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# Cold Cracking Susceptibility of Joints made of Ferritic-Austenitic Duplex Steel 2205 during Underwater Wet Welding

**Abstract:** The underwater welding of ferritic-austenitic duplex steels is arousing growing interest inspired by the urgent need for developing welding technologies used for repairing underwater pipelines transporting oil. The tests involved underwater welding using covered electrodes (process 111). The research also involved Tekken technological tests performed under water at a depth of 0.5 m and in air as well as macro and microscopic metallographic tests, ferrite content measurements and hardness measurements of joints. The test results obtained revealed that the underwater welding of duplex steels could lead to cold crack formation. In the case considered above, cold crack susceptibility was attributed to arc burning instability.

**Keywords:** underwater wet welding, 2205 duplex steel, cold crack susceptibility

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## Introduction

Modern ferritic-austenitic duplex steels are increasingly used for the construction of underwater pipelines operated by the oil extraction industry. The above named steels are characterised by high strength, good corrosion resistance and good resistance to cracking induced by stresses and hydrogen [1, 2]. Welding performed in a watery environment is characterised by increased joint cooling rates as well as increased contents of hydrogen diffusing in the weld deposit.

Underwater welding is usually wet, which means that a diver-welder, elements being welded, welding arc and filler metals remain in direct contact with water. Water increases joint cooling rates and, as the welding environment is rich in potential hydrogen [3-7]. As a result, the weldability of steels is limited by the possibility of cold crack formation. In addition, underwater wet welding performed using covered electrodes is usually accompanied by worsened arc burning stability, leading to the formation of welding imperfections. Impaired visibility and efficiency of a diver-welder caused by sea currents can additionally contribute to the formation of numerous welding imperfections. For this reason, it is necessary to perform welding procedure qualification aimed to confirm the possibility of performing works in a watery environment in accordance with the regulations specified in AWS D3.6M:2010 *Underwater Welding Code* or standard EN ISO 15614-9 *Specification and approval of welding procedures for metallic materials. Welding procedure test. Part 9: Underwater wet welding.*

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Table 1. Chemical composition of duplex steel UNS-S31803

| | Chemical element content, % by weight | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | C | Si | Mn | P | S | Cr | Ni | Mo | N |
| * | 0.03 | max. 1.0 | max. 2.0 | max. 0.35 | max. 0.015 | 21-23 | 4.5-6.0 | 2.5-3.0 | 0.10-0.22 |
| ** | 0.022 | 0.42 | 1.35 | 0.023 | 0.001 | 22.4 | 5.7 | 3.1 | 0.18 |

* chemical composition of the duplex steel according to the related standard

** chemical composition of the duplex steel according to the check analysis

Ferritic-austenitic duplex steels 2205 are sensitive to structural transformations resulting from welding thermal cycles. This could reduce mechanical properties and corrosion resistance of joints. High joint cooling rates of duplex steel 2205, resulting from underwater welding, can increase the content of ferrite in the HAZ and welds; where according to ASTM E562 the content of ferrite should not exceed 70%. In addition, the structure of joints could contain chromium nitride precipitates and micro-areas impoverished in chromium and nickel.

Underwater welding is an effective procedure for repairing structures operated under water and exposed to the corrosive environment, collisions with vessels etc. Technological guidelines concerning underwater welding works are specified in the regulations specified by the Classification Society Det Norske Veritas (DNV) (Recommended Practice DNV-RP-F113 *Pipeline Subsea Repair* and Offshore Standard DNV-OS-F101 *Submarine Pipeline Systems*). These specifications allow GMA and TIG hyperbaric welding in dry habitats. The first attempts of welding ferritic-austenitic steels in hyperbaric conditions in dry habitats proved successful [8, 9]. Therefore, it can be supposed that duplex steels should be characterised by good underwater weldability, yet such suppositions must be confirmed by appropriate tests. In spite of increased interest in duplex steels, their weldability in a watery environment has not been the subject of extensive research or scientific publications.

Available reference publications refer to the cold crack susceptibility of duplex steels in air. Related weldability tests were performed using TIG, plasma and MMA welding. It was

Table 2. Mechanical properties of duplex steel UNS-S31803

| T [°C] | $Rp_{0,2}$[MPa] | Rm [MPa] | A [%] |
|---|---|---|---|
| 20 | 512 | 777 | 35 |

ascertained that the cold crack susceptibility of duplex steels depends on the content of ferrite in the structure, linear energy (heat input) and the content of hydrogen in shielding gas. It was noticed that hydrogen added to shielding gas (Ar) decreased susceptibility to crack formation. It was also observed that duplex steels were characterised by greater susceptibility to cold cracking if the content of ferrite in the weld exceeded 50%. In addition, the shape of a weld groove could also trigger cold crack formation due to the distribution of post-weld stresses generated in the material [10-11].

## Individual Tests

The purpose of the tests was to determine the cold crack formation susceptibility of corrosion resistant ferritic-austenitic duplex steel 2205 wet welded under water using covered electrodes. The tests involved the use of a 12 mm thick sheet made of duplex steel 2205 UNS-S31803 (1.4462). The chemical composition and mechanical properties of the duplex steel are presented in Tables 1 and 2.

The objective was obtained using the following schedule of tests:

1. Development of a Welding Procedure Specification (WPS)
2. Making test joints with butt welds (Tekken) in the air and under water in accordance with PN-EN ISO 17642-2 *Destructive tests on welds in metallic materials – Cold cracking tests for weldments – Arc welding processes – Part 2: Self-restraint tests*

3. Tests involving the welded joints:
   - visual tests (VT),
   - penetrant tests (PT),
   - macro and microscopic metallographic tests,
   - hardness measurements (HV5),
   - ferrite content measurements in the weld and HAZ.

The tests were made in accordance with PN-EN ISO 17642-2, using a station for welding at shallow depths (up to 1.0 m). The test welds were made at a depth of 0.5 m in non-saline water (water line water) using covered electrodes BÖHLER FOX CN 22/9N (EN 1600 – E 22 9 3 N L R 3 2) having a diameter of 4 mm and intended for welding in the air. Field welds were made in the air using a CastoMAG 45505 S solid wire having a diameter of 1.2 mm (ISO 14343-A-G 22 9 3 N L). The shielding gas used in the tests was mixture M13 (97.5%Ar + 2.5%$O_2$) in accordance with PN-EN ISO 14175. The scheme of the making of Tekken type test joints is presented in Figure 1.

The specimens were designated with symbols including a test type, letters (W – underwater welding, P – welding in air) and a successive number. The chemical composition and mechanical properties of the weld deposit of the covered electrodes used when making the test welds are presented in Tables 3 and 4. The parameters related to the welding of the Tekken specimens in air and in water are presented in Table 5. The type of current and welding polarity were adjusted in accordance with guidelines specified by the manufacturer.

The visual (VT) and penetrant (PT) tests were performed, in accordance with related standard specifications of PN-EN ISO 17637:2011 and PN-EN ISO 3452-1:2013, 72 hours after the completion of welding. The tested specimens contained undercuts, incomplete fusions and spatters as well as were of improper shape. During the underwater welding it was observed that arc was burning in an unstable manner causing an uncontrolled increase in welding parameters, exceeding the permissible heat input (linear welding energy) for duplex steels. The underwater welding of this material group performed

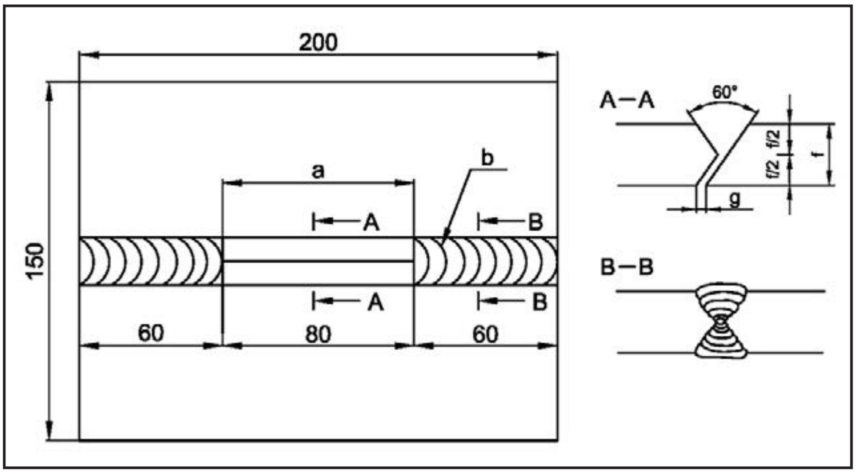


Fig. 1. Scheme of the making of the Tekken test joints used for the assessment of steel to cold crack susceptibility according to PN-EN ISO 17642-2

Table 3. Chemical composition of BÖHLER FOX CN22/9N weld deposit, % [12]

| Chemical element content, % by weight | | | | | | |
|---|---|---|---|---|---|---|
| C | Si | Mn | Cr | Mo | Ni | N |
| 0.03 | 0.9 | 0.8 | 23 | 3.2 | 9 | 0.17 |

Table 4. Mechanical properties of BÖHLER FOX CN 22/9N weld deposit [12]

| Re [MPa] | Rm [MPa] | A5 |
|---|---|---|
| ≥ 540 | ≥ 690 | ≥ 22 |

Table 5. Parameters of the welding of the Tekken specimens

| Specimen no. | Environment | Current type/ polarity | Current $I$, A | Arc voltage $U$, V | Welding time $t$, s | Welding linear energy, $q_{el}$, kJ/mm |
|---|---|---|---|---|---|---|
| Tekken W1, W2 | Water | DC/- | 192 | 37.3 | 12.69 | 1.11 |
| Tekken W3, W4 | Water | DC/- | 248 | 62.3 | 15.63 | 3.02 |
| Tekken P1 | Air | DC/- | 140 | 24.3 | 20.80 | 0.87 |

$q_{el} = U \times I / V_{sp}$

using covered electrodes caused numerous difficulties maintaining stable welding parameters, "gentle" electrode melting and obtaining welded joints free from welding imperfections. The Tekken specimens made in air were free from cracks or other welding imperfections. The underwater welding performed with arc burning in an unstable manner lead to the formation of cracks in the weld axis. The wet welding conducted with arc burning in a stable manner did not result in the formation of cracks.


Fig. 2. Cross-section of the joint welded under water: specimen W1, non-saline water, $q_{el}$ = 1.11 kJ/mm; the lack of welding imperfections; etchant: Beraha

## Macro and Microscopic Metallographic Tests

The macro and microscopic metallographic tests were performed following the requirements of standard PN-EN ISO 17639. The specimens were cut out using a frame saw, transversely in relation to the weld axis, so that they would include an entire welded joint. The specimen surfaces were subjected to grinding, polishing and etching using the Beraha reagent. Figures 2-6 present the microstructure of the Tekken test joints.

The results of the macroscopic tests largely confirmed the NDT results, additionally revealing internal welding imperfections such as gas pores, gas cavities and cracks initiated in the root. The HAZ was very narrow and unidentifiable up to a magnification of 50x. Both the welds made in air and under water


Fig. 3. Cross-section of the joint welded under water: specimen W2, non-saline water, $q_{el}$ = 1.11 kJ/mm; the lack of welding imperfections; etchant: Beraha


Fig. 4. Cross-section of the joint welded under water: specimen W3, non-saline water, $q_{el}$ = 3.02 kJ/mm; the lack of welding imperfections; etchant: Beraha


Fig. 5. Cross-section of the joint welded under water: specimen W4, non-saline water, $q_{el}$ = 3.02 kJ/mm; the crack visible in the weld (initiated in the root); gas pore; etchant: Beraha


Fig. 6. Cross-section of the joint welded in air: specimen P1, $q_{el}$ = 0.87 kJ/mm; the lack of welding imperfections; etchant: Beraha

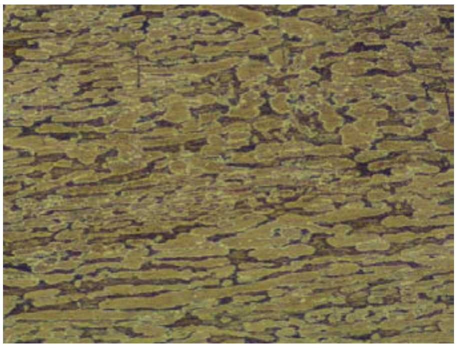

Fig. 7. Microstructure of the base material of duplex steel 2205; etchant: Beraha; mag. 200x

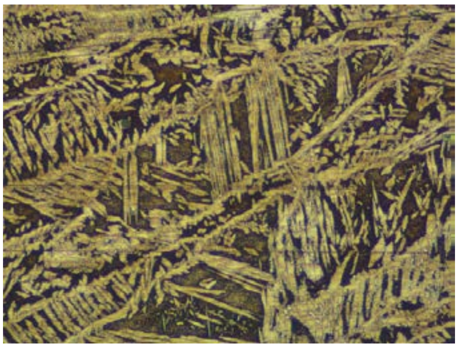

Fig. 8. Microstructure of the weld in the joint made of duplex steel 2205; etchant: Beraha; mag. 200x

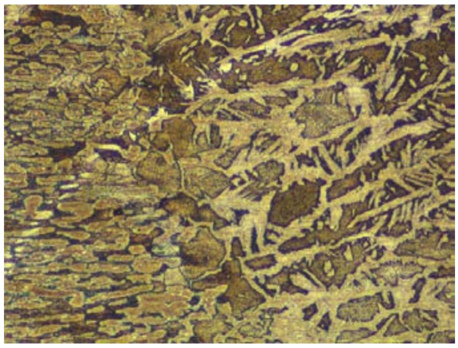

Fig. 9. Microstructure of the HAZ in the joint made of duplex steel 2205; etchant: Beraha; mag. 200x

were characterised by proper geometry and full penetration.

The microscopic metallographic tests were performed using the specimens previously used in the macroscopic metallographic tests. The specimens were subjected to further stages of treatment and prepared for etching by means of the Beraha reagent. Figures 7-9 present structure of welded joint areas subjected to the microscopic tests.

The base material of the steel contained a typical dual-phase structure composed of ferritic matrix (35÷50%) and austenite grains arranged in bands. The weld structure was composed of ferrite and acicular austenite precipitates perpendicular to the fusion line. The HAZ overheating area was characterised by the increased content of ferrite, whereas the transition zone contained local purely ferritic bands. The microscopic observations revealed the presence of a crack in the specimen made with arc burning in an unstable manner in a watery environment. The specimens welded under water using arc burning in a stable manner, and those welded in air were characterised by the lack of cracks and proper structure.

## Hardness Measurements

Hardness measurements of the test joints were performed using the Vickers hardness test in accordance with the guidelines of PN-EN ISO 9015-1:2011 *Destructive tests on welds in metallic materials. Hardness Testing. Hardness test on arc welded joints*. However, it should be noted that in accordance with standard PN-EN ISO 15614-1:2008 *Specification and qualification of welding procedures for metallic materials. Welding procedure test. Part 1: Arc and gas welding of steels and arc welding of nickel and nickel alloys*, duplex steels are not subjected to hardness measurements. The hardness tests were performed using a VEB hardness tester. The indenter load amounted to 49.03 N (HV5). The hardness measurements were performed along the line located 2 mm below the face of the test welds. A scheme showing the location of measurement points is presented in Figure 10. Exemplary hardness distributions on cross-sections of welded joints are presented in Figures 11-15.

The cross-sectional hardness distribution in the joints along the measurement line was characteristic of duplex steels. The hardness of the base material did not exceed 270 HV5. An increase in the joint cooling rate resulting from the cooling effect of water did not significantly

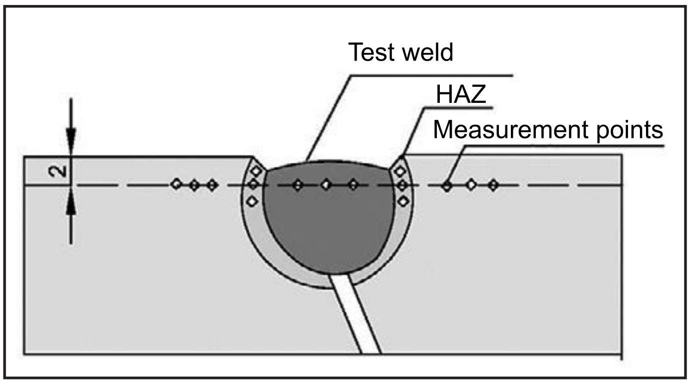


Fig. 10. Location of the measurement points on the cross-section of the test joints

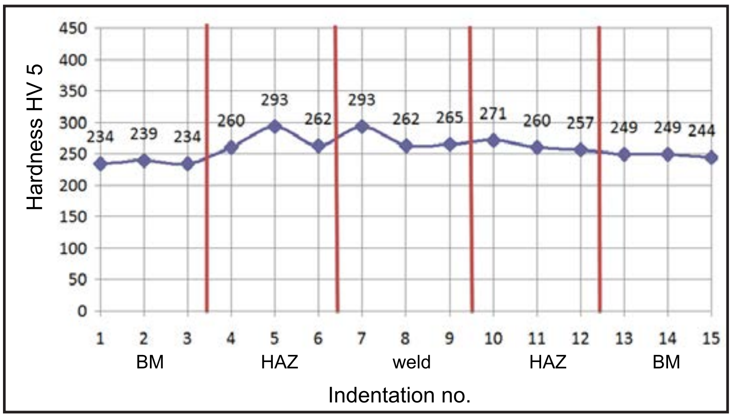


Fig. 11. Hardness distribution in the joint of Tekken P1 specimen welded in air

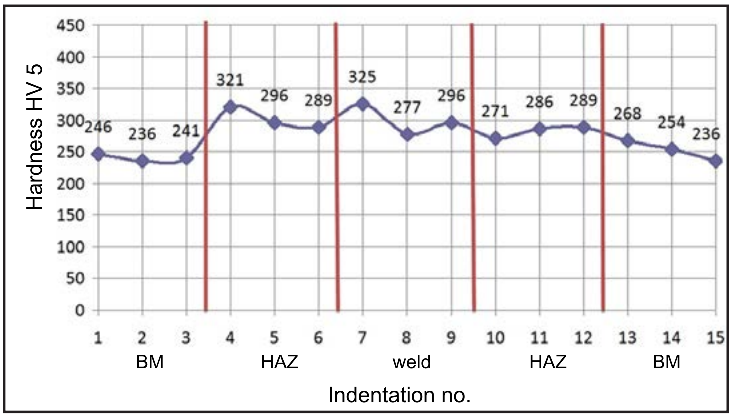


Fig. 12. Hardness distribution in the joint of Tekken W1 specimen welded under water

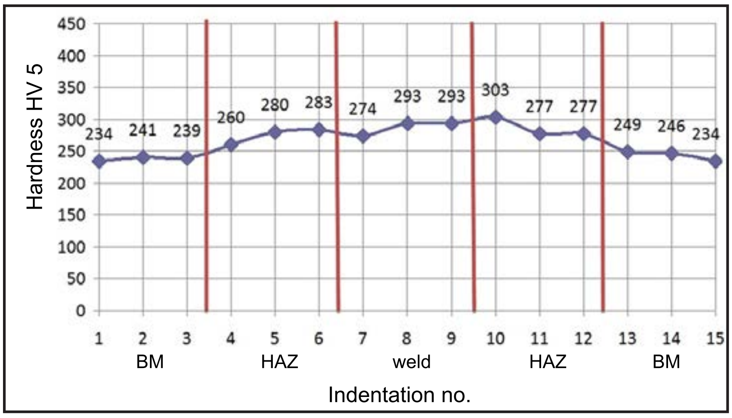


Fig. 13. Hardness distribution in the joint of Tekken W2 specimen welded under water

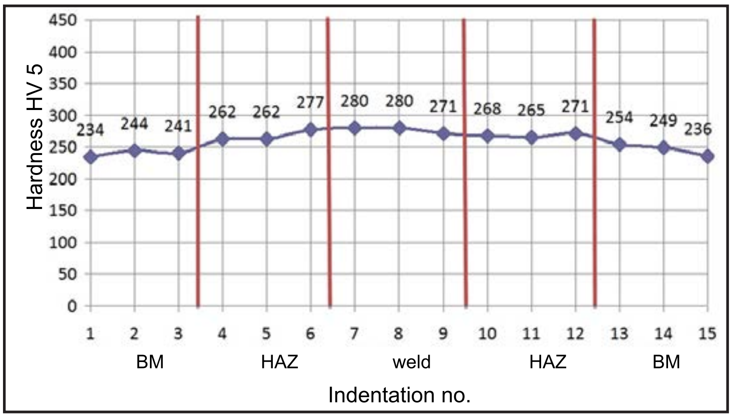


Fig. 14. Hardness distribution in the joint of Tekken W3 specimen welded under water

affect the hardness of the specimens made under water or those made in air. The critical area of the joint, i.e. the HAZ, was not significantly hardened; therefore, it can be concluded that precipitation processes of secondary phases had not taken place during the welding thermal cycle [13-14]. It should be added that the precise measurement of hardness was impeded due to the very narrow HAZ area.

## Ferrite Content Measurements

Quantitative measurements of ferrite contents in the structure were performed in accordance with the regulations specified in ASTM E562 *Standard Practice for Determining Volume Fraction by Systematic Manual Point Count*. According to the above named specification, the content of ferrite in the base material should be restricted within the range of 35 to 55%, whereas in the welded joints, root runs, face runs and in the HAZ within the range of 30 to 70%.

Measurements of ferrite contents were performed in the base material, HAZ and welds. The content of ferrite was determined using a Multi-Scan software programme for structural quantitative analyses. In the base material, the average ferrite content amounted to approximately 48%, whereas in the weld it was restricted within the range of 52 to 56%. The highest ferrite content (56%) was observed in the welds of specimens W1 and W2 welded under water with welding arc burning in a stable manner (Table 6). These results were consistent with metallographic observations and confirmed the effect of the increased joint cooling rate (due to the cooling effect of water) leading to the slowing down of transformation $\alpha \rightarrow \gamma$. In specimens W3 and W4 welded under water with welding arc burning in an unstable manner, the content of ferrite amounted to 47%. The weld made in air contained 52% ferrite. Discrepancies in ferrite contents between the

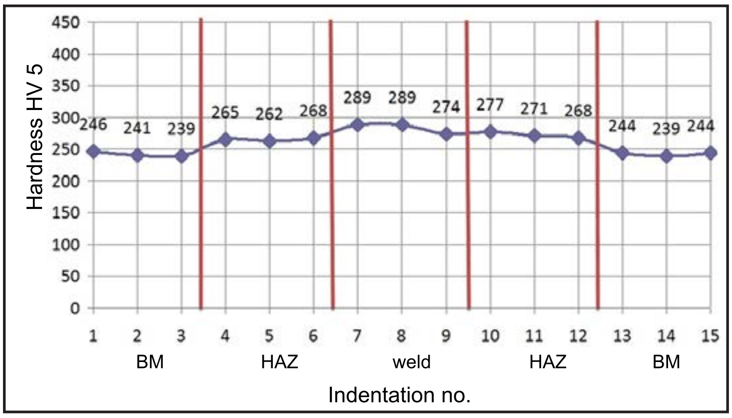


Fig. 15. Hardness distribution in the joint of Tekken W4 specimen welded under water

Table 6. Ferrite content in the tested areas of Tekken specimens

| | Ferrite content [%] | | |
|---|---|---|---|
| Specimen no. | Weld | HAZ | Base material |
| Tekken W1, W2 | 47 | 69 | 45 |
| Tekken W3, W4 | 56 | 66 | 54 |
| Tekken P1 | 52 | 54 | 44 |

base material and the weld could result from the chemical composition of the weld deposit of Fox CN 22/9N electrodes characterised by a higher nickel content.

The ferrite content in the HAZ of the Tekken joints, estimated on the basis of microscopic observations, did not exceed the boundary value of 70% and was restricted within the range of 54 to 69%. The boundary of the HAZ overheating area contained very narrow bands of a purely ferritic structure. The content of ferrite in the HAZ of the welds made under water was slightly higher than that found in the HAZ of the joints made in air.

## Summary

The study was concerned with assessing the cold crack susceptibility of welded joints made of duplex steel 2205 on the basis of Tekken type technological and additional tests. The issue addressed in the study was connected with the necessity of getting to know phenomena taking place when welding duplex steels under water, which, as a result, could lead to the development of a technology for repairing underwater structures, e.g. oil transporting pipelines. The results of tests involving Tekken type welded joints made using Fox CN 22/9N covered electrodes revealed that if welding arc burning parameters were stable, duplex steel 2205 was weldable both in air and under water. In turn, butt joints made under water when arc was burning in an unstable manner were characterised by susceptibility to cold cracking. Cold cracks were formed in the weld; the HAZ overheating area was free from them.

The welds of Tekken test joints made of duplex steel 2205 in air and under water using covered electrodes were characterised by similar structures and properties. All of the specimens welded under water (process 111) were characterised by the very narrow HAZ area. Intensive cooling provided by the water environment did not result in an increase in the ferrite content in the weld and HAZ if compared with the ferrite content established in the joints made in air.

The analysis of hardness distribution in the test joints did not reveal significant differences between values determined in the welds made in air and those made in water. The hardness values found in the HAZ were restricted in the range between the hardness value of the base material and that of the weld deposit. No increase in the hardness of the overheating area was detected. This could imply that precipitation processes of secondary phases did not take place during the welding thermal cycle. The follow-up research will be concerned with determining the effect of different welding process conditions on the possibility of cold crack formation, e.g. the effect of water type (freshwater, seawater) or changes in the geometry of weld groove.

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