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STUDY OF THE EFFECT OF ELECTRICAL DISCHARGE CUTTING ON FORMATION OF A DAMAGED LAYER DURING PROCESSING OF TUNGSTEN SINGLE CRYSTALS

Yu.O. Nikitenko, V.O. Shapovalov, V.V. Yakusha, O.M. Gnizdylo, D.M. Zhirov

E.O. Paton Electric Welding Institute of the NASU
11 Kazymyr Malevych Str., 03150, Kyiv, Ukraine

ABSTRACT

The new type of electrical discharge machining without immersion of the processed workpiece is characterized by higher cost-effectiveness, simplified maintenance, and safety. In addition, a molybdenum wire with multiple reversible feed is used as a cutting tool, instead of a consumable brass wire. This study presents the results of experiments on processing tungsten single crystals by varying the technological modes of electrical discharge cutting. The dependences of the effect of the duration of electrical discharge pulses and the pause between them on surface morphology, depth of interplane crack formation, and cutting speed were determined. Molybdenum wire with a diameter of 0.18 mm and a tungsten single crystal with a thickness of 15 mm were used as tools and working material in the experiments.

KEYWORDS: tungsten single crystal, electrical discharge cutting, damaged layer, interplane cracks

INTRODUCTION

Unique properties of single crystals which are due to structural perfection and anisotropy of the crystal lattice have an essential role in ensuring the required parameters and durability of products made from them. Therefore, the question of processing single-crystal products is relevant, both for semiconductor, and for metal materials, as the unremoved damaged surface layer completely levels out the unique properties inherent in the single-crystal structure [1]. High thermomechanical loads, which are in place during machining, result in formation of a defective layer, with a high concentration of dislocations. The surface layer with a damaged structure is one of the most common types of defects in manufacturing products from single crystals, as production of solid-state elements is related to a certain set of necessary operations of surface processing, such as cutting, grinding, polishing, and subsequent finer finishing to ensure the specified product characteristics. This question is particularly relevant for general investigation of the single crystal properties in the sense of studying the damaged layer depth, its influence on subsequent processing stages to avoid its development and investigation of the internal (actual, undistorted) crystalline structure [2].

Determination of the thickness of damaged surface layer of single crystals, i.e. after cutting, grinding and physical-chemical polishing, allows optimizing the modes of crystal machining.

As tungsten single crystal is a rather hard material, its machining by a cutting tool is quite problematic, both for the tool and for the crystal proper. Characteristic parameters of the damaged surface layer largely determine the degree of structural perfection of the single crystal proper. The value of this quantity may depend not only on the single crystal processing method, but also on the directions of force impact on the processed crystal, having the specified crystallographic orientation.

That is why, electrical discharge (electrical spark) machining is often used for primary processing of refractory metal single crystals (to eliminate hard machining). Electrical discharge machining is a controlled destruction of current-conducting material under the impact of electrical discharges between the electrode and the part. Discharges occur in the pulse mode so that the interelectrode space has enough time to restore its electrical resistance.

After electrical discharge machining, particularly of tungsten single crystals, a polycrystalline layer with an axial texture is formed on the metal surface. The fine structure of this layer, as well as its formation mechanism, is closely related to the anisotropy of metal properties in a single-crystal state.

The most widely accepted method of Wire Electrical Discharge Machining (WEDM) is the method of cutting samples, which are completely immersed into the working fluid (kerosene or water). Brass wire is used as the cutting tool, and many studies have been conducted in this field [3–5]. Development of the technologies of electrical discharge cutting allowed creation of new variants of this process. Instead of a consumable brass wire, 0.18 mm molybdenum wire with reversible feed is used, that is the wire of the specified length takes part in cutting many times, owing to winding on and unwinding from the drum. Cutting proceeds without immersion, but with feeding of the water-based

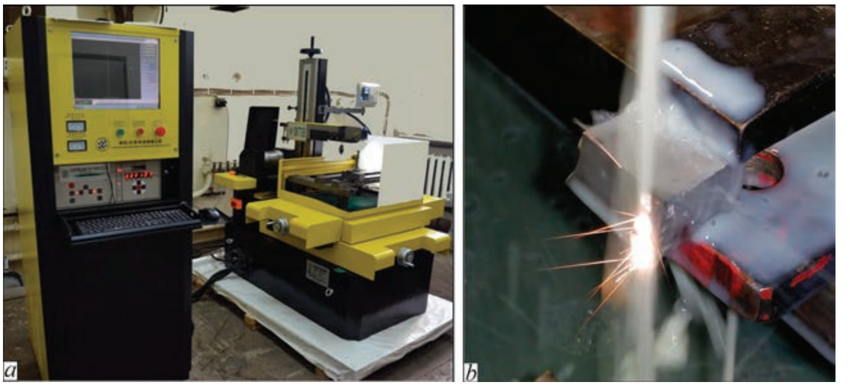

Figure 1. Appearance of the electrical discharge cutting machine DK7732 (*a*) and photo of the process of cutting a sample of tungsten single crystal (*b*)

Table 1. Characteristics for calculation of cutting parameters

Characteristic	*K*	0	1	2	3	4	5	6	7
Pulse duration	μs	1	2	4	6	9	12	16	20
Characteristic	*K*	8	9	A	B	C	D	E	F
Pulse duration value	μs	24	28	32	40	48	56	64	72

lubricating and cooling agent (LCA) from the sample top and bottom. The wire, making a reversible motion, captures a certain amount of LCA with its surface and transports it to the location of spark gap.

That is why, the performed study of the influence of technological parameters of WEDM-process of electrical discharge cutting on the properties of the damaged layer of tungsten single crystals is an important scientific-practical task, having current practical importance for their wider application in engineering.

TECHNOLOGICAL EQUIPMENT, EXPERIMENTAL PROCEDURE AND MATERIALS

Wire-cut electrical discharge machine DK7732 (TOSUN) with CNC is designed for processing any current-conducting materials, including metal-ceramic alloys, non-ferrous metals and other difficult-to-process materials, which allows producing complex shaped external and internal surfaces from them (Figure 1, *a*). DK77 series machines are jet type machine tools, where processing is conducted not in a bath with fluid, but on the working table, where LCA is supplied directly into the processing zone from the bottom and the top (Figure 1, *b*).

The main technical characteristics of electrical discharge equipment are given below.

Specification of DK7732 machine

Cooling liquid type . . . . Water with addition of JR3 emulsion (A, B, C, D, H, G)
Electrode type . . . . Reusable molybdenum wire
Overall dimensions of the working table, mm . . . . . Not less than 620×450
Working table travel (*X*, *Y*) . . . . Not less than 450×350
Maximal weight of the part placed on the working table, kg . . . . Up to 600
Maximal processed height of the part, mm. . . . . Up to 300
Usable wire diameter, mm 0.04–0.22
Part processing accuracy, mm. . . . . .Not more than 0.010
Accuracy of repeatable positioning of *X*, *Y* axes, μm . . . . Not more than ±1
Installed power, kW . . . . Not more than 3

In keeping with the user manual, the machine has four main groups of changeable processing parameters, which influence the cutting process characteristics: pulse duration (values of 0, 1, 2, 3, 4, 5, 6, 7, 8, 9, A, B, C, D , E, F); pulse interval (values of 0, 1, 2, 3, 4, 5, 6, 7, 8, 9, A, B, C, D, E, F); tracking the critical interelectrode spacing (values of 0, 1, 2, 3, 4, 5, 6, 7, 8, 9, A, B, C, D, E, F); pulse amplifier level (values of 0, 1, 2, 3, 4, 5, 6, 7, 8, 9, A)

To conduct a pure experiment, only such current characteristics as pulse duration and interval between them were studied. Tracking and amplification parameters were unchanged in all the experiments and their values were 1 and 6, respectively.

Table 1 gives the values of pulse duration (in microseconds), depending on the *K* setting parameter. Value of the interval between the pulses is calculated as $4 + 0.25K$ (where *K* is the pulse duration, in keeping with the value from Table 1).

EXPERIMENTAL RESULTS AND THEIR ANALYSIS

The problem of single crystal machining is highly relevant both in product manufacturing and in seed crystal production. Formation of deep gaps between the planes may lead to formation of parasitic grains of different orientation.

For instance, in order to produce a crystal in the form of a body of revolution, machining is used to cut off a seed crystal from a large flat crystal, which was grown with lateral face orientation in the plane (100) (Figure 2, *a*). The seed crystal is given a circular shape and

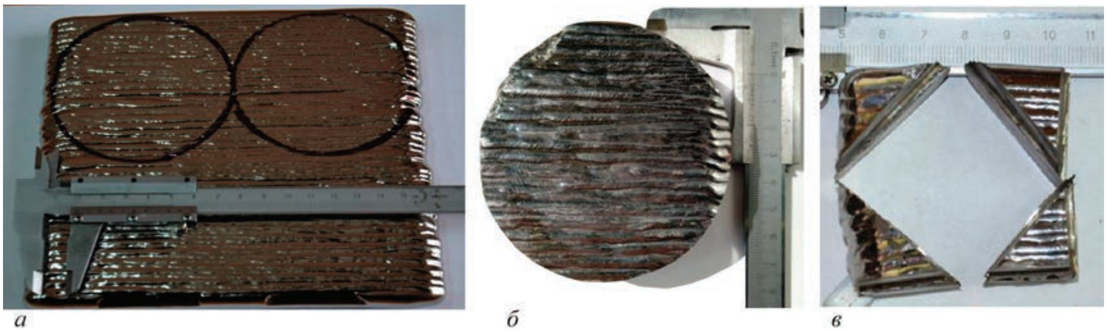

Figure 2. Stages of producing seed single crystal for growing a tungsten ingot in the form of the body of revolution: large flat single crystal of 170×160×25 mm size (*a*), round seed crystal 85 mm in diameter (*b*) and corner segments remaining after treatment (*c*)

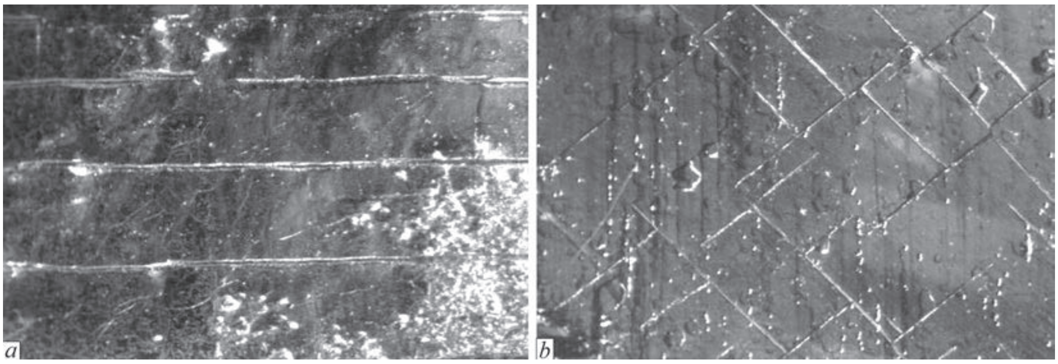

Figure 3. Crack network on the side (*a*) and bottom surface (*b*) of the seed crystal after abrasive treatment

all unnecessary elements are separated (Figure 2, *b*, *c*). Harsh processing conditions may result in formation of a network of cracks which corresponds to the crystal orientation of the ingot. Figure 3 gives an example of crack formation on the side and bottom surfaces. Presence of parallel and rectangular cracks corresponds to interplanar formations for orientations (100, 010, 001).

With application of electrical discharge cutting, the process of cutting out the seed crystal becomes much easier, and the need for additional treatment of the side surface is eliminated. The seed crystal has the set ideal cylindrical shape 85 mm in diameter (Figure 4). Even though the side surface has a damaged defective layer, it is much smaller, and during the technological process of plasma-induction growing the surface melting at a minimal speed of sample rotation ensures restoration of the single-crystal structure.

During examination, the cut surface is rough with a not more than 0.2–0.3 mm defective layer, which is related to the features of electrical discharge cutting (Figure 5). During cutting electrical discharges are sent in-depth of the base metal, forming a defective layer. Defects are manifested as chipping of material from the surface in the form of geometric shapes pointing in the same direction. During chemical etching, a set of parallel cracks is revealed (Figure 6). The same direction of the rectangle defect edges is indicative of preservation of the general orientation of the single-crystal structure. Stresses accumulated during treatment may lead not only to formation of a crack network, but also to fragment spallation from the surface. A solution of hydrofluoric (HF) and nitric (HNO_3) acids in a ratio of 1:1 was used as the chem-

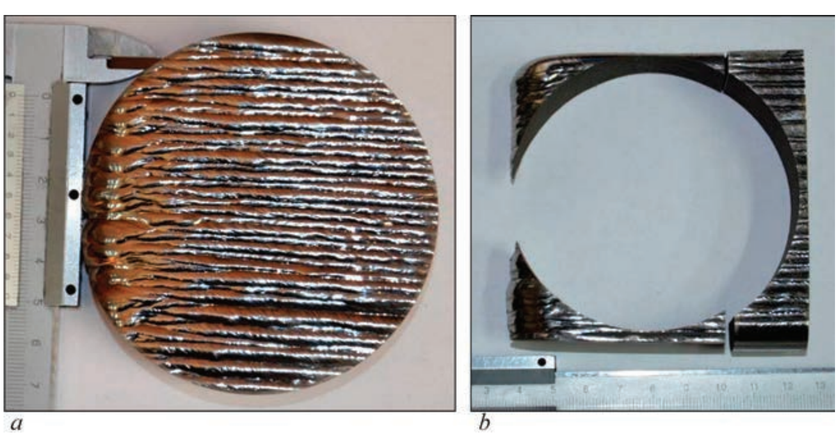

Figure 4. General view of the seed crystal (*a*) and remains after electrical discharge cutting (*b*)

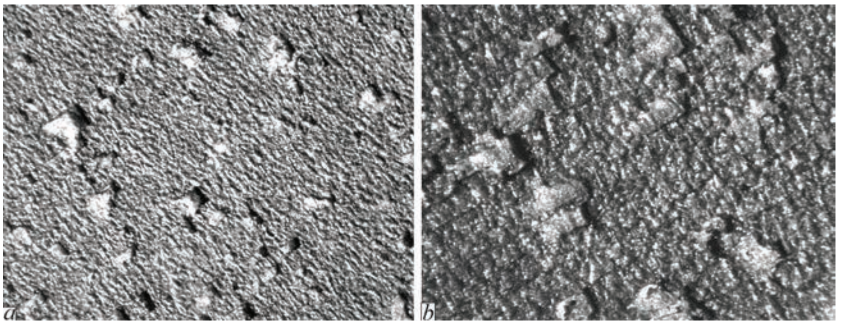

Figure 5. Appearance of the vertical plane of sample cut after electrical discharge cutting at the following magnification: *a* — ×50; *b* — ×88

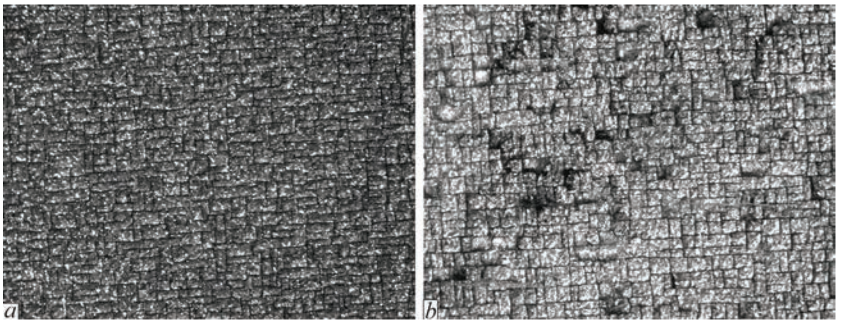

Figure 6. Formation of a crack network on the sample surface after electrical discharge cutting, which is manifested after etching by chemical reagents: *a* — horizontal; *b* — vertical plane

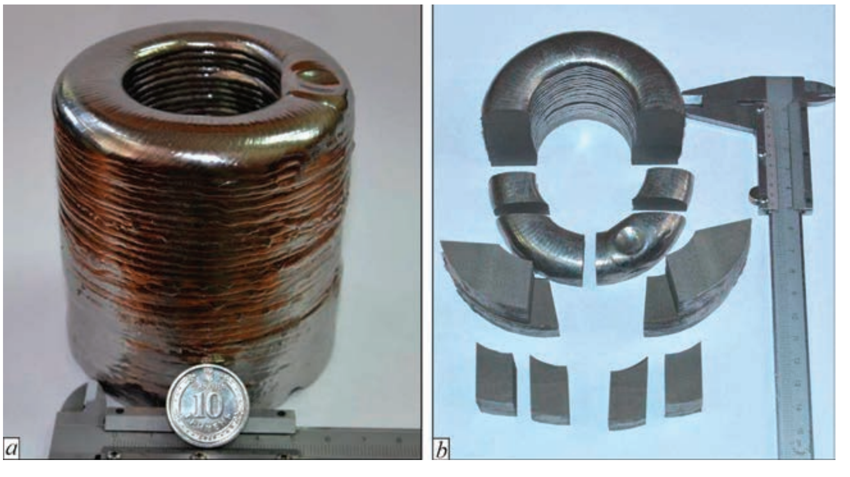

Figure 7. Tungsten single crystal grown in the form of a hollow cylindrical body 85 and 68 mm in diameter (*a*), and its separated upper part cut up into small samples (*b*)

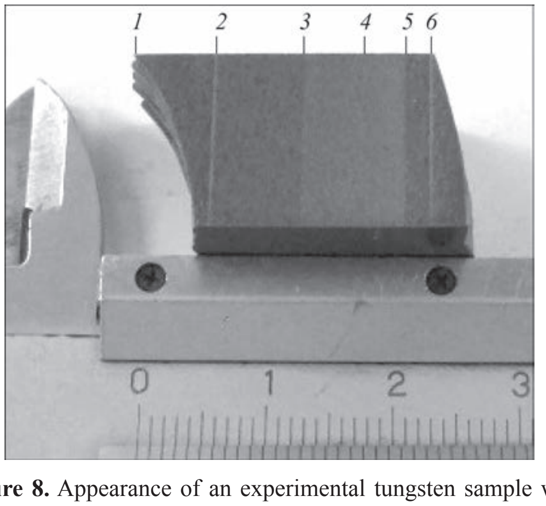

Figure 8. Appearance of an experimental tungsten sample with marked zones of different cutting modes

ical reagent for etching and identification of structure defects, etching time being 5 min.

A rather stringent treatment mode was used (AA18) to prepare a seed crystal, which ensured maximal cutting productivity.

However, further research, particularly during preparation of samples for metallographic examination, raises the question about the actual depth of the damaged layer, which should be removed in order to conduct further studies of the actual undamaged structure.

Samples, separated from the crystal in the form of a cylindrical hollow body 85 mm in diameter, were selected as material for investigations (Figure 7) [7]. Experiments were conducted with cutting of one of the samples in different modes in the horizontal plane of the ingot (Figure 8), cut height being 15 mm. Fig-

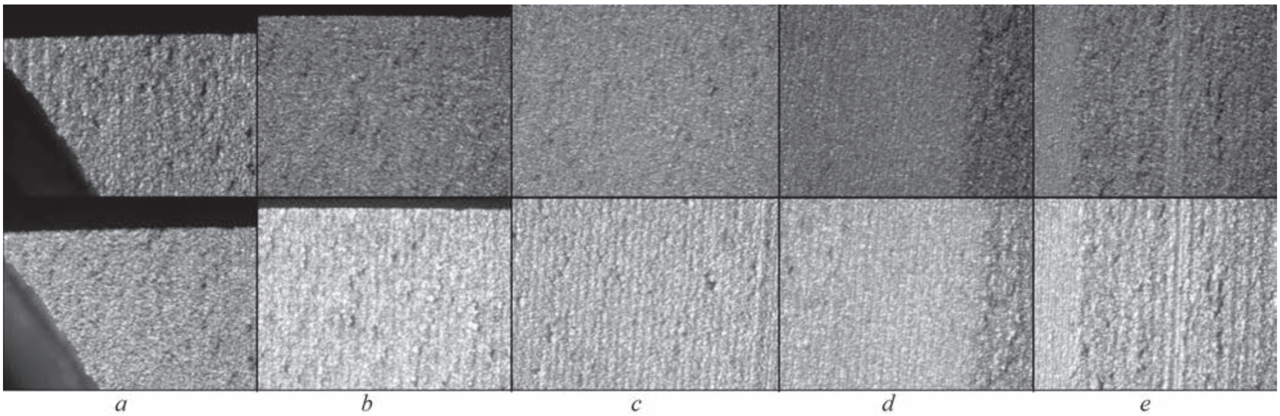

Figure 9. Enlarged view of the zones at different lighting angles (×200): *a* — 1; *b* — 2; *c* — 3; *d* — 4; *e* — 5; *f* — 6, designations, corresponding to Figure 8

Table 2. Cutting modes relative to Figure 9

Mode	1	2	3	4	5	6
Designation	9B16	7D16	5F16	3416	9616	9816
Pulse, μm	28	20	12	6	28	28
Pause, μm	14	18	22	6,25	8	10
Cutting speed, μm/s	< 15	< 13	< 11	< 9	< 16	< 14

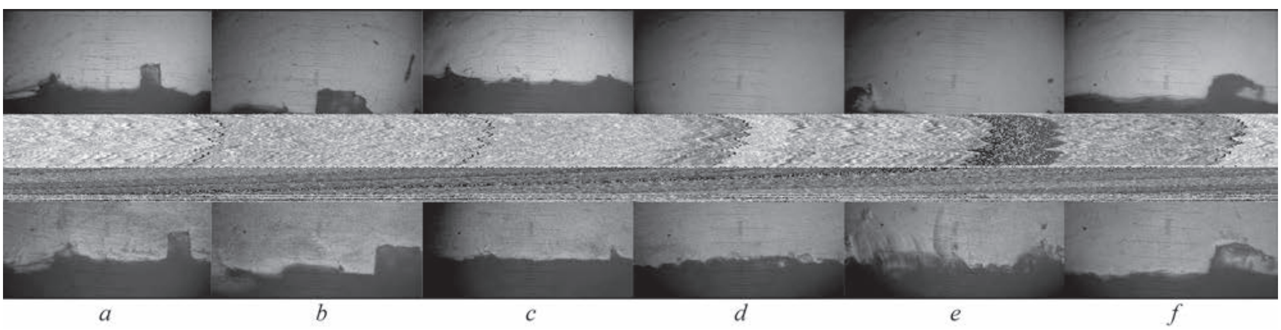

Figure 10. Depth of penetration of gaps and damage from electrical discharge cutting (×200); upper row — polishing, lower row – after etching; *a* — 1; *b* — 2; *c* — 3; *d* — 4; *e* — 5; *f* — 6; distance between two large divisions of the scale is equal to 50 μm

ure 9 gives enlarged photos of the obtained surface relief, formed in different cutting modes (Table 2). For a more voluminous and visual perception of the relief, the photos were taken at different lighting angles.

To determine the damaged layer depth, surface grinding was performed in the plane normal to the cutting area. The depth of the formed cracks propagating deep into the metal was studied directly after grinding and after chemical etching (Figure 10).

Results of the conducted studies are given in Table 3. Having analyzed the influence of pulse and pause duration, we can draw the following conclusions: during treatment in the modes with unchanged pulse time (modes 1, 5, 6) the parameter of the dura-

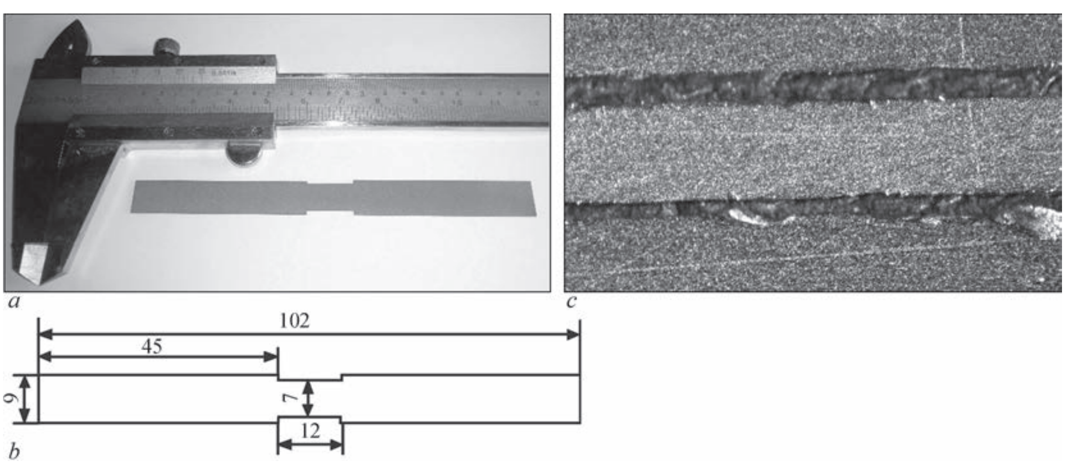

Figure 11. Heater, made from a tungsten single crystal 0.5 mm thick: *a* — general view; *b* — drawing; *c* — cross-sectional microsection

Table 3. Depth of crack propagation into the tungsten single crystal body, depending on the cutting mode

Mode	4	3	1, 2, 5, 6
Crack depth	< 50 μm	≈ 100 μm	< 200 μm

tion of pauses between the pulses practically did not influence the defective layer characteristics; reduction of pulse duration (modes 1, 2, 3, 4) lowers the influence of the treatment factor on defective layer formation, which is manifested in reduction of its depth. In mode 4 the depth did not exceed 50 μm.

Based on the conducted studies, the cutting modes were selected for manufacturing critical parts from tungsten single crystals. A defect-free thin-walled heating element 0.5 mm thick was produced (Figure 11).

CONCLUSIONS

Technological modes of tungsten single crystal treatment by electrical discharge cutting have been studied. The influence of the modes on the damaged layer depth and crack propagation in-depth of the single-crystal structure was established. It is shown that in the hard modes, ensuring the maximum cutting speed, the depth of the damaged layer may reach 200 μm. It was determined that by reducing the pulse duration it is possible to achieve formation of the treated surface almost without the damaged layer, but it will result in lower cutting speeds.

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ORCID

Yu.O. Nikitenko: 0000-0002-3603-2333,
V.O. Shapovalov: 0000-0003-1339-3089,
V.V. Yakusha: 0000-0001-5962-9194,
O.M. Gnizdylo: 0000-0001-7537-6481,
D.M. Zhirov: 0000-0002-9435-8075

CONFLICT OF INTEREST

The Authors declare no conflict of interest

CORRESPONDING AUTHOR

Yu.O. Nikitenko
E.O. Paton Electric Welding Institute of the NASU
11 Kazymyr Malevych Str., 03150, Kyiv, Ukraine.
E-mail: nikyu80@gmail.com

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