulation, etc.

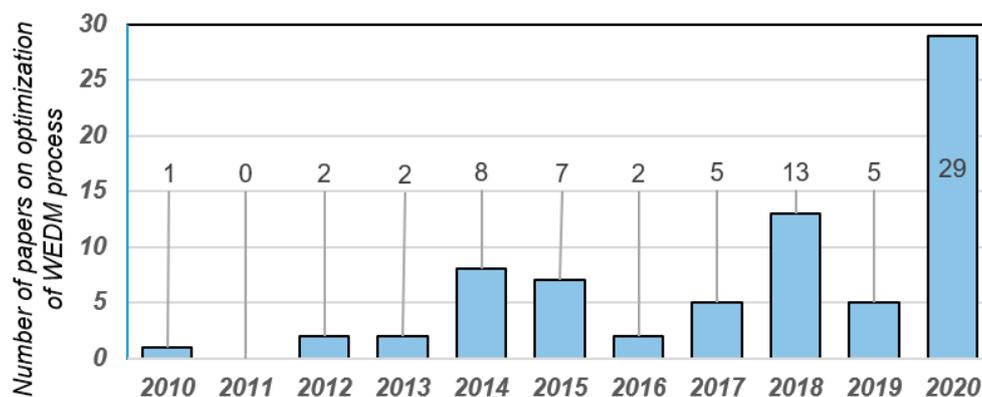
Although the first wire EDM machine was introduced to the industry around 1976, the WEDM process continues to be a research topic today, with the number of published works constantly increasing. Thus, according to the ScienceDirect database filters, over 5700 papers have been dedicated to wire EDM to date. For 2020 alone, over 850 papers on this topic have been published. This increased interest in wire EDM is due to its versatility in ensuring complex shapes, both in soft and hard conductive materials. WEDM can cut both solid and low stiffness parts.

A suggestive image of the development of research in the WEDM process can be seen in the diagram in Figure 10. This diagram was also developed by taking into account the existing information in the ScienceDirect database. It was found that in recent years there has been an impressive increase in the number of papers addressing issues related to the WEDM process.



**Figure 10.** Evolution of the number of scientific papers related to the WEDM process in the ScienceDirect database.

Appreciating that it is of interest to the research direction regarding the optimization of the WEDM process, Figure 11 was made. The increase in the number of papers whose titles aim to approach some problems of WEDM process optimization can be observed.



**Figure 11.** Increasing the number of papers addressing WEDM process optimization issues in the ScienceDirect database.

## 10. Conclusions

Wire electrical discharge machining is a way of applying electrical discharge machining. In WEDM, a reduction in the influence of tool electrode wear was achieved using a moving wire along its axis, which usually unwinds from one storage roller and is wound on another roller. The expansion of the WEDM process has been significantly favored by the emergence and development of numerical control subsystems.

Currently, there is an explosive development of research on the WEDM process, being approached in different directions of research. A brief statistical analysis highlighted the great interest of the scientific investigation, application and optimization of the WEDM process. The research's general objectives were aimed at widening the possibilities of applying WEDM and improving the performance of the WEDM processes. Thus, some research has sought to improve the various components of the WEDM system. The diversification of WEDM processes is registered. The attempt to apply the WEDM process in the case of very different materials and including for the machining of workpieces made of materials characterized by a very low electrical conductivity were developed. Many types of research have focused on identifying and characterizing how input factors act in the WEDM process. As output parameters of the process, the process's productivity, the roughness and accuracy of the machined surfaces, the thickness of the heat-affected zone, the wear of the tool electrode, and the kerf width were taken into account. Better knowledge of the influence exerted by the process input factors on the output parameters' values was followed by efforts to optimize the WEDM process. Monocriterial optimization was approached, but most often, multicriteria optimization methods were used. Both in the case of investigating the influence exerted by the input factors on the values of output parameters and in research to optimize the WEDM process, mathematical models were developed using modern mathematical tools.

The literature study has shown a significant increase in the number of works published in recent years and addresses the issues related to the WEDM process. This trend is expected to continue in the next few years. It is considered that the emphasis in the future will be on investigating the possibilities of using new versions of the WEDM process and on using this process in the machining of materials that will be identified in the future. Further efforts to optimize the WEDM processes are also expected, including new requirements specific to the Industry 4.0 stage.

**Author Contributions:** L.S. conceived the general structure of the paper and investigated the aspects concerning the modeling and optimization of the WEDM processes; O.D. investigated the aspects concerning the WEDM equipment, process input factors, and parameters of technological interest; M.C. investigated the research issues of the WEDM process in recent decades, G.N. elaborated the considerations concerning the evolution of the scientific and technical information concerning the WEDM; and I.B.B. synthesized the information concerning the influence of different factors on the parameters of technological interest corresponding to WEDM processes; A.H. investigated the improvements achieved in the last decades in the field of WEDM. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research received no external funding.

**Conflicts of Interest:** The authors declare no conflict of interests.

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