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Wire Electrical Discharge Machining Process: Challenges and Future Prospects

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Abstract

Titanium alloys, due to their distinctive properties, are widely used in modern commercial applications. However, these alloys face challenges of machining via traditional techniques such as milling and turning. One of the unique thermal machining techniques that offer an effective choice with the highest dimensional precision and surface finish for Ti alloys is Wire Electrical Discharge Machining (WEDM). This method is based on the effect of erosion, where a highly repetitive electrical spark causes the material to be removed. The key challenges in WEDM are machining mode, wire electrode, dielectric, metal removal rate, and surface integrity as related to WEDM parameters were analyzed and correlated. Furthermore, Low metal removable rates, excessive tool wear, the production of recast layers, and heat-affected zones provide additional dilemmas when applied to titanium alloys. The majority of these obstacles occur as a result of titanium alloys' remarkable properties, such as low thermal conductivity, high melting temperature, and wear resistance. The first part of this paper highlights the research trends in WEDM on finding the relationships among various process parameters, such as cutting speed, the time between two pulses, servo voltage, peak current, dielectric fluid, wire tension, and machining modes that have a crucial impact on a variety of process responses, such as MRR, Ra, sparking gap, and WWR as well as surface integrity. The second part of the article also discusses various modeling, simulation, and optimization technique for monitoring process parameters to investigate the feasibility of various control practices for achieving the optimum machining conditions. The final part of the paper highlights these advancements and includes a roadmap for the potential future directions of WEDM research.

Keywords: Titanium alloy, WEDM, Process optimization parameters, Metal removal rate, Surface roughness, modeling, and simulation.

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1. Introduction

Traditional machining methods, such as drilling, milling, turning, lapping, and grinding in general, are expensive methods to mill and remove metal from hard materials like titanium-based alloys [1]. Titanium alloys are characterized as difficult-to-fabricate materials that suffer from severe tool wear, increased machining times, and poor machinability due to their inherent mechanical properties (low modulus of elasticity) and thermophysical characteristics (low thermal conductivity, high chemical reaction) [2]. Consequently, effective non-traditional machining methods should be used to cope with the machining difficulties of titanium alloys. WEDM can serve as a practical and economical solution to produce complicated shapes from hard and refractory materials. In the late 1960s, WEDM was first made available to the manufacturing sector. The technique was developed to change the tool wire used in EDM. In 1974 [3] the optical-line follower system applied to control the component shape, which was machined during the Wire Electrical Discharge Machine. As the technique and its capabilities were commonly perceived, it had become more popular and used in industry sectors by 1975 [4]. At the end of the 1970s, a computer numerical control system was introduced to obtain three-dimensional forms [5,6]. WEDM is a thermo-electric technique in which the sparking process starts using an electrode and includes a cycle of sparks between the work material, which has been eroded, and the wire electrode. A di-ionized fluid, where the component and the wire are submerged, works as a coolant and removes debris [7]. However, to produce a very small Kerf width, WEDM employs a regularly moving wire made of special materials and has certain diameter specifications. During the WEDM process, there is no direct communication between the workpiece and the electrode, hence mechanical stress is reduced during the machining process. In addition, WEDM technology eliminates the change in shape that occur during the machining of steels and can machine exotic, high-temperature strength alloys

2. Wire Electrical Discharge Machine process

Figure 1 shows the actual and schematic diagram of the wire electrical discharge machine equipment. Thin copper, brass, or tungsten wire is used. The electrode motion and feeding are guided using a control unit and coils made of diamond to be abrasion resistance. The workpiece functions as an anode and the wire as a cathode when connected to a power source. Spark discharge develops when the electrode, in this case, the wire, is located near the workpiece, which removes metals from the workpiece and the wire, and in the presence of dielectric fluid, this material moves away.

The di-ionized fluid between the electrode and workpiece establishes a channel for each discharge. Furthermore, cooling, disposal of decompressed material, and also flushes the debris away.

3. Material removal mechanism in WEDM

In machining, electrical wire discharge is regarded as a unique technique, where material removal is dependent on erosion effects according to a thermo-electric theory wherein electrical power is converted into thermal energy.

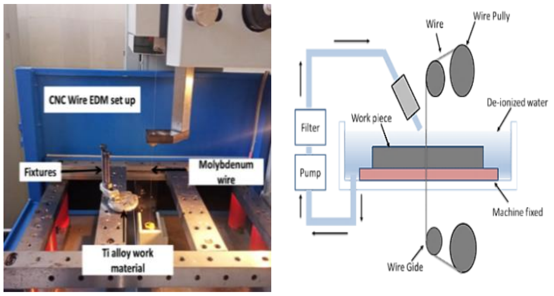

Fig. 1. Actual and schematic Wire electric discharge machining

A flux of periodic electric discharge is generated between the tool and workpiece, which are positioned at a close distance from each other, and are immersed in a di-ionized medium [8]. Figure 2 provides an explanation of the metal removal mechanism in WEDM. A pre-ignition period, in which no current passes between the workpiece and tool, fluid work as an insulator in Fig.2 (i). After that two electrodes are linked to a direct power supply during the ignition phase (Fig. 2 (ii)). The circuit is closed in order to pass the electric current which in turn generates a potential difference between the workpiece and the tool. As a result of an increased electrical potential generated between the two separate electrodes, electrons are emitted from the cathode. These electrons rush in the direction of the anode and crash into the dielectric fluid, where they separate into electrons and positive ions. A thin line of molecules is produced between two electrodes creating a spark, which is cycled thousands of times per second. Between the cathode and anode, these sparks create the plasma channel (Fig. 2(iii)), which in turn generates thermal energy at temperatures between 8,000 ^{o}C and 20,000 ^{o}C to melt and vaporize the materials on the surfaces of each pole [9]. The workpiece is continuously heated during the last stage of WEDM as ions and electrons bombard the electrodes constantly, and finally cause the workpiece to be intensely heated. As the plasma channel continues to widen throughout this phase, the size of the pool of molten metal keeps growing (Fig. 2(iv)). A tiny fraction of the workpiece material is removed as molten metal, which then solidifies and becomes debris. This debris is washed out of the discharge zone by dielectric fluid. Similarly, several craters are formed on the workpiece surface, providing a rough machined appearance [10,11].

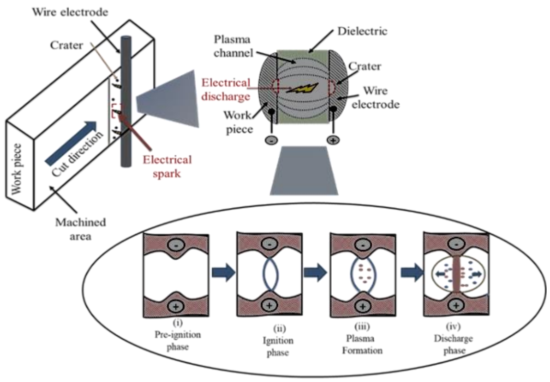

Fig. 2 Spark erosion mechanism in WEDM [11].

4. WEDM Parameters

Figure 3 illustrates the process parameters that may have an impact on the performance of the material as a function of surface quality and other mechanical properties. These parameters are divided into electrical factors (time between two pulses, servo voltage, peak current), electrode parameters (types and size of wire), Non – electrical parameters (feed rate, time of machining, and di-electric fluid (viscosity, type, and other flow properties).

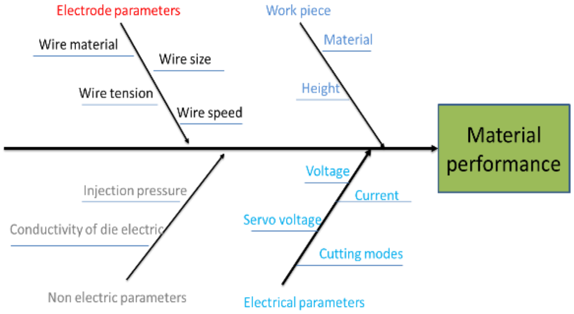

Fig. 3 Cause and effect diagram for WEDM techniques [12].

5. Characteristics of WEDM

The most crucial features of a WEDM operation are Metal Removable Rate and surface integrity, which are governed by a wide range of process parameters and are also contributed to the complexity of the WEDM machining process [12].

5.1 Material removal rate (MRR)

Numerous studies have explored different approaches to increase the rate of removing material and wire speed. Because of their potential to significantly increase WEDM's economic benefits. Cutting speed and metal removal rate almost equally influence the phenomenon known as machining rate [13]. Rajurkar and Wang [14] used thermal analysis and experimental methods to analyze the wire rupture phenomena. It was discovered that the time between two pulses has a noticeable influence on the metal removal rate. By reducing time initially, MRR is increased. However, a low machining rate occurs at a small pulse time [15]. There are combined effects of two factors on MRR, Singh et al [16] discovered that MRR declines as both pulse off time and voltage increase while it rises with a pulse on time and peak current increase. On the other hand, there are process variables such as flushing pressure, machining and servo voltage, tension force, and speed of wire, which are not significantly alter wire feed that has an effect on MRR. Peak current, which affects MRR, is a crucial parameter, as mentioned in [17]. In general, as pulse-on-time rises, MRR increases, but as wire tension rises, MRR declines. Additionally, MRR is relatively lower at low dielectric pressure (7 MPa), and with increasing the injection pressure, MRR significantly increased. At lower flushing pressures, it was observed that the crash particles move away from the working area and charges happen without any metal being removed. In contrast, higher fluid pressure leads to a practically constant material removal rate.

5.2 Surface integrity

The other important indicator for machining performance is surface consistency which can be expressed with re-solidification layer (RL), heat affected zone (HAZ), surface roughness (Ra), and density of micro-cracks. RL is created as a result of the deposition of rapidly solidified molten metal, while the layer of base metal beneath the re-solidification cast layer has different metal characteristics [18]. Figure 4 shows cross-section area produced from rough wire electrical discharge machining, and highlights the machined surface cracks, heat-affected zone, and re-solidification layers [19]. Based on the theory of surface roughness, peak current and cutting speed have inverse relationships with surface roughness and are strongly affected by pulse-on time, machining modes, and pulse-on time. With a surface roughness of 2.44 µm at a machining speed of 2.65

mm/min, Ra linearly decreased as the cutting speed rises. In this regard, surface roughness deteriorates drastically with a significant increase in machining speed [20]. Turning on the pulse time, there is no effect on the surface quality or dimensional errors. These features are particularly important because, under certain processing parameters, the time between two pulses could be altered to meet system stability and cutting precision requirements [21]. The electrical input factors such as current and pulse-on time are crucial, according to Rao, et al. [22]. It was found that the speed of the wire and the fluid pressure are minor parameters that have an observed effect on surface roughness, whereas wire tension, pulse-off-time, and servo voltage are all important. With regard to the wire feed rate, the surface topographical difference is barely noticeable. When MRR is lower, a surface that seems to be comparatively smoother is produced [23]. When welding titanium alloys, the size of the crater increases as the feed rate increases [24].

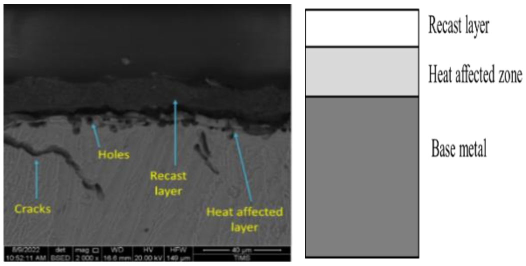

Fig. 4 Machined surface by wire EDM

6. Modeling and Optimizing the WEDM Process

Figure 5 displays the mathematical tools and artificial intelligence methods employed in WEDM processing. These techniques are used to simulate the WEDM process over time. Taguchi method and RSM technique are used to find the relation between different parameters [25-27], and other models such as ANN model [28], and genetic algorithm model [29] have also been reported. In reference [30,35,37], for optimization parameters, desirability-based multi-objective particle swarm optimization, A genetic algorithm, and the multi-objective particle swarm optimization technique were used. Grey relational analysis (GRA) [33], and integrated non-dominated sorting genetic algorithm II (NSGA-II) [34] were also utilized in several papers. Furthermore, for optimum energy efficiency, the NSGA-II tool was the preferred choice [36].

As indicated above, using special software for evaluating experimental data and establishing mathematical equations for the output response. These models included independent variables for some or all process input parameters. The need to employ specific models becomes prominent particularly when the problem of process optimization emerges. Most of these mathematical models are based on regression analysis to build empirical models (first or second-order functions and power functions), and are applied even for the WEDM process. Examples of mathematical equations have been built to define the input factors influencing the output responses kerf width and the surface roughness (Ra) [38]. An example of the higher-order mathematical model was recently proposed in [39]. In order to estimate output processes, such as SR and SW, Speeding et al. [40] created modeling methodologies using response surface methodology and artificial intelligence technology within a different input level. The cutting geometry in WEDM can be precisely introduced using solid modeling techniques [41]. This model has been developed to predict the MRR by using deflection that occurs in wire and mathematically estimate the erosion behavior of titanium alloy available in [42].

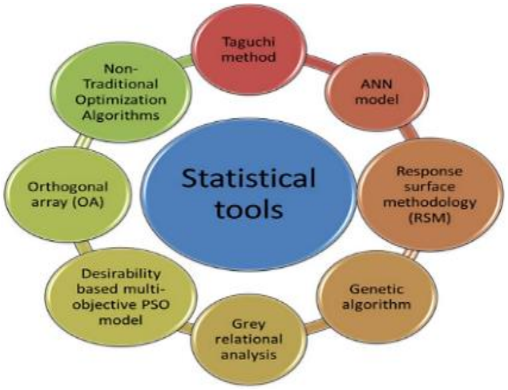

Fig. 5 Mathematical tools applied in WEDM [36].

To sum up, the crucial factors that have a direct impact on the metal removal rate, roughness, and waviness of the surface, are peak current, the time between pulses, and servo voltage. As a result, the optimization process to determine the ultimate parameters is critical.

7. Future aspects

Numerous scientific challenges are still unsolvable despite huge interest in this area. A deep understanding of the improvements to the properties of products and processes, such as profitability, efficiency, life expectancy, sustainability, and flexible automation is required by recent technologies, which are being used to design innovative methods. It is expected that several crucial research topics required for future growth will need to be identified in order to develop the predicted processes and products. The projected scope of WEDM is shown in Fig. 6.

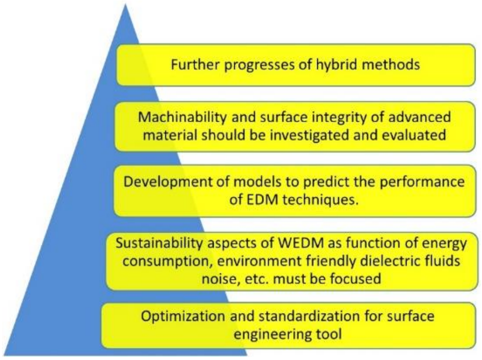

Fig. 6 Future scope of WEDM [38].

8. Conclusion

The growing demand properties of titanium alloy added difficulty to their manufacturing methods and specifically, more challenging machining processes. In the current review, the WEDM process was emphasized and the important points were summarized as follows:

1. WEDM is a competitive machining process since it provides various options for tool wire types and materials, uses environmentally acceptable dielectric fluids, and uses controllable machining parameters for removing materials.
2. Different EDM techniques use the same mechanism for removing metals based on the erosion phenomenon, where a continuous electric arc is generated adjacent to the workpiece. This repetitive spark generates high thermal plasma which caused melting and vaporizing for the workpiece along the tool electrode motion.
3. The wire electrode movement is monitored numerically to maintain the required three-dimensional shape, workpiece precision, and machining performance. Furthermore, because the wire travels continuously, the machining features are less altered by tool wear.
4. Rapid solidification, high thermal energy and low thermal conductivity cause the machined surfaces produced by WEDM processes to have cracks recast layer, residual stress, tool breakage, tool wear, and heat-affected zone which are key problems in WEDM.
5. Attempts of using the WEDM process, identifying and describing input parameters' functions for different materials, and machining workpieces with very low electrical conductivity were introduced.
6. Mathematical models have been built utilizing a variety of modern mathematical tools in order to investigate the influence of the input factors on the values of output parameters and optimization of the WEDM process.
7. According to the literature, there has been significant growth in the number of works published that highlight the problems related to the WEDM process.
8. Future efforts should be channelized into exploring a new version of the WEDM process, optimizing process parameters to improve the performance of the WEDM processes, and focusing on the new requirements for the industry 4.0 era such as securing, affordable and sustainable techniques.

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