Investigation of welding bridge occurrence and short circuit impact on wire breakages during WEDM

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Abstract. The paper provides the results of a short circuit impact on wire breakages during wire electrical discharge machining (WEDM) of AISI 9840 steel by the SODICK VZ300L machine. A method of scanning electron microscopy (SEM) is used for debris size, morphology and shape analysis. The carried out investigation led to the conclusion that the most probable reason of the welding bridge formation is due to the non–spherical (conglomerates) particles’ presence with a large number of surface irregularities in a dielectric liquid. A classification of debris particles is proposed from the point of view of their dimensions and ability to overlap the spark gap – «effective» and «ineffective» particles.

1. Introduction
At present wire electrical discharge machining (WEDM) is widely used in the manufacture of products used in various fields of industry (medicine, aerospace, etc.). High productivity, precision, the ability to manufacture products from hard–to–process materials are the main, but by no means the only advantages of WEDM in comparison with other methods. However, there are reasons that can significantly reduce the productivity and quality of processing. It includes wire breakages that not only contribute to the defects formation on the processed surface, reducing its quality [1], but also lead to an increase in electricity consumption by 47% [2].

Nowadays, among the most probable reasons of wire breakages is allocated 1) mechanical stresses; 2) thermal stresses; 3) short circuit. It was found that the maximum heating temperature of brass wire should not exceed 1000 ° C [3].

Due to the concentration of local discharges in this region of the wire its overheating and breakage may occur [4], but in modern equipment the problem of discharge concentration is solved [5]. It was shown [6] that the total effect of the temperature and mechanical stresses does not exceed the strength of the eroded brass wire and does not lead to breakages.

2. Experimental details and simulation of flashing conditions
Parallelepiped samples with dimensions of 50×50×135 (L×W×H) mm of steel AISI 9840 were used as workpieces. Hard brass wire (60% Cu and 40% Zn) with a 0.25 mm diameter was used as a tool electrode. Machining was carried out by the wire EDM machine SODICK VZ300L.

Deionized water has been used as dielectric fluid. During the experiment, the nozzles positions were also changed while machining (figure 1).
1) OPEN U – one side open clearance machining (lower nozzle is at the distance of 0.1 mm from the workpiece, upper nozzle is at the distance of more than 0.1 mm from the workpiece);
2) CLOSE – close-contact machining (both nozzles are at the distance of 0.1 mm from the workpiece).
3) OPEN – open clearance machining (both nozzles are at the distance of more than 0.1 mm from the workpiece).
The current amperage and voltage values, as calculated by the machine software, were not changed during the WEDM, and were recorded by an on-board ammeter and voltmeter, respectively. The average current value was 10.5 A within the current value range of 10.4 to 10.6 A, the average voltage was 40 V, and the voltage varied within the range of 38 to 42 V.

After the workpiece processing, the tank with the dielectric liquid was dried without blowing, heating, etc. Debris particles were collected from the surface of the working tank and from the bottom of the tank.

The collected debris was examined via scanning electron microscope JEOL JCM–5700 microscope in high vacuum mode (the signal type was SEI). The spotsize parameter was 50, the value of accelerating voltage was 15 kV, magnification was in the range from 300× to 3000×.

A double stick current–conduction tape was located on the bottom of the sample holder for the SEM analysis of debris. The excess quantity of debris attached on the tape was removed by the compressed air flow.

Simulations of flashing conditions for dielectric fluid in the working gap was carried out in the SOLIDWORKS Flow Simulations software (figure 2). The initial data for simulating were the workpiece dimensions, the wire diameter, the nozzle diameter (6 mm), the distance from workpiece to
nozzles (figure 1), and the liquid pressure during flashing, by which the fluid velocity was calculated. To simplify the calculations, the wire speed was not taken into account.

3. Result and discussion

As a result of flashing conditions simulation in the CLOSE mode in SOLIDWORKS software, an example of the motion of a dielectric liquid is obtained, in which debris particles flows during the processing. In Figure 2, the arrows indicate the flow direction of the dielectric fluid. The results of the simulation show that the lower and upper flows of the dielectric liquid converge almost in the middle of the workpiece, forming a turbulent flow. Similar results were obtained in [15]. In a turbulent flow, the probability of a several debris particles collision is higher than in any other area.

Based on the simulation results of the flashing conditions and conducted experimental studies, the main reasons of the short circuit occurrence were suggested, as well as the classification and description of the debris particles morphology was conducted.

3.1. Conditions of short circuit occurrence

Short circuit can occur in the following cases: 1) direct contact of the workpiece and wire; 2) the presence of a conductor between the wire and the workpiece. The first case is practically excluded due to operation of control and monitoring systems. The width of the working gap is monitored by a system that does not allow the electrode tool to approach the workpiece beyond a specified value by the system. Only with problems or errors in the system the direct contact of the workpiece and wire is possible.

The second case seems more possible. At WEDM the molten material is removed from the processed workpiece surface during the explosion of the gas bubble. The appeared particles is entered the working gap, along which the dielectric liquid is flashed, cooled and removed to the tank by a liquid flows.

The dimensions that the particles acquire in the process of crystallization range from tenths of a micrometer to several tens of micrometers [11]. The size of the working gap is 50 μm. Some particles, having dimensions close to the value of the working gap, can overlap it, generating the electric current occurrence from the tool to the workpiece, thus causing a short circuit. It should be mentioned that the wire can be subjected to vibration [7], while its amplitude achieve 25 μm.

With respect to the working gap dimension, oscillations with such amplitude increase the probability of a short circuit occurrence and wire breakage [12]. A current passes through the conducting particle during the wire oscillations if a debris with a size of 25 μm or more overlapping the working gap at the moment of the amplitude deviation of the wire.

The probability of a short circuit occurrence and, as a consequence, a wire breakage, is the highest at simultaneous implementation of the mentioned conditions.

3.2. The process of welding bridge formation

Debris particles with a predominantly spherical shape and a smooth surface are visible in the micrographs obtained via scanning electron microscope (figure 3a). It is explained by a fact that a molten material entered to a working fluid under the influence of surface tension forces obtained a shape of a particle that is optimal from the viewpoint of a minimum surface energy. The size of such particles can be characterized by a single parameter – the particle diameter. As can be seen from figure 3a, the diameter of the majority debris particles varies in the range from 10 to 20 μm, which, from the point of view of the considered conditions for the short circuit occurrence, does not lead to increase of its occurrence probability. At the same time, particles with a diameter exceeding 25 μm (figure 3b) are visible on microphotographs. The presence of particles with such sizes in debris increases the probability of welding bridge formation.
Microphotographs also contain debris particles (shown with a black arrow) (figure 3c), whose dimensions cannot be described with just the one parameter. These are so-called conglomerates of debris particles. For a dimensional description of such particles, several parameters (width, length, height) are needed. It can be assumed that this kind of conglomerate 1 (figure 3a) is formed during the process of particles sticking to each other. Particle sticking can occur as a result of their contact in the interaction area of the upper and lower flows of the dielectric liquid, on condition that the particles have different crystallization temperatures.

Still uncrystallized particles enter the working medium, and, moving in a liquid flow [13], collide with other particles of the debris. As a result of the colliding particles interaction, conglomerates, having dimensions comparable to the value of the working gap, can be formed.

The process of the conglomerates formation is chaotic. The description of this process with high accuracy is difficult. However, it can be argued that such conglomerates will most probably form a welding bridge.

During the experiments, wire breakages in OPEN mode were most often observed, although machine manufacturers take measures to protect the wire for this mode, underestimating the electrical processing parameters. In our opinion, the formation of a welding bridge in this mode is most possible due to the lowest level of the debris flashing from the working gap. This is evident from figure 4, which shows three samples processed in the CLOSE, OPEN U, OPEN modes. On each of the samples, several characteristic zones can be distinguished.
Figure 4. AISI 9840 steel samples processed at a different positions of the flashing nozzles: 1 – CLOSE; 2 – OPEN U; 3 – OPEN.

On a sample processed in CLOSE mode, three zones are clearly distinguished: zone 1, zone 2, zone 3. As can be seen, zone 1 is located in the upper and lower parts of the sample. It has the lightest tone, which indicates the minimal amount of debris sticking to it, therefore, the flow level of dielectric fluid and debris flashing in this area was the best. This is explained by the fact that the upper and lower nozzles are approximated to the part by 0.1 mm and the flow of deionized water falls directly into the working gap, in which an intensive debris flashing takes place. Zone 2 follows immediately behind zone 1 and is also located at the top and bottom of the sample.

Obviously, the flashing level in Zone 2 was less intense than in zone 1, therefore, there was more sticking debris in this zone. On the processed samples (figure 4), an interference pattern with clearly distinguishable tones from violet–blue to red–orange is visible. In all probability, this is due to the interference of light in a thin oxide film, the formation conditions of which in zone 2 are favorable. After zone 2, zone 3 is allocated on all samples, which has the largest extent. The color of zone 3 is black, which is explained by the large amount of sticking debris. This indicates the lowest flashing level of dielectric fluid and, as a consequence, the flashing level of debris. In the center of zone 3, a segment of a lighter color is seen compared to the rest of this zone. As the simulation results of the flashing conditions show, the area of light color in zone 3 corresponds to the area of contact between the upper and lower flows of the dielectric liquid. The flashing level of debris in this area is higher than in the rest of zone 3, so its sticking occurs less intensively.

The surfaces of samples processed in OPEN and CLOSE modes differ significantly. The sample processed in OPEN mode lacks zone 1, which is explained by the low level of debris flashing due to the greater distance between the workpiece and the nozzles (both nozzles are moved away from the part by more than 0.1 mm). Zone 2 looks darker than zone 2 of the sample processed in CLOSE mode. This is due to the fact that the flashing conditions in OPEN mode are significantly worse and, consequently, the debris sticking occurs more intensively. Zone 2 follows zone 3, which is longer than
the sample processed in CLOSE mode. Also in the center of zone 3 is the presence of a section (indicated by a black arrow) which corresponds to a higher level of debris flashing. In our opinion, the formation of the welding bridge is more possible in zone 3, from its edge to the site with a higher level of l of debris flashing.

The sample processed in the OPEN U mode combines features characteristic for samples processed in the CLOSE and OPEN modes. In OPEN U mode, one of the nozzles is moved away from the workpiece by more than 0.1 mm, while the levels of dielectric fluid flow and debris flashing are significantly different for various sides of the sample (fig. 4).

3.3. Debris particles classification

The results of the particle size SEM analysis conducted make it possible to conclude that the majority of particles (≈70–80%) have sizes from 3 to 20 μm, the rest of the particles (≈20–30%) have sizes from 20 to 140 μm, which is confirmed by the data of other authors [13, 14]. Moreover, particles with dimensions larger than 140 μm were found when exploring the debris collected from the bottom of the tank, which excludes their occurrence in the working gap during processing. The formation of larger particles is possible at debris compacting [11]. Particles with dimensions of the order of 25 μm under the wire vibration are capable of causing a short circuit. The filling of the working gap by a particle formed at sticking of 2 other particles with dimensions of the order of 25 μm also increases the probability of a short circuit.

Thus, from the point of view of the dimensions and, as a consequence, the ability of the debris particles to overlap the working gap, two types of particles can be distinguished: «effective» and «ineffective» particles.

To «ineffective» particles refer fully crystallized particles, possessing a smooth spherical shape and a diameter of less than 25 microns. Due to the characteristic shape and size, «inefficient» particles are not able to interlap of the working gap and to form conglomerates during a collision.

Debris particles with a size larger than 25 μm and nonspherical shape refer to «effective» particles.

4. Conclusion

An investigation of the flashing conditions of a dielectric liquid during WEDM, carried out in this paper, allows formulating the following conclusions:

a) As experimental data shown, the flashing level of the dielectric liquid is minimal when processing in the OPEN mode, and the probability of the welding bridge occurrence in this mode is higher than in the CLOSE and OPEN U modes. Welding bridge formation is presumably taking place in zone 3, from its edge to the site with a higher level of debris flashing in the center of zone;

b) Simulation of flashing conditions of the dielectric liquid in SOLIDWORKS FlowSimulations software allows visualizing the liquid flow and simplifies the experimental results interpretation;

c) In the total volume of particles of the flashing debris, a sufficiently large number of particles of non–spherical form (conglomerates) occur, which lead to the formation of welding bridge and are the most probable reason of the short circuit occurrence. A classification of debris particles is proposed from the point of view of their dimensions and the ability to overlap the working gap: «effective» and «ineffective» particles. «Ineffective» debris particles are fully crystallized particles, possessing a smooth spherical shape and a diameter of less than 25 microns. Due to the characteristic shape and size, «ineffective» particles are not able to interlap of the working gap and to form conglomerates during a collision. Debris particles with a size larger than 25 μm and nonspherical shape refer to «effective» particles.

The use of sections to divide the text of the paper is optional and left as a decision for the author. Where the author wishes to divide the paper into sections the formatting shown in table 2 should be used.

5. References
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