Modern trends in the development of electrical discharge machining

P Kuchta¹, L Straka¹, J Zajac¹ and S Radchenko¹

¹Technical University of Kosice, Faculty of Manufacturing Technologies with a seat in Presov, Bayerova 1, 08001 Presov, Slovakia

Corresponding author: luboslav.straka@tuke.sk

Abstract. The current time is characterized by the rapid development of modern production methods. These modern production methods are in many cases closely linked to progressive production methods, including EDM. The required high productivity and product quality is the reason for using such production methods. In addition to flawless production processes and highly sophisticated production equipment, these requirements can only be met using high-quality production tools. This paper, therefore, aims to describe the results of the analysis of current approaches in the field of modern trends in the development of electrical discharge machining, closely focusing on the development of control systems for generating electrical impulses in connection with the development of advanced tool electrodes. The performed analysis is also supplemented by the definition of mutual relations between selected properties of wire tool electrodes, their cutting power, and the achieved quality of the machined surface after electrical discharge machining. This should significantly help in increasing the quality level of the machined surface during wire electrical discharge machining and at the same time higher productivity of the electroerosive process. This will make this technology more competitive compared to other advanced technologies.

1. Introduction
The development of modern wire electrodes, which enable the achievement of a higher cutting speed and at the same time a higher quality of the machined surface, also required the development of modern control systems [1]. The original control systems of the generated electrical pulses allowed to generate only very short discharges, while the discharge duration was at the level of $10^{-4} - 10^{-7}$. The connection of the workpiece as an anode and the tool electrode as a cathode was required. This connection method was used mainly due to the need for lesser material decrements from the tool electrode during the electroerosive process compared to the loss of material from the workpiece [2]. Using a DC power supply in a given circuit, the ions were shifted in only one direction with a limited possibility of regulating the shape and frequency of the discharges. This resulted in reduced machining productivity [3] and at the same time comparatively high relative wear of the tool electrode. Therefore, in light of the current demands for increasing the quality and productivity of electrical discharge machining, this method of controlling the generated electrical pulses was insufficient [4,5].

2. Analysis of the current state in the development of control systems for EDM equipment
Nowadays, the trend is focused on modern control systems, which differ from the previous ones in many ways [6]. The most striking difference is the principle of control of generated electrical
impulses, which is supported by measuring the effective voltage in the working gap. Unlike their former predecessors, these types of control systems do not measure the effective voltage in the working gap but the duration of each electric shock separately. These times are then added up and, based on their total value, the magnitude of the electric discharge intensity is subsequently regulated. The speed of movement of the individual portals must also be adapted to the magnitude of the intensity of the electric discharge \[7\]. The reaction time and the speed of movement of the individual portals via the servo drives must correspond to the conditions in the discharge gap. The following Fig. 1 shows a method of controlling electrical impulses during electrical discharge machining by an older and modern control system.

![Figure 1](image1.png)

**a) Old control system**

**b) Modern control system**

*Figure 1. Control systems for electrical impulses during EDM*

In the figures presented above, a difference in the resulting quality of the machined surface can be observed. The application of the modern control system according to Fig. 1b, in which the electrical pulses are controlled based on the monitoring of the duration of the individual discharge cycles with the support of information about the efficiency of the separate electric discharge, resulted in much higher quality of the machined surface \[8,9\] in comparison with the previous control system according to Fig. 1a, in which the electrical pulses have been controlled based on monitoring the duration of the individual discharge cycles by monitoring the effective voltage in the discharge gap. In this context, we understand the quality of the machined surface in terms of surface roughness \[10,11\] and its geometric accuracy \[12,13\].

In addition to the above-mentioned system of control of generated electrical impulses in modern technical practice, in recent years control systems that enable the generation of alternating electrical impulses have also come to the forefront. Using these control systems, a significantly narrower gap can be achieved, which is advantageous in low-waste machining \[14\]. With this machining method, both parts of the product \[15\] can be produced simultaneously. In this way, for example with regard to cutting tools, it is possible to produce both parts of the cutting tool simultaneously from one block of material.

![Figure 2](image2.png)

*Figure 2. Manufacturing of both parts of the tool by low-waste machining [16]*
The control systems, in which an electrical voltage of the same polarity is applied between the tool electrode and the workpiece are also coming to the forefront [17]. In these control systems of generated electrical pulses, the ion passes in only one direction [18]. However, the main drawback of applying these control systems is the increased risk of corrosion on the top of the eroded surface during electrical discharge machining. Luckily, based on the latest experimental research, it has been shown that if the control system for generating electrical pulses allows the polarity of the voltage to change with a certain frequency, this undesirable effect of corrosion of the machined surface can be eliminated relatively effectively. Simultaneously, by the given management of the generated electrical pulses, the heat-affected zone of the machined surface is demonstrably reduced [19]. These types of generated electrical pulse control systems allow a wide range of settings of the parameters of the electric discharges [20], while the frequency range of the electric discharges can be varied in the range of 0.5 to 50 kHz. Its application can also significantly reduce the range of corrosive effects that occur during the electro-erosive process. The following Fig. 3 shows a basic diagram of the mentioned electrical pulse generation control system.

![Figure 3](image-url)

**Figure 3.** Scheme of a modern control system for generated electrical impulses during electrical discharge machining

However, in the current modern technical practice, there are many cases where the mentioned methods of control of generated electrical impulses are insufficient in terms of the achieved quality level of the machined surface after WEDM [21]. For these cases, one of the possibilities is an advanced and very sophisticated modification of the control system of generated electrical impulses. Notwithstanding, it should be emphasized that at present, most cases include experimental devices in which the traditionally used systems of control of generated electrical impulses during the electro-erosive process undergo a substantial intervention. Another reason for the need to use these innovative methods of controlling the generated electrical impulses during the electro-erosive process is, in addition to achieving a high quality of the machined surface [22,23] in terms of roughness [24] and geometric accuracy [25], to constantly increase the performance of the electro-erosive process. These objectives can only be achieved through the synergy of the application of highly sophisticated adaptive control systems with the active support of online monitoring systems [26].
Figure 4. Adaptive control of generated electrical pulses during WEDM with the active support of the online monitoring system

The main disadvantage of current approaches to controlling generated electrical pulses is the fact [27] that they are controlled only based on the information about the current value of the parameters of the electric discharge [28]. Of these, the magnitude of the voltage, current and working gap is monitored. However, even in these modern electrical discharge devices, the control of the generated electrical impulses does not take into account all the phenomena that occur in the working gap. One of the consequences is, for example, the formation of vibrations of the wire tool electrode, which negatively affect especially the geometric accuracy of the machined surface after WEDM [29]. A certain solution is applying an adaptive electrical pulse control system with the support of one of the indirect methods of measuring selected indicators of the current state of the wire tool electrode [30]. With the support of at least one of the monitored parameters of the wire tool electrode during WEDM in the form of an input parameter to the process of controlling the generated electric discharges, it is possible to achieve a substantial increase not only of the machined surface quality but also of the overall productivity of the electro-erosive process [31]. By monitoring other parameters that characterize the state of the wire tool electrode, a substantial increase in the level of intelligent adaptive control of the EDM process can also be achieved [32]. By applying a given adaptive control system of generated electrical pulses, it is possible to relatively successfully eliminate the occurrence of undesired electrical discharges, which, for example, increase the amplitude of the oscillation of the wire electrode. This information is very valuable because it allows a strategy application of adaptive control of electric discharges, and thus eliminates the adverse impact of improper setting of electric discharge parameters. As a result of putting this system into practice, an increase in the stability of the electro-erosive process, an increase in productivity, but above all a substantial improvement in the quality of the machined surface in terms of its geometric accuracy is achieved.

3. Analysis of the current state in the area of applying modern wire tool electrodes for the needs of electrical discharge machining

As mentioned above, the development of modern wire tool electrodes is closely related to the development of modern control systems [33]. In order to achieve a high quality of the machined surface after WEDM, especially in terms of its roughness and geometric accuracy, it is necessary to ensure precise guidance of the wire tool electrode at all times [34]. To meet this most important condition concerning the guidance of the wire tool electrode [35], it is crucial to tension it with a suitable force $F_w$ (N). This is standardly selected in the range of 5 to 25N. Furthermore, it is important to charge the tool electrode with electrical impulses, wrap it with a coat of dielectric fluid and constantly renew it because of its wear. Enabling the movement of such a delicate and unstable tool as a few tenths of a millimeter thin wire electrode demands very precise and sensitive guides. (Fig. 5)
Figure 5. System of precise guidance of a wire tool electrode on an electrical discharge machine

The system of precise guidance of the wire tool electrode on the electrical discharge machine is there to ensure that it does not deviate from the desired position during the electro-erosive process [36]. Its deviation during WEDM is mainly due to the cyclic action of electric discharges that occur between the tool and the workpiece (Fig. 6).

Figure 6. Deviation of the wire tool electrode due to the cyclic action of electric discharges during WEDM

Partial compensation for this adverse phenomenon can be done by applying special measures [37]. One suitable measure is to include a counterforce in combination with a system that ensures optimal tension of the wire tool electrode. Still, this measure does not have a completely satisfactory effect. Even though a higher value of the compensating force of the wire tool electrode has a favorable effect on reducing its vibrations and narrowing the working gap, there is a risk of frequent destruction. Wire tool electrodes with strength in the range of 400 to 2000 N.mm² are used as standard in technical practice, while the lower value is typical for the so-called soft electrodes, the mean value for so-called semi-hard electrodes, and the upper value is typical for the so-called hard electrodes. The following figure 7 demonstrates the behavior of individual types (soft, semi-hard, and hard) of wire tool electrodes during the electro-erosive process.
As already mentioned above, by including a higher compensating force $F_w$ of the tension of the wire tool electrode, a partial improvement of the geometric accuracy of the machined surface can be achieved, however, the productivity of the electro-erosive process is reduced at some point, which, naturally, is not the desired effect [38]. The following Fig. 8 demonstrates the impact of the magnitude of the compensating force $F_w$ of the wire tool electrode tension on the quality of the machined surface and the cutting power of the electro-erosive process.

![Figure 7. Bending character of individual types (soft, semi-hard, and hard) of wire tool electrodes during the electro-erosive process.](image)

**Figure 7.** Bending character of individual types (soft, semi-hard, and hard) of wire tool electrodes during the electro-erosive process.

An important factor that has a significant impact on the quality of the machined surface after WEDM is the material composition of the wire tool electrodes. The material properties include mainly electrical conductivity, which determines the sufficient magnitude of the transmitted current to the spark gap. The wire electrode is heated due to the discharge energy, which has a positive effect on increasing the cutting speed [39]. If the electrical conductivity of the wire tool electrode is not
sufficient, it would lead to a drop in the spark gap. This is consequently related to the decrease in discharge energy and the associated insufficient melting of the machined material. A no less important property of the wire tool electrode material is its melting temperature. Its high value guarantees adequate resistance to melt due to electric discharges, which again contributes to achieving higher cutting power. Another relevant factor that has a significant impact on the quality of the machined surface after WEDM is the composition of the wire tool electrodes. In the past, one-component compact wire tool electrodes have been used predominantly for WEDM, with standard materials used such as Cu, Ms, Mo, and others. The advantage of a wire tool electrode made of pure copper is low decrements of discharge energy. However, the disadvantage is the low tensile strength, which negatively affects the geometric accuracy of the cut. Therefore, these wire electrodes are no longer used and were later replaced by brass wire electrodes. It has been shown that the presence of Zn in the alloy of the wire tool electrode material significantly reduces the risk of its rupture. This allows the application of higher values of the compensating force $F_w$. Aluminum brass also appears to be a suitable material for the production of tool wire electrodes. This material is characterized by the tensile strength of the material at the level of 1200 N.mm$^{-2}$, without the presence of adverse effects on its elongation. Although these types of tool electrode materials are less susceptible to damage, their practical applicability is relatively limited [40]. For special purposes, it is customary in technical practice to use wire tool electrodes with the base made of Mo. These are mainly used in cases where a very high tensile strength and at the same time a very small wire diameter are required. In addition to a high value of tensile strength, this material also has a high melting point. However, a significant disadvantage of the practical application of these wire tool electrodes for common use is their high cost. Wire tool electrodes made of tungsten have even greater tensile strength. These electrodes allow the application of relatively high compensating forces for tensioning the wire tool electrode, thus achieving a very high geometric accuracy of the machined surface. Due to their high cost, they are applicable only for very small diameters of wire tool electrodes (≤0.05mm).

Therefore, in the current modern production, which requires high accuracy of the machined surface, the use of one-component compact wire tool electrodes loses its application. Consequently, coated wire tool electrodes are gradually being introduced into production, meeting all the conditions imposed by the current modern production. They are essentially used when high geometric accuracy of the machined surface is required. The simplest of these is a multi-component wire tool electrode, the core of which consists of Cu, Ms, or steel, and the surface being formed by a thin layer of pure Zn or Ms containing 50% zinc. In the following Fig. 9, selected compositions of coated wire tool electrodes used in current modern production are shown.

![Figure 9. Composition of modern types of coated wire tool electrodes used in electrical discharge machining](image-url)
The composition of modern types of coated wire tool electrodes used in electrical discharge machining makes it possible to combine commonly used materials that have a low cost with the materials that have specific properties but cost a lot. However, the effectiveness of these coated wire tool electrodes is limited [41]. The limiting factor is the thickness of the coated layer, which normally ranges from 5 to 10 μm. At lower thicknesses of the Zn coating, it falls off. Greater Zn coating thickness can be achieved by diffusion annealing, which ensures that the atoms reach lower concentration sites. Unfortunately, the higher thickness of the coated layer disproportionately increases its cost. For special cases, composite three-component wire tool electrodes are used. The core of these electrodes is made of steel wire, which is characterized by high strength. The other layers consist of copper and brass with a 50% Zn content. These three-component wire tool electrodes are characterized by specific properties, the main advantage of which is the use of very high compensating forces $F_w$ while maintaining high productivity of the electro-erosive process. Yet, the problem is its high price. A special group of wire tool electrodes is represented by gamma-coated wires. These electrodes are characterized by a high Zn content, while the surface is very brittle. The Zn surface layer is only a few micrometers thick and not continuous, but slightly cracked. This allows achieving a higher cutting speed. The disadvantage of these wire tool electrodes is the small contamination of the machined surface and again the high investment costs [42]. In light of the above, it is therefore clear that significant progress has been made in the field of EDM in recent years, but there is still large room for further improvement, especially in the area related to increasing the cutting speed as well as the overall efficiency of the EDM process.

4. Conclusions
Although extraordinary successes have been recorded in the field of electrical discharge machining with a wire tool electrode in recent years, not all customer requirements regarding the achieved quality of the machined surface are always 100% satisfied. These successes have been noted particularly in the development of control systems for generating electrical impulses. Other significant advances have been made in the development of wire tool electrodes. The new approaches in the development of control systems for generating electrical impulses in combination with modern wire electrodes provide a suitable basis for achieving a high quality of the machined surface both in terms of its roughness and geometric accuracy. However, there is still some scope for achieving an even higher quality of the machined surface in terms of these parameters. Therefore, our future research will be focused on the development of new wire tool electrodes with a unique composite composition. At the same time, their development will be based on proposals for solutions of highly sophisticated control systems. They should meet even the most demanding requirements for the quality of the machined surface after WEDM. In addition, our future research will also focus on achieving higher cutting speeds. This will make it possible to achieve a significantly higher overall efficiency of the electroerosive process. When we meet all the set goals, WEDM technology will become comprehensively competitive.

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