Investigation of the impact of WEDM modes on surface morphology, roughness and cracking of zirconium, niobium and vanadium

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Abstract. Zirconium, niobium and vanadium are the high costly refractory metals that cause the topicality of economically processing and waste minimization during manufacture the products from such metals. The purpose of this work is to establish the quality of the surface layers after wire electrical discharge machining (WEDM) of Zr, Nb and V. The morphology and crack formation in the surface layers of zirconium, niobium and vanadium was investigated by SEM and profilometry methods. The results of the WEDM regimes influence on morphology, roughness and crack formation in the surface of Zr, Nb and V are presented. It is established that refractory metals are processed more difficult than steel, copper and aluminum alloys, although the morphology of the treated surfaces are practically no different.

1. Introduction

It is known that traditional methods of machining are not always suitable for the products’ manufacture from refractory metals. High cost of refractory metals causes the necessity of the waste minimization. This can be achieved by cutting width reduction, thereby reducing the amount of chips. Good results in solving this problem have been achieved by using wire electrical discharge machine, as the diameter of the wire electrode 0.2 mm the cutting width does not exceed 0.3 mm. However, manufacturers equip the machines with a set of processing modes only for the most common materials (steel, copper and aluminum alloys, graphite, tungsten carbide-based hard alloys). When processing metals that are not of the machine’s database, including the zirconium, niobium and vanadium processing, a necessity for experimental selection of appropriate modes arises. The treatment of metals at the modes which are not optimal for each particular metal or alloy involves a number of problems. At overstated modes, a tool, such as brass wire, breaks, in this case the processing time increases, and at lowered modes the processing speed reduces, that also leads to the growth of machine time and, as a consequence, to the part’s cost.

One of the key criteria of the parts quality after their processing is the purity of the surface layer. Many researchers study the EDM process. For example, in order to determine the optimal processing modes the simulation of EDM process of some steel grades is carried out [1]. It is noted that erosion resistance depends on heat-transfer properties of materials (the higher metal enthalpy, the slower is its processing) [2].

Researchers, who study the morphology of refractory materials surface treated with EDM method first of all, note the presence of cracks on the processed surfaces. For example, the paper [3] describes EDM treatment of tungsten carbides with zirconium oxides content, which surface becomes less flexing resistant after treatment by EDM method due to formation of cracks (before treatment...
1536±131 MPa, after treatment 926±160 MPa). It was also found that processing of zirconium ceramics leads to reduction of its flexing resistance [4]. In this case, the use of final smoothing provides the restoration of the original properties, which indirectly confirms the influence of cracks presence in the surface layer of materials on their strength characteristics.

As provided in paper [5], the reduction of flexing resistance is connected with the formation of cracks that appear due to residual stresses that exceed the tensile strength of material. It is reported that for the surfaces processed by WEDM a presence of the diffusion layers formed as a result of the molten metal movement is typical [6]. High cooling rate of the near-surface layers causes the microcrack formation due to the thermal stresses arising during WEDM of metals and ceramic materials. Formation of cracks occurs due to the effect of thermal tensions exceeding the ultimate strength of material, as well as due to its plastic deformation during WEDM [7]. It was found that some cracks are formed in the lower part of the craters and oriented in the radial direction, while other cracks can be oriented parallel to the surface. The cracks density increases with the growth of the energy and pulse duration, as well as the thermal stresses [8].

In the work [9] deformation zones are pointed out that give rise to the cracks formation. At the same time, cracks formation is explained by extension of crystal grains in the shear direction and by the formation of a lamellar not equiaxial structure [10]. It was found that for some metals the depth of the crack-saturated defective layer exceeds the width of the diffusion layer [11]. This indicates a decrease of crack formation degree with the thermal conductivity increasing of the processed material.

As evidenced by the literature review, the great attention is paid to investigation of the surface quality in WEDM of different materials.

2. Task definition
The purpose of the present study is to establish the quality of the surface layers after wire electrical discharge machining (WEDM) of Zr, Nb and V. The samples of zirconium, niobium and vanadium were prepared and processed in one, two, three and four passes. The quality of Zr, Nb and V surface layers was estimated by SEM and profilometry methods.

3. Experiment
The During the experimental part of the study zirconium, niobium and vanadium were processed on the wire electrical discharge machine SodickVZ300L. Average values of processing modes for all metals were selected (table 1). In this work zirconium (E110), niobium (NB–1P, TU 48-4-241-73) and vanadium (GNP–1, TU 48-4-374-76) rods were used as billets. Brass wire (Cu 60%, Zn 40%) with a diameter of 0.2 mm was used as a tool. Distilled water was used as a dielectric fluid.

| Ucp | Icp | H   | On  | Off  |
|-----|-----|-----|-----|-----|
| 1 pass | 60  | 2.3 | 0.106 | 0.8 | 0.14 |
| 2 pass | 55  | 2.1 | 0.031 | 0.2 | 0.11 |
| 3 pass | 45  | 1.1 | 0.011 | 0.1 | 0.01 |
| 4 pass | 40  | 1.0 | 0.005 | 0.1 | 0.01 |

Ucp – average voltage, Icp – average current strength, H – offset, On – pulse length, Off – pause between pulses.
Experimentally established processing variables ensure the stability of processing without wire breaks. After processing, it was carried out the study of morphology and surface roughness of the samples after each pass. The morphology of the sample’s surfaces was carried out by using JEOL JCM–5700 scanning electron microscope in high-vacuum mode. Signal type - secondary electrons (SEI). The SpotSize parameter (spot size) is 50, the value of accelerating voltage is 10 – 20 kV, zoom is from 5000 to 15000 times. Surface roughness was studied by using profilometer TR–220 (TimeGroup) at base lengths of 0.8 and 0.25 mm.

4. Experimental results

SEM analysis of zirconium, niobium and vanadium surfaces after WEDM allows to make a conclusion that morphology of the processed surface layers is typical for metal materials and is practically do not vary from morphology of steels, copper and aluminum alloys (Fig.1-3). During WEDM at the time of spark discharge microscopic volume of molten metal distracts from the billet followed by a microscopic crater formation. The splintered material spreads chaotically on the surface and solidifies. After WEDM of zirconium, niobium and vanadium the cracks was found in the surface layer after each pass.

Cutting conditions on the first and second passes are more intense than on the subsequent passes. In this case the maximum width of the cracks reaches 1 µm on the surface of zirconium and vanadium (Fig. 1 a, b; Fig. 3 a, b), while for niobium (Fig. 2 a, b) this parameter does not exceed 0.5 µm. The cracks length for each material are different (for zirconium from 3 to 15 µm (Fig. 1 a, b), for niobium from 8 to 25 µm (Fig. 2 a, b), and for vanadium from 5 to 30 µm (Fig. 3 a, b). After cutting on the third and fourth passes, the crack sizes for all materials are reduced, which is especially typical for zirconium (the maximum width does not exceed 0.2 µm, and the length differs from 3 to 7 µm (Fig. 1 C, d)). For niobium and vanadium, only the cracks width varies greatly (for niobium, the width does not exceed 0.2 µm (Fig. 2 V, g), while for vanadium the cracks with a more than 0.5 µm width were not found (Fig. 3 c, d)), the length decreases by about 15-20%.

Surface roughness for each material after all four passes was measured on the profilometer (table. 2). Profilograms (Fig. 4-6) illustrated that in the first two passes Ra for zirconium does not exceed 3.82 µm and not less than 3.08 µm, for vanadium the same value is from 2.27 µm to 2.57 µm, and for niobium it is from 2.57 µm to 2.86 µm. On the third and fourth passes there is a sharp decrease in the roughness from 0.68 µm to 0.47 µm for zirconium, for vanadium from 0.57 µm to 0.43 µm, and for niobium from 0.55 µm to 0.44 µm.
Figure 1. Morphology of zirconium surface after EDM process with zoom of 5000 and 10000 times: A) after one pass, B) after two passes, C) after three passes, D) after four passes.

Figure 2. Morphology of vanadium surface after EDM process with zoom of 5000: A) after one pass, B) after two passes, C) after three passes, D) after four passes.
Figure 3. Morphology of niobium surface after EDM process with zoom of 5000: A) after one pass, B) after two passes, C) after three passes, D) after four passes.

Table 2. Roughness (Ra) of zirconium, niobium and vanadium after 1 pass, 2 passes, 3 passes and 4 passes.

|       | 1 pass | 2 pass | 3 pass | 4 pass |
|-------|--------|--------|--------|--------|
| Zr    | 3.82   | 3.08   | 0.68   | 0.47   |
| Nb    | 2.86   | 2.57   | 0.55   | 0.44   |
| V     | 2.57   | 2.27   | 0.57   | 0.43   |

Figure 4. Zirconium profilograms: A) after 1 pass, B) after 2 passes, C) after 3 passes, D) after 4 passes.
Figure 5. niobium profilograms: A) after 1 pass, B) after 2 passes, C) after 3 passes, D) after 4 passes.

Figure 6. vanadium profilograms: A) after 1 pass, B) after 2 passes, C) after 3 passes, D) after 4 passes.

5. Results and discussion

Footnotes As the melting point of materials varies, so the equal pulse energy leads to melting of different metal volume, which randomly spreads over the surface, forming cavities and flows of various forms and sizes, which explain the differences in surface roughness of materials.

Cracks formation occurs due to rapid heating of a billet surface over 5000°C and rapid cooling by dielectric fluid with temperature of 20 °C. Due to thermal stresses the cracks formation occurs. The presence of cavities and holes, which are the stress concentrators, also plays an essential role in the cracks formation. Cracks arranged a randomly form grid. In case of zirconium and niobium the cracks traverse at different angles, and in case of vanadium, a frequent traversal at right angle may be seen. This fact may indicate that cracks pass along grain boundary, further research is needed for this hypothesis examination.

In the work [13] maximum depth of zirconium layer, in which identification of copper diffused from the wire is found out. The maximum depth of the layer was: for the first pass – 15 µm; for the second-8 µm; for the third-5 µm and for the fourth– 2 µm. Further studies have shown that for niobium and vanadium the results are similar. It should be noted that in this work the interrelationship between the depth of cracks and the width of diffusion layer, which can be removed by finish machining (for example, grinding or polishing), was not taken into account. The literature review showed a necessity to take into account the named interrelationship for each of processed metals. At the same time, crack formation at WEDM can act to raise adhesion of surfaces which are not expected to be used in conditions of increased pressures.
Figure 7. Transverse microsections of zirconium samples: A) after one pass, B) after two passes, C) after three passes, D) after four passes.

Study of transverse microsections of zirconium samples (Fig. 7) showed that with each pass the depth of cracks penetration decreases due to reduction of parameters of machining conditions. For the first pass, the crack depth was 10.19 µm (Fig. 7a), for the second pass 1.7 µm (Fig. 7b), for the third pass 0.8 µm (Fig. 7b), for the fourth pass in average, 0.5 µm (Fig. 7G).

6. Summary and conclusion

WEDM is an economical method of refractory metals processing. Based on data of the cracks penetration depth, it could be concluded about necessity of increased allowances presence for final grinding or smoothing before using the products for their intended purpose. Finish machining of the surfaces subjected to WEDM is especially relevant in cases when products manufactured through this method will function in conditions of significant mechanical effects. This causes the further studies of zirconium, niobium and vanadium surfaces after WEDM to specify the optimal machining conditions of grinding or polishing.

7. References

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