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Investigation and Identification of Ship Hull Steel Grade for Maintenance and Repair Procedures on Scientific Research Vessel RSV 421 "St. St. Cyril and Methodius"

Momchil Manov
Ship Machinery
Nikola Vaptsarov Naval Academy
Varna, Bulgaria
m.manov@nvna.eu

Hristo Hristov
Ship Machinery
Nikola Vaptsarov Naval Academy
Varna, Bulgaria
h.hristov@nvna.eu

Abstract: **The Bulgarian scientific research vessel RSV 421 "St. St. Cyril and Methodius" conducts regular maritime expeditions from Bulgaria to Antarctica. During these missions, the ship navigates through diverse global waters, encountering a wide range of seawater temperatures and salinity levels, extreme weather conditions, and severe environmental challenges. Ensuring the structural integrity of the ship's hull under such harsh marine environments is of major importance for the safety of the crew, cargo and the success of these polar expeditions. The present study is focused on the precise identification of the ship's hull steel grade as a fundamental prerequisite for executing adequate and high-quality maintenance and repair procedures. To establish the exact classification and properties of the material, a comprehensive analytical approach was applied. The experimental methodology encompasses optical microscopy for microstructural evaluation, X-ray diffraction (XRD) for phase composition analysis, Vickers microhardness testing to assess the mechanical characteristics, potentiodynamic Tafel and Open Circuit Potential (OCP) corrosion resistance tests to evaluate the electrochemical corrosion behaviour of the tested material. Determining the precise steel grade through these combined methods is a crucial step that dictates the correct technological approach to future maintenance. Ultimately, this accurate material identification significantly enhances the reliability, durability, and overall longevity of the ship's hull, ensuring the safe and uninterrupted conduct of future challenging expeditions.**

Keywords: microhardness testing, potentiodynamic and open circuit potential corrosion resistance tests, ship's hull steel grade, X-ray diffraction.

I. INTRODUCTION

The Bulgarian scientific research vessel RSV 421 "St. St. Cyril and Methodius" plays a pivotal role in conducting regular maritime expeditions to Antarctica. During these demanding voyages, the vessel navigates through some of the most challenging global waters, continuously encountering severe meteorological conditions, extreme temperature fluctuations, and seawater with highly variable salinity levels and temperatures. Furthermore, operating in polar and sub-polar regions exposes the ship's hull to severe dynamic loads, potential ice impacts, and highly aggressive corrosive environments. Consequently, preserving the structural integrity and operational reliability of the hull is of paramount importance to ensure both the success of these scientific missions and the absolute safety of the crew [1] - [4].

To maintain the vessel's hull in an optimal operational state, comprehensive maintenance and repair procedures must be executed periodically. The primary techniques employed for structural hull maintenance are above-water and underwater cutting and welding operations. The adequate and safe execution of these highly demanding procedures relies heavily on a precise understanding of the base material. Without exact knowledge of the ship hull steel grade and its fundamental thermomechanical characteristics, there is a significant risk of utilizing incompatible welding consumables or improper thermal regimes during both dry-dock and in-water interventions. Such technological mismatches could inevitably lead to structural degradation, cold cracking, or accelerated localized corrosion within the weld joints and heat-affected zones [3], [5] - [8].

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To address this critical engineering challenge, the present study focuses on the precise identification of the hull steel grade of RSV 421 and the evaluation of its specific properties to establish the optimal conditions for conducting these essential cutting and welding maintenance operations. To achieve this, a comprehensive analytical approach was employed. The experimental methodology utilizes optical microscopy to evaluate the microstructural features and X-ray diffraction (XRD) analysis to determine the exact phase composition of the alloy. Additionally, mechanical hardness testing was conducted to establish a reliable baseline for the material's mechanical strength, while electrochemical corrosion resistance tests were performed to evaluate its degradation behaviour in aggressive marine environments. By accurately establishing these essential material characteristics, this research provides the necessary scientific foundation to define the optimal technological parameters for above-water and underwater repairs, ultimately guaranteeing the hull's long-term durability and the uninterrupted conduct of future Antarctic expeditions [2], [4], [8] - [12].

II. Materials and Methods

To accurately identify the grade and evaluate the operational properties of the ship hull steel of RSV 421, a comprehensive experimental methodology was conducted, encompassing microstructural characterization, phase analysis, mechanical testing, and electrochemical corrosion evaluation.

A. Sample Preparation and Optical Microscopy.

The steel specimens for microstructural and microhardness analyses were carefully extracted and cut to dimensions of 5×10×8mm using a DTQ-5 precision low-speed saw under continuous liquid cooling to avoid microstructural changes. The samples were subsequently hot-mounted in transparent acrylic resin using an XQ-2B mounting press at a temperature of 170°C and a pressure of 290Bar. The surface preparation was carried out on a MoPao-260E grinding and polishing machine. The specimens were successively ground using SiC abrasive papers with decreasing grit sizes (from 180 to 2400 grit), followed by final polishing using a 0.25μm diamond suspension to achieve a mirror-like surface finish. To reveal the microstructural features, the polished surfaces were chemically etched using a standard Nital (nitric acid and ethanol) solution. The microstructural observations and surface analyses were conducted using an iMet-222 optical microscope, equipped with a high-resolution digital camera and specialized image processing software [6], [7], [9] - [11].

B. X-ray Diffraction (XRD) Phase Analysis.

To determine the exact phase composition and crystalline structure of the investigated ship hull steel, X-ray diffraction (XRD) analysis was performed on specimens specifically machined to dimensions of 3×5×2mm. The experiments were conducted using a TDM-10 X-Ray Diffractometer, operating in a standard θ-θ geometric configuration. The diffractometer is equipped with a Cu Kα radiation source (λ=1.5405Å). The diffraction patterns were recorded over a wide angular range with a precise step size, achieving an angular position accuracy of ±0.001°. The experimental diffraction peaks were subsequently analysed and compared with standard crystallographic databases to accurately identify the present phases (e.g., α-Fe and Fe_3C) and confirm the structural characteristics of the alloy [7] - [9], [11], [12].

C. Microhardness Testing.

The mechanical characterization of the steel was performed by measuring the surface microhardness using the Vickers method on the previously prepared 5×10×8mm metallographic samples. The measurements were carried out on a digital microhardness tester HVS-1000 in accordance with standard test methods defined by ISO 6507-2 and ASTM E384. A standard pyramidal diamond indenter with an apical angle of 136° was used. To ensure statistical reliability, multiple indentations were made across the polished surface of the sample. The applied test load was precisely controlled, and a standard dwell time of 10 to 15 seconds was maintained for each measurement to allow for adequate plastic deformation [6], [7], [9] [11].

D. Electrochemical Corrosion Testing.

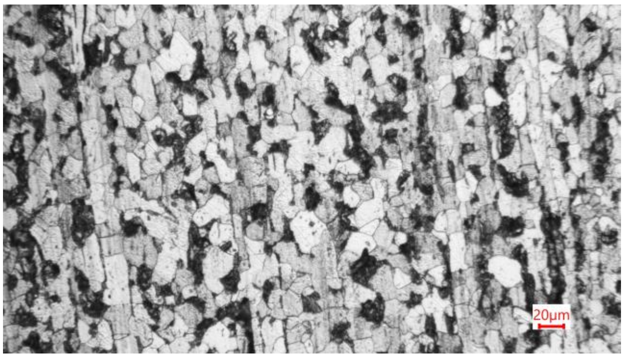
The corrosion resistance of the RSV 421 hull steel was evaluated through potentiodynamic polarization Tafel and open circuit potential (OCP) testing to simulate the degradation behaviour in a marine environment. The electrochemical measurements were performed using a computer-controlled Corrtest CS350 potentiostat - galvanostat system. A standard three-electrode electrochemical cell configuration was employed, consisting of the steel specimen, prepared with dimensions of 30×50×8mm, as the working electrode (WE) with an exposed testing surface area strictly limited to 1cm². A high-density platinum counter electrode (CE) and an Ag/AgCl reference electrode (RE) completed the cell. The tests were conducted at room temperature in a corrosive electrolyte consisting of a 0.9% wt. sodium chloride (NaCl) aqueous solution, representing standard saline conditions. Prior to the potentiodynamic sweep, the open circuit potential (Ecorr) was monitored until a steady state was achieved. The potentiodynamic polarization curves (Tafel plots) were then recorded to determine crucial electrochemical parameters, including the corrosion potential (Ecorr) and the corrosion current density (Icorr). The experimental procedures and subsequent corrosion rate calculations were strictly executed in accordance with ASTM G102-89 and ASTM G3-14 standards [1], [2], [4], [7], [9], [12].

III. Results and Discussion

This section presents, analyses, and discusses the results obtained from the comprehensive experimental investigations. The primary objective of these analyses is to accurately identify the specific grade and characteristics of the RSV 421 hull steel. Evaluating these fundamental microstructural, mechanical, and electrochemical properties is essential for determining the feasibility and defining the optimal technological parameters for employing above-water and underwater cutting and welding techniques during the routine maintenance and repair of the vessel's hull.

A. Optical Microscopy.

The microstructural evaluation of the RSV 421 hull steel was performed in accordance with the methodology outlined in Section II. A. Representative optical micrographs obtained at different magnifications are presented in figure 1.



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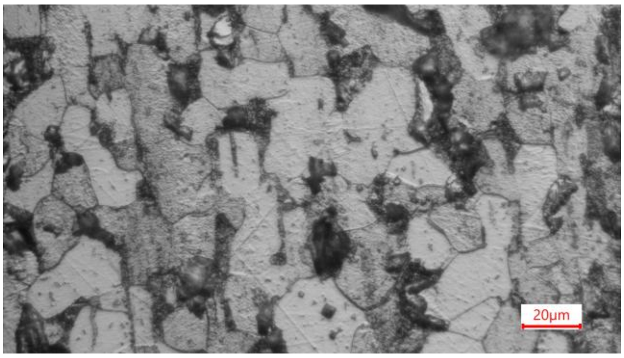

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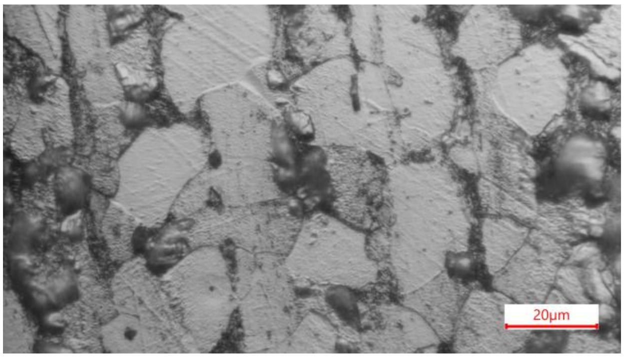

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Fig. 1. Optical micrographs of RSV 421 hull steel, showing a dominant ferritic matrix (light phase) and dispersed pearlite colonies (dark phase) at different magnifications: (a) general overview, (b) intermediate magnification, and (c) detailed view of grain structure.

The analysis of the micrographs reveals a classic dual-phase microstructure consisting of a continuous matrix of ferrite (light areas) with uniformly dispersed pearlite colonies (dark areas). Based on the high volume fraction of ferrite (visually estimated at approximately 80-85%), the material is explicitly identified as a hypoeutectoid, low-carbon unalloyed structural steel (Grade A) with an approximate carbon content of 0.16% [5] - [7], [10], [11].

The optical observations confirm that the ferrite grains are polygonal and exhibit a highly uniform, equiaxed morphology. Utilizing the provided 20µm scale bar, the average grain diameter is estimated to be in the range of 10–15µm. This fine-grained structure indicates that the steel was likely subjected to a controlled thermomechanical rolling process. Such microstructural refinement is a critical feature for marine grade steels, as it simultaneously maximizes yield strength and guarantees the high low-temperature impact toughness required for navigating in the severe conditions [5] - [7], [10], [11].

From the perspective of ship hull maintenance and repair, this specific phase composition is highly advantageous. The pronounced dominance of the ferrite phase confirms a low carbon equivalent for the RSV 421 steel. This is the most critical metallurgical prerequisite for conducting reliable above-water and, more importantly, underwater welding and cutting operations. The low carbon content suppresses hardenability, thereby minimizing the risk of forming brittle martensitic microstructures in the heat-affected zone, even under the extreme quenching conditions and rapid cooling rates inherent to underwater welding and cutting. Consequently, the observed microstructure indicates significantly reduced susceptibility to hydrogen-induced cold cracking [6], [7], [10].

B. X-ray Diffraction (XRD) Phase Analysis.

To precisely determine the crystallographic structure and validate the phase composition of the RSV 421 hull steel, an X-ray diffraction analysis was conducted in accordance with the experimental methodology detailed in Section II. B. The resulting XRD pattern of the investigated ship hull steel is presented in figure 2.

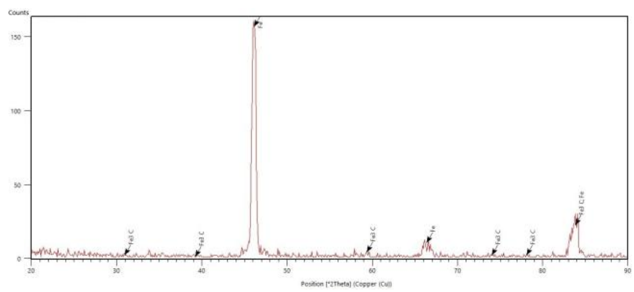


Fig. 2. X-ray diffraction (XRD) pattern of the RSV 421 ship hull steel, demonstrating a predominantly body-centered cubic (BCC) α-Fe (ferrite) matrix with trace low-intensity peaks of Fe3C (cementite).

The diffractogram reveals a highly crystalline structure dominated by a distinct, high-intensity primary diffraction peak located at an angular position of 2θ≈45°, along with secondary peaks at approximately 2θ≈65° and 2θ≈82°. These diffraction lines are the definitive crystallographic signature of the body-centered cubic lattice of alpha-iron (α-Fe), which constitutes the primary ferrite matrix of the steel.

In addition to the dominant α-Fe peaks, the analysis detected several minor, low-intensity diffraction peaks identified as cementite (Fe_3C). The exceptionally low intensity of these cementite peaks directly corresponds to the low overall carbon concentration in the alloy and perfectly corroborates the optical microscopy observations, which showed a minimal volume fraction of pearlite colonies dispersed within the heavily ferritic matrix.

The absolute dominance of the ductile α-Fe phase and the minimal presence of the harder, more brittle Fe_3C phase confirm that the RSV 421 is a low-carbon, unalloyed structural steel with an approximate carbon content of 0.16%. From a practical engineering standpoint regarding ship hull maintenance, this phase composition is highly favourable. The absence of complex alloy phases or pre-existing hardened microstructures establishes a stable baseline for thermal processing. This structural stability is particularly vital for above-water and underwater cutting and welding operations, where the surrounding aquatic environment acts as a severe quenching medium. The inherently low carbon equivalent, proven by the overwhelming presence of α-Fe, guarantees excellent metallurgical compatibility, significantly mitigating the risk of brittle phase transformations in the heat-affected zone and ensuring the structural integrity of the repaired hull sections [7], [8], [10].

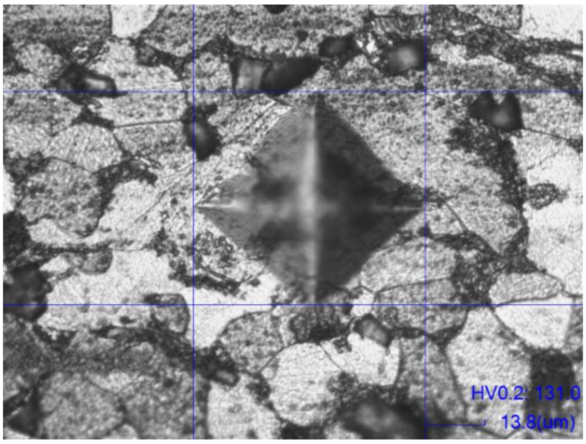
C. Microhardness Testing.

To evaluate the mechanical characteristics of the RSV 421 ship hull steel, microhardness profile was measured using the Vickers method, strictly following the experimental protocols defined in Section II. C. The detailed results of the microhardness measurements, conducted with a test force of 0.2kgf (HV0.2) and a 10-second dwell time, are summarized in table 1. Additionally, the visual representations of the corresponding pyramidal diamond indentations on the metallographic sample are shown in figure 2.

TABLE 1. RESULTS FROM MICROHARDNESS TESTING OF RSV 421 HULL STEEL

№	*D1, um*	*D2, um*	*Davg, um*	*Hardness value (HV0.2)*
1	55.48	50.92	53.20	131.0
2	51.61	52.30	51.96	137.4
3	50.92	55.89	53.41	130.0

The statistical analysis of the acquired data reveals a consistently low hardness profile across the tested surface. As presented in table 1, the individual microhardness values recorded during the testing were 131.0HV0.2/10, 137.4HV0.2/10, and 130.0HV0.2/10, resulting in a calculated average microhardness of 132.8HV0.2/10. The narrow range between the minimum and maximum values, coupled with a very low standard deviation of 3.28HV0.2/10, demonstrates a high degree of mechanical and microstructural homogeneity throughout the steel matrix.



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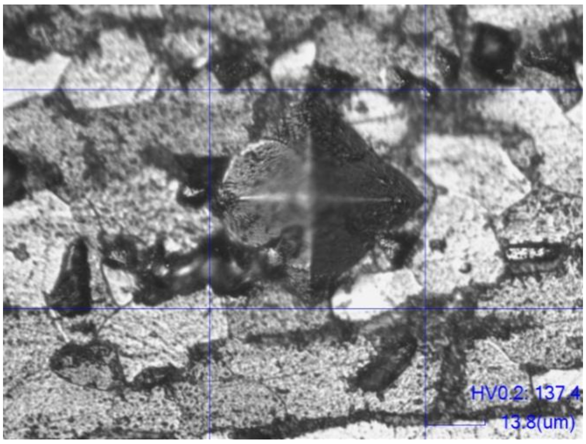

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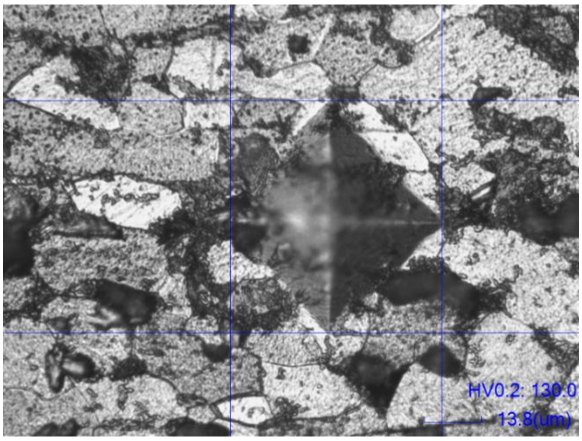

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Fig. 3. Optical micrographs showing the corresponding Vickers (HV0.2/10) microhardness indentations (shown in table 1) on the RSV 421 ship hull steel sample.

These mechanical results perfectly correlate with the microstructural and phase analyses presented in the previous sections. The relatively low average hardness of 132.8HV0.2/10 is highly characteristic of an unalloyed structural steel dominated by a soft, ductile ferritic matrix with a low carbon concentration [5], [7], [9], [10].

From an operational perspective, particularly concerning ship hull maintenance and repair, this specific mechanical profile is highly advantageous. The low inherent hardness and high ductility of the base metal are critical factors for ensuring excellent underwater welding and cutting operations. When performing underwater cutting and welding, the surrounding water acts as an aggressive quenching medium, drastically increasing the cooling rate and typically promoting the formation of localized hard, brittle microstructures in the heat-affected zone. Because the RSV 421 steel possesses a soft and homogeneous baseline structure, the overall susceptibility to extreme hardening and the subsequent risk of hydrogen-induced cold cracking during both above-water and underwater welding and cutting operations is substantially minimized. This inherent ductility provides a highly reliable foundation for executing underwater welding and cutting operations [5], [7], [9] - [11].

D. Electrochemical Corrosion Testing.

To evaluate the degradation behaviour of the RSV 421 ship hull steel in an aggressive marine environment, potentiodynamic polarization (Tafel) and open circuit potential (OCP) tests were conducted in a 0.9% wt. NaCl solution, following the methodology described in Section II. D. The acquired electrochemical parameters for the investigated steel, alongside comparative data from previous investigations on 316L stainless steel [9], [12], are summarized in table 2.

TABLE 2. RESULTS FROM ELECTROCHEMICAL CORROSION TESTING OF RSV 421 SHIP HULL STEEL AND STEEL 316L

№	*Parameter*	*RSV 421*	*Steel 316L*
1	b_a, mV	97.752	535.03
2	b_c, mV	506.29	158.67
3	i_0, A/cm^2	7.3791E-06	5.0489E-08
4	E_0, V	-0.67737	-0.080192
5	Corrosion rate, mm/a	0.085769	0.0005923
6	Residual	0.0070635	1.508E-14

1. Electrochemical behaviour of the investigated RSV 421 ship hull steel.

The thermodynamic stability of the RSV 421 steel in the saline electrolyte was initially evaluated by monitoring the open circuit potential, as shown in figure 4. Upon immersion, the potential rapidly shifted towards more negative values and relatively quickly reached a steady state, stabilizing at approximately -0.677V. This rapid stabilization without any significant positive potential shifts clearly indicates the absence of a protective passive oxide film, which is a characteristic thermodynamic behaviour for unalloyed low-carbon steels in chloride-containing environments [1], [2], [4], [9], [12].

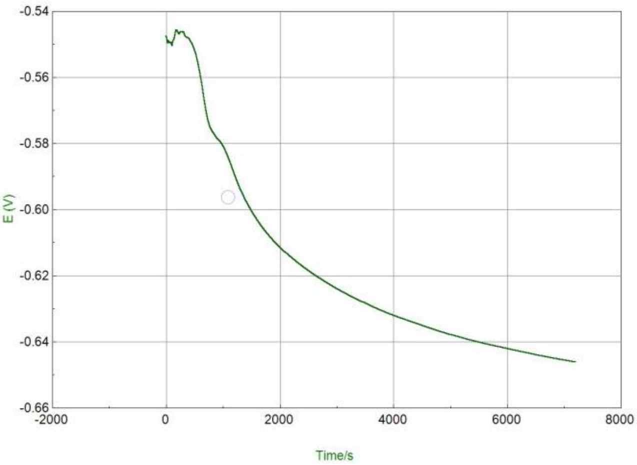

Fig. 4. Open circuit potential (OCP) evolution over time for the RSV 421 ship hull steel in 0.9% wt. NaCl solution.

Following the OCP stabilization, a potentiodynamic polarization test was performed. The resulting Tafel plot for the RSV 421 steel (figure 5) displays a continuous active dissolution profile in the anodic branch. The extracted electrochemical data reveals a corrosion potential E_0 of -0.677V and a corrosion current density i_0 of 7.38A/cm^2. Based on this current density, the calculated uniform corrosion rate for the RSV 421 ship hull steel is approximately 0.086mm/a. This active corrosion regime is entirely expected for an unalloyed ferrite-pearlite structural steel operating in seawater [1], [2], [4], [9], [12].

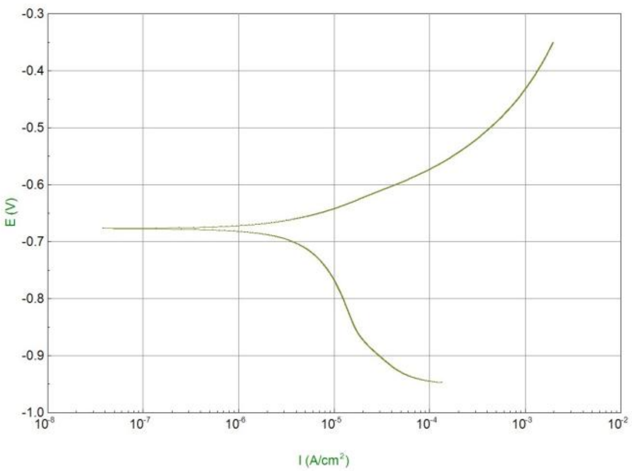

Fig. 5. Potentiodynamic polarization (Tafel) curve of the RSV 421 ship hull steel exhibiting active dissolution behavior.

2. Comparative analysis with previously investigated 316L steel.

To provide a clear benchmark for the corrosion resistance of the RSV 421 ship hull steel, its electrochemical response was directly compared to the results obtained from previous research on 316L a highly corrosion-resistant austenitic stainless steel widely used in marine engineering.

The comparative OCP evolution over time (figure 6) prominently illustrates the fundamental thermodynamic differences between the two alloys. While the RSV 421 stabilizes at a highly active potential of -0.677V, the previously tested 316L steel reaches a more positive steady-state potential of approximately -0.080V.

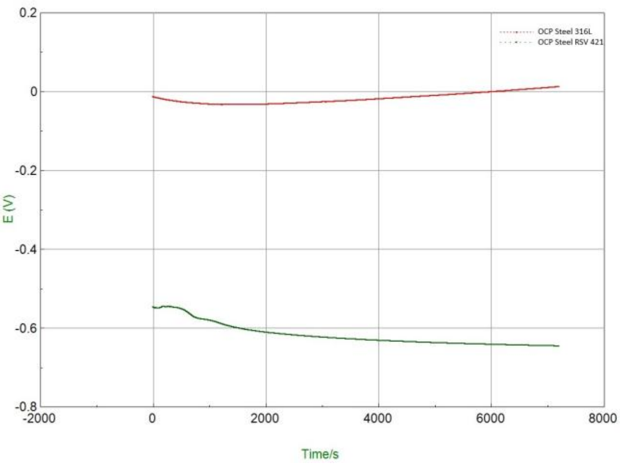

Fig. 6. Comparative OCP curves illustrating the highly active potential of RSV 421 ship hull steel versus the potential of 316L stainless steel.

This drastic difference in corrosion kinetics is further highlighted by the comparative potentiodynamic polarization curves (figure 7).

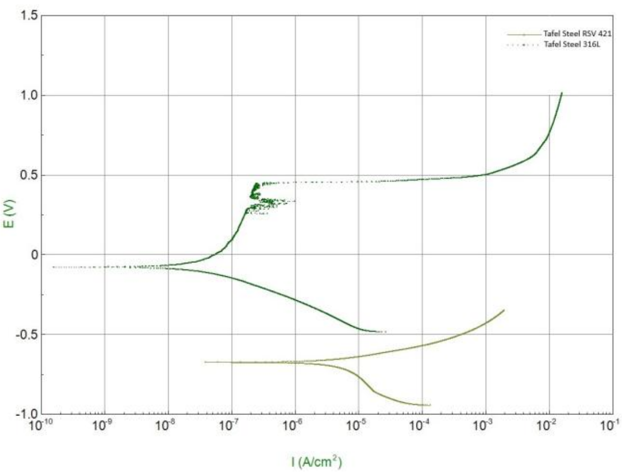

Fig. 7. Comparative potentiodynamic polarization curves emphasizing the distinct difference in corrosion kinetics between the actively corroding RSV 421 ship hull steel and the passive 316L stainless steel.

The Tafel plot for steel 316L exhibits a significantly lower anodic current and characteristics of stable passivity, which strongly contrast with the active dissolution curve of the RSV 421 ship hull steel. According to the data in table 2, the corrosion current density of steel 316L is more than two orders of magnitude lower than that of RSV 421 ship hull steel. Consequently, the corrosion rate of the steel 316L reference sample is exceptionally low (0.00059mm/a), compared to the 0. 085769mm/a calculated for the RSV 421 ship hull steel [1], [2], [4], [9], [12].

3. Implications for RSV 421 ship hull steel maintenance and above-water and underwater welding and cutting operations.

The electrochemical findings carry critical implications for the maintenance of the RSV 421 hull, particularly concerning above-water and underwater welding and cutting operations. The results confirm that the RSV 421 ship hull steel lacks inherent passivity and undergoes steady active corrosion in seawater.

When underwater welding and cutting operations are performed, the intense heat input inherently alters the local microstructure of the steel, creating an adjacent heat-affected zone. Because the RSV 421 ship hull steel actively corrodes, any significant microstructural or compositional differences between it, the heat-affected zone, and the chosen above-water or underwater welding and cutting operation will result in the formation of strong localized galvanic cells. If an improper, overly noble welding electrode is used, the highly active RSV 421 ship hull steel or the localized heat-affected zone will act as a small anode against a large cathode, leading to severe, accelerated pitting or galvanic corrosion right at the processed zone. Therefore, to ensure optimal underwater repair conditions and long-term structural integrity, it is crucial to utilize compatible welding consumables that closely match the electrochemical potential of the low-carbon base metal, coupled with the immediate application of appropriate marine protective coatings to isolate the active steel surface from the aggressive saline electrolyte [3], [5] - [7], [13].

IV. Conclusions

Based on the comprehensive microstructural, mechanical, and electrochemical investigations of the RSV 421 ship hull steel, conducted to optimize above-water and underwater welding and cutting operations, the following main conclusions can be drawn:

A. Microstructural and Phase Homogeneity.

Optical microscopy and XRD analyses confirm that the RSV 421 ship hull steel is a hypoeutectoid, low-carbon unalloyed structural steel (Grade A) with an approximate carbon content of 0.16%. The microstructure is highly homogeneous, consisting predominantly of an α-Fe (ferritic) matrix (80–85% volume fraction) with fine, equiaxed grains (10–15μm) and uniformly dispersed pearlite colonies. This refined structure, resulting from controlled thermomechanical processing, is the primary factor ensuring the material's structural stability and high impact toughness - critical for hull integrity in polar environments.

B. Mechanical Suitability for Welding.

The surface microhardness measurements, conducted at a load of 0.2kgf (HV0.2/10) and a 10s dwell time, reveal a consistently uniform profile with an average value of 132.8HV0.2/10. This low hardness is a direct consequence of the soft ferritic matrix and low carbon equivalent. From a technological standpoint, this inherent ductility effectively suppresses the hardenability of the material, significantly mitigating the risk of brittle martensite formation and hydrogen - induced cold cracking. This ensures excellent weld ability even under the extreme quenching rates characteristic of underwater welding.

C. Corrosion Dynamics and Maintenance Requirements.

Electrochemical testing in 0.9% wt. NaCl demonstrates that the RSV 421 ship hull steel operates in a continuous active dissolution regime (E_0=-0.677V, corrosion rate=0.086mm/a), lacking the thermodynamic ability to form a protective passive film. Consequently, the thermal input from above-water and underwater welding and cutting operations will inevitably induce microstructural gradients that act as localized galvanic cells. To prevent accelerated galvanic degradation at the weld interfaces, it is mandatory to utilize welding consumables that are electrochemically compatible with the active base metal, followed by the immediate application of specialized marine coatings to isolate the repaired sections from the electrolyte.

ACKNOWLEDGMENTS

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