The Influence of Steel 35 Wire EDM Parameters on the Surface Roughness and Morphology

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ABSTRACT

The electrical discharge machining (EDM) is a non-traditional machining method that has been widely used in various industries recently. The two important EDM performance measures are the surface roughness and the surface morphology. The research results of the influence of steel 35 wire EDM parameters, particularly the number of cuts on the surface roughness and the surface morphology are presented. Using the methods of atomic force microscopy, scanning electronic microscopy and profilometry, it is shown that the roughness and morphology of the machined surfaces differs much from the theoretical one, and has some peculiar characteristics. The reasons of the difference between practical results and theory are also described. The main are suggested to be the fast front spreading of a gas bubble, turbulent eddies formed by the flow of the pumped liquid. Besides, a crater with a different structure is found and an attempt to explain its nature is made.

Keywords: *Wire-EDM; roughness; surface morphology; steel 35; SEM; AFM*

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Introduction

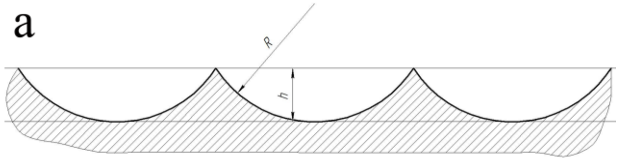
The EDM has been used for high precision machining of complex-shape workpieces made from hard materials. This type of machining was described by Lazarenko in 1946 [1]. The EDM process is based on the erosive effects of discharges flowing between the electrodes in liquid dielectric. Successive electrical discharges occur at high frequencies, and each discharge results in a tiny crater, both on the tool and on the workpiece surface [2]. This process produces a cratered surface [3]. Roughness is formed as result of many pulses as a complex of erosive craters and can be described by the scheme shown in Figure 1. The form of craters can differ from a theoretical (spherical) one, and can involve many factors: mainly, the electrodes material, the pulse duration, the discharge frequency, and the discharge current intensity [4-6].

Therefore, the actual profile formed by a plurality of craters differs from the theoretical one. The debris on the surface is also possible, which is normal for the EDM, but can cause differences from the theoretical scheme.

This paper aim is to analyze the influence of steel 35 GOST 1050-88 (analog AISI 1035) wire EDM parameters, and particularly the number of cuts on the surface roughness and the surface morphology, and to compare theoretical scheme of the surface morphology formed by sequential cuts during wire EDM with experimental results. Theoretically, material removal, as a result of EDM cuts, has the following sequence: after the 1st cut the surface profile is made of a number of craters with specific radius and depth (Figure 1a); after the 2nd cut the material is removed from the tops of the craters appeared after the 1st cut which leads to less rough surface (Figure 1b). If the surface profile presented in Figure 1b is viewed from above, after two cuts the surface morphology should look like as shown in Figure 1c and should form a kind of shapes as hexagons and circle elements with step Sx, Sy. During the third, and the following cuts, the material removal should have the same sequence. The general image of the surface is made-up by a number of craters crossing each other, and limited by rims or by bulges. The formation mechanism of the bulges around the crater is clarified by Yang at al. [7].

The same scheme about metal surface forming is described in Serebrenitsky [8]. The author points out the difference between the theoretical and the experimental data, too.

a



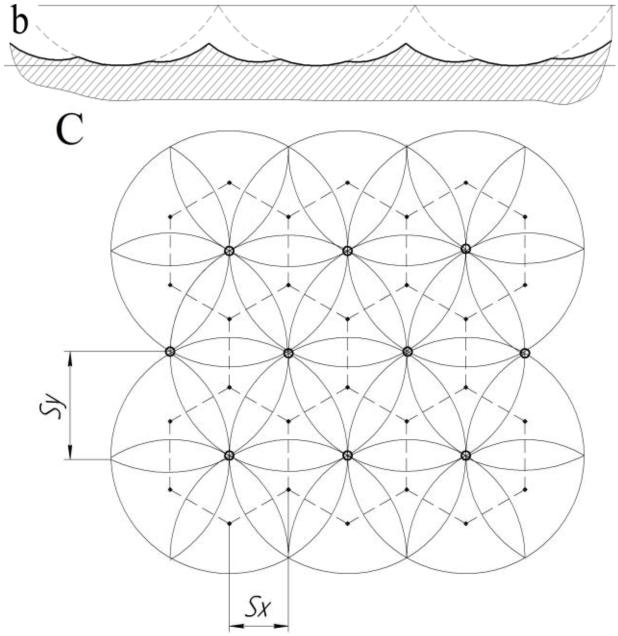


Figure 1: Theoretical scheme of the surface morphology and the surface roughness form: a – surface profile after the 1st cut, b – surface profile after the 2nd cut, c – surface morphology

Methodology

The workpieces were flat samples of 140×50×10 mm constructional steel 35. The content of the main elements in steel 35 is as follows: C = 0.35 %; Si = 0.21 %; Mn = 0.69 %; Cr = 0.1 %; Ni = 0.15 % (by weight). The workpieces machining was carried out by EDM machine SODICK VZ300L during the first, second, third and fourth cut. Deionized water has been used as dielectric fluid. During the experiment, the nozzles positions were also changed while machining (Figure 2a – 2c). The schemes corresponding to these positions are shown in Figure 3a – 3c:

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);

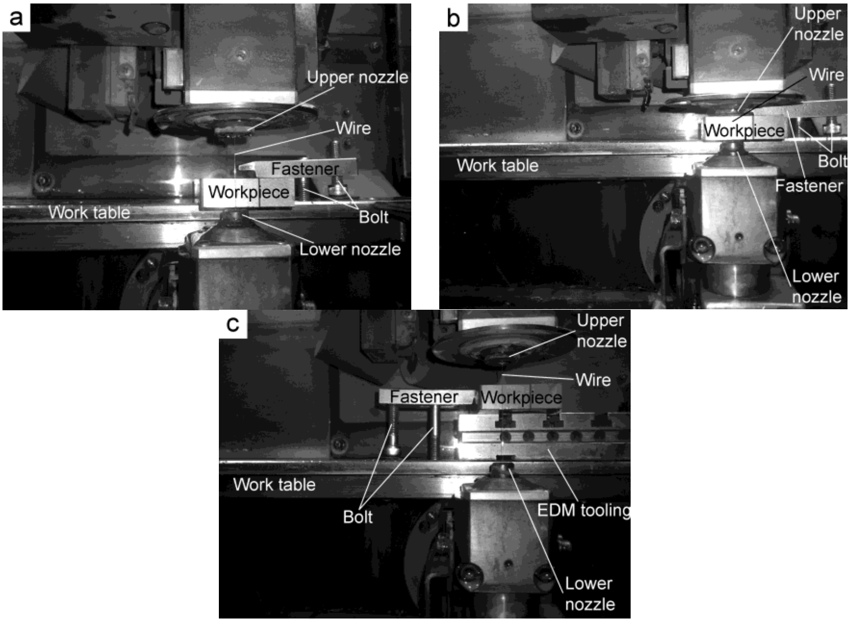


Figure 2: Nozzle positions: a – OPEN U, b – CLOSE, c – OPEN

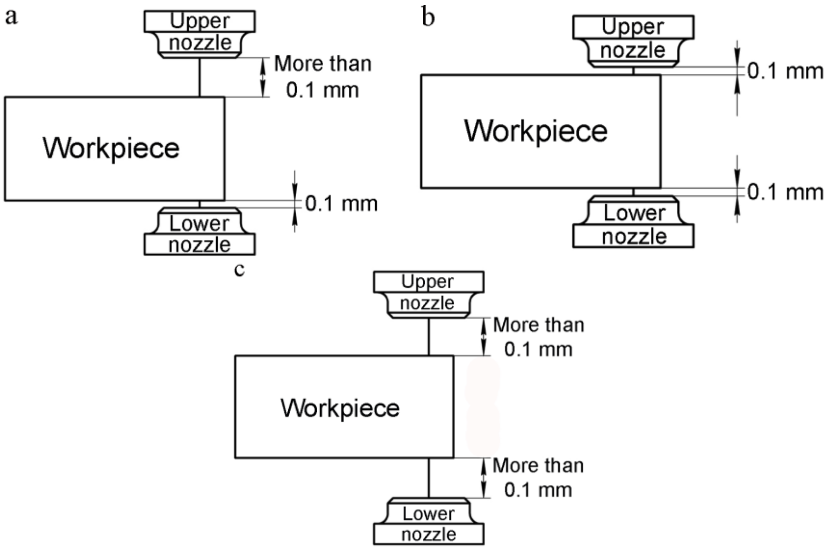


Figure 3: Nozzle positions schemes: a – OPEN U, b – CLOSE, c – OPEN

The machining parameters are shown in Table 1. Uav and Iav calculated by the machine software were monitored by the indication of the on-board voltmeter and ammeter.

Table 1: Machining parameters

№ of cut	**Uav, V**	**Iav, A**
The first cut	43	12.3
The second cut	70	1.1
The third cut	59	0.8
The fourth cut	15	0.5

Where Uav is the average voltage value; Iav is the average electric current value.

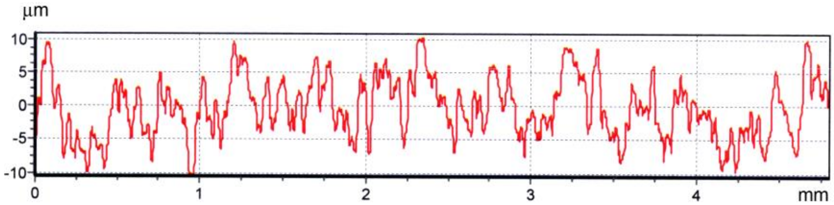
The study of the surface morphology and roughness was carried out using three methods: first, the profilometry, performed with the surface roughness tester TR220; second, atomic force microscopy of the workpieces, carried out by the NTEGRA Prima scanning probe microscope in the air contact mode, (the images obtained were analyzed by IMAGE ANALISIS (NT-MDT) program module); third, scanning electron microscopy, carried out by JEOL JCM-5700 microscope in high vacuum mode (the signal type was SEI). The spotsize parameter was changed in the range from 20 to 71, the value of accelerating voltage was changed in the range 5 – 20 kV, magnification was in the range from 300× to 11000×.

Results and discussion

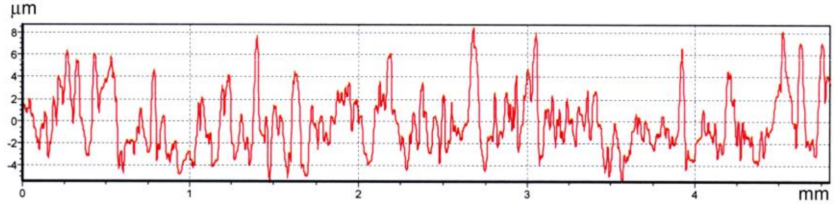
Workpieces profilograms obtained after cuts 1 – 4 were given in Figure 4a – 4d, correspondently, while obtained values are listed in Table 2.

Table 2: Ra/Rt values after the 1 - 4 cuts

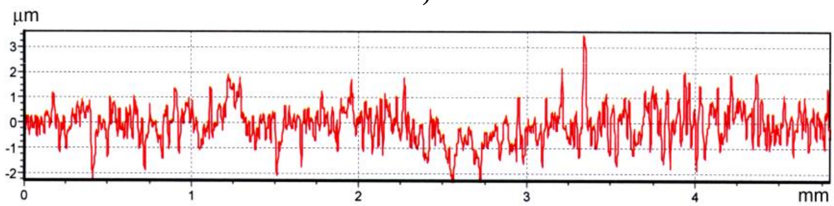
№ of cut	**Ra1, µm**	**Ra/Rt, µm**
The first cut	2.8	3.04/20.21
The second cut	1.8	1.88/14.43
The third cut	0.8	0.53/5.56
The fourth cut	0.4	0.36/2.99



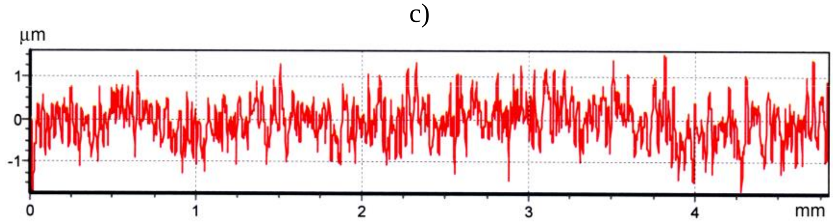
a)



b)



c)



d)

Figure 4: EDM-ed surface steel 35 profilograms: a – after the first cut, b – after the second cut, c – after the third cut, d – after the fourth cut

Where Ra1 is the roughness, stated by a machine manufacturer, i.e. such surface roughness that should be obtained if steel SKD 11 (HRC 58) is machined according to SODICK VZ300L manual; Ra/Rt is the real roughness value obtained by profilometry.

The actual roughness obtained after the machining differs from that stated by a manufacturer, due to the differences in the chemical composition of the material. In the machine software there is only one mode for steel, which can differ significantly in chemical composition from the machined steel 35 resulting in the described differences. Before the discussion, it is necessary to note that all the images showed below are taken of the surfaces machined in the OPEN U mode, which is between “OPEN and CLOSE” modes positions, and proved to be quite informative.

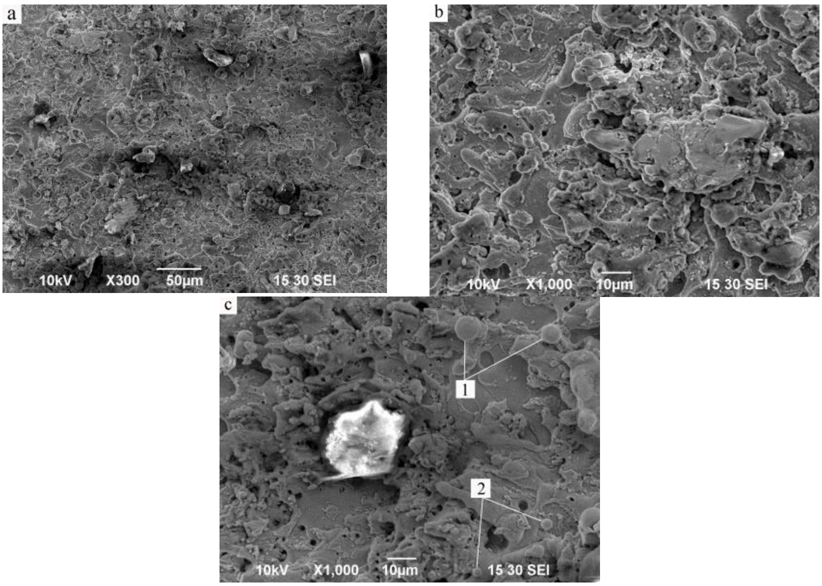


Figure 5: Morphology of EDM-ed steel 35 surface after the 1st cut obtained by SEM: a – 300×, b – 1000×, c – amorphised spheres stuck to the surface as a result of insufficient machining, 1000×

However, it should also be noted that after the first cut (Figure 5) the surface has a morphology acutely different from that obtained after the mechanical machining, as well as from the theoretical one obtained after EDM-ing (Figure 1c). In particular, there is no microrelief regularity formed by adjacent or crossing craters, possibly, the micro-relief in this case is formed by craters, but their boundaries are worn down much by the metal splashed from craters and formed numerous bulges. As the first cut is made at high-energy mode, the surface varies in height. There are areas sized 50-100 µm and more, located below the mean line (black spots in Figure 5a). Besides, there are plenty of details on the surface, looking like swarf and EDM-debris, which could not be swept away by the fluid, but, on the contrary, were welded to the surface while being molten. Probably, the highest peaks in the corresponding profilogram (Figure 4a) are determined by this swarf and EDM-debris. Metal spheres are detected in Figure 5c. As the analyses showed, they are different: some spheres 1 are larger, 7.2 – 9.6 µm in size, some spheres 2 are smaller, 3.2 - 4 µm in size. It is obvious that the spheres under study are amorphized and present the result of over-freezing metal being spurtled from the crater. The process of sticking the spheres to the surface seems to be very much like the process of EDM debris lapping to the surface as described below.

The sticking of the workpiece discharged metal to the machined surface is caused by EDM conditions deterioration, because the spark gap is about 0.05 mm and, inside it, gas bubbles appear as the erosion result. The bubbles break down the continuous flow of dielectric fluid thus disturbing erosion product discharge.

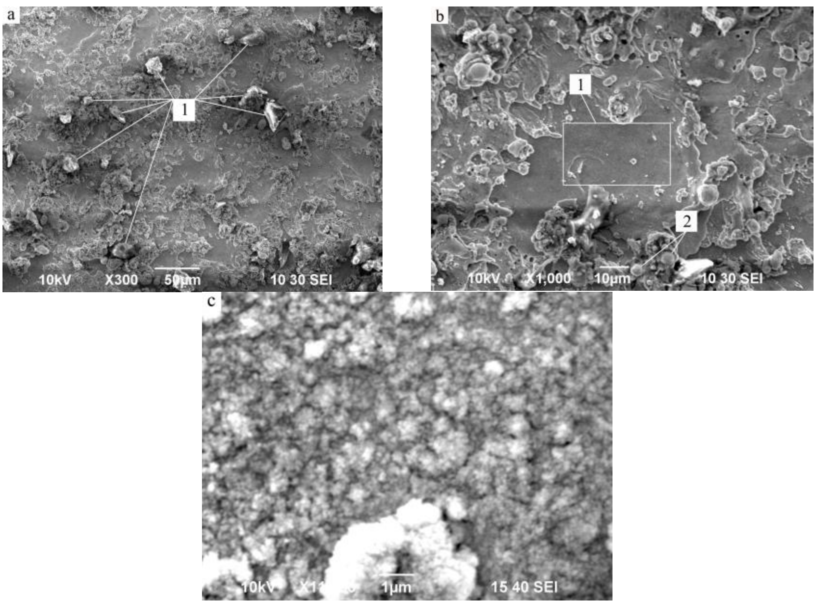


Figure 6: Morphology of EDM-ed steel 35 surface after the 2^{nd} cut obtained by SEM: a – 300×, b – 1000×, c – surface morphology in the area, marked by a rectangle in Figure 6b 1, 11000×

After the third cut, the surface becomes more homogeneous (Figure 7), and it looks like theoretical microrelief, but has some differences and consists of a variety of craters with the average size being 15 – 20 µm. There are also large craters with 30 – 40µm size, and there are only few stuck EDM debris particles 1 (Figure 7a).

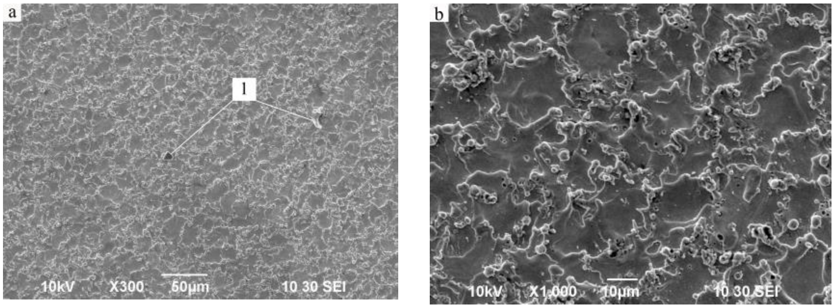
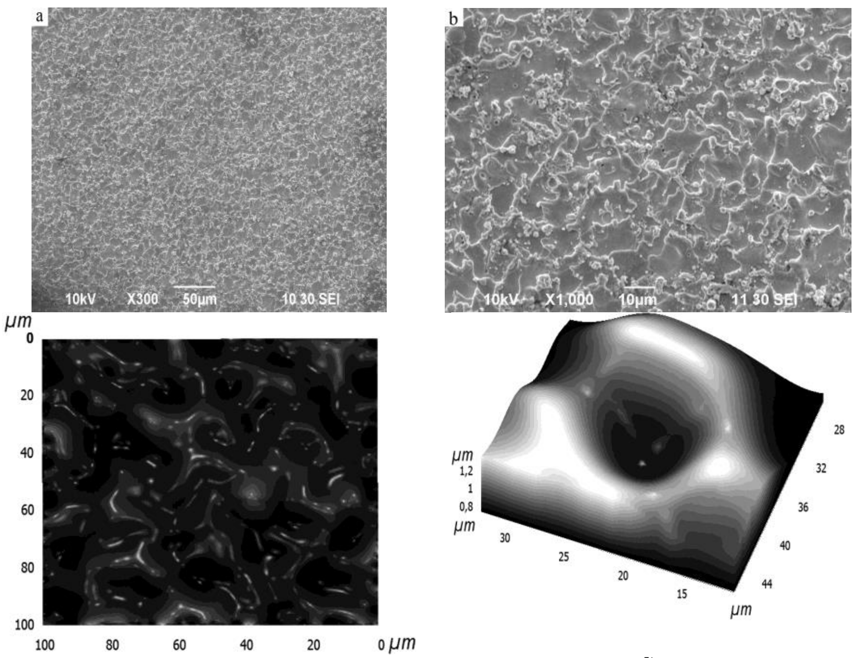


Figure 7: Morphology of EDM-ed steel 35 surface after the 3rd cut obtained by SEM: a – 300×, b – 1000×



c) d)

Figure 8: Morphology of EDM-ed steel 35 surface after the 4th cut obtained by: a – SEM, 300×; b – SEM, 1000×; c – AFM, 2D image; d – AFM, single crater 3D image

The fourth cut provided the smoothest surface (Figure 8a, 8b). Stuck EDM debris is not observed. The size of a single crater is 12.5 - 13µm. It is necessary to note that the overall relief look is the similar after the 3rd and the 4th cuts, but craters sizes and Ra parameter values differs much (Figure 4c - 4d and Table 2). Atomic force microscopy of surface and a single crater after the fourth cut (Figure 8c, 8d), and the scanning electronic microscopy result is proved (Figure 8a, 8b). Particularly, it can be noted, that a single crater is surrounded by bulges formed by discharged metal laps.

Let us consider some more characteristics of the surface morphology. In particular, crater 1 shown in Figure 9a, seems to be interesting for this research. More carefully studying was on this area after 7500× magnification (Figure 9b).

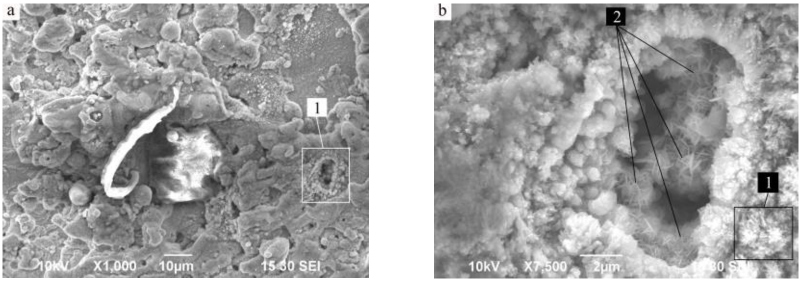


Figure 9: Morphology features on steel 35 surface after wire EDM: a – abnormal crater area, one cut, 1000×; b – abnormal crater area, one cut, 7500×

It was noted that the crater boundaries have coral-like relief 1, while the crater bottom has a profile made of spikes 2 with 0.5-1 µm length and about 100-200 nm thickness, looking like martencite plates, it is necessary to note that such microstructures have never been described before by scientists working in the sphere of EDM. The describing of their occurrence process is rather difficult nowadays. However, we suppose that the crater itself appeared after the single impulse, which is much stronger in its electric parameters than a working mode average impulse. The spikes are a result of fast cooling of metal micro volume under high pressure. Below is our view on the mechanism of this area formation. Today, material scientists already describe the mechanism of martensite plates forming: if steel cooling rate ν after high temperatures (higher than the A_3 point) becomes higher than critical cooling rate ν_{cr}, decomposition of austenite into ferritic-cementitic mixture is suppressed, and austenite experiences martensitic transformation. Point A_3 is equal to 810° C for steel 35. As known from the wire EDM process physics, plasma channel temperature can reach 5000° K or more, which is much higher than A3 point that is why metal starts melting and even evaporating. Under the melted metal zone, there is an area, heated higher than A3 (Figure 10).

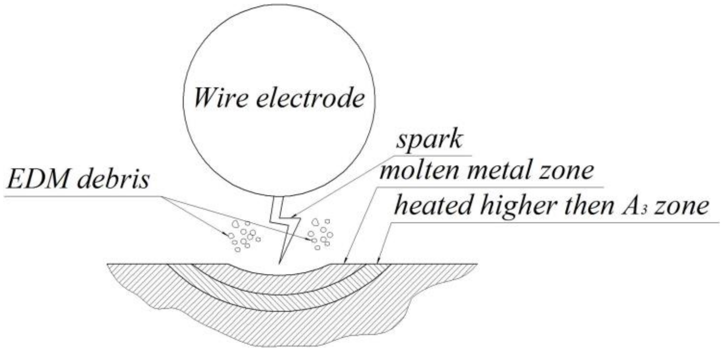


Figure 10: Position of heated higher then A3 zone

A part of the top layer evaporates while the melted part is spurtled from the crater and taken away by the flushed fluid stream. At this moment, the area heated higher than A3 becomes open. Continuous flushing provides not only the erosion by-products taking away but also required cooling rate of the area heated higher than A3, i.e. condition $v > v_{cr}$ is met. We have the necessary set of conditions (heating higher than A3, followed by cooling) for surpassing austenite decomposition into ferritic-cementitic mixture and its martensite transformation.

As known from Nishiyama [9], martensite transformation does not reach its end and that is why there is always retained austenite in steel, possibly found between martensite plates (Figure 9b). It is also known from Gulyaev [10] that in low-carbon and medium-carbon steels the martensite plates width is 0.2-2 µm while its length should be 4-5 times bigger. This fact corresponds well with the photos obtained in the given experiment.

Still, the following question seems to be interested: if such area is a defect leading to strength, cracking resistance and other characteristics decrease. However, verification of this idea is the object of an independent research, in the future. In our opinion, it is possible, that this area is neutral and does not have any negative effects. This crater does not have any positive effect either, because such elements can be rarely found on the surface.

The results of the surface morphology analysis have shown, that the surface resulting after EDM (Figure 5-9) does not correspond to the theoretical one (Figure 1c). In our opinion, there are two reasons for this. The first reason is the fact that the idealized theoretical model does not account for the formation of a gas bubble at each elementary act of removing microscopic metal volume. It is known that the pressure in the gas bubble may reach 20 GPa. It does not also account for the spreading of the gas bubble front, which may have different effects on the molten metal micro volume. Generally, the impact is reduced to the sticking of the molten metal to the craters surface and partial displacement of a certain volume of metal. In addition, the theoretical modeling becomes even more complicated if we try to consider the interaction of several gas bubbles fronts.

Given that in 1 second a few hundred or even thousand of pulses occur, the impact of gas bubbles at each other will definitely take place. The second reason is that the theoretical model does not take into account the counter flows of the pumped liquid. The pumped liquid is supplied from the upper and lower nozzles. Having met in a narrow inter-electrode gap, the flows form turbulent eddies, which in addition to the removal of sludge can cause sticking to the surface. Finally, in our view, the most difficult situation for modeling is the simultaneous effect of the two factors described above.

Besides the above, we can say that the actual surface shape mismatch is caused by a variety of the single crater forms, which in its turn, is caused by the anisotropy of the material being machined.

Conclusion

In conclusion, the present research has shown that the surface morphology and roughness obtained during the research differs very much from the theoretical one. The relief described in theory and consisting of closely located craters is reached only after the third cut. At the same time, there is no one crater with the round form on the surface under study. Zigzag lines form all the craters boundaries. The size of the craters varies considerably, too, and can double in size. We could suggest the following main reasons of the difference between the theoretical model and the result obtained in practice:

- The presence of a gas bubble in every elementary displacement of metal micro volume.
- Turbulent eddies, formed by the flows of the pumped liquid.
- Anisotropy of the material being machined.

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