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Determination of Optimal Underwater Cutting Parameters for Ship Hull Steel of Scientific Research Vessel RSV 421 "St. St. Cyril and Methodius"

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Abstract: **This article presents an in-depth study of underwater exothermic cutting technology with exothermic electrodes, applied to the hull steel of the Bulgarian research vessel RSV 421 "St. St. Cyril and Methodius". Having identified the steel type in previous studies as low-carbon Grade A, the focus here shifts to the optimization of underwater repair procedures. The thermodynamic fundamentals of the exothermic reaction, the impact of hydrostatic pressure on cutting parameters, and the strict safety protocols required for operations in extreme marine conditions are examined. The energy characteristics, the specifications of EP-1 and EP-3 type electrodes, and the metallurgical transformations in the cutting zone are analysed.**

Keywords: cutting parameters, exothermic electrodes, safety protocols, underwater cutting, underwater repair procedures.

I. Introduction

The operation of research vessels in polar conditions, such as the RSV 421 "St. St. Cyril and Methodius", involves a constant risk of structural damage due to ice collisions, dynamic loads, and aggressive electrochemical corrosion.

Ensuring the structural integrity of the hull during these missions often necessitates urgent underwater repair activities. The ability to quickly and precisely cut damaged metal elements is critical both for the success of the expeditions and for the safe operation of the ship as a whole. Underwater cutting is a complex engineering process in which the aquatic environment directly affects arc stability, temperature distribution, and the safety of the diver-operator. The present work defines the technological standard for these interventions on the specific material of RSV 421 [1], [2], [3], [4], [5].

II. Characteristics of the Base Hull Steel of the Research Vessel RSV 421 "St. St. Cyril and Methodius"

Based on previous comprehensive analyses (optical microscopy, XRD, and mechanical testing), the hull of RSV 421 is defined as being made of hypoeutectoid low-carbon unalloyed structural steel, corresponding to marine Grade A, shown on figure 1 [6], [2], [7].

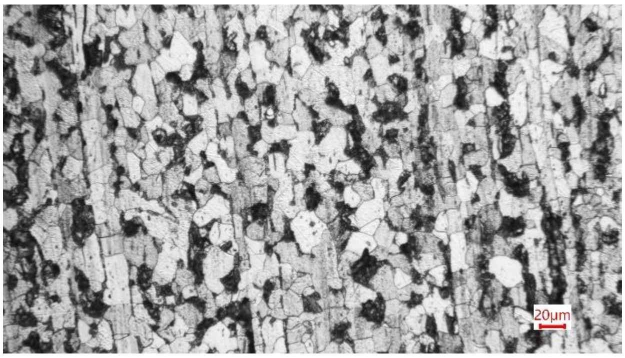

Fig. 1. Optical micrograph of RSV 421 hull steel, showing a dominant ferritic matrix (light phase) and dispersed pearlite colonies (dark phase).

The main material parameters that determine its technological applicability for underwater cutting are summarized in the following points:

- Chemical composition: An approximate carbon content of 0.16%, which provides a low carbon equivalent.

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- Microstructure: A dominant ferrite matrix (80–85%) with fine pearlite colonies, guaranteeing high plasticity and resistance to brittle fracture at low temperatures (Fig. 1) [1], [6], [8], [7].

- Mechanical properties: Average microhardness of 132.8 HV0.2/10 with pronounced homogeneity of the metal matrix (Fig. 2).

- Weldability and hardenability: The low carbon equivalent suppresses the steel's tendency to form hard martensitic structures under extreme underwater cooling rates. This minimizes the risk of cold cracking in the heat-affected zone (HAZ) during the cutting process.

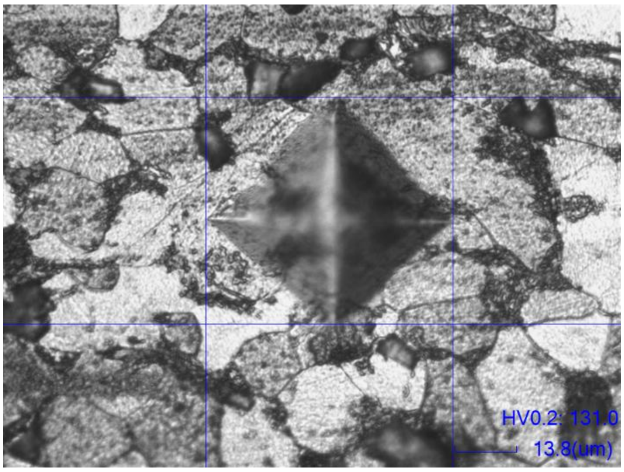

Fig. 2. Optical micrographs showing Vickers (HV0.2/10) microhardness indentation on the RSV 421 ship hull steel sample

These characteristics make the steel of RSV 421 an excellent base for the application of thermal processing methods, as it tolerates temperature deviations that are unavoidable in a marine environment.

III. Theoretical Fundamentals of Underwater Exothermic Cutting

The exothermic cutting process with exothermic electrodes is based on combining the heat of an electric arc and the energy from the chemical oxidation of iron in a stream of pure oxygen. Unlike standard oxy-fuel cutting, the primary heat source here is the exothermic metal oxidation reaction.

A. Thermodynamics of the Exothermic Reaction.

The foundation of the process is the oxidation reaction of the steel; when the metal is heated to its kindling temperature by an electric arc and pressurized oxygen is supplied, a reaction begins that releases a large amount of heat. The temperature at the centre of the arc can reach over 10,000°F (approximately 5500°C), which is sufficient to melt any metallic and non-metallic formations on the hull [8], [9].

B. Dynamics of the Vapour-Gas Cavity.

Underwater, the electric arc burns in a pulsating gas bubble (vapour-gas cavity) [10]. The stability of this bubble is crucial for the quality of the cut. The oxygen pressure must be high enough to keep the cavity open against the hydrostatic pressure of the water while simultaneously blowing molten metal out of the cutting zone.

IV. System Configuration and Technical Equipment

The underwater cutting setup intended for use on RSV 421 is designed to be mobile and adaptable to ship conditions. The diagram on Fig. 3 shows an example setup for underwater exothermic cutting, including its mandatory components:

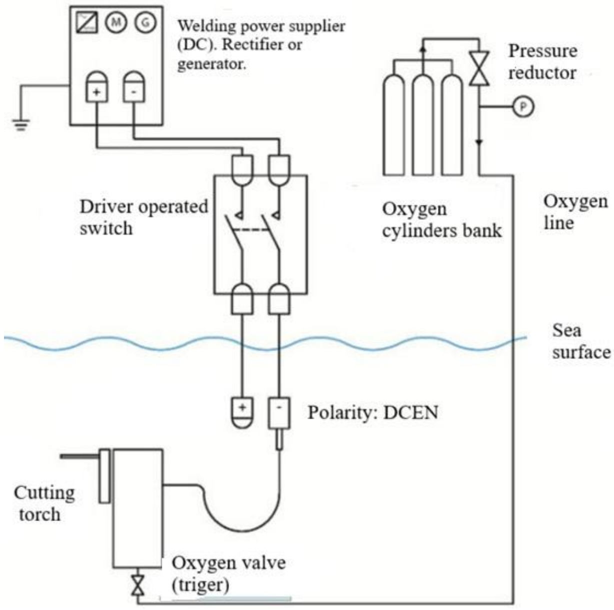

Fig. 3. Diagram of example setup for underwater exothermic cutting, including its mandatory components.

The main components of the setup for underwater exothermic cutting include:

- Power source: Standard welding power sources, rectifiers, or direct current (DC) generators providing at least 300A are used. It is important for the power source to have a suitable volt-ampere characteristic to maintain a stable arc under pressure;

- Oxy-gas line: Includes a bank of oxygen cylinders, a high-flow pressure regulator, and flexible hoses resistant to seawater. The oxygen must have a purity of no less than 99.5%, as even 1% impurities reduce cutting efficiency by 25% [11];

- Torch (Holder): A specialized tool with an ergonomic design, providing complete waterproofing and an airtight connection for the electrode. It features a lever mechanism (trigger) allowing the diver to control the oxygen flow;

- Command-communication system: Mandatory telephone connection between the diver and the surface station, as well as a double-pole circuit breaker (knife switch) on the surface for emergency shutdown;

- Auxiliaries: A submersible platform to stabilize the diver, underwater lighting, and specialized light filters for the helmet, matched to water visibility (filters No. 4 for murky water and No. 8 for clear water are recommended, ISO 4850 [12]).

V. Optimization of Technological Parameters of Underwater Exothermic Cutting for the Hull Steel of RSV 421

Efficient cutting of Grade A steel up to 10-12 mm thick (typical for the vessel's shell plating) requires precise balancing of electrical and gas parameters.

A. Energy regimes:

- Operating current: A current in the range of 300–400 A is recommended. High current is necessary to compensate for the intense heat dissipation into the surrounding water;

- Voltage: The open-circuit voltage of the power source should not exceed 65 V to ensure the diver's safety in the event of an insulation breach [2];

- Polarity: Direct current electrode negative (DCEN) straight polarity is strictly used—the torch (holder) is connected to the negative pole of the power source. This prevents accelerated electrolysis and the destruction of the torch's brass components [13];

- The power cables should be kept to a minimum length whenever the cutting depth allows. Cables with a cross-section of 75 mm² are used for lengths up to 2x25 m. For greater lengths, a larger cable cross-section is required. If there is excess cable while operating at maximum power settings, it is advisable to submerge the extra length in the sea to ensure better cooling. It is recommended that the welding circuit be connected to the hull ahead of or behind the cutting line.

B. Adjustment of oxygen pressure relative to depth and hose length:

The oxygen pressure on the surface must be set so that an effective pressure of at least 0.6 MPa above ambient pressure is achieved at the working depth. Line losses directly depend on the hose length. The following table presents the corrected values for the surface pressure gauge relative to the working depth and oxygen hose length [9], [11].

Table 1 presents specific data regarding oxygen pressure as a function of depth and oxygen hose length.

Table 1. Results from microhardness testing of RSV 421 hull

Depth, m	***Pressure at 15 m. hose, MPa***	***Pressure at 30 m. hose, MPa***	***Depth, m***	***Pressure at 45 m. hose, MPa***	***Pressure at 60 m. hose, MPa***
0	0.65	0.65	0	0.72	0.75
3	0.68	0.68	6	0.78	0.82
6	0.71	0.71	12	0.84	0.88
9	0.74	0.75	18	0.91	0.94
12	0.77	0.77	24	0.97	1.00
15	0.80	0.81	30	1.03	1.06
18	-	0.84	36	1.08	1.12
21	-	0.87	45	1.18	1.22
24	-	0.90	54	-	1.31
27	-	0.93	60	-	1.37
30	-	0.96			

Insufficient pressure leads to inadequate clearing of oxides from the cut, while excessive pressure causes unnecessary spatter and arc instability.

VI. Specification and Applications of Exothermic Electrodes

When underwater exothermic cutting of the hull plates of RSV 421 is required, two main types of electrodes are used, covering the entire spectrum of necessary thicknesses.

A. Type EP-1 electrodes (diameter - 8 mm).

These electrodes are optimal for precise repair work and cutting thinner plates (up to 7 mm.). They provide a narrow kerf and maximum oxygen economy.

- Efficiency: A single electrode can achieve a cut length of 500–600 mm on a 7 mm thick material;

- Application: Ideal for cutting out corroded sections on superstructures or the upper shell plating layers near the waterline.

B. Type EP-3 electrodes (diameter - 10 mm).

These are preferred for greater thicknesses (up to 25 mm) and in poor visibility conditions, as they generate a more powerful cavity and a brighter arc.

- Efficiency: With a steel thickness of 12 mm, one electrode provides a 300–500 mm cut;

- Application: Primary tools in emergency situations requiring rapid separation of massive structural elements or cutting in the lower part of the hull.

Both electrode types, EP-1 and EP-3, feature the construction shown on Fig. 4, which ensures stable burning of the electrode without extinguishing throughout the entire process.

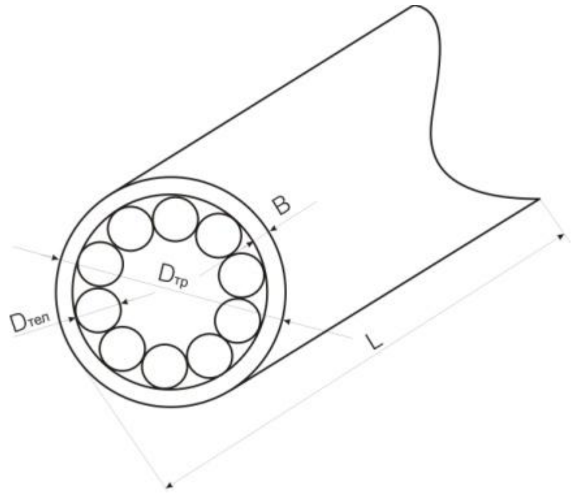

Fig. 4. Construction of electrode types, EP-1 and EP-3, where: D – outer diameter of the electrode, B – electrode wall thickness, and D_{tel} – wire diameter. These electrodes contain 10 wires.

Table 2 presents data, regarding the two most applicable types of electrodes for this specific case.

TABLE 2. SPECIFIC PARAMETERS OF ELECTRODES TYPE EP-1 AND EP-2

Electrode type	*Metal thickness, mm*	*Cutting length, mm*
EP-1	7	500-600
	12	250-350
EP-3	12	300-500
	25	200-350

VII. METALLURGICAL ANALYSIS OF THE HEAT-AFFECTED ZONE (HAZ)

Although Grade A steel is resistant to hardening, thermal underwater cutting creates an extremely severe processing regime. A steep temperature gradient is observed at the boundary of the cut—from the melting temperature to the ambient seawater temperature within a few millimetres [4], [14]. This causes certain microstructural changes.

Martensitic-bainitic type microstructures can be observed in the outermost layer of the HAZ (width up to 0.1-0.2 mm). Due to the low carbon content (0.16%), these structures are not brittle enough to cause spontaneous cracking. However, when preparing for subsequent welding, it is mandatory to mechanically remove this layer by grinding to ensure a defect-free weld seam [15].

Another potential issue during underwater welding/cutting operations is hydrogen induction.

The aquatic environment is a source of atomic hydrogen, which easily diffuses into the heated metal. Rapid cooling, traps the atomic hydrogen in the metal, creating a risk of subsequent defects (micro cracks - flakes) [16]. When working with the hull steel of RSV 421, , this risk can be managed by maintaining a high cutting speed (over 300 mm/min), which limits the time available for hydrogen to diffuse deep into the material [14] [17].

VIII. SAFETY MEASURES FOR APPLYING OXY-FUEL CUTTING IN SPECIFIC SITUATIONS

The specifics of the operations on RSV 421 mandate the application of the highest safety standards, as medical assistance is limited in polar conditions.

A. Prevention of gas explosions.

The underwater cutting process generates hydrogen and free oxygen [3], [16]. Their accumulation in enclosed spaces (pontoons, double bottoms) creates an explosive mixture.

- Ventilation: Before starting work, it is mandatory to drill ventilation holes at the highest points of the compartment;

- Cutting direction: Work must always be performed from top to bottom. This allows gas bubbles to float freely through the already made cut instead of accumulating beneath the uncut surface.

B. Electrical safety of the operator.

Electric shock is a major hazard when working in saltwater.

- Insulation: The diver must wear heavy-duty rubber gloves over neoprene ones. Any tear in the suit is a signal to immediately halt work [18];

- Grounding: The ground clamp must be placed as close to the cutting site as possible, on a surface cleaned to a metallic shine [19]. The diver must never stand between the ground and the electrode.

IX. CONCLUSIONS

Based on the investigations conducted in this paper, the following main conclusions can be drawn:

A. The study confirms that underwater exothermic cutting technology with exothermic electrodes is fully compatible with the Grade A hull steel of RV 421. Optimal technological regimes include an operating current of 300–400 A and oxygen pressure compensated relative to hydrostatic pressure and supply line length.

B. The use of EP-1 and EP-3 type electrodes provides the necessary flexibility for both precise and heavy-duty destructive underwater operations.

C. Strict adherence to ventilation and electrical protocols remains a mandatory condition for safety.

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