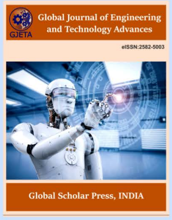
Global Journal of Engineering and Technology Advances

eISSN: 2582-5003

Cross Ref DOI: 10.30574/gjeta

Journal homepage: https://gjeta.com/



(REVIEW ARTICLE)

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Wire electrical discharge machining technology from the perspective of geometric accuracy, cut surface quality and electrode wear

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Global Journal of Engineering and Technology Advances, 2026, 26(02), 098-113

Publication history: Received on 09 January 2026; revised on 15 February 2026; accepted on 18 February 2026

Article DOI: https://doi.org/10.30574/gjeta.2026.26.2.0042

Abstract

The article summarizes wire electrical discharge machining (WEDM) with a focus on the process principle, quality factors, and the development of wire electrodes. It is a non-contact machining method for conductive, hard-to-machine materials using controlled pulsed arcing in deionized water; accuracy and surface quality are determined by thermo-electrodynamic phenomena, pulse settings, flushing, and cooling. Multiple passes with lower energy improve roughness, geometrical accuracy, and surface integrity.

The text further analyzes the influence of parameters on kerf width and corner accuracy, including arcing gap phenomena (energy, gap size, hydraulic/electrostatic/electromagnetic forces) that affect material removal, wire deformation, and stability. It identifies sources of corner defects (wire bending, field reinforcement, loading variations) and provides strategies for their reduction: trajectory compensation, adaptive feed and pulse adjustments, wire tension and flushing control, sensor-based monitoring, and multi-stage finishing. A key role is played by the wire electrode (material, diameter, coating, strength), with a trend from copper and brass toward coated and multi-layered wires with higher performance, which increases productivity and reduces costs.

Keywords: WEDM; Geometric accuracy; Electrode; Wear; Cut quality

1. Introduction

Wire electrical discharge machining (WEDM) is today one of the key unconventional machining processes. It enables efficient fabrication of parts from advanced and hard-to-machine materials, such as metal-matrix composites (MMC), superalloys, titanium composites, or polycrystalline diamond (PCD). Since the late 1960s, its market share has steadily grown, especially in the aerospace, nuclear, and automotive industries, where high precision and complex shapes are required [1].

Electrical discharge machining is a non-contact material removal method for electrically conductive materials using repeated electrical discharges between two electrodes in a dielectric, with the workpiece forming one electrode and the tool the other. It encompasses electrical-discharge machining (EDM Sinking), wire cutting (WEDM), and electrical discharge grinding (EDG). Unlike chip machining, there is no direct contact between the tool and the workpiece, and therefore no cutting forces [2]. Material is removed by melting and vaporization of micro-particles that are flushed away by the dielectric fluid from the inter-electrode gap [3, 4].

The physical principle of EDM involves converting electrical energy into heat in the form of controlled discharges. The process can be divided into several stages: polarization and the formation of a strong electric field in the dielectric,

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separation of positive and negative charges during a rapid current rise, creation of a plasma channel, temperature rise to about 4,000–12,000 °C, melting and partial vaporization of material, and finally particle detachment and crater formation, with larger craters forming on the anode. These specific physical-mechanical material-removal mechanisms predispose electrical discharge machining, and especially WEDM, for use in situations where conventional chip-making technologies fail or are economically inefficient [5, 6].

2. Technology of WEDM

The basic principle of wire electrical discharge machining (WEDM) is very similar to the conventional EDM process. In WEDM, material is removed by a series of electric discharges that occur between a precisely guided moving wire and the workpiece. High-frequency pulses generate sparks in a narrow spark gap between the wire and the workpiece, which is filled with dielectric liquid – deionized water. The heat released by these discharges causes melting and, to some extent, vaporization of a small volume of material from the surface of the workpiece. At the same time, the wire itself undergoes gradual wear. Released material and wire particles are flushed away from the cutting space by the flow of deionized water, supplied at high pressure through the upper and lower flushing nozzles. The basic schematic of the WEDM technology is shown in Fig. 1 [7].

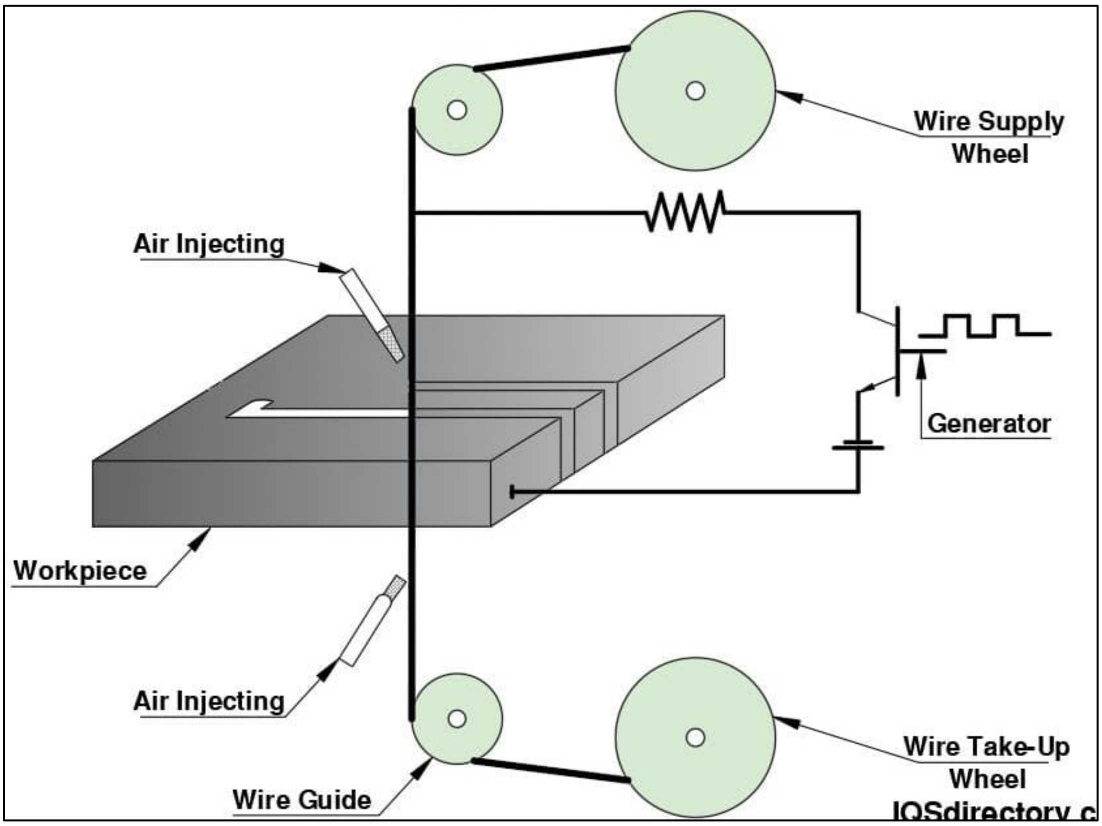

Figure 1 Basic schematic of WEDM technology [7]

Electrical discharge wire cutting is a method intended for machining electrically conductive materials using precisely controlled spark discharges occurring between the electrode and the workpiece in a liquid dielectric. It represents a specific variant of electrical discharge machining (EDM). While conventional EDM uses the tip (front surface) of a shaped electrode to gouge cavities, in WEDM the electrode is a continuous wire, and sparking occurs between its side surface and the workpiece. The material removal mechanism itself is, however, fundamentally the same in both EDM and WEDM [8].

Unlike conventional milling, electrical discharge cutting does not require direct mechanical contact between the electrode and the workpiece. The electrode is separated from the workpiece by a small gap, the so-called spark gap, which is essential for spark initiation. Typically, only one spark forms at a given moment, although the sparking frequency ranges from about 2,000 to 500,000 discharges per second, which may give the impression of multiple sparks occurring simultaneously [8].

The discharge between the cathode and the anode is created by a direct-current voltage applied in the form of short pulses to a circuit with resistance R and capacitor C, known as a Lazarenko RC circuit. The distance between electrodes required to initiate the discharge is usually in the range of 0.01 to 0.4 mm. Under ideal conditions, each voltage pulse will elicit a spark discharge, during which a brief, highly intense concentration of electrical and mechanical energy of electrons occurs at the anode. In the immediate vicinity of the discharge, an extremely high temperature is generated, causing melting and possibly vaporization of a portion of the metal from both the anode and the cathode surfaces. Due to the temperature field, electrodynamic forces, and internal stresses, the melted metal is ejected into the surrounding dielectric, creating a characteristic crater at the discharge site [9].

In terms of the quality of the machined surface of the part and its dimensional and geometric accuracy, the most significant influence is exerted by the pulse generator, which controls the time course of the electrical discharge, characterized by the following parameters:

- Pulse duration,
- Pause duration,
- Discharge ignition delay time,
- Discharge duration,
- Period time,
- Open-circuit voltage,
- Discharge working current,
- Average discharge current,
- Average discharge voltage,
- Discharge extinction voltage.

Traditional machining processes (turning, drilling, milling, etc.) remove material by chip formation, abrasive machining, or micro-cutting; however, for advanced materials they are often uneconomical or unsuitable. This is mainly due to the high hardness and strength of these materials, which causes rapid tool wear in conventional machining [1].

Wire electrical discharge machining (WEDM) has therefore gained a significant position in manufacturing engineering, especially for machining hard and electrically conductive materials. The main advantages include: non-contact machining of very hard materials (without direct cutting forces), more stable “tool” geometry thanks to continuously fed wire, high accuracy and surface quality under CNC control, and the ability to cut very complex shapes (Fig. 2), including small internal radii [10].

The disadvantages of WEDM include the inability to machine non-conductive materials, the need for a dielectric during the process, lower productivity on softer materials, workpiece size requirements for clamping, higher initial investment, and a trade-off between productivity and surface quality [10].

WEDM has broad industrial applications: manufacturing punches and parts of shearing/stamping tools, precision gauges (templates, standards, gear gauges), small components (e.g., for pacemakers and watchmaking), production of graphite/copper electrodes for EDM, and components for the electrical, aerospace, and medical industries, confirming its flexibility in modern manufacturing [11, 12].

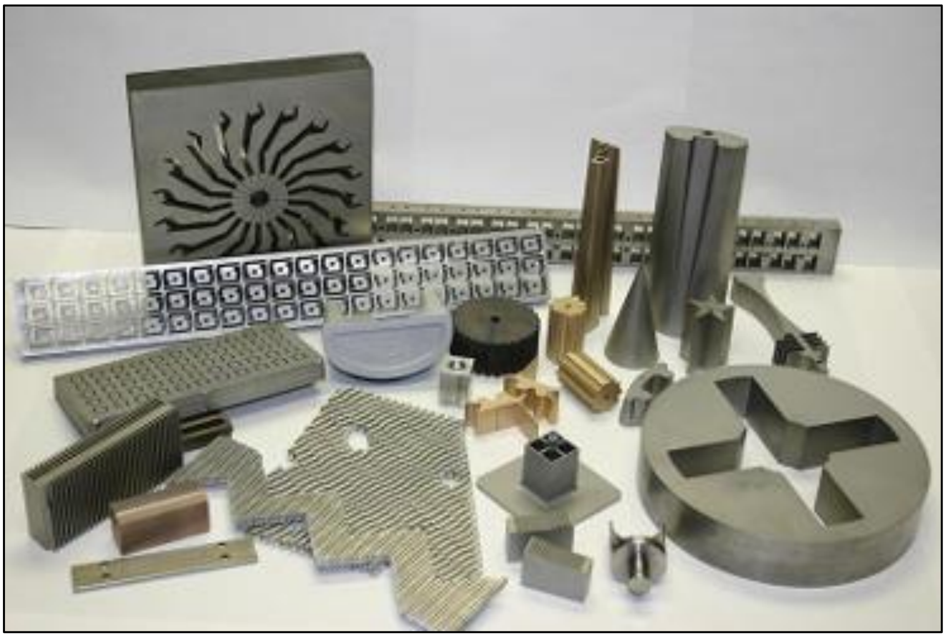

Figure 2 Example of various components manufactured using WEDM technology [13]

3. Tool electrode and its wear

The development of wire manufacturing technology for WEDM has led to the emergence of a wide range of materials and design types, each with specific properties and an optimal area of application. The correct choice of wire is crucial for stable and efficient operation, especially when machining with large taper angles, thicker workpieces, automatic wire threading, and long-term unattended machine operation [1].

3.1. Materials of wire electrodes used for manufacturing by WEDM

Historically, the development of EDM wire electrodes can be divided into two main stages: the transition from pure copper to brass wires, and subsequently from brass wires to modern coated and multilayer electrodes. In the early 1970s, mainly pure copper wire was used, but it did not provide sufficient strength or accuracy. In the second half of the 1970s, it was replaced by brass wires. Around 1980, zinc-coated copper wires were introduced for high-speed cutting, and shortly thereafter zinc-coated brass wire electrodes intended for high-precision cutting. Later, core materials made of stainless steel coated with copper appeared. By increasing the zinc content and adding elements such as titanium and aluminum to brass wires, new types of electrodes were developed with higher thermal resistance and higher cutting speed, especially for thick workpieces. Today, brass wires are commonly used, while demand is growing for high-performance types—coated, composite, and diffusion-annealed wires with high conductivity and good sparking capability. These are mostly zinc-coated wires with a core made of copper and brass alloys or steel; the brass may contain small amounts of chromium or a high zinc content [1].

The machining capability of a wire electrode depends on its electrical, physical, mechanical, and geometric properties, as well as on the setting of process parameters (cooling, pulse duration, cutting speeds). The quality of the resulting surface is directly influenced by the wire's properties. Above all, the electrode must have good electrical conductivity and sufficient tensile strength to reduce the risk of breakage during the process. Although the cost of the wire electrode accounts for approximately 10% of total manufacturing costs, the correct choice of wire material and type can significantly improve process efficiency and reduce overall costs [14].

From a geometric standpoint, the wire is characterized by its diameter, coating type, and internal layered structure. Typical diameters range from 0.05 to 0.3 mm, with 0.25 mm being the most common in industrial practice. In micro-WEDM, wires with diameters around 0.03 mm are also used. A larger wire diameter allows the transfer of higher pulse energy and thus a higher material removal rate [14].

Tensile strength and the modulus of elasticity are among the key mechanical properties. During machining, the wire must be sufficiently tensioned to prevent breakage or vibration. Wires with lower tensile strength are more suitable for angled and tapered cuts, whereas wires with higher strength are used in high-precision machining where minimal shape and positional deviation is required [14].

The material of the wire electrode (Fig. 3) fundamentally influences the behavior and performance of the WEDM process. Historically, the first material used was copper, which excels in electrical conductivity but has low tensile strength and a high melting temperature, which significantly limits its use. Today, copper wires are used practically only on older machines whose power supplies are specifically designed for copper wire [15].

The first real alternative was brass. Brass EDM wire is an alloy of copper and zinc, typically containing 63–65% Cu and 35–37% Zn. The presence of zinc increases vapor pressure, improves tensile strength, and lowers the melting point. During cutting, zinc evaporates, contributing to cooling of the wire while also increasing the energy transferred to the workpiece. The remaining zinc particles in the dielectric promote ionization in the spark gap. Thanks to these properties, brass has become the standard wire material for common WEDM applications and is available in various strength and hardness grades [13, 14].

The next step was the development of aluminum–brass alloys, where a small amount of Al in a composition of approximately 65Cu–33Zn–2Al makes it possible to achieve tensile strengths of up to about 1,200 MPa without a significant reduction in ductility. These wires are less prone to breakage compared with conventional brass wires [15, 16].

When high demands are placed on geometric accuracy, the mechanical and dynamic properties of the wire play an important role. During sparking, the wire is subjected to forces opposite to the cutting direction, together with electrostatic and electromagnetic effects, which cause deviations of the wire's actual position from the programmed path. This can lead, for example, to rounded corners instead of the desired sharp edges. To eliminate these problems, wires with very high tensile strength are used, such as molybdenum and tungsten (> 1,900 MPa). Due to their high cost and poor flushing characteristics, a high-strength pearlitic steel wire with C > 0.06% and a zinc coating without copper was developed, enabling higher mechanical loading and improved accuracy [16, 17].

Molybdenum wires are used in special applications where very small diameters (≈ 0.1 mm and below) and extremely high tensile strength are required. Their advantages are a high melting point and strength; their disadvantages include low electrical conductivity, very poor flushing, high cost, and significant abrasiveness toward power contacts and guiding elements. In addition, they cause problems during automatic wire threading [16, 17].

Tungsten wires are a more cost-effective alternative to molybdenum wires at diameters of 0.05 mm and smaller, while offering even higher tensile strength and a higher melting point. They make it possible to achieve very small internal radii (≈ 0.025–0.1 mm), where brass and coated wires are impractical due to their low load-bearing capacity. However, tungsten is not suitable for thick workpieces because of its limited electrical conductivity, high melting temperature, and lower cutting speed [16, 17].

A compromise between strength and flushing performance is the composite MolyCarb wire, in which a molybdenum core is coated with a layer of graphite and molybdenum oxide. This surface significantly improves flushing and makes the wire particularly suitable for very small diameters [16, 17].

In terms of surface finishing, coated WEDM wires are classified into single-layer, double-layer, multilayer, and diffusion-annealed coated wires, which combine the advantages of the core material and functional surface layers [18].

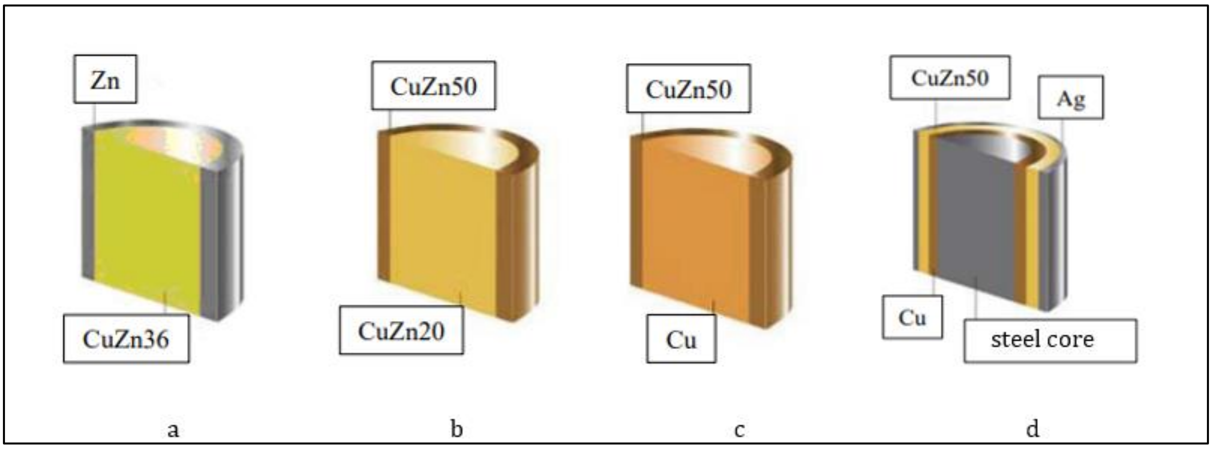

Figure 3 Different types of wire electrodes (a—brass core + zinc coating, b—brass core (20% zinc) + brass coating (50% zinc), c—copper core + brass coating (50% zinc), d—steel core + intermediate copper layer + brass (50% zinc) + silver) [19]

3.2. Electrode wear in WEDM

During electrical discharge machining, a plasma channel is formed between the tool and the workpiece, acting as a spatially confined, extremely intense heat source. Each discharge that removes material from the workpiece simultaneously causes wear of the tool electrode [9]. Electrons impinging on one electrode and positive ions on the other raise the surface temperature to such an extent that local melting and evaporation of material occur. The amount of material removed in this way is determined mainly by the polarity of the connection, the physical properties of the materials used, and the pulse parameters; mechanical properties play a much smaller role, so even soft materials such as brass can successfully machine significantly stronger materials [20, 21].

The main causes of electrode wear include a high concentration of incident electrons or positive ions, extremely high local temperatures, cavitation effects, mechanical abrasion by particles of eroded material, improperly selected operating conditions, and defects arising during electrode manufacture [3].

Relative volumetric wear is expressed as the ratio of the volume loss of the tool electrode to the volume loss of the workpiece. Ideally, depending on the nature of the operation (roughing vs. finishing), this value should remain below approximately 10%, with the aim of achieving the lowest possible wear, since in sinker EDM the cost of electrode manufacture can account for up to 50% of total machining costs [21].

4. Geometric accuracy of WEDM technology

During electrical discharge machining (EDM), very high temperatures are generated, causing significant metallurgical changes in the surface layer of the workpiece. As a result of rapid cooling, a characteristic surface layer with a thickness of approximately 10–40 μm is formed, while contamination by electrode material may extend to a depth of about 250 μm. The heat-affected zone can penetrate up to 400 μm in depth, where a heavily carburized layer with high hardness is created. At the same time, chemical reactions may occur, in particular the formation of carbides and oxides (Fig. 4b). Due to thermal cycles, residual tensile stresses develop in the surface layer, which can initiate microcracks and thus reduce the functional reliability and service life of components. In such cases, subsequent mechanical removal of the affected layer may be appropriate [9, 20].

The surface after EDM has a characteristic structure formed by randomly distributed craters (Fig. 4a). Their size and geometry depend on the properties of the workpiece material, the type of electrode used, the dielectric type, and the settings of the technological parameters. A finer, higher-quality surface layer is achieved by using short, high-frequency pulses. Any minor defect on the electrode is immediately reflected in the morphology of the machined surface, which has a typical matte appearance [9, 20].

Compared with conventional EDM, wire electrical discharge machining (WEDM) is a considerably more complex process, whose course and outcome strongly depend on a large number of technological parameters and control factors. The achievable accuracy is influenced mainly by the positioning accuracy of machine components, the stability of the wire feed system, and the effectiveness of dielectric flushing. Typical WEDM accuracy is approximately 0.2 μm [22, 23].

Surface quality depends on the size of the craters produced by individual sparks on the eroded surface. With an appropriate selection of process parameters, the surface roughness Ra can be improved to the range of 0.8–0.1 μm. Although after a single cut the geometric accuracy and surface roughness may be sufficient for many applications, WEDM makes it possible to achieve significantly higher accuracy by using multiple successive cuts—from a roughing cut to fine finishing. During these finishing passes, lower pulse energy is used, which leads to the formation of smaller craters and improves the resulting surface quality [22, 23].

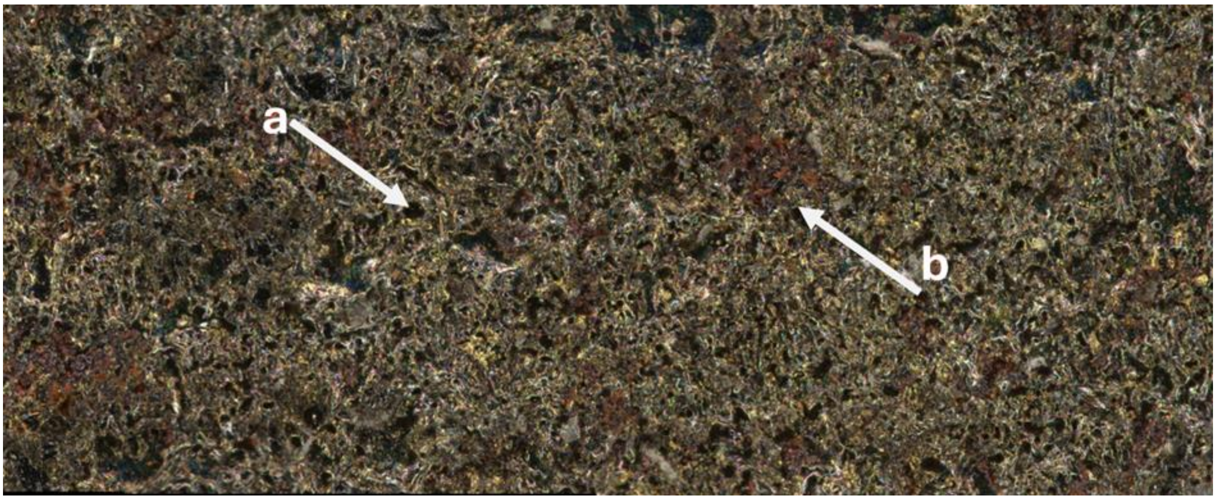

Figure 4 Surface layer of the material after WEDM machining (a—randomly distributed craters, b—formation of oxides, 500× magnification)

4.1. Kerf width

The wire electrode uses controlled, repeated electrical discharges to cut the workpiece. The workpiece moves along a prescribed path and maintains a constant distance from the wire electrode so that no contact occurs. This distance, called the spark gap, is influenced by various process parameters during WEDM. However, there is always a risk of a short circuit caused by contact between the workpiece and the wire, which may occur due to disturbances in a small spark gap during machining. A short circuit can cause wire breakage, which prevents further cutting and impairs machining accuracy. To maintain a stable process, the spark gap must be maintained; therefore, the kerf width is always slightly larger than the wire diameter. As shown in Fig. 5, the kerf width includes the spark gap, the wire diameter, and the crater depth. A commonly used wire with a diameter of 0.25 mm typically produces a kerf width of 0.35 mm. Thus, the wire diameter determines the minimum possible kerf width, which is given by the sum of the spark gap and the average crater depth. To reduce the kerf width, it is necessary to reduce the spark gap and crater depth, which can be achieved by lowering the discharge energy under stable machining conditions [3, 5].

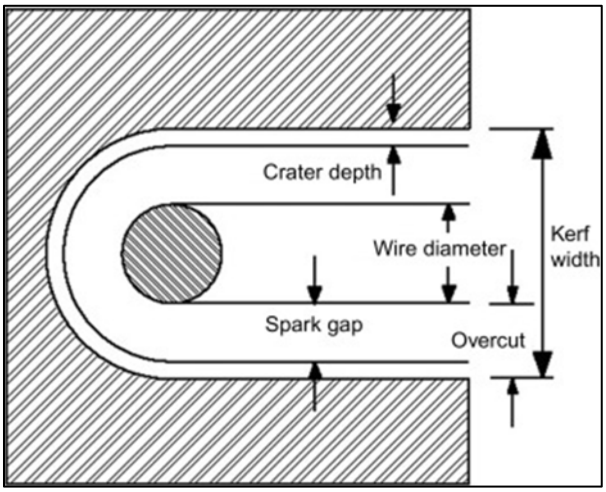

Figure 5 Kerf width [22]

4.2. Corner rounding

Recent advances in the WEDM process make it possible to achieve excellent dimensional accuracy in the manufacture of components with complex shapes. The material removal mechanism does not depend on the hardness of the processed material [25]. In some cases, this process is the best and only alternative for machining electrically conductive, high-strength, and heat-resistant materials, including some modern composite materials [26, 27].

The forces acting on the wire are the main cause of geometric inaccuracies in machined parts. The efficiency and accuracy of the process are limited by the risk of wire breakage, bending, and vibration, as well as by other process parameters such as pulse voltage and waveform, the viscosity of the working fluid, and the potential drop across the gap. Among these forces are hydraulic forces caused by cooling, electrostatic and electromagnetic forces associated with spark generation, forces arising during material removal, and the tensile force that straightens the wire [28].

When cutting corners, geometric inaccuracy is mainly caused by the following factors [29]:

- Wire deflection phenomenon: forces acting on the wire pull it backward, causing it to bend. To compensate for this effect, tensile force is applied to the wire; however, it is not possible to completely avoid wire bending without breaking it.
- Change in the wire's direction of motion: this change leads to deviations in wire deflection caused by external loads. Forces associated with material removal and cooling also change their direction and magnitude, disrupting the equilibrium of the cutting process.
- Electric field intensification near the corner: this intensification causes instability in the material removal rate.
- Increase in material removal rate at the corner due to a temperature rise,** caused not only by the above-mentioned field intensification but also by the fact that the generated heat is difficult to dissipate in the corner area.

In most previous studies, inaccuracy has been considered a result of the wire deviating from the defined path. The literature distinguishes three groups of corner angles. The first group includes angles greater than 135°, the second group angles between 30° and 135°, and the third group angles less than 30°. This classification reflects the main phenomena causing inaccuracies. For the first group, the error is relatively small and is mostly caused by wire bending. In the third group, the main cause is intensive sparking at the corner apex. For the second group, both wire bending and intensive sparking are significant [25, 30].

In the past, several methods have been investigated to improve the geometric accuracy of corners. Some of these methods propose various strategies for correcting the programmed electrode path, either offline or online. Other methods focus on monitoring and controlling the wire position using an optical sensor. Further studies propose path-control strategies based on fuzzy logic and expert systems. Another approach involves changing machining parameters, such as feed rate and pulse-off time, near the corner [12, 13].

According to Lin et al. [30], corner error is defined as the height loss, Δl, i.e., the distance between the apex of the ideal corner and the intersection of the actual corner contours with the bisector (Fig. 6). To increase machining accuracy in taper cutting by wire electrical discharge machining, a guiding electrode wire can be used to prevent local sharp wire bending.

Hsue et al. [33, 34] carried out a geometric analysis of wire electrical discharge machining in corner cutting; they developed a mathematical model to estimate the material removal rate with respect to wire deflection.

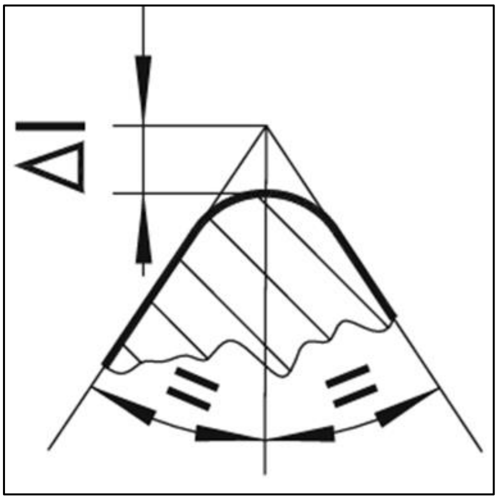

Figure 6 Corner errors in WEDM [35]

Sanchez et al. [36] investigated the possibility of using a computer-aided system to optimize corner-cutting accuracy in WEDM. The system combined experimental knowledge and numerical simulations. Additional research led to the development of software that accounts for the effect of friction to adequately model the cutting of surfaces intersecting at large angles. In a paper published in 2007, certain aspects regarding the influence of cutting speed on corner-cutting accuracy in WEDM were highlighted. The study showed that, for a corner geometry produced by successive cuts (roughing and finishing), the corner-accuracy optimization procedure must take into account errors caused by the previous cuts [37, 38].

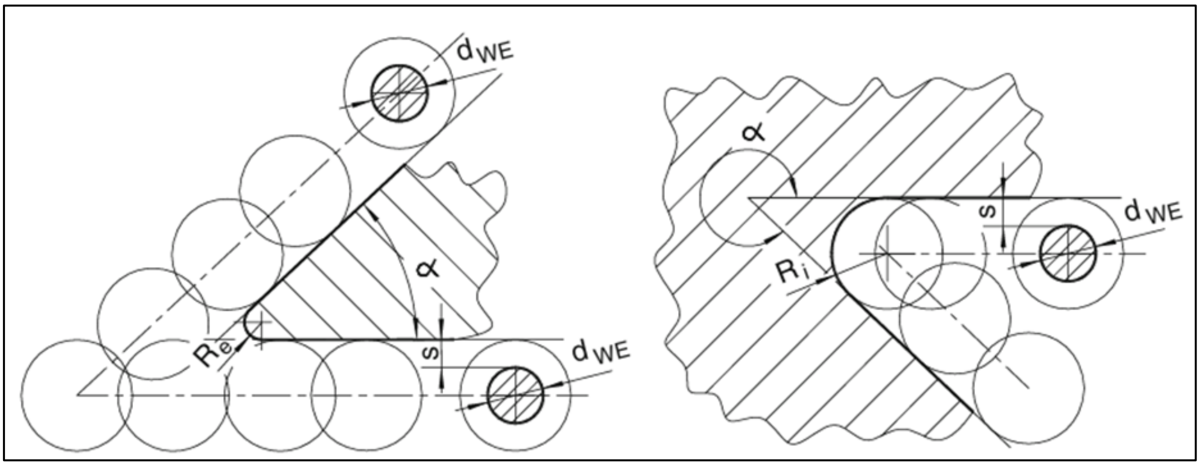

Figure 7 WEDM corners: (a) inner radius, (b) outer radius [29]

Figure 7 shows how to obtain inner and outer corners. Ideally, the minimum radius of an inner corner is equal to the wire offset value, and the minimum radius of an outer corner is zero. The following applies:

$$R_i \geq s + \frac{d_{WE}}{2} \quad (1)$$

$$R_e \geq 0 \quad (2)$$

Where: d_{WE} – diameter of wire electrode,

s - the size of the gap, i.e. the overlap.

4.3. Barrel-shaped effect of the cut surface

Due to various factors, the wire electrode is not always perfectly perpendicular and may deviate from the cutting path of the part contour, especially in corners and radii. These deviations, caused by so-called wire lag, often lead to the formation of a barrel-shaped cut on the machined surfaces [38].

The barrel-shaped effect on the cut surface (Fig. 8) is caused by two factors, either individually or acting simultaneously: flushing pressure and wire vibration at the cutting location. During flushing, most impurities are driven toward the center of the cut, where the pressure is much lower. Secondary discharges then occur in this region. A secondary discharge is a condition in which eroded conductive or semiconductive particles in the dielectric come into contact with the electrode or the workpiece and generate random discharges on the already machined walls of the workpiece [39].

The barrel-shaped effect of the cut is particularly pronounced in thicker workpieces. This effect can be minimized by appropriate parameter settings or by using a finishing cut [22], which, however, significantly increases production times.

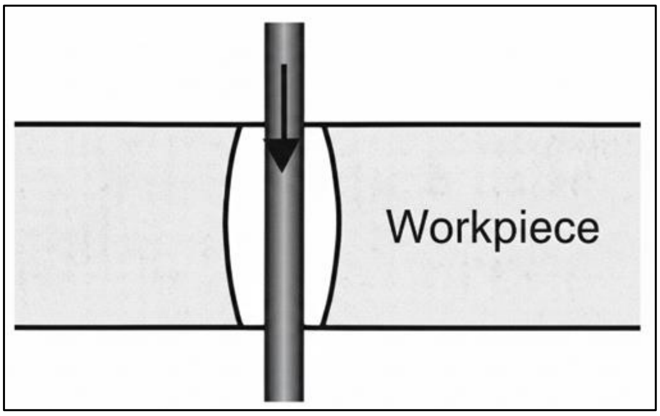

Figure 8 Barrel-shaped cut effect [39]

4.4. Incomplete cut

When cutting a profile, a small amount of material is left at the end point over a short section, after which the wire returns along a predefined path to increase cutting accuracy. This remaining portion of material is then removed to separate the cut-off piece from the rest of the material, leaving an imprint (a so-called “comb”) on the cut profile (Fig.9). However, this slight undercut does not, in most cases, have a significant effect on the result [22].

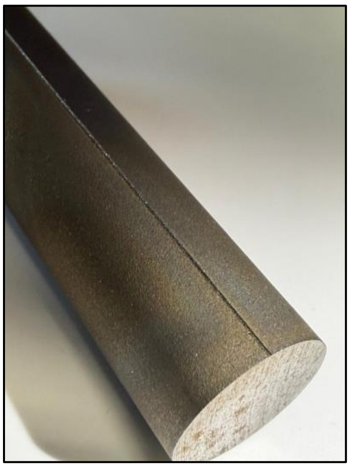

Figure 9 Leaving an imprint (a so-called “comb”) on the cut profile

4.5. Surface roughness of the cut

Surface quality is one of the key technological characteristics of wire electrical discharge machining (WEDM) that determines the possible applications of this technique. It is closely related to parameters such as:

- Discharge current – a higher discharge current leads to greater material removal, a larger spark gap, and also higher surface roughness,
- Pulse duration – a shorter pulse reduces the material removed per electrical discharge and increases surface quality,
- Discharge frequency – depends on the conditions of the required process and the distance between the machined material and the tool electrode,
- Open-circuit voltage – a higher voltage increases the gap between the workpiece and the wire, thereby improving the flushing of impurities from the sparking zone,
- Electrode polarity – during the main cut and the first trim cut, the wire is connected as the negative pole. During the final trim cut, the polarity is changed according to the cutting conditions and process settings.

These factors determine the size of the crater produced by a single discharge; as the energy increases, the crater depth and diameter increase, which reduces overall surface quality. Final surface quality is therefore achieved through successive machining—first a rough cut and then finishing passes. As mentioned, higher surface quality is usually achieved at lower current values, with short pulses and high discharge frequencies [38].

Surface roughness is significantly affected by pulse duration, peak current, and cutting speed. There is an inverse relationship between surface roughness and cutting speed.

Pulse duration is the most significant factor influencing surface roughness, and increasing it causes surface roughness to rise due to the “double sparking” phenomenon, which results in an inadequate surface finish. In other words, double sparking and localized sparking become more frequent as pulse duration increases. Cutting parameters affect the size of the eroded craters (diameter and depth) on the wire electrode. Larger craters on the wire increase the risk of wire breakage and also lead to poor workpiece surface quality and machining accuracy. Increasing pulse duration, peak current, and wire speed increases crater size, whereas excessive dielectric flushing pressure reduces crater size [40, 41].

5. Surface contamination of the cut surface by tool electrode material

In wire electrical discharge machining (WEDM), the workpiece is typically connected as the anode and the wire as the cathode. A working gap of approximately 0.025–0.05 mm is maintained between them, while the wire diameter ranges from 0.05 to 0.3 mm. A plasma channel forms within this gap, where temperatures on the order of 8,000–12,000 °C are reached. Such high temperatures cause localized melting and evaporation of a small amount of material from the workpiece surface; the molten and vaporized particles are then flushed away from the discharge site by the dielectric fluid [42].

The thermo-electrical nature of WEDM directly affects the surface integrity of the workpiece—chemical composition, hardness, microstructure, and surface topography are altered [43]. A remelted (recast) layer forms on the surface, beneath which lies a zone affected by thermal exposure (heat-affected zone, HAZ). The morphology of the recast layer depends on the process parameter settings, the chemical composition of the workpiece, and its thermophysical properties [44, 45].

In the context of WEDM, element migration plays an important role. This refers to the transfer of chemical elements between the tool and the workpiece, or within the workpiece itself, due to high thermal loading and concurrent electrochemical processes (Fig. 10). During electrical discharges, the material surface melts and partially evaporates; part of the molten material is carried away by the dielectric, while part may remain on the surface or be transferred to other areas. At the same time, material transfer from the electrode (e.g., a brass wire) into the surface layers of the workpiece may occur. EDX (energy-dispersive X-ray spectroscopy) analysis often confirms the presence of copper and zinc originating from the wire electrode [46].

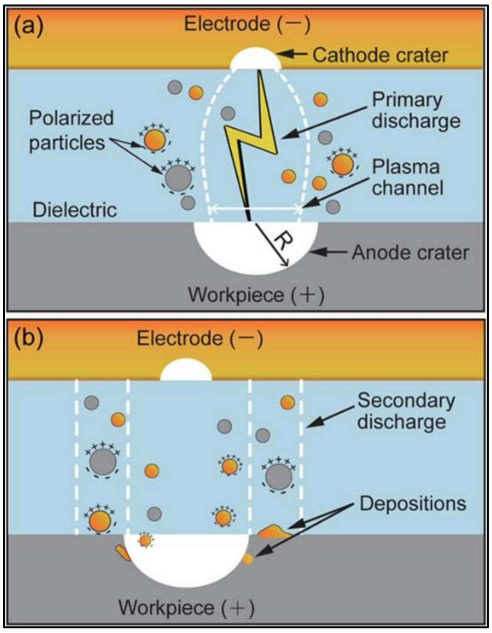

Figure 10 Schematic illustration of electrode material deposition on the workpiece surface [47]

During the subsequent rapid cooling, new phases such as martensite may form in the surface layer, significantly affecting the material's mechanical properties. These phase transformations (Fig. 11) are typically accompanied by atom migration and changes in microstructure [46].

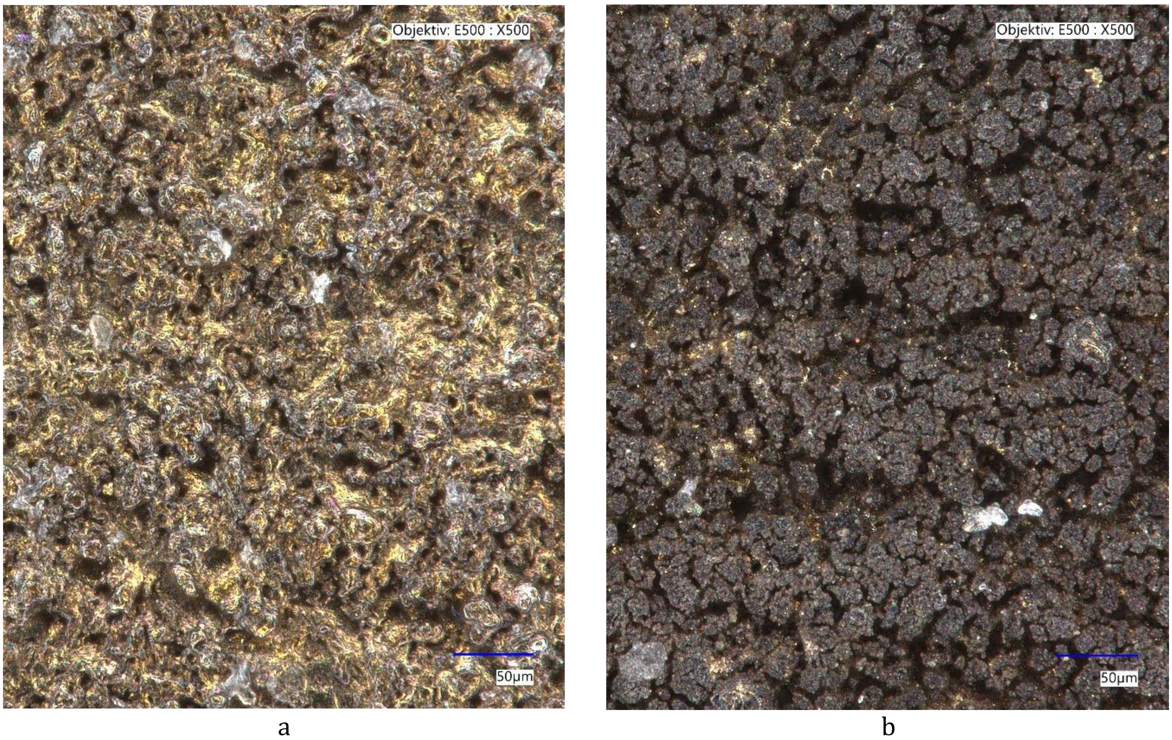

Figure 11 Image of the sample surface (E500 objective, 500× magnification): (a) upper part of the sample, (b) middle part of the sample

6. Conclusion

WEDM is a key non-conventional technology for precision machining of electrically conductive, difficult-to-machine materials in industries with high demands for geometric complexity and accuracy. It uses controlled electrical discharges in a dielectric without cutting forces, enabling the shaping of complex contours, but it also produces a thermally affected layer and possible residual stresses that may require additional finishing. Geometric accuracy and surface quality depend on pulse settings, the stability of wire feed, flushing conditions, and multiple finishing passes. The choice of wire electrode plays a crucial role: modern coated and multi-layer brass or composite wires increase speed, stability, and achievable surface quality at acceptable cost. The right combination of wire, process parameters, and cutting strategy makes it possible to achieve both high productivity and low surface roughness, allowing WEDM to reliably complement or replace conventional chip-forming technologies where those fail.

The presented review confirms that the resulting geometric accuracy and surface quality in WEDM are determined by the combination of thermophysical phenomena in the spark gap, wire dynamics, and the selected settings of the pulse generator and flushing. The surface layer after WEDM shows features of a rapid thermal cycle: a recast layer, a heat-affected zone, possible residual tensile stresses, and microcracks. Surface quality can be improved by multiple lower-energy passes and appropriate post-processing. Surface roughness and dimensional accuracy are closely linked to pulse energy and spark-gap stability; short, high-frequency pulses lead to a finer surface and smaller craters. The kerf width is always larger than the wire diameter due to the spark gap and crater depth. Minimizing kerf width requires reducing discharge energy while maintaining process stability. Geometric corner errors arise from a combination of wire deflection and local electric-field intensification; they can be reduced by path modification (compensation), controlled parameter changes in corner regions (offset, off-time, wire tension, flushing), multiple passes, and advanced monitoring/predictive modeling. For complex shapes and small corner angles, it is advisable to combine offline/online path corrections with adaptive process control and to verify the result using subsequent finishing passes. By implementing these approaches, consistently high cutting accuracy, low roughness, and repeatable internal and external corners can be achieved, expanding the applicability of WEDM in the production of precision parts from complex and difficult-to-machine materials.

Compliance with ethical standards

Acknowledgement

This work was supported by the call for doctoral students and young researchers of Slovak University of Technology in Bratislava to start a research career (Grant 23-02-05-A), and within the project VEGA 1/0181/24 “Research and design of adaptive control for production technology based on optimisation of technological parameters of solid biofuel production” funded by the Scientific Grant Agency of the Ministry of Education, Research, Development and Youth of the Slovak Republic and the Slovak Academy of Sciences.

Disclosure of conflict of interest

The Authors proclaim no conflict of interest.

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