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MATHEMATICAL ANALYSIS OF THE INFLUENCE OF THE FLUX-CORED WIRE CHEMICAL COMPOSITION ON THE ELECTRICAL PARAMETERS AND QUALITY IN THE UNDERWATER WET CUTTING

ABSTRACT

The paper presents research in the field of underwater wet cutting with the use of flux-cored wires in order to improve the quality and performance. The research has resulted into the development of gas and slag systems for flux-cored wires and determination of , optimal parameters for cutting stability and quality. The underwater wet cutting mechanism is a cyclical process with the formation of periodic keyholes in metal, and it consists of operating and idle cycles. Efficiency of the cutting process can be determined by analyzing cycle times, welding current, voltage, power and a number of short circuits. To assess the stability and efficiency of the underwater wet cutting process, the authors have developed the method for analyzing oscillograms to calculate the probability density of current, voltage and power. To determine the quality of cutting, the authors have provided a criterion based on the ratio of the voltage probability density in the idle and operating cycles.

Keywords: *underwater wet cutting; flux-cored wire; mathematical analysis*

INTRODUCTION

Development of the underwater technology is a prerequisite for exploring the Arctic region, ship building, construction of port facilities, which is possible on condition of implementing advanced technology solutions for steel structural welding and cutting. Underwater wet welding and cutting is performed in underwater technical and rescue operations, during installation and repair of underwater pipelines, structures of offshore wind turbines, oil and gas platforms, port facilities, and ship lifting [1]. In addition, underwater welding and cutting are required in the nuclear power industry, when repairing reactors and containers for the storage of nuclear waste in water pools [2–4].

Underwater wet welding and cutting are carried out under complex conditions with limited diving time, the presence of hazardous factors that threaten the health of a diver. The use of manual methods of welding and oxy-arc cutting with stick electrodes leads to an increase in the labor intensity of work, limits visibility of the working area due to cloudy water and exposes the diver to the risk of electric shock when replacing the electrode [5,6].

With increasing depth and pressure decreases arc stability, increase oxidation and hydrogen saturation of the weld metal, increase the amount of non-metallic inclusions and gas pores in weld metal, the susceptibility of weld metal and heat affected zone (HAZ) to hydrogen-assisted cracking (HAC) [7–10].

Welding metallurgy is an advanced research area for improving the quality of underwater wet welding and cutting. In the mechanism of forming non-metallic slag inclusions and HAC, the key role belongs to processes that occur in a liquid slag under the influence of the dynamics and composition of a vapor-gas bubble as well as the pressure of a medium [11,12].

Promising methods in welding metallurgy are optimal alloying, deoxidization and refining, reduction of non-metallic slag inclusions, reduction of diffusible hydrogen content, development of effective gas-slag systems for coated electrodes and for flux-cored wire [13,14]. Flux-cored wires can be applied to improve the quality of welds and cutting process [15–17].

Active development of numerical simulation, digital equipment and technologies allowed obtaining positive results on quality control of weld formation during underwater welding and reducing the number of defects [18–22]. Development of digital equipment with neural network control algorithms, along with welding metallurgy are the most promising research areas for underwater wet welding and cutting [24,25].

For these reasons, the world is actively developing alternative solutions based on mechanization and automation of underwater welding and cutting. Advanced underwater technologies are based on the active development of arc, plasma and laser cutting [6,15,26,27], as shown in Figure 1.

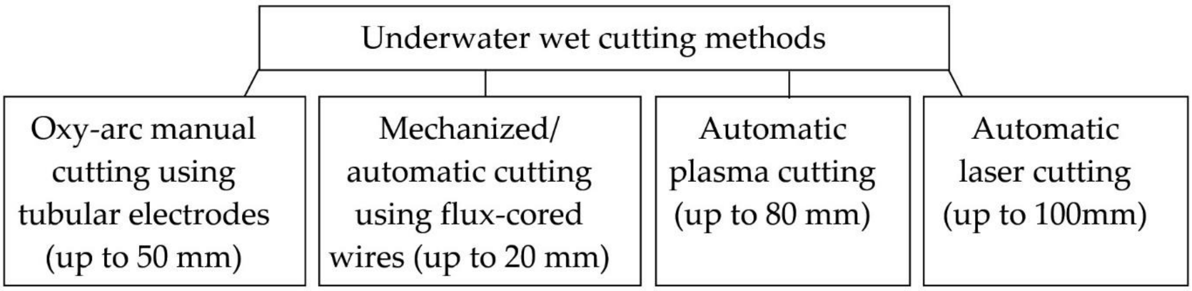


Fig. 1. Methods for underwater cutting of steels and maximum cutting thickness

The purpose of work was to improve the technological characteristics and efficiency of underwater wet cutting of carbon steel based on the development and optimization of a gas-slag composition for special flux-cored wires.

MATERIALS AND METHODS

For underwater wet cutting, the researchers used plates in the size of 200×100×8 mm of S235 structural steel according to ISO 630-2:2011 with the composition, wt. %: 0.12C; 0.03Si; 0.8Mn with the yield strength of 235 MPa and the tensile strength of 360–510 MPa. Underwater wet automatic cutting was carried out on a laboratory setup using flux-cored wires with the diameter of 2 mm in accordance with ISO 12224-1 and GOST 26271-84 (in Russian) with the filling factor of 12 %, as shown in Figure 2.

Fig. 2. Underwater cutting setup: 1 – water tank; 2 – source of power; 3 – water supply system and pump; 4 – wire feed system; 5 – submersible stand with sample; 6 – automat of torch movement; 7 – USB-oscilloscope; 8 – current and voltage sensors; 9 – laptop; 10 – torch for underwater cutting

Tests included 5 compositions of experimental flux-cored wires with different contents of the oxidizing mixture, as shown in Table 1.

Table 1. *The composition of experimental flux-cored wires*

Wire number	Flux-core composition, wt.%
1	$FeCO_3$+KNO_3 – 60; Na_3AlF_6 – 30; Al – 10
2	$FeCO_3$+KNO_3 – 55; Na_3AlF_6 – 25; Al – 20
3	$FeCO_3$+KNO_3 – 50; Na_3AlF_6 – 20; Al – 30
4	$FeCO_3$+KNO_3 – 60; Na_3AlF_6 – 35; Al – 5
5	$FeCO_3$+KNO_3 – 70; Na_3AlF_6 – 20; Al – 10

The power source was ESAB Origo MIG L405 with idling voltage 45 V, with the wire feed rate of 5–9 m/min, the cutting speed of 190 mm/min, the cutting length of 100 mm. The immersion depth of the samples in freshwater was 300 mm. Arc voltage and current were measured using a digital USB oscilloscope and Multi VirAnalyzer software (Harbin Instrustar) at the frequency of 32 kHz.

RESULTS AND DISCUSSION

Underwater wet cutting like welding is carried out in a vapor-gas bubble with the intensive decomposition of the flux-core components, as shown in Figure 3.

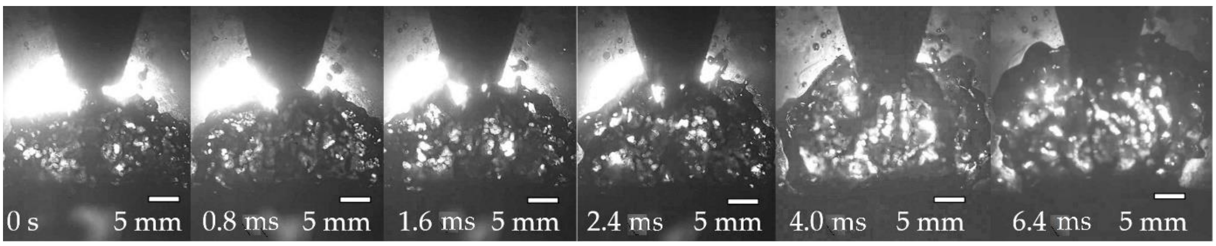


Fig. 3. Shadow video of the growth of the vapor-gas bubble during the underwater arc process with a flux-cored wire

The main difference between the wet cutting process and the wet welding process is that when the components decompose, cutting oxygen is formed, which oxidizes the iron. After that the slag is forced out of the cut zone under arc pressure. Flux-cored wire No. 1 showed the stable cut quality in a wide range of parameters, as shown in Figure 4.

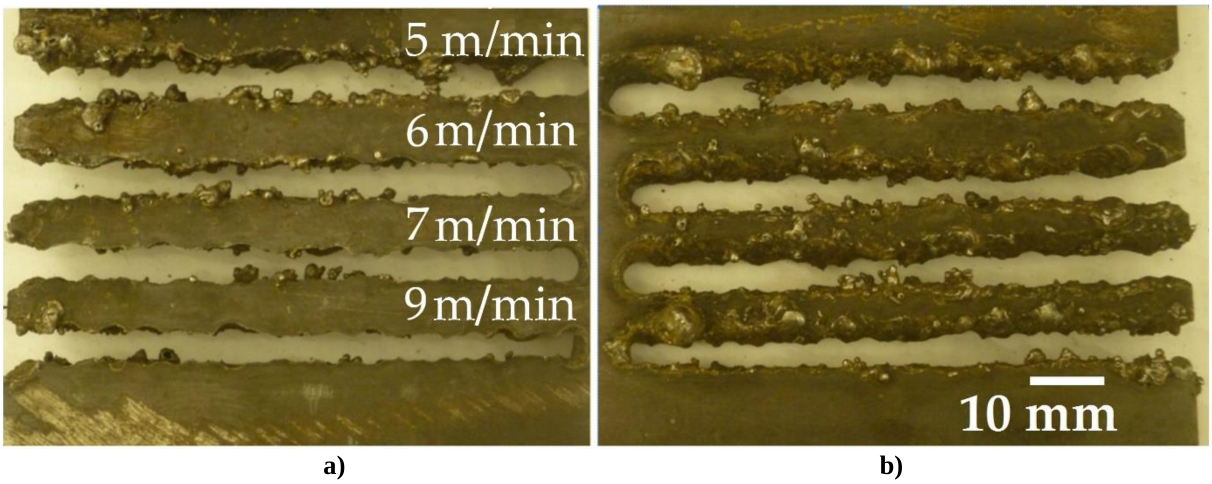


Fig. 4. Outer (a) and back side (b) of 8 mm plate after cutting with wire No 1. Wire feed rate of 5–9 m/min

The analysis of the oscillograms revealed the second feature of the cutting process, which consists in the presence of operating and idle cycles of the electrical process related to the cyclic ignition and welding arc quenching during the formation of periodic keyholes in metal, as shown in Figure 5.

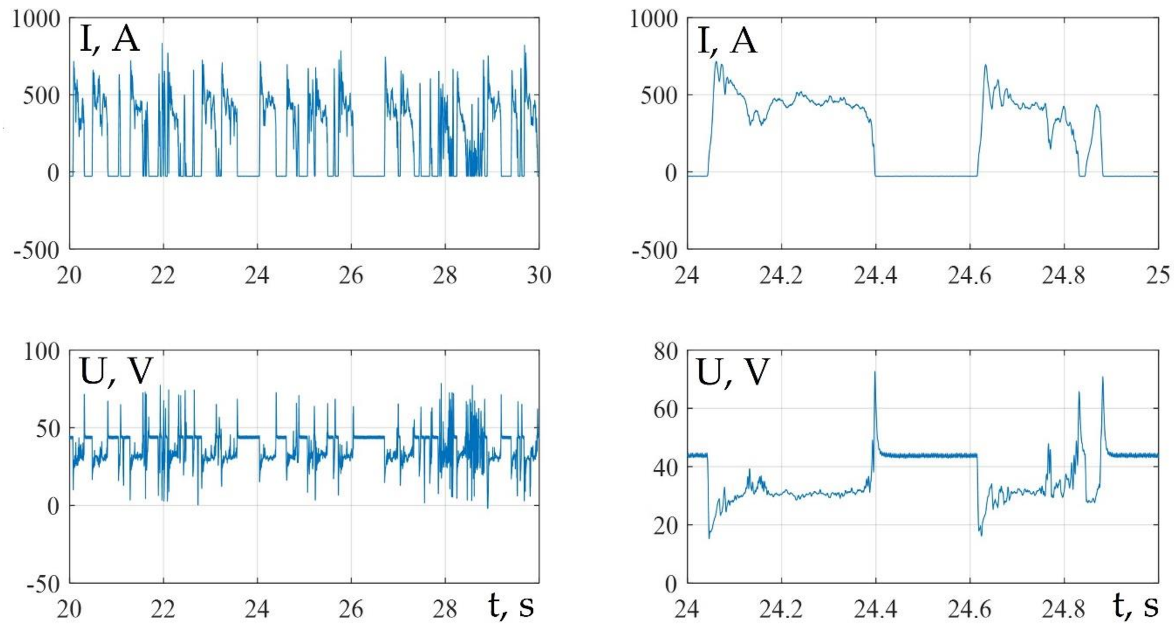
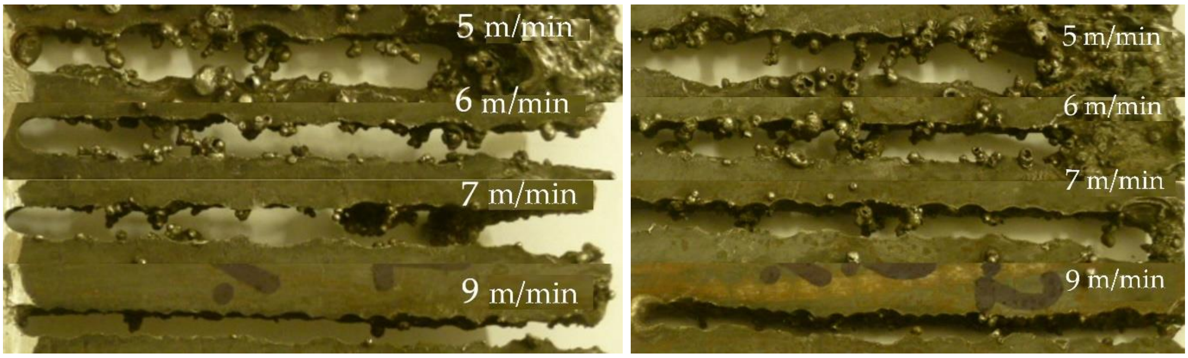


Fig. 5. Oscillograms of the cutting process with wire No 1. Wire feed rate of 9 m/min

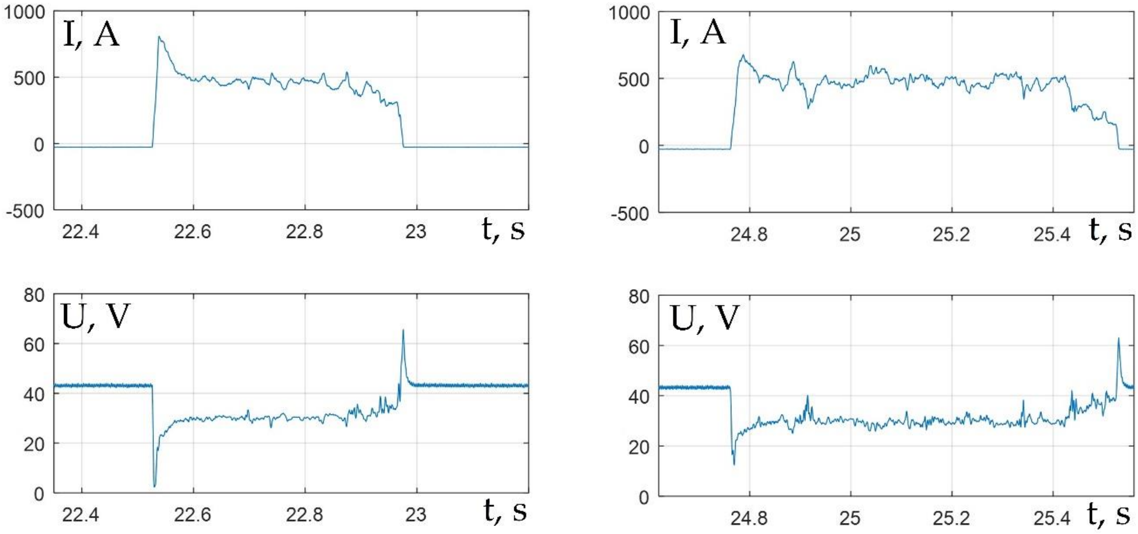
Figure 5 shows changes in the current and voltage during underwater wet cutting with the use of flux-cored wire No. 1. In 10 seconds, there were about 16 operating cycles with a duration of up to 0.4 s.

To determine the effect of the chemical flux-core composition on the electrical characteristics of the process and the cutting stability, a series of experiments were carried out at various wire feed rates, as shown in Figures 6–9.



a) **b)**

Fig. 6. Outer side of 8 mm plate after cutting with wire No 2 (a) и No 3 (b). Wire feed rate of 5–9 m/min



a) **b)**

Fig. 7. Oscillograms of the cutting process with wire No 2 (a) и 3 (b). Wire feed rate of 9 m/min

Figure 7 shows changes in the current and voltage during underwater wet cutting using flux-cored wire 2 and 3 with a duration of operating cycles of up to 0.5 s and 0.8 s accordingly.

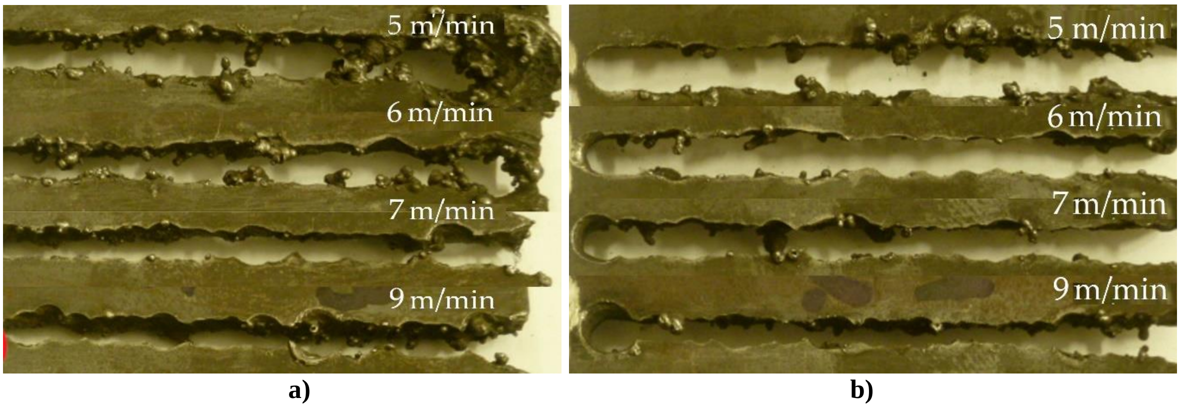


Fig. 8. Outer side of 8 mm plate after cutting with wire No 4 (a) и No 5 (b). Wire feed rate of 5–9 m/min

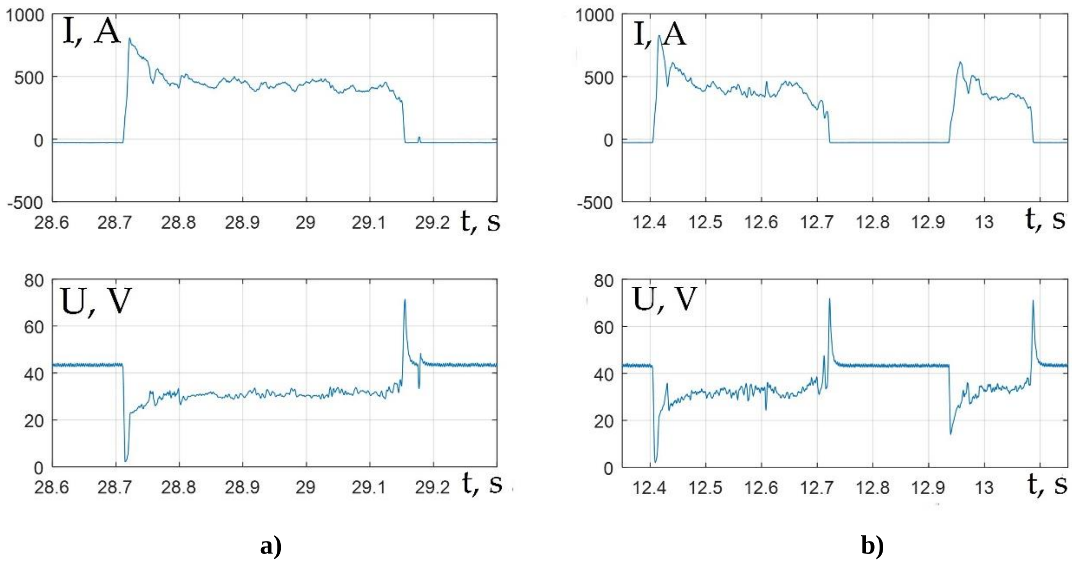
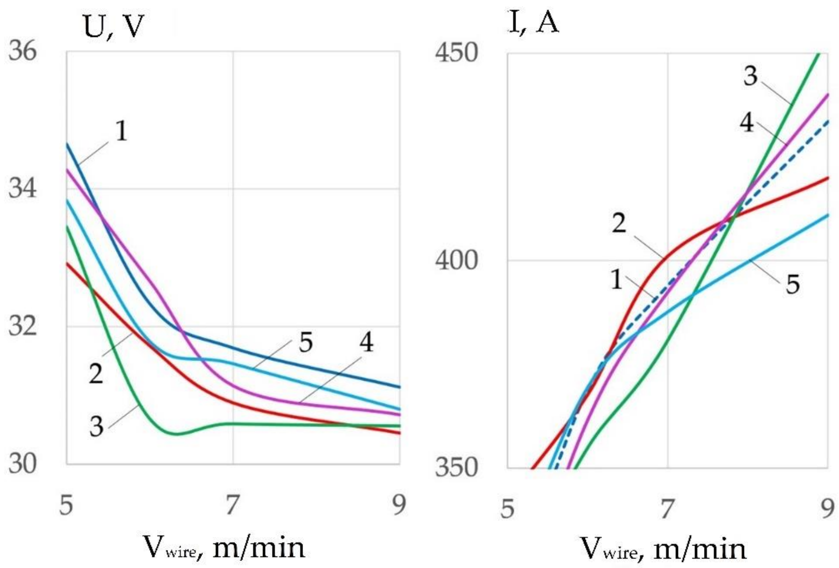


Fig. 9. Oscillograms of the cutting process with wire No 4 (a) and with wire No 5 (b). Wire feed speed 9 m/min

Figure 9 shows changes in the current and voltage during underwater wet cutting using flux-cored wire 4 and 5 with a duration of operating cycles of up to 0.45 s and 0.2–0.3 s accordingly.

The analysis of oscillograms to determine the average values of voltage and current was conducted using mathematical statistics in the MatLab program, as shown in Figure 10.



a) **b)**

Fig. 10. Average voltage and current distribution when cutting with flux-cored wires No 1–5

With the increase in the aluminum content in wire No 1–3, the voltage decreases and the current increases, especially in wire No 3 with the aluminum content of 30 wt.%. However, a decrease in the oxidant content to 50 wt.% reduces the cut quality. A decrease in the aluminum content to 5 wt.% with the high content of the oxidant causes an increase in the arc voltage and decreases the current, especially at the wire feed rates of 5–6 m/min, but at 7–9 m/min, the cut depth and the quality improve. Increasing the oxidant content up to 70 wt.% with the increasing aluminum content of up to 10 wt.% leads to an increase in the cut width, particularly when the wire feed rate of 5–6 m/min.

For further analysis of oscillograms, the kernel density estimation method, which uses a function "ksdensity", was used in MatLab to calculate the probability density for values of a random variable in the data sample in evenly distributed points.

Based on the results of the analysis, the probability density of the voltage and current were plotted at different rates of wire feed, as shown in Figures 11–15.

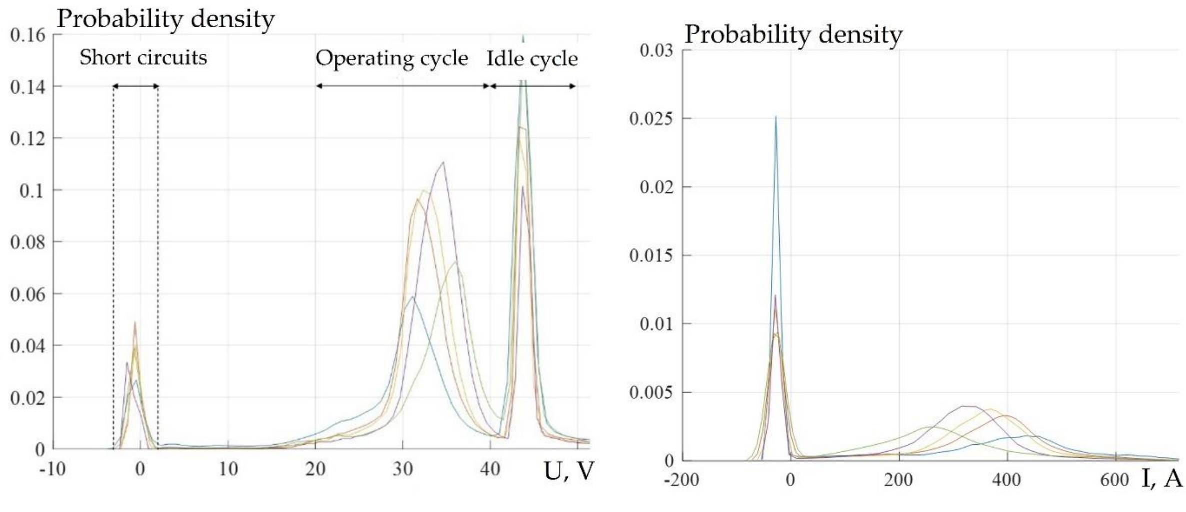


Fig. 11. Probability density of voltage and current when cutting with wire No 1

Figure 11 shows the probability density of voltage and current in operating and idle cycles, as well as in short circuits for wire 1. The probability densities of voltage and current in idle cycles reach the values of 0.16 and 0.025 respectively.

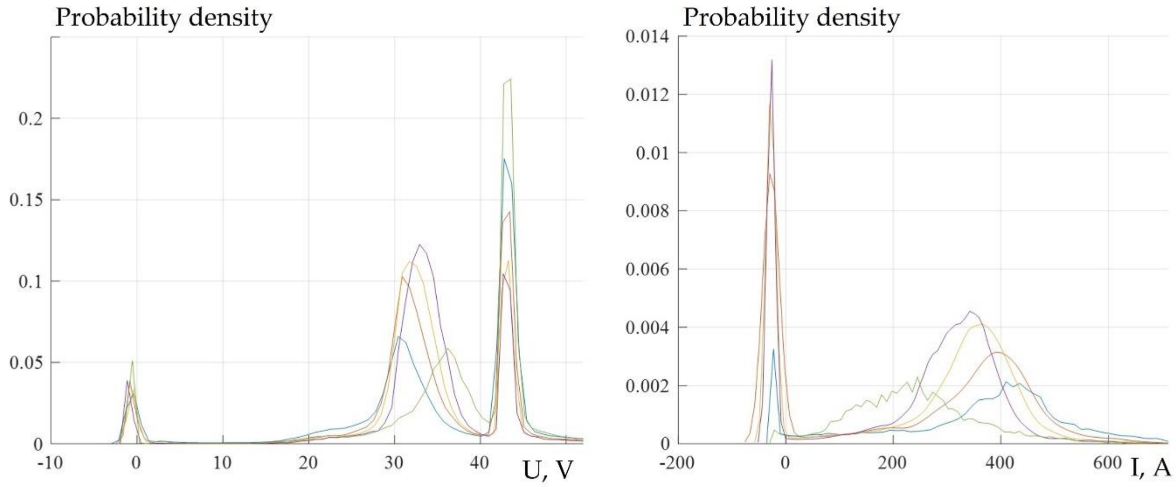


Fig. 12. Probability density of voltage and current when cutting with wire No 2

Figure 12 shows the probability density of voltage and current in operating and idle cycles for wire 2. The probability densities of voltage and current in idle cycles reach the values of 0.22 and 0.013 respectively. This indicates a decrease in the duration of idle cycles or the duration of pauses between operating cycles.

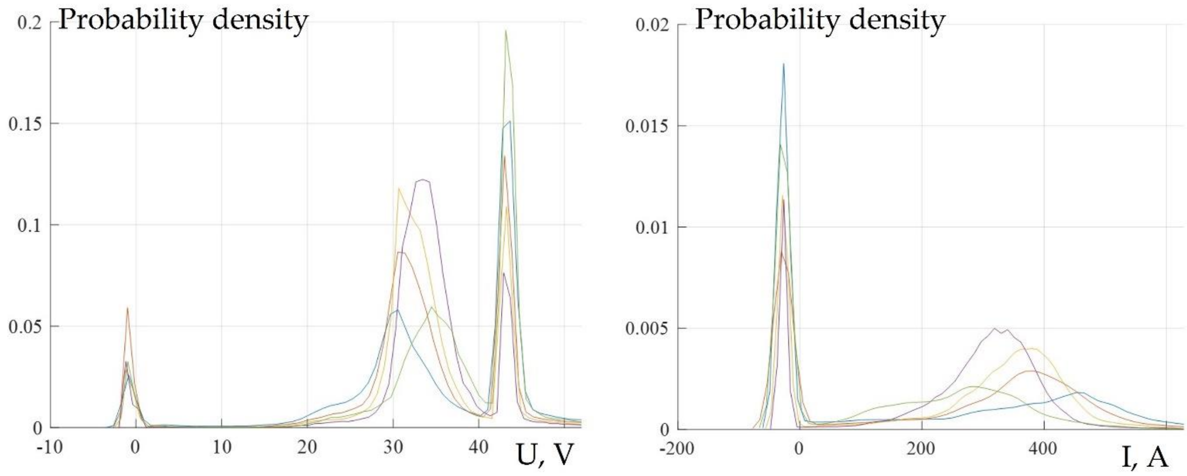


Fig. 13. Probability density of voltage and current when cutting with wire No 3

For wire 3, the probability densities of voltage and current in idle cycles reach the values of 0.2 and 0.018 respectively. This indicates improvement in the stability of the welding arc, a reduction in the duration of idle cycles with an increase in the aluminum content to 30%, however, it can reduce stability of the cutting width.

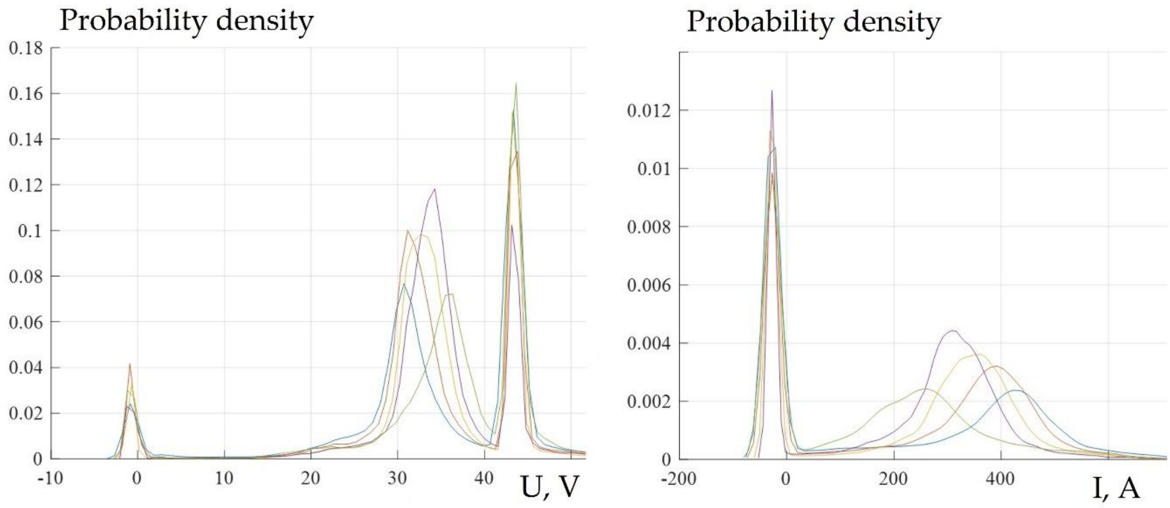


Fig. 14. Probability density of voltage and current when cutting with wire No 4

For wire 4, the probability densities of voltage and current in idle cycles reach the values of 0.16 and 0.012 respectively. This indicates improvement in the efficiency of the cutting process and a decrease in the number of short circuits, but leads to an increase in the arc voltage and to a decrease in the welding current.

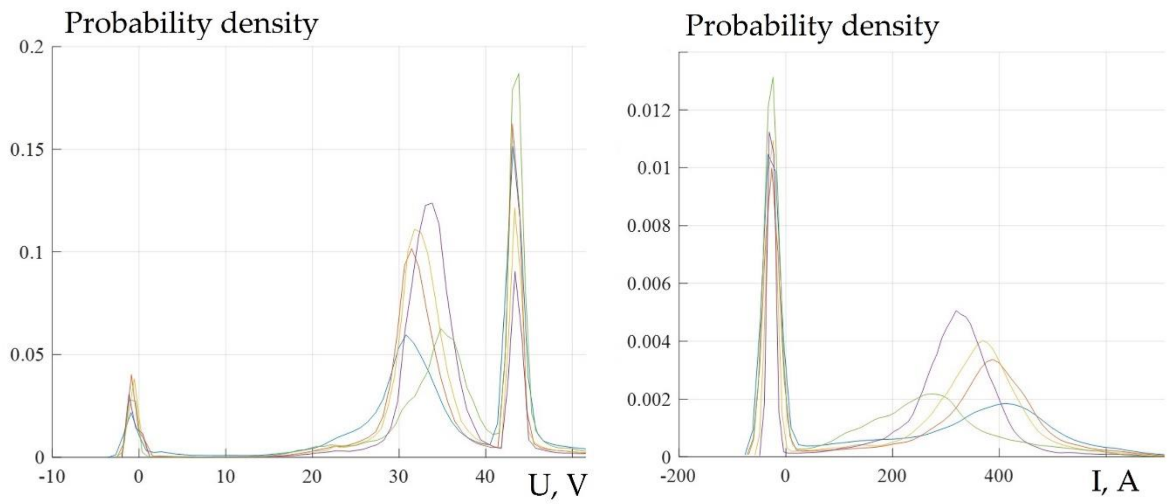


Fig. 15. Probability density of voltage and current when cutting with wire No 5

The energy efficiency of the cut can be estimated by the distribution of the current density, voltage and power in operating cycles, by losses in idling cycles and short-circuits. With a decrease in fluoride Na_3AlF_6 content from 30 to 20 wt.% with the oxidant content of 50–60 wt.% a decrease in energy losses occurs – the probability density of voltages and currents in operating cycles increases, and in idling cycles and in short-circuits decreases.

Analyzing the distribution of current density, voltage and comparison with deviations in the width of the cut made it possible to determine the criterion of the cut quality, which is the ratio between the probability density of the voltage in the idling cycle to the probability density in the operating voltage cycle. According to this criterion, the best cut quality is achieved at the wire feed rate of 6 to 9 m/min with the probability density ratio equal to unity, as shown in Figure 16.

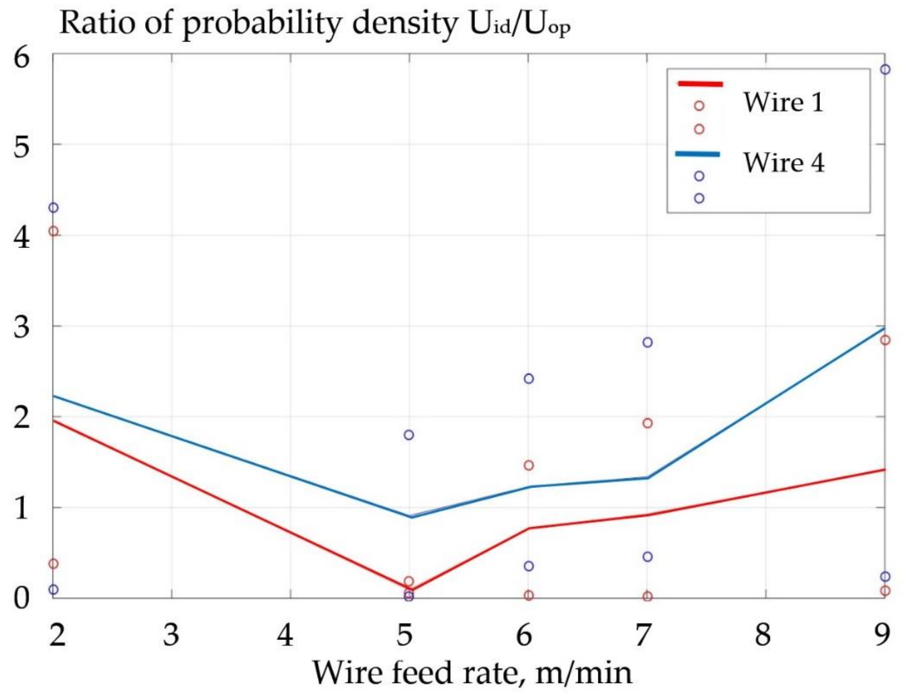


Fig. 16. Criterion of the cut quality depending on the wire feed rate with wire No 1 и No 4

Analysis of the power density distribution shows a significant effect of the wire feed rate on the cutting efficiency, as shown in Figure 17.

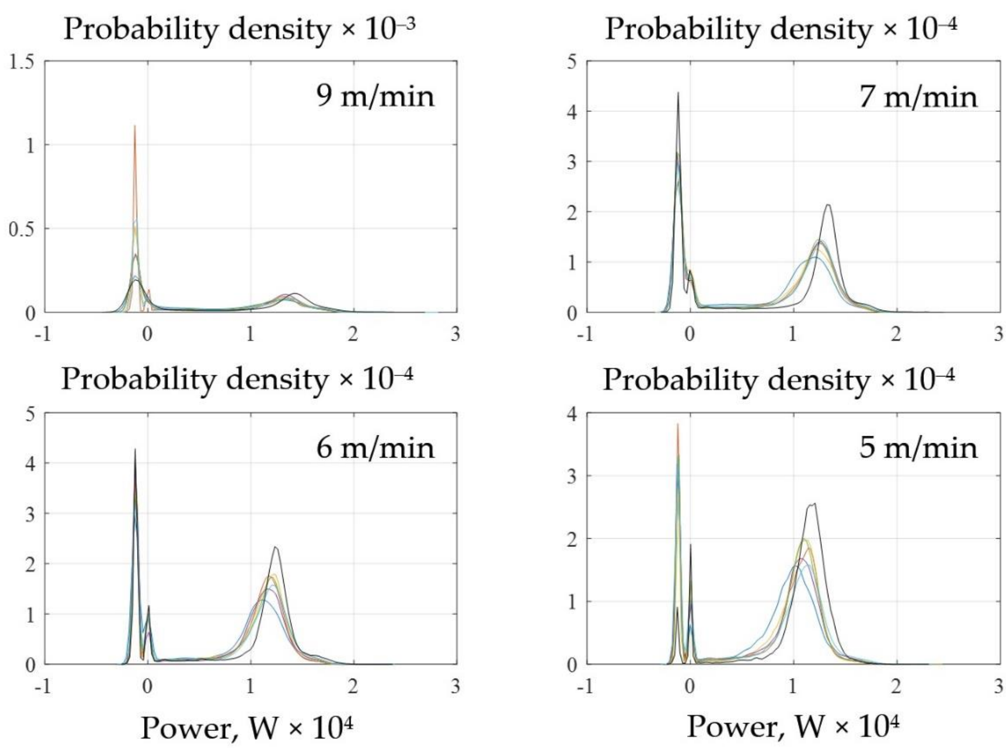


Fig. 17. Power density probability in cutting with various wires

In particular, an increase in the feed rate to 9 m/min leads to an increase in power and the formation of a narrow keyhole, but the energy efficiency of the cut decreases due to an increase in density in short-circuit cycles. Similar losses due to short circuits occur when the feed rate is reduced to 5–6 m/min. Thus, the cutting parameters of the wire feed rate from 6–9 m/min within the range of the oxidant mixture content of 50–60 wt.%, Na_3AlF_6 of 20–30 wt.% and aluminum of 10–20 wt.% are most efficient in the cutting processes.

CONCLUSIONS

- The research resulted into the development of flux-cored wires for automatic underwater wet cutting of steels, and the determination of the content of components for oxidizing compositions of the flux-core wires and optimal parameters, which ensures a stable quality of cut under water using the standard welding equipment.
- The authors proposed the model of underwater wet cutting using flux-cored wires, which considers the cutting mechanism in water as a cyclic process of forming periodic keyholes that consist of successive operating and idle cycles. The efficiency of the cutting process is determined by the duration of the cycles, the values of the welding current, voltage, power, and the number of short circuits.
- To assess the stability and efficiency of the underwater wet cutting process, the authors developed the technique for analysis of oscillograms based on mathematical statistics to calculate the normal distribution of the probability density of current, voltage and power. To determine the quality of underwater cutting, the criterion of the cut quality was proposed; the criterion is based on the ratio of the voltage probability densities in idle and operating cycles.

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