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THE EFFECT OF WET UNDERWATER WELDING ON COLD CRACKING SUSCEPTIBILITY OF DUPLEX STAINLESS STEEL

ABSTRACT

The present work was conducted to assess the weldability of duplex stainless steel in underwater conditions. Metal manual arc welding (MMA) with the use of coated electrodes was used in the investigations. Tekken weldability tests were performed underwater at 0.5 m depth and in the air. Nondestructive tests, metallographic examinations of welds, ferrite content assessment in microstructure and hardness test were performed. The good weldability at underwater conditions of duplex stainless with the use of MMA method was confirmed, however difficulties in stable arc burning were revealed.

***Keywords**: duplex stainless steel, underwater welding, cold cracking*

INTRODUCTION

Development of underwater welding techniques is mainly connected with the exploration and exploitation of subsea natural resources, primarily for petroleum and natural gas. Mobile and stationary off-shore units with a draft exceeding 50 m, as well as underwater pipelines laid on the seabed, require a permanent inspection and repairs using welding techniques [1,2]. Underwater welding is needed in cases of emergency, and sometimes to produce joint assembly. Damage of subsea pipelines and constructions may have various causes. Usually arise as a result of corrosion processes, from the movements upon an unstable surface and as a result of collisions with thrown anchors or directly with the flowing vessels.

Underwater welding repairs are also widely used in the hulls of vessels and port facilities. These works are carried out at relatively shallow depths and allow significantly reducing unit downtime and repairing costs, for example by eliminating the docking of the ship. These needs have become the main cause for the development of underwater welding technology and application of this technique in practice.

Currently, there are many techniques used in underwater welding. They can be classified according to the environment in which work takes place [1-3]: (-) dry welding (-) wet welding.

The main factors influencing the weldability of steel in underwater conditions include [1,4-7]:

- high cooling rate of the joints,
- high levels of hydrogen in deposited metal,

- the impact of hydrostatic pressure on the arc and metallurgical processes.

Dissociation of water, during the wet welding process is the source of large quantities of atomic hydrogen gas in the bladder surrounding the welding arc, which goes rapidly to weld pool. The water pressure in underwater welding conditions significantly affects the physicochemical equilibrium in the weld pool. High cooling rates causes susceptibility to phase transformations in the HAZ, retain of slag and generation of porosity. While welding in the air heat transfer takes place mainly from the heat source to the base material, in underwater conditions the main quantity of heat is discharged by the environment, namely through the water.

During the wet welding electrode and the base material are in direct contact with water, which significantly affects the weldability of steel. Welding is carried out mostly by coated electrodes and flux cored wires [1,8,9,10]. This method does not apply to any additional equipment designed to remove water from weld area. High cooling rate of the joints causing undesirable structural changes in the weld and HAZ together with high content of hydrogen in the weld metal would cause the formation of cold cracks [2]. These observations apply to joints of carbon steel. In the case of high alloyed austenitic or ferritic-austenitic stainless steels contents of diffusible hydrogen in a weld metal may be totally distinct because of big differences between hydrogen solubility and diffusion rate at austenite and ferrite phases.

According to [11] diffusivity (at 25°C) of austenitic AISI 316L steel is $3.1\cdot10^{-16}$ $m^2\cdot s^{-1}$ and diffusivity of ferritic AL 29-4-2 steel is $1.1\cdot10^{-11}$ $m^2\cdot s^{-1}$. Obviously the diffusion rate of hydrogen is about five orders of magnitude higher in ferritic than in austenitic stainless steels. However, the solubility is about two orders of magnitude higher in the austenitic than in the ferritic stainless steels.

Underwater welding is subject to the same quality control as welding on the surface. So far, approval of welding technology is based on the specification AWS D3.6M, which establishes three classes for joints made under the water [12]. Class A includes joints with properties similar to those performed on the surface and usually is used for joints made under hyperbaric dry welding. Class B for less important welds with lower required impact energy, and increased porosity - is used for joints made by the wet welding method. Class C - for little mechanically loaded joints, with lower requirements in relation to Class B

Ferritic-austenitic stainless steels of duplex type are becoming increasingly important in various industries due to the higher mechanical properties compared to commonly used austenitic stainless steel and very good corrosion resistance. In the offshore industry it is a material often used for underwater pipelines and tanks. Wrought duplex stainless steel undergo welding processes using various techniques. Welding technology of duplex stainless steels is well known, however to obtain sound joints strict observance of technological regimes is necessary. The information on underwater welding of these steels is hardly available. In the literature there is no broader studies and reports on the behavior of duplex steels during underwater welding and properties of joints. Duplex steels, however, are very sensitive to structural changes occurring under the influence of welding thermal cycle. Most of the problems of welding of these steels are associated with the HAZ area, not a weld. The mechanical properties and corrosion resistance of duplex steel welds are dependent on: the proportion of ferrite and austenite in the structure, morphology and size of grains of ferrite and austenite, the type and morphology and distribution of intermetallic phases, which can precipitate from the ferrite. The structure of the weld and HAZ depends on the choice of welding and cooling rate of the joints. Too high cooling rates give a high content of ferrite in the HAZ, which causes a reduction in strength and corrosion resistance of the joints. In turn, too low cooling rate resulting from the use of high heat input of welding, can lead to precipitation of harmful intermetallic phases. The hot cracks in duplex steels joints are less common. This is due to a smaller coefficient of linear expansion and higher thermal conductivity compared to austenitic steels [13]. These problems of duplex steels weldability may be strengthened during underwater welding, where cooling rates are higher and the effect of hydrogen can play a decisive role in creating the cold cracks.

The aim of the study was to determine the susceptibility to form cold cracks in the ferritic-austenitic 2205 duplex stainless steel welded under water with the use coated electrodes.

EXPERIMENTAL

The specimens for cold cracking susceptibility tests were made of duplex stainless steel UNS-S31803 (1.4462), the plate 12 mm in thickness. As the consumable BÖHLER FOX CN 22/9N (EN 1600 - E 22 9 3 N L R 3 2) electrodes ø 4.0 mm was used. Chemical compositions of the steel plate and electrodes are presented in Table 1.

Table 1. *Chemical compositions of used materials, wt %*

Material	C	Si	Mn	Cr	Ni	Mo	N
Duplex steel 2205, 1.4462	0.022	0.42	1.35	22.4	5.7	3.1	0.18
BÖHLER FOX CN 22/9N	0.03	0.90	0.80	23.0	9.0	3.2	0.17

Tekken samples according to PN-EN ISO 17642-2 standard were used (Fig. 1). Welding was performed in the air and under water at small depth of 0.5 m, hence the influence of increased pressure on the welding process can be omitted. Tap water was used. Deposits were made by the MMA welding method with DC/- polarity. Assembly welds were made in the air using GMA welding method.

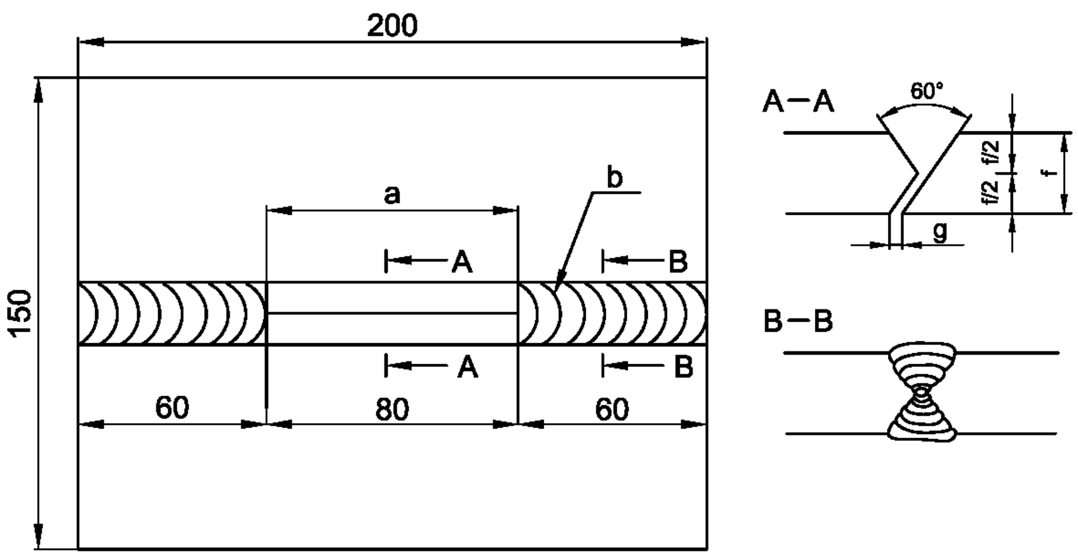

Fig. 1. The view of Tekken sample for evaluates the tendency of steel to form cold cracks in the welded joint. A-A - test weld, B-B – assembly weld

Six Tekken samples were performed. Two of them were performed in the air and 4 under water. The test beads were performed with the various parameters of welding current/arc voltage and welding speed. Underwater beads were welded with heat inputs of 1.1 and 3.0 kJ/mm. Average welding parameters are shown in Table 2.

Table 2. *Welding parameters of Tekken samples*

Sample	Environment	Arc voltage [V]	Welding current [A]	Welding time [s]	Heat input [kJ/mm]
W1	water	37	192	12,5	1.1
W2	water	37	192	12,5	1.1
W3	water	62	248	15,5	3.0
W4	water	62	248	15,5	3.0
P1	air	24	140	20,5	0.87
P2	air	24	140	20,5	0.87

Visual testing (VT) and penetrant testing (PT) were carried out 72 h after the end of welding in accordance with the PN-EN ISO 17637: 2011 and BS EN ISO 3452-1: 2013 standard specifications. Underwater welding with the use of coated electrodes caused numerous difficulties in maintaining stable welding parameters and "soft" electrode melting. The test beads showed numerous imperfections like undercuts, shape errors, arc strike and spatter. Unstable arc burning resulted in uncontrolled growth of the welding parameters, exceeding the accepted limit of heat input for duplex steels and sometimes exceeding maximum welding current for used electrodes. Tekken samples welded in the air showed no cracks and other imperfections.

Macroscopic cross section examinations (Fig. 2-6) indicate no cracks in the welds expect sample W4 welded underwater with high heat input, Fig. 5.

Fig. 2. Tekken sample W1. Welding bead performed underwater with heat input 1.1 kJ/mm. No imperfections. Beracha's etch.

Fig. 3. Tekken sample W2. Welding bead performed underwater with heat input 1.1 kJ/mm. No imperfections. Beracha's etch.

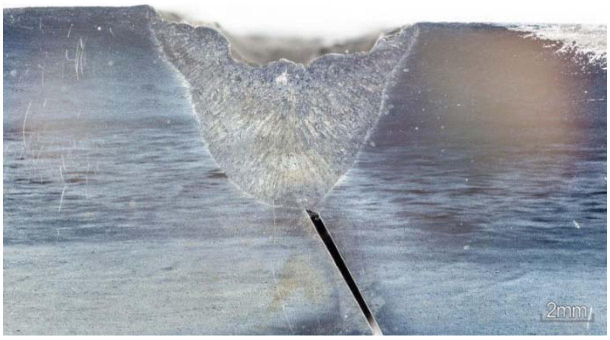

Fig. 4. Tekken sample W3. Welding bead performed underwater with heat input 3.0 kJ/mm. No imperfections. Beracha's etch.

Fig. 5. Tekken sample W4. Welding bead performed underwater with heat input 3.0 kJ/mm. Crack in the weld. Beracha's etch.

Fig. 6. Tekken sample P1. Welding bead performed on the air with heat input 0.87 kJ/mm. No imperfections. Beracha's etch.

The macroscopic test results confirmed the results of non-destructive tests, revealing in addition the presence of internal imperfections such as porosity, voids and cracks initiated at the root of the weld. Heat affected zone was very narrow and it could not be identified at a magnification of up to 50x. Welds performed in the air and under water showed correct geometry and full penetration.

Metallographic examinations

Metallographic examinations were performed with the use of light microscopy. Structures of weld metal differ slightly depending on the cooling rate which in turn depends on the welding heat input and welding environment (air, water).

During solidification of duplex weld metal an almost completely ferrite structure is formed. Further cooling initiates the formation of the austenite phase nucleating at the ferrite grain boundaries. In examined welds a dendritic microstructure developed in fast cooling conditions. In the face of the weld boundary, austenite (GBA) and inter-granular austenite (IGA) were found (Fig. 7). Underwater welds show smaller austenite acicular precipitates compared to those obtained during welding in the air. It is a consequence of shorter $\gamma \rightarrow \alpha$ transformation time.

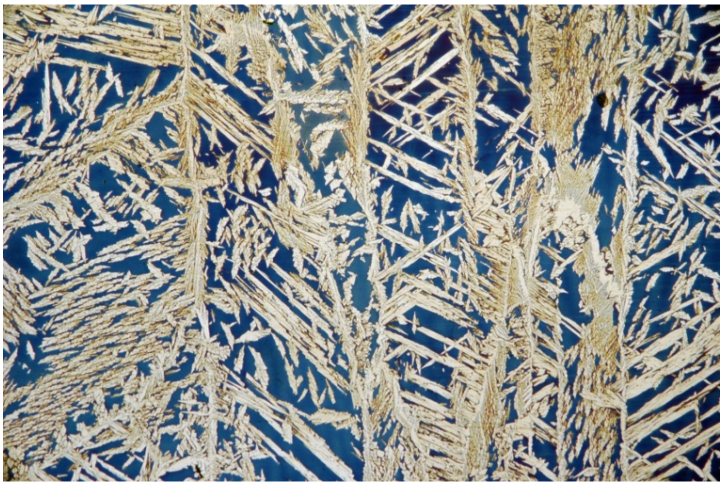

Fig. 7. Weld metal microstructure (W1). Magn. 100x

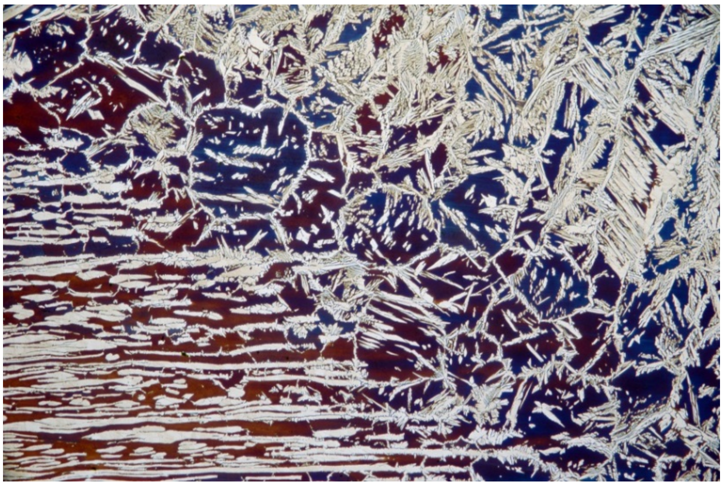

Fig. 8. Heat affected zone microstructure (W1). Magn. 100x

Heat affected zone microstructure could be critical for welded joint properties. For examined welds the very narrow zones of about 200-400 μm were observed depending on welding heat input. There were no large differences in HAZ width in welds made in the air and under water. The ferrite content in those zones was significantly higher in comparison to bulk weld metal. The microstructure consists of lamellar austenite precipitates that surround equiaxial, large ferrite grains, Fig 8.

The ferrite contents in the weld metal, HAZ and base material were measured by systematic manual point count according to ASTM E562 standard with the use of computer image analysis program.

In the base material of duplex steel average ferrite content was 48%. Ferrite content in weld metal structures ranged from 47-56%. The highest ferrite content of 56% was found in the W1 and W2 samples welded under water with rather low heat input and stable welding conditions. This is consistent with the results of metallographic observation and confirms an influence of cooling rate on the phase transformation $\gamma \rightarrow \alpha$ rate. Increasing the welding heat input at W3 and W4 samples caused reduction in ferrite content in weld metal structure to 47%. Deposits made in the air contained approximately 52% ferrite. Differences in ferrite content in the base material and weld pad also result from differences in chemical composition of BÖHLER FOX CN 22/9N electrodes and 2205 duplex steel.

The ferrite content in heat affected zones was within 54-72%. Smaller ferrite content was found in HAZ samples welded on the air (54-58%) and higher ferrite content in HAZ of underwater welded samples (66-69%).

Hardness tests

Hardness measurements of welded joints were made using Vickers method and a load of 49,03N (HV5). Location of indentations on the cross section of welded joint is shown in Fig. 9.

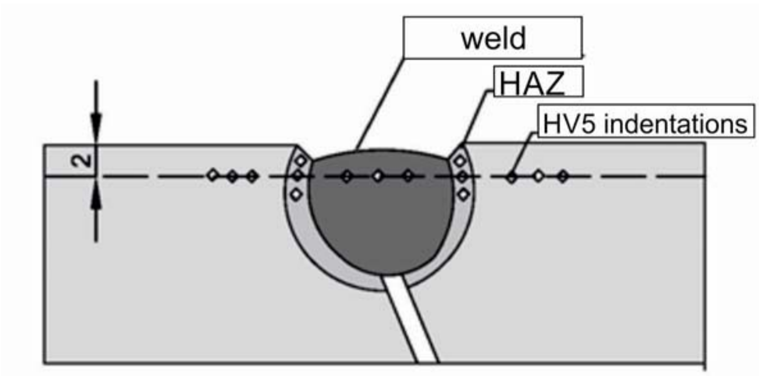

Fig. 9. Distribution of measuring points on the cross-section of test joints

The hardness values HV5 obtained on cross sections showed no significant differences between weld metals of beads performed in the air and the water environment. Small differences in the phase balance of austenite and ferrite do not influence the hardness. A higher weld metal hardness of 280 HV5 was recorded compared to base material - about 250 HV5. Heat affected zones hardness were in the range 260 – 303 HV5. There was no considerable increase in hardness in this zone. This indicates that there was no secondary phases precipitation during welding thermal cycle. In addition precise measurements of hardness in this area were difficult due to the small width of HAZ. Figures 10-12 show an example of hardness distributions on the cross sections of welds.

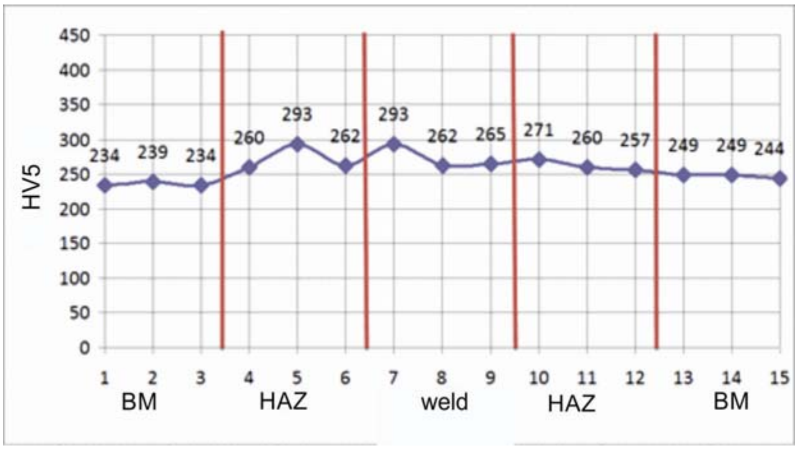

Fig. 10. Hardness distribution on joint cross section performed in the air (P1) with heat input 0.87 kJ/mm

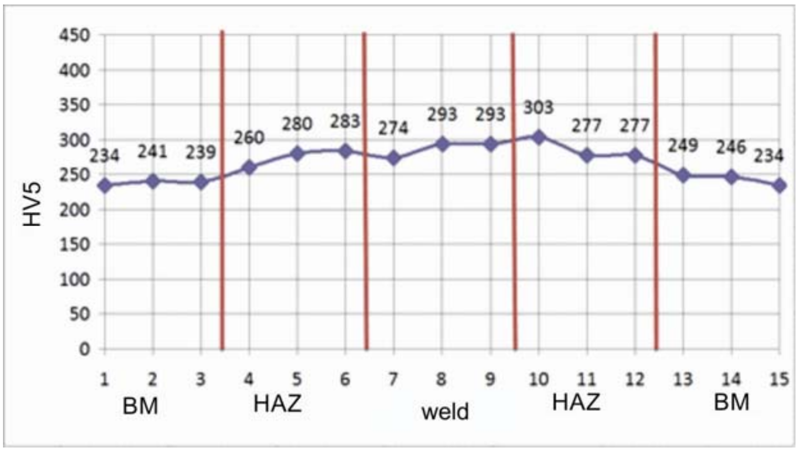

Fig. 11. Hardness distribution on joint cross section performed under water (W2) with heat input 1.1 kJ/mm

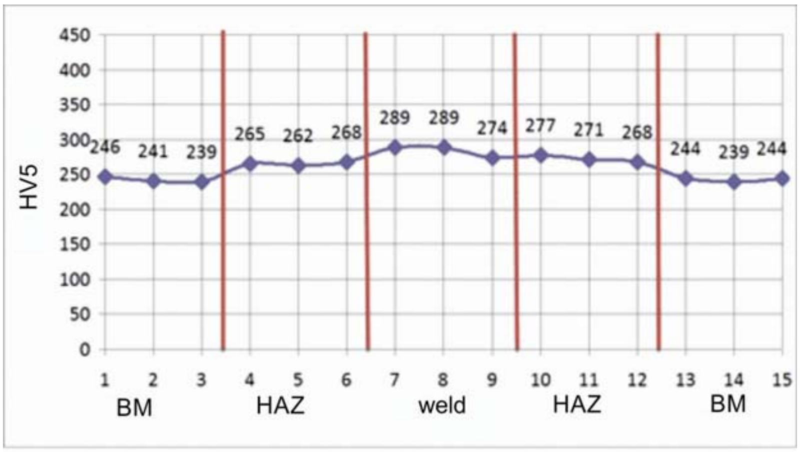

Fig. 12. Hardness distribution on joint cross section performed under water (W4) with heat input 3.0 kJ/mm

CONCLUSIONS

Studies have shown that the duplex stainless steels can be successfully welded in water environment without fear of undesirable structural changes and susceptibility to cold cracking. Strongly restrained Tekken joints proved to be not susceptible to cold cracking after underwater welding on the assumption of a stable arc burning and the use of low heat input. In the case of high heat inputs and unstable arc burning cracks can occur after welding. Under such conditions, cracks occurred in the weld, while HAZ was free of them. It should be noted that commercial electrodes for welding in the air were used in the investigations, since there are not available yet electrodes dedicated to the underwater welding of duplex steel.
Other findings from the research are as follows:

- Welded deposits performed on 2205 duplex stainless steel made in the air and under water by the MMA method showed similar microstructures.
- Effect of rapid cooling during welding in the water environment did not cause a significant increase in the ferrite content in weld metal and heat affected zone compared to welds made in the air.
- Small differences in ferrite content in the weld metal were observed in joints made underwater with different heat inputs. The deposit made with the lower heat input exhibited larger ferrite content.
- In all joints very narrow heat affected zones were recorded with width ranged from 0.2 to 0.4 mm. Increasing welding heat input only slightly increased the width of the HAZ.
- There was no considerable increase in hardness in HAZ of joints made under water and in the air. This indicates that there were no secondary phases precipitation processes during welding thermal cycles.

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