Investigating wire breakage during EDM with fractographic analysis

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Abstract. Wire electrical discharge machining (WEDM) is widely used in various fields of production. Its disadvantages include a relatively low productivity rate caused by wire breakages among other factors. In this article, the method of fractographic analysis is used to study a wire that has undergone a breakage during machining. The results indicate that the tool–electrode is subjected to mechanical tension followed by a ductile fracture. The most probable reason of wire breakages is a decrease in the wire cross–section, which can be caused by an electrodes short circuit.

1. Introduction

Electrical discharge machining is widely used in various fields of production – from instrumentation to rocket and aircraft production. The necessity to increase the efficiency of mechanisms and machines dictates the usage of existing and elaboration of new materials with high thermal and mechanical strength. However, cutting machining can lead to a change in the geometry of these materials due to elastic deformations. Electrical discharge machining makes it possible to avoid such consequences due to the fundamental feature of this method (the removal of a part of the processed material by electrical impulses), which justifies the possibility of WEDM application for machining virtually any conductive materials. However, to increase the competitive advantages of electrical discharge machining, it is necessary to raise its efficiency [1, 2]. One of the main factors affecting the efficiency of WEDM is the instability of the machining process. Optimization of parameters and modes of electrical discharge machining allows to increase its efficiency. For example, the use of trapezoidal pulses provides a reduction of the wire wear ratio for up to 0.1% [3]. The application of various algorithms to generator programming also leads to a decrease of the tool–electrode wear due to pulse shape optimization [4]. Based on the analysis of the above research articles, it was concluded that the pulse shape has virtually no effect on the material removal rate (MRR) if the pulses energy is constant, but has a significant effect on the wear of the tool–electrode [5]. Thus, the probability of wire breakage can only be reduced, but not completely excluded. As a result of wire breakage during EDM, power consumption increases [6], and the quality of the workpiece’ surface layer deteriorates [7].

Analysis of research articles on the problem of wire breakages in the case of WEDM allows to identify several ways for interpreting the reason of breakages: 1) wire breakages occur due to the thermal stresses; 2) wire breakages are caused by mechanical stresses; 3) wire breakages occur for other reasons. Considering thermal stresses as the cause of breakages, the authors of [8] come to the conclusion that local overheating of the wire has occurred, which contributed to its break. It was established in [9] that thermal stresses arise due to the effects of random pulses. Moreover, the concentration of debris particles at the boundaries of bubbles formed during machining in the
inter electrode gap leads to an increase in the charge accumulation in these local areas [10]. However, in modern equipment, the problem of charge accumulation is solved [11]. The studies of wire erosion [12] have confirmed that the combined thermal and mechanical impact cannot cause the wire breakage. Thus, one of the most probable reason of wire breakage is a short circuit arising from the formation of the so-called «welding bridge» [13, 14].

A review of studies on the problem of wire breakage during EDM did not reveal any research articles related to the study of a damaged wire by the method of fractographic analysis. Currently, the fractography is widely used in fundamental and applied research to predict the destruction of products during its operation, and can also serve as a tool for analyzing the possible reasons of their destruction. The purpose of the article is to investigate the brass wire breakages that occur during the electrical discharge machining of 36CrNiMo4 steel samples using the method of fractographic analysis.

2. Methodology

Machining was carried out by the wire EDM equipment SODICK VZ300L. When machining, a hard brass wire (60% Cu, 40% Zn) was used as an electrode, its diameter was 0.20 mm, and the tensile strength according to the manufacturer had a value of 900 N / mm2. Parallelepiped samples with dimensions of 50x50x50 mm (LxWxH) were used as a workpiece; workpieces were made of 36CrNiMo4 steel (analogue of AISI 9840).

The OPEN mode was used for machining, since wire breakages are mainly observed during roughing cuts, and in OPEN mode washing is difficult, the pulse frequency and the current magnitude are high, which leads to formation of a large amount of debris. In OPEN mode, the lower and upper nozzles are at a distance of more than 0.1 mm from the workpiece (Fig. 1).

![Figure 1. Nozzle positions schemes in OPEN mode](image)

The values of current and voltage were calculated by the software of the machine and did not change during processing. The effective values of voltage and current were recorded by an onboard voltmeter and ammeter. The average current strength was 10.5 A. The voltage value varied from 38 to 42 V, the average value was 40 V.

When a wire breakage occurs, the processing stops, and the CNC system of the machine starts a cycle to eliminate the breakage, unless otherwise specified by the operator. Machine moves to the «main reference point» position (set by the program), cuts the end of the wire and drains the dielectric fluid below the table level, then a standard wire threading cycle occurs. If at any stage there are any problems, processing stops for operator intervention. The torn end of the wire is placed in a special container. One of the wire edge is the place where the wire broke off which has the defects that are of interest for investigation, the other edge is cut with electric scissors of the machine and is not of interest for analysis. Only wire elements above the breakage point were used as samples, because upon breakage the lower part of the wire is pulled into the collection bucket through the ejection rollers, being exposed to significant impact that can affect the research data. Therefore, only the upper wire fragments were used in the study.
The 10 collected samples were carried out using a JEOL JCM–5700 microscope, equipped with an energy dispersive X–ray spectrometer JED–2300 in a high vacuum mode. The signal type was secondary electrons (SEI). The SpotSize parameter was selected as 50, with the accelerating voltage value 20 kV and magnification was from 300 × to 400 ×.

3. Results and discussion
In the course of the research, it was carried out a study of 10 wire samples after their breakages during electrical discharge machining. However, the article analyzes only a few types of breakages, since the rest of the samples are characterized by similar types of breakages. As shown in micrographs (Figures 2 and 3), the surfaces of the most samples are typical for fracture resulting from mechanical tension. Since the wire is made of brass, the breakage points are ductile fractures that are characteristic of samples during the tensile test. One of these samples is shown in Figure 3.

Figure 2. Wire micrographs after breakage: A) top view magnification 400×; B) side view magnification 300×.
A typical ductile fracture during stretching of cylindrical samples on micrographs can be conditionally divided into 3 zones: 1 – fibrous zone (in Figure 2A it is designated by number 1); 2 – radial zone (in Figure 2A it is designated by number 2); 3 – shear–lip zone (in the figure with number 3). The fibrous zone is represented in micrographs by a porous pit structure. This is an area of slow crack growth, usually located in the center of the fracture and surrounding the crack propagation source. In the fibrous zone, the fibers are arranged in a random direction. The radial zone is usually located along the perimeter of the fibrous zone. In this region, a transition occurs from the initiation and slow growth of a crack to its rapid propagation in the material. In the radial zone, the fibers of the material are directed towards the crack propagation site and at higher magnification can look like grooves. Moreover, the higher the viscosity of the material, the smaller the width of the grooves. The next area is the shear–lip zone.

It is formed with a significant increase in the rate of crack propagation. Its spread is limited to free sample surfaces. Figure 2B shows a micrograph of the sample breakage (side view). As can be seen from Figure 2B, the wire, which before the breakage had a diameter constant along the length, after the breakage has the shape of a truncated cone at the end at the breakage point. This shape is also indicative of mechanical tension.

During the tensile test, cylindrical samples develop a neck – a decrease in diameter at the fracture zone. Apparently, the wire breakage at this stage occurs in a similar way. The investigated wire fragment also showed traces of melting and adhered debris. This confirms the fact of thermal and mechanical impact on the wire in operation.

It should be noted that a breakage is not always characterized by a complete set of all three zones. Figure 3 shows micrographs of a sample containing two zones corresponding to a ductile fracture. In Figure 3A, 1 indicates the fibrous zone, and 2 the radial zone. There is no shear–lip zone for this
sample, which is explained by its high viscosity. Reducing the wire diameter at the breakage point is also shown in Figure 3B.

Figure 3. Wire micrographs after breakage: A) top view magnification 400×; B) side view magnification 300×.

In the course of the study, a wire was found after a breakage with a smooth and homogeneous structure at the top of the break, which indicates both the occurrence of a brittle fracture and local melting of the wire (Figure 4). A brittle fracture is characterized by the presence of a shear–lip zone. In this zone, the structure is a smooth surface, the material must be very brittle, which is not typical for brass. Under conditions of high temperatures, arising from the impulse current, and the subsequent sharp cooling due to the dielectric liquid, embrittlement of brass becomes possible. This assumption requires additional verification. However, with a brittle fracture, a decrease in the section in the fracture region is not observed. Figure 4B demonstrates a decrease in the wire cross–section at the breakage point, which is characteristic of the previously studied samples (Fig. 2B and 3B), which indicates that the wire was subjected to mechanical tension followed by breakage.

Figure 4. Wire micrographs after breakage: A) top view magnification 400×; B) side view magnification 300×.

The formation of a smooth structure in a fracture area can occur due to thermal action (melting of the wire under the influence of residual heat), as well as the tendency of brass to embrittlement (under the influence of mechanical action, a brittle fracture occurs, the fractographic pattern of which may resemble a smooth structure).

The data obtained by the method of fractography contradict the results proving that the total stresses arising during WEDM in the eroded wire are not capable of causing its breakage [12]. However, this
research did not consider cases of significant wire erosion. With a decrease in the section of the wire, its tensile strength in this place decreases. And the reason for the decrease in the cross–section of the tool–electrode may be a short circuit.

In a short circuit a much greater amount of heat is released than in an ordinary breakdown of the interelectrode gap. Therefore, the effect of brass evaporation and melting on the change in the cross–section of the wire electrode, which is schematically shown in figure 5, is possible.

The wear of the wire electrode after a short circuit is also much greater, and, therefore, the cross–section of the wire decreases by a large amount, which leads to a decrease in its tensile strength. Thus, the total effect of thermal stresses during processing and the preload from the wire tension mechanism becomes sufficient to breakage the wire exactly at the point where its cross section decreases due to a short circuit [12].

![Figure 5. Schematic representation of wire cross-section: A) before EDM; B) after EDM; B) after short circuit](image)

**4. Conclusion**

Fractography is a functional method for analyzing the causes of destruction and breakdowns and is widely used in fundamental and applied research. Wire breakages in the course of WEDM reduce processing productivity, therefore, the identification of possible reasons of breakages through fractographic analysis contributes to this problem solvation.

After analysis of brass wire samples, the following types of structures originating in the place of breakage were established: 1) a smooth, homogeneous structure at the top of the breakage, specific for a brittle fracture; 2) a porous dimpled structure in the fibrous zone, characteristic of a ductile fracture. In the course of the study, it was found that the overwhelming number of samples has ductile fracture elements, and therefore the destruction occurs not as a result of thermal, but joint thermal and mechanical impact on the wire.
In the future, it is planned to conduct a study of how a short circuit influences on the cross-sectional area of an eroded brass wire, and its effect on the electrode breakages.

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