Chapter

Intelligent Control System of Generated Electrical Pulses at Discharge Machining

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Abstract

The book chapter provides a comprehensive set of knowledge in the field of intelligent control of generated electrical impulses for wire electrical discharge machining. With the designed intelligent electrical pulse control system, the stability of the electroerosion process, as well as the increased surface quality after wire electrical discharge machining (WEDM), can be significantly enhanced compared to standard impulse control systems. The aim of the book chapter is also to point out the importance of monitoring in addition to the established power characteristics of generated electrical pulses, such as voltage and current, as well as other performance parameters. The research was mainly focused on those parameters that have a significant impact on the quality of the machined surface. The own's theoretical and knowledge base was designed to enrich the new approach in increasing the geometric accuracy of the machined surface, as well as the overall efficiency of the electroerosion process for WEDM through intelligent control of generated electrical pulses.

Keywords: adaptive system, acoustic emission, automation, control system, discharge machining, pulse generator, spark, quality

1. Introduction

The current trend in the development of mechanical engineering carries signs of complexity and dynamism. At the same time, it is increasingly influenced by new scientific and technical knowledge and requirements for their rapid deployment. For the production of high-precision components of state-of-the-art and highly-sophisticated technical equipment, fully automated production systems and progressive manufacturing technologies are often used. In most cases, an integral part of them is a management system that manages demanding technological processes. Application of the given system provides a suitable precondition for ensuring the required high quality of manufactured products.

Another, not less significant trend at present is the focus on the development of scientific and technical principles of modern engineering production. At the same time, links with classical teachings are being sought, with emphasis on their direct use in technical practice. This trend is also aided by statistical, optimization and simulation methods. These have been used only in the past in the field of mechanical engineering for the solution of partial technological tasks. For example, they allowed a basic selection of technological process variants.

The current rapid development of computer technology creates wide scope for the use of mathematical methods in both theoretical and practical technological tasks. Cybernetic methods, probabilistic logic, mathematical modeling and simulation of production processes are used in connection with the development of computer technologies. All of this increases the demands on the degree of exactness of the formulation of knowledge, as well as the efficiency and quality of technological solutions, which aim to save the work of engineers, technicians and workers.

In addition, the continuous development of modern mechanical engineering places increased demands on the introduction of advanced production methods, advanced production facilities and their control systems. Particular attention is paid to machining processes in which, in particular, the mechanical properties of the workpiece and the tool do not impose almost any limits. These are, in particular, machining methods in which the degree of machinability of a material is dependent only on physical properties such as e.g. thermal and electrical conductivity, melting temperature, atomic valence and the like. As already mentioned, their essential part is computer support. A computer-aided production process has a huge advantage in that the human factor of poor product quality is almost excluded. In this case, the quality of the machined surface depends directly on the design of the machine, its software management and the setting of technological and process parameters.

Undoubtedly these processes include WEDM, where the decisive link with the primary impact on the quality of the machined surface is the electrical pulse generator. Nowadays, various types of electrical pulse generators are used for WEDM, the vast majority of which control performance parameters to maximize performance. It is exactly the new type of generator of electrical impulses applicable in the conditions of the electroerosion process which is described by Qudeiri et al. [1]. In the control algorithm of a given type of electric pulse generator, there is absolutely no criterion relating to the geometric accuracy of the machined surface. Researchers Yan and Lin [2] in turn dealt with the development of a new type of pulse generator which, unlike the previous type, is not oriented to maximize performance, but minimize the surface roughness of the machined surface. A similar type of pulse generator is also described by Świercz and Świercz [3]. However, even in this case, there is no qualitative criterion for the geometric accuracy of the machined surface. Researchers Barik and Rao [4] participated in the development of a special type of electrical pulse generator designed for electrical discharge machining in laboratory conditions. Although their newly developed generator allows to set the operating parameters of the electric pulse generator according to the specific quality requirements of the machined surface, the criterion of geometric accuracy of the machined surface is missing again.

Thus, it is clear from the above overview that insufficient attention is paid to the development of electrical pulse generators with a focus on the geometric accuracy of the machined surface. Therefore, the aim of this chapter of the book is to contribute to the database of existing knowledge in the field of intelligent system design for precise control of generated electrical pulses for WEDM with the focus on maximizing the geometric accuracy of the machined surface. These findings are intended to help improve the quality of components produced by the progressive WEDM technology, the practical application of which is described in detail in Chapter 2. This is based on the physical nature of the material removal described in detail in Chapter 3. Chapter 4 deals with the current state of electrical discharge parameter control during WEDM, which highlights the current deficiencies of current approaches in the control of generated electrical pulses. Chapter 5 describes possible approaches to eliminate tool electrode vibration during WEDM, by applying measures regarding technological and process parameters. It also points to the application of one of the acceptable options that concerns the innovation of an intelligent control system for generated electrical pulses during the electroerosion process. Further, based on an analysis of current modern approaches in the construction of electrical pulse generators used for WEDM, detailed in Chapter 6, an adaptive control system for generated electrical pulses was designed during WEDM. This innovated control system for generated electrical pulses, designed to increase the geometric accuracy of the machined surface for WEDM, is described in detail in the Chapter 7.

2. Application of progressive technologies in technical practice

As already mentioned in the introduction, modern engineering production currently places high demands on the mechanical properties of the materials used. The emphasis is mainly on their high strength, hardness and toughness. Therefore, materials such as various types of high-strength and heat-resistant alloys, carbides, fiber-reinforced composite materials, stelites, ceramic materials and advanced composite tooling materials, etc., are at the forefront. At the same time, with the use of these high-strength materials, the demands on accuracy and also on the performance of machine tools and equipment increase. These facts necessitate the development and deployment of machining methods that allow high material removal while achieving high quality machined surfaces. In this respect, there are some advantages to those machining methods in which there is no mechanical separation of the material particles. The application of these progressive machining methods to technical practice is particularly accentuated by the fact that not only the mechanical properties of the material, but also other properties such as thermal and electrical conductivity, melting temperature, atomic valency, density and the like, determine the machinability limits. Another not less important reason for implementing progressive machining methods is the complicated geometrical shapes of the workpiece, which often require demanding manufacturing processes. This results in long machining times, the use of special tools, special fixtures and the like. These are usually very expensive. A perfect control system is needed to meet all the above requirements. Standard processes for managing production processes are already inadequate today. Especially those who can adequately adapt to the current situation and the needs of the machining process are entering the forefront.

One of the progressively developing technologies in the field of machining process management is electrical discharge machining (EDM). Moreover, the essence of the production of components with the application of this progressive technology is based on the fact that the mechanical properties of the machined material do not impose almost any limits on its machining. The only limiting factor for the machinability of these materials is their appropriate chemical and physical properties. This technology is principally based on the use of thermal energy to which the electrical discharge generated between the two electrodes is transformed, of which the first electrode represents the tool and the second workpiece. It is a machining process in which material removal occurs through cyclically repeated electrical discharges. Through these, the microscopic particles in the form of beads are removed from the material by melting and subsequent evaporation in conjunction with high local temperature. It moves at a level 10,000°C. However, the electroerosion process must be precisely controlled by a reliable control system.

3. Physical nature of material removal for WEDM

To ensure precise management of the electroerosion process during WEDM, it is essential to base it on its physical principle. The physical principle of material removal for WEDM can be regarded as a relatively challenging and complicated process. Its essence lies in the formation of a discharge between two electrodes (tool—workpiece) either in very thin gas, in air, or in gas at normal temperature and pressure, or in a dielectric fluid, i. e. in a fluid with high electrical resistance. However, the classical electrical discharges that occur between the two electrodes (tool—workpiece) in the gas dielectric have relatively little effect. Therefore, such an environment is not quite ideal for the needs of precision and high-performance machining. In this regard, the application of fluid dielectric media is much more advantageous. These dielectrics significantly increase the effect of electrical discharges between the electrodes (tool—workpiece). Electrically charged particles, electrons and ions are the active agents in the erosion of material particles from the surface of both electrodes. They are formed as a product in the ionization process. Subsequently, in the electric field, they acquire the kinetic energy that, along with the output work, is passed on the surface of both electrodes. The shape and size of the eroded metal particles from the material being machined, as well as the size and shape of the resulting crater (**Figure 1**) depend not only on the polarity of the electrodes, but also on the particular application of the technological parameters.

By default, 10^{-3} až 10^{-5} mm^3 of material is removed by WEDM during a single discharge cycle by electroerosion. Its size can be empirically determined by the relationship (1):

$$V_i = K \cdot W_i \tag{1}$$

where, V_i (mm^3) is the volume of material taken, K ($mm^3.J^{-1}$) is the proportionality factor for cathode and anode, W_i (J) is the discharge energy.

As mentioned above, the shape and size of the crater formed in both electrodes during one discharge cycle depends mainly on the magnitude of the applied discharge energy. This is given by the specific setting of technological parameters. The time course of individual discharges is characterized by several indicators. These are indicators relating to the discharge current I (A), the discharge voltage U (V) and the duration of the individual discharges t_{on} (μs), as well as the breaks t_{off} (μs) between discharges. The events that take place between the two electrodes during the electroerosion process are comprehensively described the volt-ampere characteristic. This is shown in **Figure 2**.

The total volume of V_T, material taken from both electrodes during the electroerosion process is directly dependent on the magnitude of the transmitted

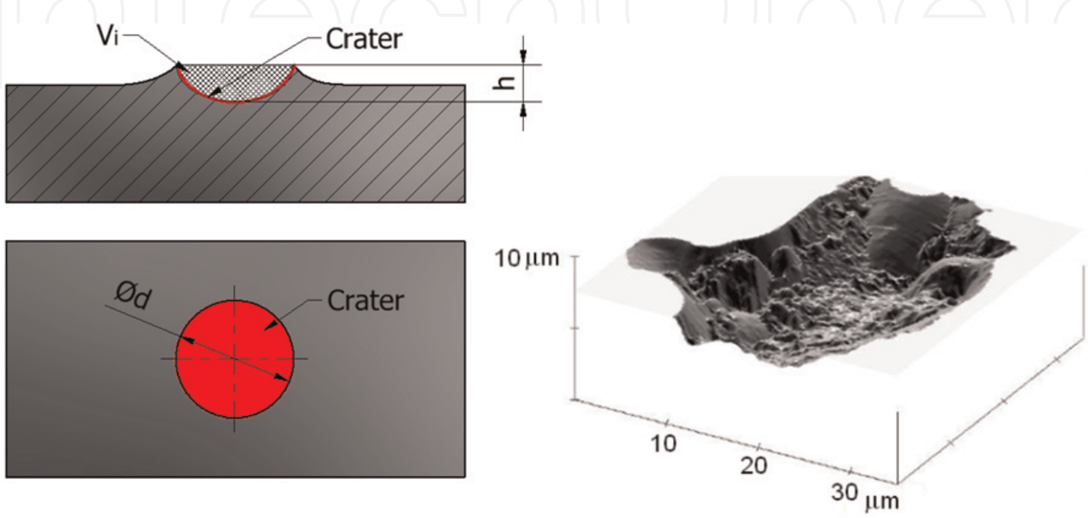

Figure 1.
The shape and size of the crater formed during one discharge cycle. V_i—volume of material taken, h—depth of crater, d—crater diameter.

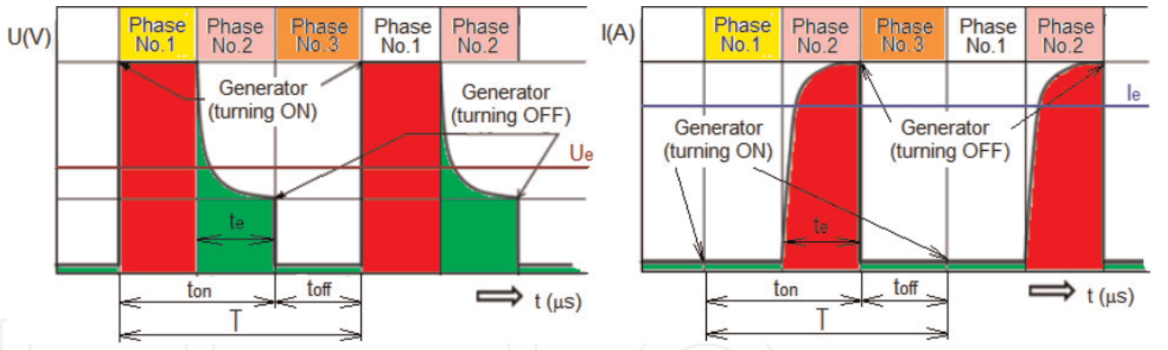

Figure 2.
Volt-ampere characteristic of one discharge cycle during the electroerosion process.

energy W_e. This in turn results in a series of cyclically repeating electrical discharges between the electrodes (tool—workpiece) over time t. The total discharge energy W_e transmitted during a series of discharge cycles can be empirically determined by the relationship (2):

$$W_e = \int_0^T U(t) \cdot I(t) \mathrm{d}t \tag{2}$$

where, W_e (J) is the total discharge energy, $U(t)$ (V) is the electrode discharge voltage at time t, $I(t)$ (A) is the maximum discharge current at time t, T (µs) is the duration of one period of electrical discharge.

By deriving the relation (2), the amount of energy transmitted during one discharge cycle can then be empirically determined (3):

$$W_e = I_e \cdot U_e \cdot t_{on} \tag{3}$$

where, I_e (A) is the average discharge current, U_e (V) is the average discharge voltage on the electrodes, t_{on} (µs) is the duration of discharge during one discharge cycle (delayed generator operation).

In order to complete all the parameters of the electroerosion process related to one discharge cycle, it is also necessary to empirically determine the magnitude of the average discharge current I_e and the discharge voltage U_e between the electrodes. These values can be determined based on the relationship (4) for I_e and the relation (5) for U_e:

$$I_e = \frac{1}{t_e} \int_{0_{t_e}} I(t) \mathrm{d}t \tag{4}$$

$$U_e = \frac{1}{t_e} \int_{0_{t_e}} U(t) \mathrm{d}t \tag{5}$$

where, $I(t)$ (A) is the maximum discharge current (A), t_e (µs) is the current discharge time (generator operation).

Based on these and other parameters of the electroerosion process, the total amount of material taken per time unit t can then be empirically determined by relation (6):

$$Q_T = k \cdot r \cdot f \cdot \mu \cdot W_e = k \cdot r \cdot f \cdot \mu \cdot \int_0^T U(t) \cdot I(t) \mathrm{d}t \tag{6}$$

where, Q_T (mm^3·s^{-1}) is the total amount of material withdrawn per time unit t, k is the factor of proportionality for cathode and anode, r is the efficiency of electrical discharge, f (s^{-1}) is the frequency of electrical discharges, μ is the efficiency of the discharge generator.

Another not less important parameter in specifying electroerosion process parameters is the discharge period t_d. This characterizes the overall efficiency of one discharge cycle between the electrodes. It is empirically determined as a proportion of the duration of the electrical discharge t_{on} during one discharge cycle, that is, the time between the generator on and off and the period of time T, that is, the time interval between two consecutive generator starts. Its value can be determined by relation (7):

$$t_d = \frac{t_{on}}{T} = \frac{t_{on}}{t_{on} + t_{off}} \tag{7}$$

where, t_d is the discharge period, t_{on} (μs) is the duration of the discharge during one discharge cycle (delayed generator operation), t_{off} (μs) is the break time between two consecutive discharges, T (μs) is the electric discharge period time.

Figure 3 describes the effect of the discharge period t_d on the machined surface quality for WEDM in terms of the roughness parameters Ra and Rz.

In addition, by using the discharge period t_d, we can empirically express the overall efficiency of one discharge cycle between the electrodes during electroerosion, we can also quantify individual types of electrical discharges. Its

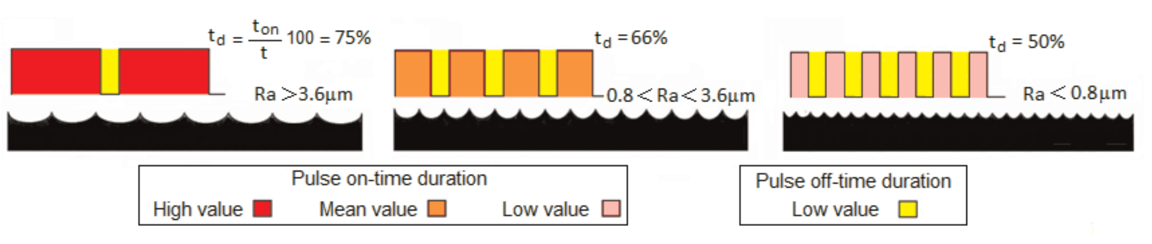

Figure 3.
Effect of discharge period td in the range of 50–75% on the machined surface quality forWEDM in terms of parameters Ra and Rz.

Electrical discharge parameters	Type of discharge	
	Electric spark	**Short term electric arc**
Total discharge duration t_i (μs)	Short time (0.1 až 10^{-2})	Long time (>0.1)
Time usage of discharge period t_d	Low value (0.03 až 0.2)	High value (0.02 až 1)
Discharge frequency	High value	Low value
Current density at the discharge point (A.mm^{-2})	Approx. 10^6 A.mm^{-2}	10^2–10^3 A.mm^{-2}
The discharge channel temperature (°C)	High (over 10,000)	Low (in the range of 3300–3600)
Energy individual discharges W_e (J)	Low (10^{-5}–10^{-1})	High (approx. 10^2)
Practical use for WEDM	High quality machined surface (finishing)	Low quality of machined surface (rouhing)

Table 1.
Basic property specification of stationary and non-stationary type of discharge.

value makes it easier to identify the type of electric arc, i.e. whether it is stationary electric spark or nonstationary short term electric arc. At the same time, its value is to some extent influenced by the total amount of Q_T of the withdrawn material per time unit t, as well as the resulting quality of the machined surface.

It can be seen from **Table 1** that precise control of the individual electrical discharge parameters between the two electrodes during a single discharge cycle has a significant impact on the quality of the machined surface for WEDM as well as the overall efficiency of the electroerosion process.

4. Current state in the field of electric discharge parameter control for WEDM

From the point of view of achieving the high quality of the machined surface for WEDM as well as the high overall efficiency of the electroerosion process, the discharge process must be precisely software controlled. The current trend in the development of electrical pulse generators is mainly focused on control systems that do not measure effective voltage, but separately the duration of each discharge. These times are summed and the intensity of the electric discharge is regulated accordingly. This data is then used to control the actuator, while the response time and magnitude of the servo motion correspond to that in the working gap (**Figure 4**).

Recently, mainly used so-called alternating electric pulse generators. There are also generators of electrical impulses in which is voltage with the same polarity supplied between tool electrode and workpiece. This causes the ions to pass in one direction, causing increased corrosion of the eroded material. However, if the electrical voltage polarity is alternated with a certain frequency, this effect is suppressed and corrosion does not occur. Moreover, the practical advantage of applying these types of pulse generators is a narrower working gap. This type of generator finds its application especially in the erosion of carbide alloys.

As mentioned above, the process of controlling electrical impulses during WEDM is in some cases based on predetermined mathematical models. Important pioneers in this area were Scott et al. [5]. In particular, they focused their research on modeling performance parameters for electroerosion machining in various conditions and modes. In their research, they also found that there is no single combination of levels of important factors that can be optimal at all times. Research in the field was also addressed by Tarng et al. [6, 7]. They then formulated mathematical models that allow predicting the achieved quality of the machined surface depending on the setting of the electric discharge parameters using simulation and optimization elements. Researchers Sarkar et al. [8] have devoted a substantial part

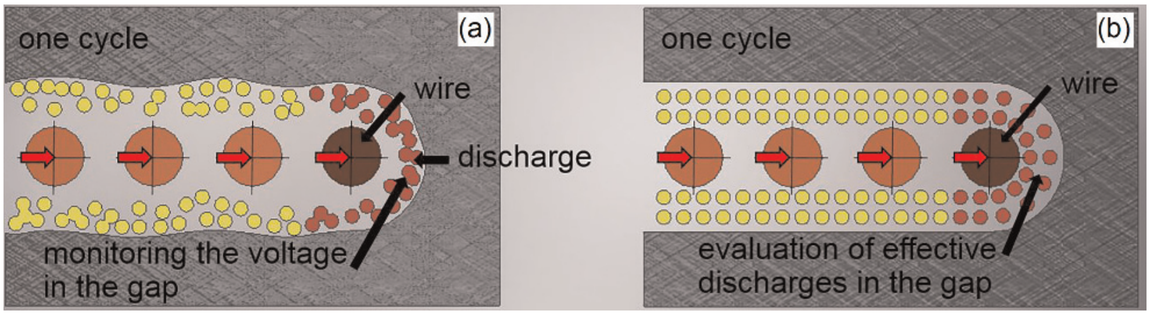

Figure 4.
Controls of actuators for WEDM based on the system for monitoring the duration of individual discharge cycles. (a) Monitoring the effective voltage in the gap and (b) evaluation of the time duration of the discharge.

of their research to the mathematical modeling of the achieved surface quality at WEDM depending on the current electrical discharge parameters using neural networks. A detailed study of the electrical discharge performance parameters during WEDM based on their mathematical modeling was done by Puri and Bhattacharyya [9]. The areas of modeling of electrical discharge parameters, considering the polarity change of electrodes during WEDM, have been researched by Liao and Yub [10]. At the same Mahapatra and Patnaik [11] they described in detail the possibilities of using the nonlinear modeling method to optimize these parameters. A specific area of electroerosion process control has been studied by Jin et al. [12]. In their research, they have developed a combined structural model that describes the use of thermal energy, including a balance of the effects of vibration on the stability of the electric arc. In addition, the model also included high temperature effects due to high-power electrical discharges. Yan et al. [13, 14] described a new approach in electrical discharge parameters optimization during electrical discharge machining based on selected performance characteristics such as maximum discharge current I (A), maximum electrical discharge voltage U (V), discharge duration during one discharge cycle t_{on} (μs) and the duration of the break between discharges t_{off} (μs). All these parameters have been optimized with regard to the quality and efficiency of the electroerosion process, as well as to minimize wear on the tool electrode. The physical aspect of the electroerosion process was addressed by Kopac [15]. In his experimental research, he tested various power parameters of the electric arc with respect to the content of electrically conductive parts in the discharge channel during the electroerosion process. He found that with the increasing share of electrically conductive parts in the discharge channel during the electroerosion process, its performance and productivity increased. At the same time, it points out that the main electrical parameters of the electric arc during the electroerosion process have the smallest influence on the crater size after the electric discharge of the maximum discharge voltage U. Only its crater shape changes with its size. The study of vibration of the tool electrode due to electrical discharges during the electroerosion process was investigated by Shahruz [16]. They found that tool electrode vibration has a significant contribution to the geometric inaccuracy of the machined surface after WEDM. They also argue in their study that the high tool electrode tension forces near critical values have a positive effect on reducing the amplitude of the wire electrode vibration during the electroerosion process, but cannot completely eliminate them. The vibration of the tool electrode was also investigated by Altpeter and Roberto [17]. In particular, their research was substantiated by the fact that the issue of damping tool electrode vibration during WEDM has been poorly addressed in the past. The shape and size of the craters after the individual electrical discharges during the WEDM were dealt with by Hewidy and Gokler [18, 19]. They tried to describe mathematically the influence of the magnitude of the discharge energy during the electroerosion process on the size and shape of the craters. They found that higher values of maximum discharge current I (A) and duration of discharge during one discharge cycle t_{on} (μs) contribute to increase in crater size.

From the above overview, it is clear that several experimental investigations have been conducted in the field of electrical discharge between the two electrodes during one discharge cycle. Despite the increasing emphasis on the complexity of learning about the set of electrical discharge characteristics during WEDM, there is still a lack of comprehensive identification of their interconnections. At the same time, there are no suggestions for minimizing the adverse effect of electrical discharges on the quality of the machined surface after WEDM in terms of geometric accuracy.

5. Elimination of tool electrode vibration for WEDM

During the duration of the individual electrical discharges, due to the precise guiding of the tool electrode, it is necessary to adequately tension it with the force *Fw* (N). It is normally selected in the range of 5–25 N. Furthermore, it is necessary to charge the tool electrode with electrical impulses, enwrap it with a dielectric fluid and because of its wear and tear it is constantly renewed. To be able to move with such a delicate and labile tool as a few tenths of a millimeter of a thin wire electrode, very precise and sensitive guide are needed. In **Figure 5**, a part of the electroerosion CNC machine can be seen, which provides accurate guidance of the wire electrode.

The tool electrode tensioning and guiding system in the CNC electroerosive equipment consists of a supply section that grips, clamps, feeds, and controls the wire Furthermore, from the working part that guides the tool electrode through the working zone, where it is washed with dielectric fluid, supplied with electric current and subsequently eroded. The lead electrode guidance system is terminated by a drain portion, which retracts the electrode, rechecks it, and wraps it onto the coil.

As already mentioned, in addition to the inaccuracy in the wiring of the wire electrode, its deflection from a straight position causes forces that arise due to the cyclic action of the electrical discharges between the two electrodes [20]. The rules applies that the greater the thickness of machined material, the greater the deflection. Partial compensation for this adverse event is carried out by special measures. In particular, the inclusion of counter force in conjunction with a system that ensures optimum tension of the tool electrode. However, neither of these measures has a sufficient effect.

In addition to the thickness of the material being machined, the choice of the optimum tensioning force also adapts to the intensity of the electrical discharge, the type of material of the workpiece, the type of tool electrode material and its diameter, the properties of the dielectric fluid, and the like. In particular, wire electrode tension compensation serves to minimize its sag in the middle due to the cyclic action of electrical discharges with varying intensity [21]. In **Figure 6**, an extreme deflection of the tool electrode during the elektroerosion process can be observed as

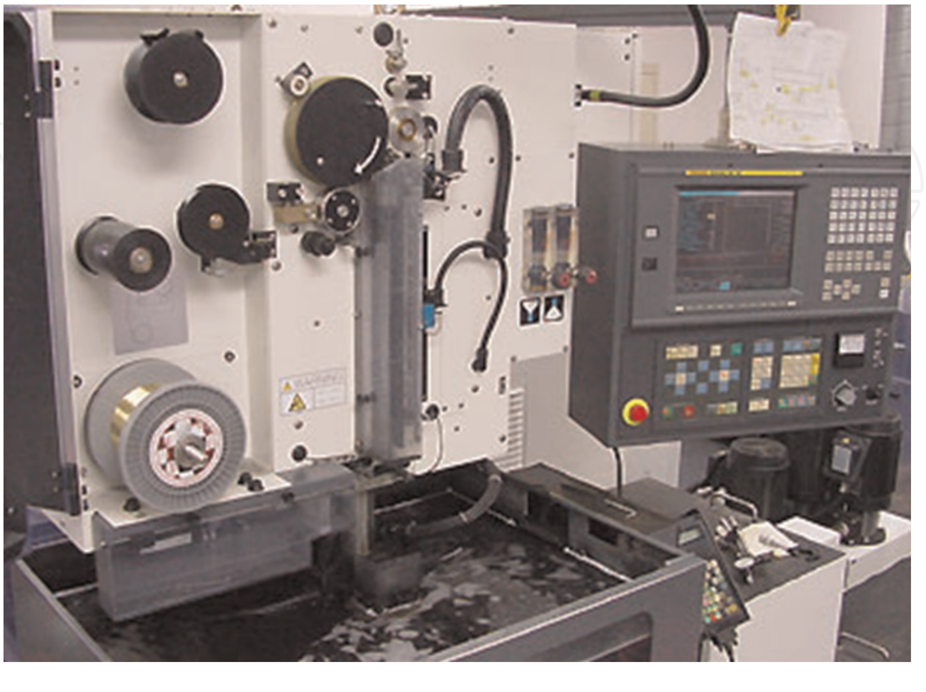

Figure 5.
Tool electrode tensioning and guiding system during the electroerosion process.

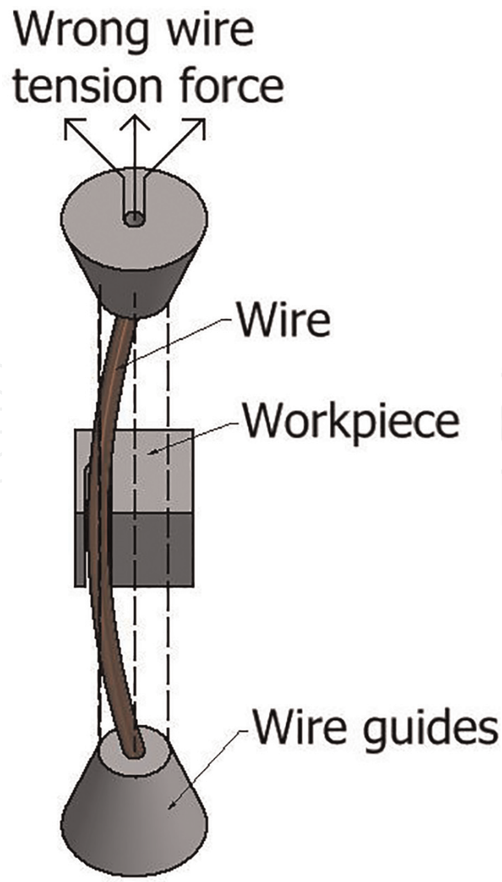

Figure 6.
Extreme deflection of the tool electrode due to the application of an improperly selected value of the compensating force during its tensioning.

a result of the inappropriate selection of the compensation force size in its stretching.

As a general rule, the higher the value of the tool electrode compensation force when it is tensioned reduces the vibration amplitude. This also leads to a reduction of the working gap, thus achieving a higher accuracy of the machined surface for WEDM. Ideally, the value of the tool electrode compensation force should be chosen to approach the material tensile strength limit [22]. However, the limit value must not be exceeded during the electroerosion process. Otherwise, the tool electrode will break. Tool electrodes with a strength in the range of 400–2000 $N.mm^{-2}$ are used as standard. Tool electrodes with a strength of up to 490 $N.mm^{-2}$ are called soft, tool electrodes with a strength of between 490 and 900 $N.mm^{-2}$ are called semi-hard and tool electrodes with a strength above 900 $N.mm^{-2}$ are called hard. **Figure 7** shows the impact strength (hardness) of the wire tool electrode on its deflection in the electroerosion machining process when applying a constant tension force.

With increasing material thickness, it is necessary to increase the value of the tensioning force Fw of the tool electrode in order to eliminate vibrations. This allows, as already mentioned, a higher tensile strength value of the tool electrode material used or its increasing diameter. However, too high values of the tool electrode tension force have an adverse effect on the performance and productivity of the electroerosion process. This can be seen from the following graphical dependence on **Figure 8**.

From this graphical dependence, it can be seen that increasing the magnitude of the compensating force Fw when tensioning the tool electrode is in terms of productivity it has meaning only to a certain extent. When it is exceeded, there is a significant drop in the electroerosion process productivity.

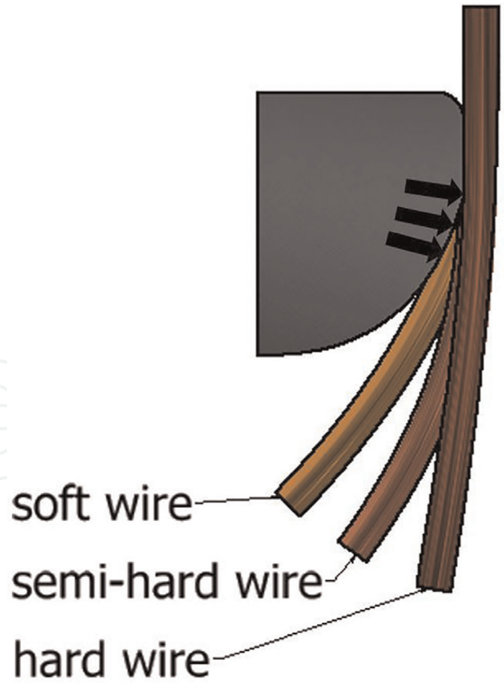

Figure 7.
Effect of hardness of wire tool electrode material on its deflection during electrical discharge machining.

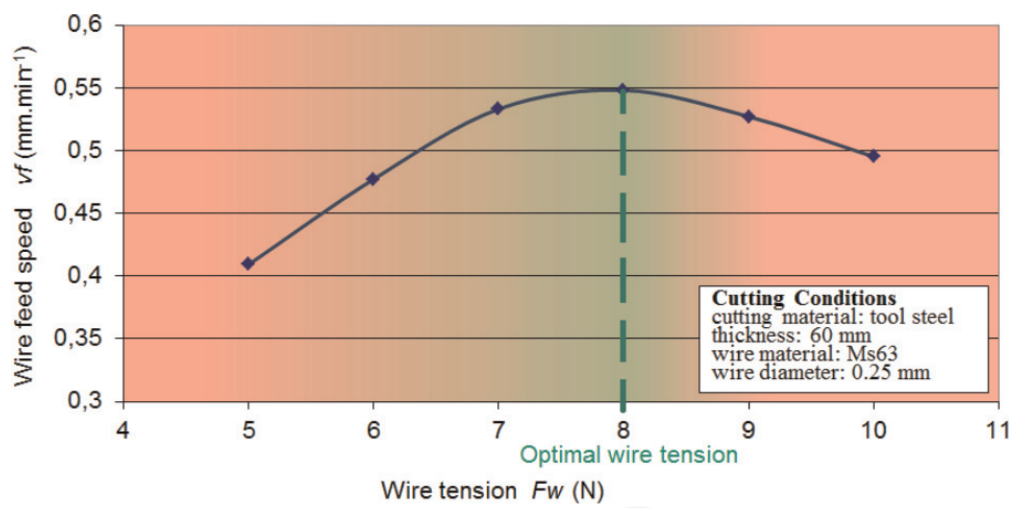

Figure 8.
The dependence of the electroerosion process productivity on the value of the compensation force Fw when the tool electrode is stretched.

Thus, it is clear from the foregoing that when applying the critical values of the compensating force *Fw* when the wire tool electrode is being tensioned, the productivity of the electroerosion process will be even lower. On the other hand, as the value increases, the vibration amplitude of the tool electrode is substantially reduced, resulting in greater geometric accuracy of the machined surface after WEDM [23]. Since the tensile strength of the wire tool electrode material is a limiting factor in the tension force selection, the choice of material type is also important [24]. By default, a single-component compact tool electrode is selected for WEDM. Materials such as Cu, Ms., Mo and the like are used. In the past, pure copper was used quite often as a tool electrode material, mainly because of its high electrical conductivity, but also in its relatively simple production. However, a significant drawback of the application of pure copper to the production of wire tool electrodes is its very low tensile strength [25]. Therefore, the Cu tool electrodes were later replaced with brass. Practical application results have shown that the presence of Zn in the tool electrode material significantly reduces the risk of breakage. This allows the application of higher values of compensation force *Fw*. Also suitable for producing tool wire electrodes is aluminum brass. This material is characterized by a tensile strength of 1200 N.mm^{-2}, without any adverse effect on its elongation. Although these types of tool electrode materials are less prone to damage, their usefulness in practice is relatively limited. The tooling electrodes, which are based on Mo, are used where very high tensile strength and very small wire diameter are required. In addition to the high tensile strength, this material also has a high melting point. A significant disadvantage of the application of this material is its high cost. The tungsten tool electrodes have an even greater tensile strength and a higher melting point than molybdenum. From an economic point of view, this type of material is applicable only to very small diameters (≤0.05 mm) of tool electrodes [26].

As mentioned, the presence of Zn in the tool electrode material has a positive impact on its mechanical properties. However, the practical use of single-component tool electrodes with a Zn content above 40% is inefficient for economic reasons. Therefore, multi-component, for example coated electrodes have been developed for the application of higher tool electrode tensioning forces, allowing higher zinc content on the electrode surface while maintaining a homogeneous core. These tool electrodes are particularly useful when specific material requirements are required because of the high geometric accuracy of the machined surface after WEDM. In this respect, the high tensile strength of the material as well as its good electrical conductivity are decisive.

For this purpose, multi-component tool electrodes are used, the core of which is Cu, Ms. or steel and coated with pure Zn or Ms. with a zinc content of 50%. **Figure 9** shows selected combinations of multi-component tool electrodes that are used in practice for special operations. This is particularly the case when increased demands are placed on the quality of the machined surface after WEDM in terms of geometric accuracy.

These composite wires make it possible to combine traditional materials that are relatively inexpensive with expensive materials to achieve the unique properties of wire tool electrodes [27]. However, the efficiency of these coated tool electrodes is limited by the thickness of the coating which is relatively thin. The standard ranges from 5 to 10 μm. A special case consists of three-component tool electrodes, whose core is a steel wire. It is coated with a layer of copper and brass with 50% zinc content. The coated tool electrodes allow the application of relatively high tension forces *Fw* while maintaining an acceptable electroerosion process productivity.

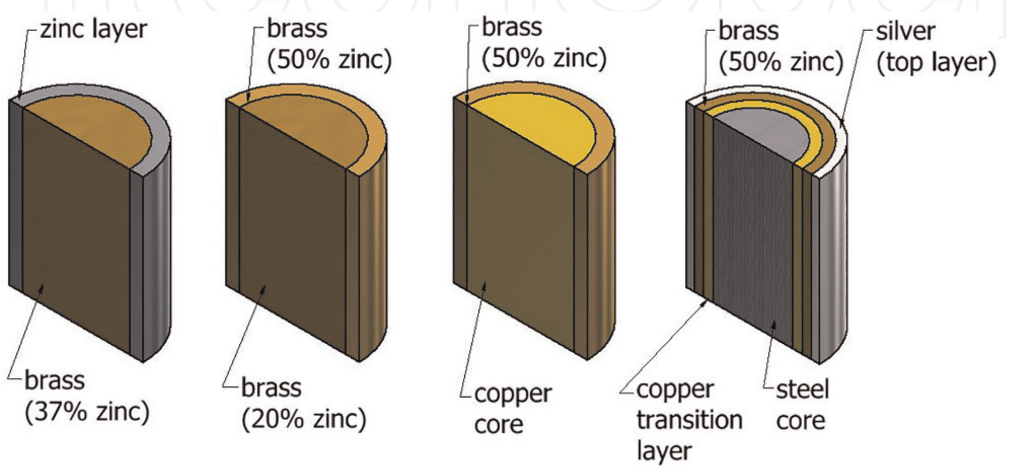

Figure 9.
Selected combinations of multi-component tool electrodes used for WEDM in the case of increased quality requirements for the machined surface.

Type of specific application	Recommended wire electrode composition	The advantage of practical application
Power machining (high MRR)	• Steel wire coated Ms and Cu • Cu wire with Ms coating • Galvanized brass wire	• Better rinsability • A higher wire electrode feed rate
Very small workpiece thickness	• Steel wire coated with Ms and Cu • Graphite coated wire	• Higher resistance to breaking the wire • Better rinsability
Carbide machining and hardly machinable alloys	• Steel wire coated with Ms and Cu • Cu wire with Ms coating	• Higher resistance to breaking the wire • Higher output energy
Machining under different angles so-called conical machining	• Steel wire coated with Ms and Cu • Ms alloy	• Higher resistance to breaking the wire • Increased wire elasticity

Table 2.
Basic properties of composite multi-component tool electrodes and their practical application in specific cases of WEDM.

Their significant disadvantage, compared to single-component compact tool electrodes, is again too high a price. **Table 2** provides an overview of the properties of composite multi-component tool electrodes, including their practical application for specific purposes.

Based on this review, it is evident that composite multi-component tool electrodes provide a number of advantages over conventional single-component compact electrodes. The decisive advantage, however, is their higher tensile strength, which allows the application of higher tension forces Fw. In this way, the amplitude of the vibration of the tool electrode can be substantially reduced, thereby achieving a significantly higher quality of the machined surface in terms of its geometric accuracy. All this can be achieved while maintaining the acceptable productivity of the electroerosion process [28]. But the problem is their high price. Therefore, from the point of view of economic efficiency for WEDM in practice, the standard compact single-component tool electrodes continue to be used. However, their limiting factor is the relatively low tensile strength. Therefore, no further significant improvements can be expected in this respect while maintaining an acceptable price of the applied material. It is therefore necessary to draw attention to other possibilities of increasing the geometric accuracy of the machined surface after WEDM. One of the acceptable options is to apply an innovative intelligent control system for generated electrical pulses during the electroerosion process.

6. Analysis of current approaches in the construction of electrical pulse generators used for WEDM

In the past, dependent generators were often used as a source of impulses In the past, dependent generators were often used as a source of impulses. Their running consists in repeated recharging and discharging the capacitor. With this control system discharges the capacitor is normally powered from a DC voltage source, which is connected in parallel to the circuit. Discharging the capacitor occurs when the voltage reaches a breakover value. The size of the breakover voltage depends mainly on the contamination of the dielectric and on the electrode distance. Subsequently, the control system instructs the servo drive to maintain the required working gap size based on the evaluation of the voltage conditions at the discharge location. Changing the time ratios within each discharge also changes their frequency and total discharge energy. From this comes the term "dependent pulse generators."

Thus, it is clear from the above principle that these types of pulse generators allow very short discharges to be produced, while the discharge duration t_i is 10^{-4}–10^{-7}. These are relatively simple construction equipment. For these types of pulse generators, it is required to connect the workpiece as an anode and a tool electrode as a cathode. This type of connection is used because of the need for less material loss from the tool electrode during the electroerosion process. By using a DC power source in a given circuit, the ions are only moved in one direction. This provides a suitable precondition for the formation of corrosion of the eroded particles, which is considered an undesirable phenomenon. In addition, a significant disadvantage of the above-mentioned types of electrical pulse generators is the limited control of the shape and frequency of the discharges, low machining productivity, but also a relatively high wear of the tool electrode [29]. Therefore, these types of electrical pulse generators are no longer used in modern electroerosive equipment.

New types of electrical pulse generators are constantly being developed to continually improve production quality and productivity. These allow, for example, a variable selection of individual electrical discharge parameters, regardless of the actual ratios in the working gap. In addition, the new types of electrical pulse generators have a much longer discharge time than the dependent generators, while lowering the operating voltage. Some types even allow changing the polarity of the discharges during the electroerosion process. In these types of electrical pulse generators, ion conductivity predominates, with the workpiece being normally engaged as a cathode and a tool such as an anode. They are also referred to as independent generators because they allow variable variations in the electrical discharge pulse amplitudes, their polarity, frequency, and so on, regardless of the current situation in the working gap. In technical practice, there are several types of independent generators. For example, a rotary generator. It represents a dynamo that is powered by an asynchronous motor. An essential part of this type of generator is also a semiconductor diode. Its task is to prevent the breakove in the opposite direction. In this type of generator, the tool electrode in the circuit engages as an anode and the workpiece as a cathode. **Figure 10** shows a schematic diagram of an independent electrical pulse generator of a rotating member electroerosive equipment including its volt-ampere characteristic.

These types of independent generators allow relatively high performance, $i.j.$ high values of material removal rate (MRR up to 5000 $mm^3.min^{-1}$) at constant frequency of electrical discharges. Therefore, in practice, they are mainly used for roughing operations. However, for the finishing operations, an additional RL generator is required, which is essentially their main disadvantage.

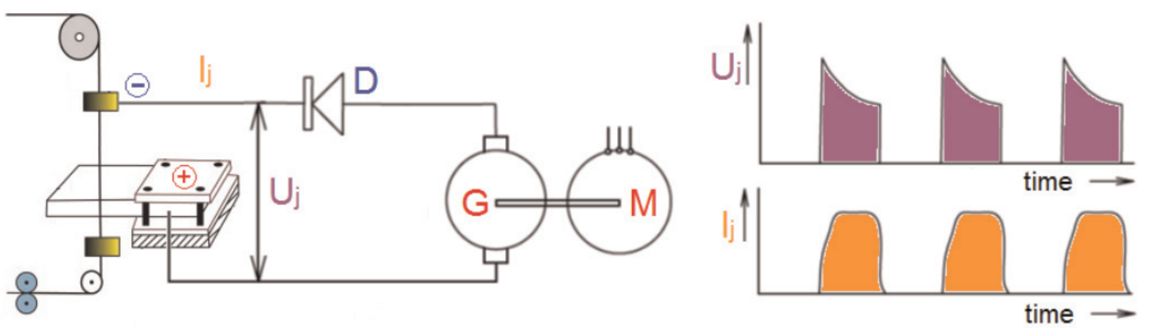

Figure 10.
Scheme of an independent rotary member electrical pulse generator and its volt-ampere characteristic.

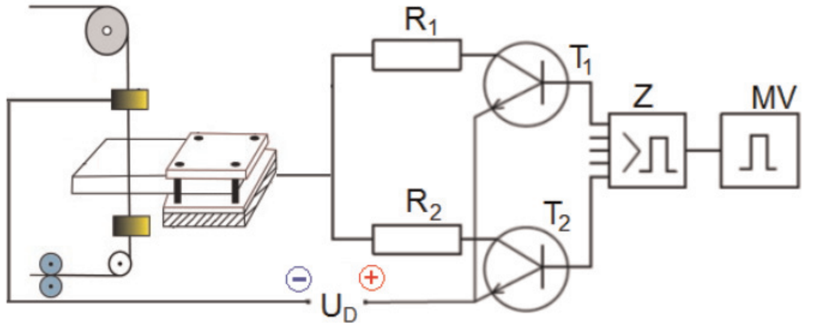

Figure 11.
Schematic of a semiconductor independent electric pulse generator used in modern electroerosion machines.

Higher levels are represented by semiconductor generators. Thanks to the use of semiconductor elements, their main advantage is high reliability, but in particular the possibility to change the parameters of electric discharge in a wide range of values. They allow changing frequencies in the range of 50–500 Hz. Their basic structural element is the semiconductor pulse generator, the so-called multivibrator (MV), which supplies pulses to the amplifier *Z*. This then drives the amplified pulses power transistors T1, T2. Their number determines the amount of current required to be delivered to the discharge location. The frequency of the electrical pulses and their power parameters is determined by the multivibrator. **Figure 11** shows a schematic of an independent generator of electrical impulses electroerosive equipment with semiconductor devices.

Microcomputer controlled generators are currently the most widely used type of independent electrical pulse generator used in state of the art electroerosion machines. These independent semiconductor generators are considered second generation generators. Their main advantage is the application of alternating electric voltage to the discharge, resulting in a reduction of the working gap and the associated reduction in the volume of material withdrawn. They allow a wide range of electrical discharge parameters to be set, with the frequency range of the electrical discharges varying from 0.5 to 50 kHz. The main advantage of the practical application of this type of independent electric pulse generator is the demonstrably less heat affected zone of the eroded area. At the same time, its application can significantly reduce the extent of corrosive effects occurring during the electroerosion process. **Figure 12** shows a diagram of an electroerosion equipment electrical pulse generator that is controlled by a microcomputer.

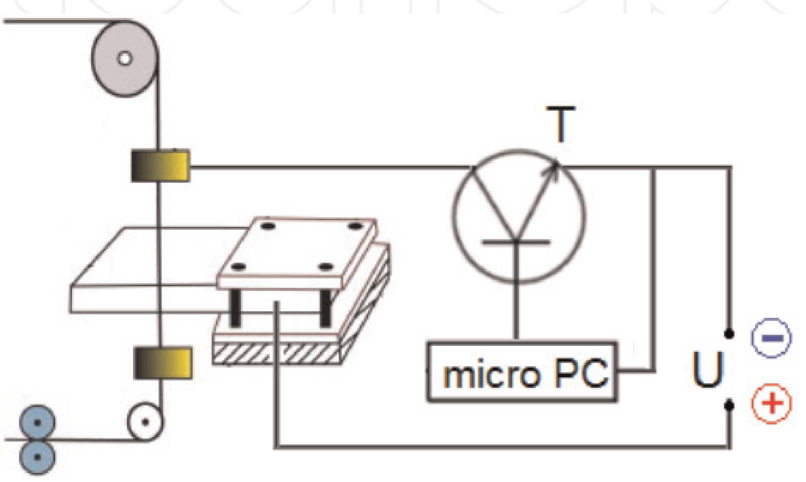

Figure 12.
A diagram of an electrical pulse generator controlled by a microcomputer.

7. Adaptive control system of generated electrical pulses for WEDM

In practice, there are several cases where all of the above possibilities have been used to increase the geometric accuracy of the machined surface in terms of the application of the specific properties of the wire tool electrodes for WEDM. However, despite the application of modern control systems of generated electrical pulses, not all of the expected requirements for the achieved surface finish in terms of geometric accuracy are always met. In this case, one option is to modify the control system of generated electrical pulses. However, it should be pointed out that this is a substantial intervention in the traditionally used system of generated electrical impulses during the electroerosion process.

Another of the requirements for WEDM is, in addition to achieving high quality machined surface in terms of geometric accuracy, also increasing the performance of the electroerosion process. These goals can only be met with the help of highly sophisticated online monitoring systems. At present, information that is derived from the actual value of the electrical discharge parameters is used to control the electroerosion process. In particular, the size of the voltage, current and working gap are monitored. However, setting the current value of these parameters does not take into account all the phenomena that occur in the working gap. They result in the formation of wire electrode vibrations [30]. However, the direct measurement of the amplitude size of the vibration of the wire tool electrode in real life conditions of the electroerosive machine is a problem. One solution is to measure it through one of the indirect methods. Subsequent inclusion of a given parameter as one of the monitored parameters during the WEDM in the form of an input parameter into the process control of generated electric pulses will allow for a new dimension in the field of increasing the productivity of the electroerosion process and the achieved surface quality. At the same time, by monitoring the parameter, a substantial increase in the level of intelligent adaptive control WEDM can be achieved [31]. With its help, it is also possible to detect and then by appropriately adjusting the generated electrical pulses to eliminate the occurrence of unwanted electrical discharges that increase the amplitude of the wire electrode vibration. These informations are very valuable because it allows the use the strategy of an adaptive electrical discharge control to eliminate the adverse impact of inappropriate electrical discharge parameter settings. Improper setting of electrical discharge parameters results in a loss of electroerosion process stability, a decrease in productivity for WEDM, but also a deterioration in the quality of the machined surface. Since a stable electroerosion process is characterized by a constant and uniform vibration of the wire tool electrode with very low amplitude, it is necessary that this deviation at the point of contact of the electrode with the workpiece is regarded as one of the regulatory parameters that ensures the stability of the electroerosion process.

As mentioned above, due to the generation of electrical discharges with inappropriate parameter settings, wire tool electrode vibrations occur. During the electroerosion process, the thin wire electrode primarily vibrates in the X and Y directions. The magnitude of its vibration amplitude is directly subordinated to the frequency and intensity of the generated electrical pulses. **Figure 13** shows the amplitude and direction of vibration of the wire tool electrode during the electroerosion process.

The individual parameters of the generated electrical pulses are currently set with respect to achieving the highest possible efficiency and productivity of the electroerosion process. However, these parameters do not take into account the vibration of the wire tool electrode, which has a significant contribution to the geometric inaccuracy of the machined surface.

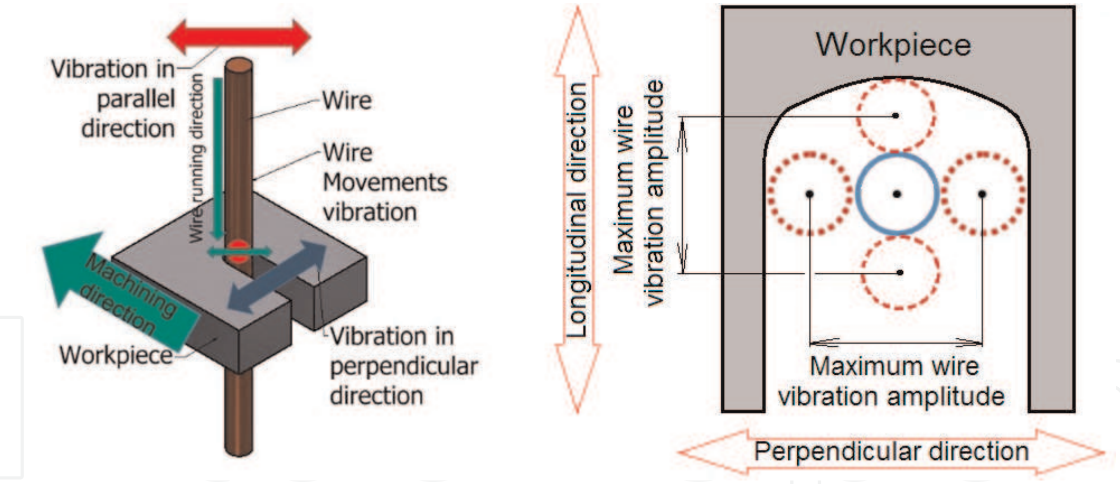

Figure 13.
Amplitude and direction of vibration of the wire tool electrode during WEDM.

As mentioned above, the magnitude of the vibration amplitude of the wire tool electrode is dependent on the size of the wire tensioning force and the current electrical discharge parameters. Of these, priority is given to the frequency of generated electrical discharges. However, based on the results of several investigations, it has been shown that the vibration of the wire electrode in the *X* axis direction becomes slightly higher than the *Y* axis vibration [32]. However, in terms of consequences, the vibration of the wire electrode in the *X* axis direction has a significantly lower effect on the geometric inaccuracy of the machined surface because they are generated in the feed direction. However, the problem is the vibrations that are generated transversely to the wire electrode feed, *i. j*. in the *Y* axis direction. Based on the experimental investigations carried out, it has also been shown that the magnitude of the vibration amplitude of the tool electrode is not directly proportional to the discharge frequency. As can be seen from the graph in **Figure 14**, its maximum value is reached when applying the critical frequency of generated electrical discharges.

However, the critical frequency of the generated electrical discharges, in addition to the electrical discharge parameters, also depends on other parameters, such as the thickness of the material being machined, the diameter of the wire electrode,

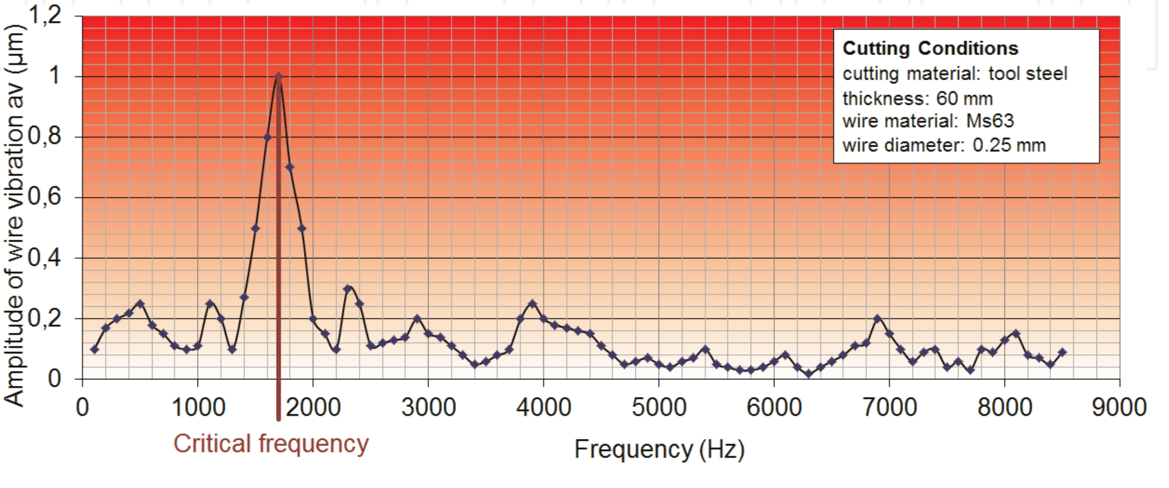

Figure 14.
Dependence of vibration amplitude of wire tool electrode on frequency of generated electrical discharges during WEDM.

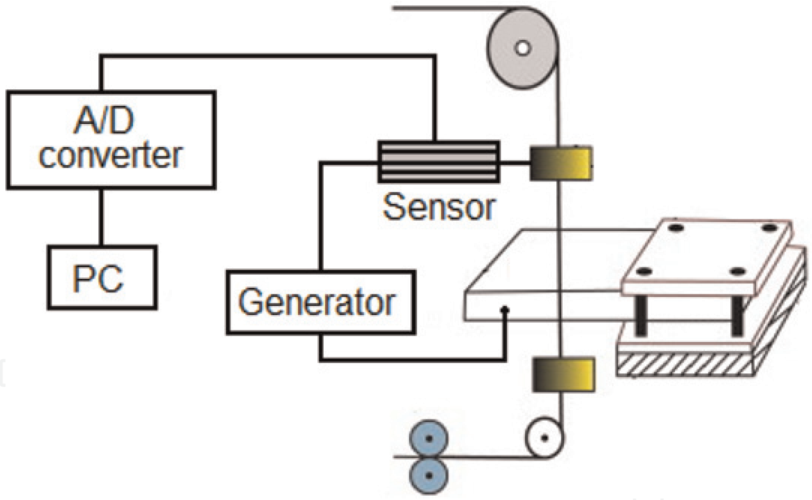

Figure 15.
The principle of indirect measurement of the vibration amplitude of a wire tool electrode during the electroerosion process.

its tension force, and many other parameters. Therefore, the critical frequency of generated electrical discharges during WEDM cannot be implicitly determined.

Since the critical frequency of vibration of the wire tool electrode during the electroerosion process cannot be implicitly determined, the only way to identify it is to monitor the magnitude of the vibration amplitude of the tool electrode It is possible to apply a number of methods to continuously measure the magnitude of the vibration amplitude of a wire electrode during the electroerosion process. Each of these methods has a number of advantages, but also disadvantages. One suitable indirect method for measuring the vibration amplitude of a wire electrode during an electroerosion process that is also applicable to electroerosion machines is the method of acoustic emission signals. Its value can be accurately determined in practice using suitable sensors (**Figure 15**).

An indirect measurement of the vibration amplitude of the tool electrode during WEDM requires a separate approach, since a thin wire is used as a tool in this machining method. The decisive factor in the indirect measurement of the vibration amplitude of the tool electrode is the appropriate positioning of the sensors. Barot et al. [33] research has been conducted in this area who presented a contactless indirect method of measuring the amplitude of the tool electrode vibration by acoustic emission (AE). This is based on comparing the relative intensities of the electromagnetic discharge signals measured by the Hall sensors. However, this method has its limitations because of the need for a magnetic field concentrator to compensate for exponential signal attenuation. At the same time, it requires complicated processing of high frequency electromagnetic signals, which is additionally to be obtained at speeds of up to 30 MHz. Another type of indirect measurement of vibration amplitude of the tool electrode was applied by Okada et al. [34]. The high accuracy of the measurement of the given parameter was achieved by distributing the discharge energy in the wire electrode during WEDM together with direct high-speed digital monitoring of the working gap size. However, this measurement method is only applicable in laboratory conditions. Its application in real electroerosion machine conditions during production is very complicated and therefore impractical.

A special concept of indirect measurement of the vibration amplitude of the tool electrode was performed by Kozochkin et al. [35], and Mahardika et al. [36]. Measurement of the vibration amplitude of the tool electrode was performed by induced discharge with respect to the velocity of the acoustic wave propagated in the machined material (**Figure 16**).

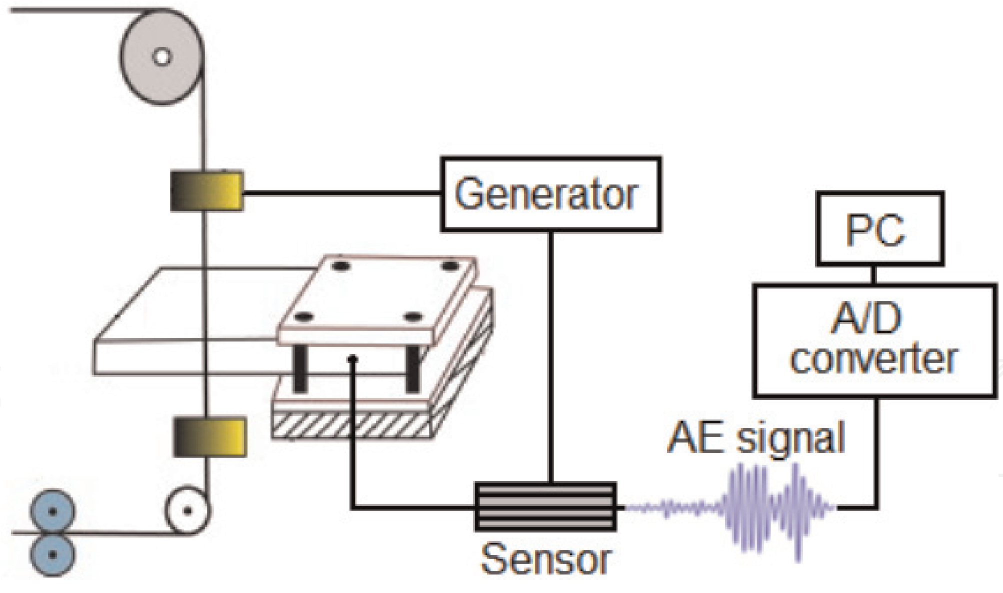

Figure 16.
Measuring the vibration amplitude of the tool electrode by means of an acoustic wave propagating in the machined material.

Smith and Koshy [37] in this indirect method of measuring the amplitude of the tool electrode vibration, they used sensors with a resonance frequency of 20 MHz. However, the measurements performed have shown that this method is only suitable for individual isolated electrical discharges. However, for cyclically repeated discharges, the acoustic waves overlap each other. This results in an unreliable estimate of time delays, which is again impractical for real operation under electroerosion machine conditions.

Another suitable method for indirectly measuring the vibration amplitude of a tool electrode during WEDM appears to be a method of measuring acoustic emission propagating in a tool wire electrode. **Figure 17** demonstrates the appropriate location of the sensors to measure the AE propagated in the tool during WEDM.

The sensors AE may be disposed at one of the ends of the wire tool electrode near the guide rollers or on both at the same time. Since there are cases during

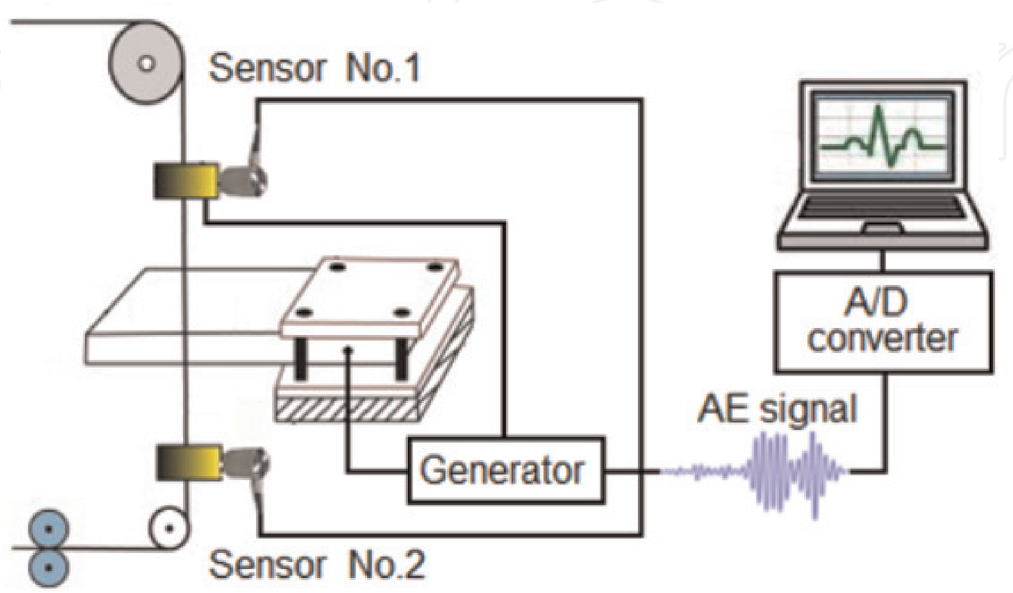

Figure 17.
Measuring the amplitude of the vibration of the tool wire electrode through an acoustic wave propagating in the tool during WEDM.

electrical discharge machining, where the amplitude of the vibration of the wire electrode at one of its ends is slightly increased due to the high thickness of the material being machined or the specific values of the electric discharge parameter settings, it is preferable to install sensors at both the top and bottom of the lead electrode. In a case of only one sensor is applied either at the top or bottom of the wire lead, we could observe distorted values. In this indirect measurement method, electromagnetic interference (EMI) overlap may occur in some cases with the AE signals being sensed. However, this is not a disturbing element in this case, since in both cases it is essentially a noise.

As the decisive criterion for the validity of the recorded data is the location of the sensors, it is necessary to consider the alternative of the AE combination of sensors for the complexity of the solution. In addition, if some research points to some of the advantages of locating the sensors on the wire electrode guide, other on the machined material. In **Figure 18**, a combined way of positioning sensors for AE measurement can be seen. Sensor no. 1 is located on an electroerosion machine in the region of the upper guide of the tool electrode. Sensor no. 2 is located on the workpiece.

However, based on the results of several researches, it was shown that sensor no. 1 placed in the upper guide electrode guide area, indicated more reliable results, as sensor no. 2 placed on the workpiece. At the same time, it is preferable to install AE sensors in the area of the wire tool electrode in terms of practical application. If the AE sensor is located on the workpiece, it must always be re-installed after each workpiece positioning.

However, based on the results of several researches, it was shown that sensor no. 1 placed in the upper conduction of electrode area, indicated more reliable results, as sensor no. 2 placed on the workpiece. These systems allow relatively effective determination of the optimal parameters of the electroerosion process with respect to the required quality of the machined surface. The design of the adaptive control system is implemented based on the principle of self-organization using methods and elements of artificial intelligence. **Figure 19** shows a schematic diagram of the connection of AE sensors to an adaptive electroerosion machine that will eliminate unwanted tool electrode vibrations during WEDM.

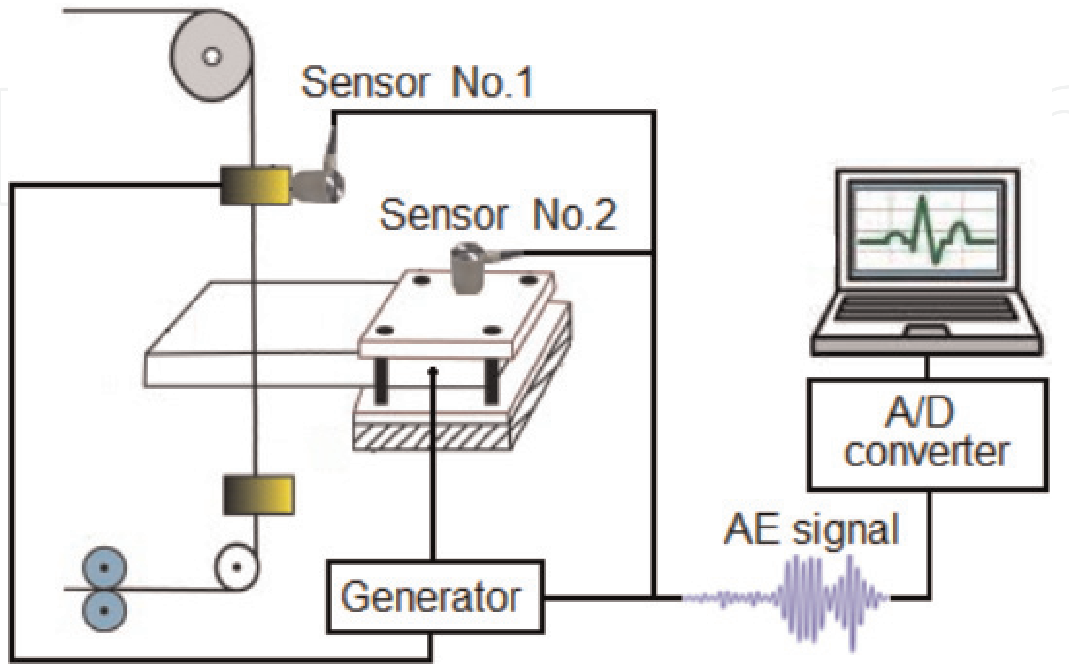

Figure 18.
Method of combined positioning of sensors for measuring AE during WEDM.

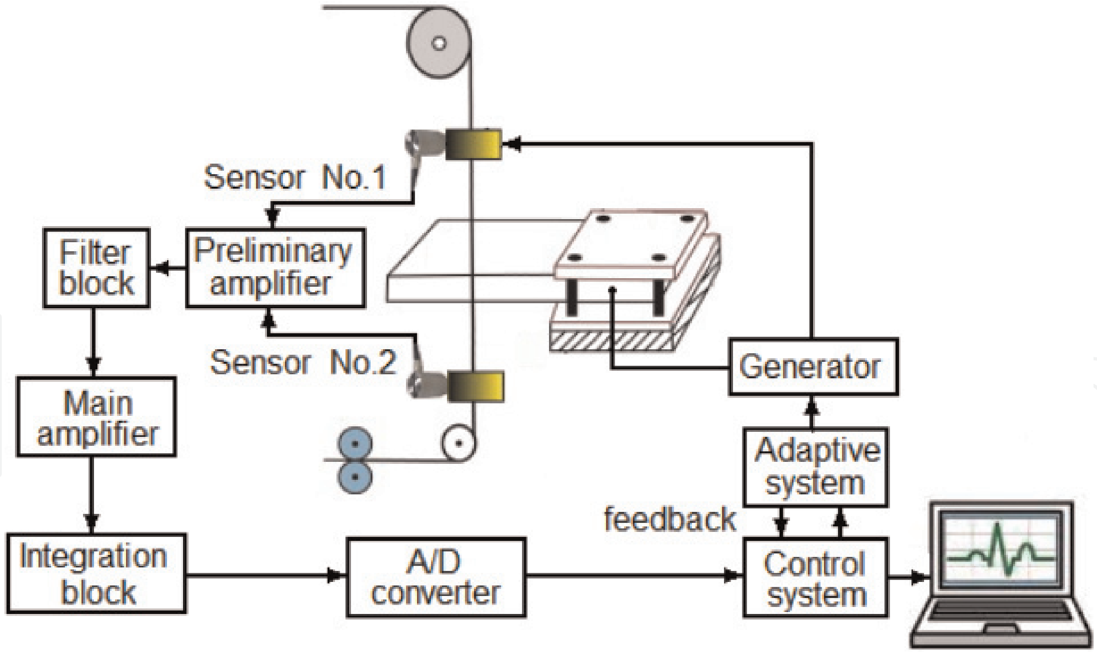

Figure 19.
Principal block diagram of the proposed adaptive system to eliminate unwanted vibrations of the wire tool electrode during WEDM.

The signals received from the AE sensors will be transmitted to the ACD converter. Subsequently, the modified information will be imported into the control system of the electroerosion machine. Based on this input information, it adjusts the electrical discharge parameters by increasing or decreasing their frequency and intensity to minimize unwanted tool electrode vibration.

At the same time, the characteristic feature of the adaptive system for controlling the frequency and intensity of electric discharge during WEDM is the possibility of using optimization techniques based on process algorithms. It is appropriate to apply algorithms that guarantee high convergence in the process of identifying the optimum. To ensure the ideal functionality of the control system of generated electrical pulses, there is a need for a mechanism to be implemented in the system to enable the desired selection of the optimization criterion. This means that in real operation would be possible to choose a priority optimization criteria focused on achieving high quality machined surface, high productivity electroerosion process, high efficiency electroerosion process, eventually their combination. To do this, an expert system based on a large information database is needed. Its suitable connection with the CNC control system of the electroerosion machine would enable efficient operation not only in serial but also piece production.

8. Conclusion

The aim of the book chapter "Intelligent control system of generated electrical pulses at discharge machining" is to provide a comprehensive set of knowledge in the field of intelligent control of generated electrical impulses for WEDM. As is generally known, generated electrical impulses with inappropriate parameters have a negative impact not only on the quality of the machined surface but also on the overall efficiency of the electroerosion process. In addition, since many input parameters change during WEDM, the electroerosion process may become unstable at any time. However, by integrating state-of-the-art monitoring and adaptive control technologies in the field of electroerosion process, not only process stability and performance, but also the quality of the machined surface can be substantially increased. The application of an intelligent control system for generated electrical pulses during WEDM based on electrical discharge input information can effectively prevent the occurrence of an unstable condition or stop the electroerosion process. Although a large number of input factors enter the electroerosion process, the implementation of an intelligent control system for generated electrical pulses is possible through electronic signals. In the case of electroerosion equipment normally produced, the electric discharges generated are controlled on the basis of actual conditions in the working gap. The control system of a traditional CNC electroerosion machine adjusts the performance characteristics of the pulse generator by measuring the average values of electrical voltage and current in the working gap according to predetermined reference values. However, in order to meet the demanding criteria imposed on the quality of the machined surface in terms of achieved geometric accuracy, monitoring of only the mentioned parameters is insufficient. Therefore, the book chapter highlights the importance of monitoring in addition to the established process characteristics such as voltage and current, or the size of the working gap, and the importance of monitoring other process characteristics. Due to the existence of deficiencies reflecting the lack of geometric accuracy of the machined surface, a phenomenon has been identified that causes the poor quality. It is a tool electrode vibration. Although modern electroerosion machines are equipped with algorithms that can to some extent eliminate this unwanted phenomenon, but not at a level that completely eliminates it. Since it has been shown, based on the results of several studies, that the maximum variation in flatness of the machined surface is largely due to the maximum amplitude of vibration of the tool electrode, it is necessary to look for ways to eliminate it. Based on the results of experimental research, it has also been demonstrated that the maximum vibration amplitude of the wire tool electrode is achieved with a specific combination of several factors. However, these cannot be precisely determined. The only solution for identifying its size is to apply one of the measurement methods. The book chapter describes in detail the indirect method of measuring the amplitude of the tool electrode vibration through AE. At the same time it describes possible ways of installing sensors, as well as structure of interconnection of individual components of proposed system. A characteristic feature of the proposed intelligent control system performance parameters of electric discharge during WEDM is its flexibility and openness to the real conditions of practice. Based on an extensive database of information, as well as a rapid and precise exchange of information with an external environment, the system will enable the electroerosion process to be managed with respect to the optimum operation of the electroerosive device according to the individually selected optimization criteria.

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Conflict of interest

The authors declare no conflicts of interests.

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