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Problems of Underwater Welding of Higher-Strength Low Alloy Steels

Abstract: The article characterizes the presently used techniques of underwater welding and the problems connected with obtaining the required properties of joints. The text also presents test results related to the weldability of higher-strength steels in underwater conditions and indicates the main R&D trends in welding technologies aimed at reducing the effect of inconvenient underwater welding conditions and improving the quality of joints made under water.

Keywords: underwater welding, cold cracking, welding thermal cycle, weldability of steel

Introduction

Underwater welding is an effective method for repairing damaged elements of hydrotechnical and ocean technical structures and systems due to the following [1-6]:

- failures/breakdowns,
- corrosion,
- collisions of vessels and warfare activities,
- necessity of structural modifications,
- accidents during assembly,
- designs and execution errors,
- exceeding active life,
- material fatigue and excessive operational stresses.

In underwater conditions welding processes are significantly less frequently used for making structures. Underwater welding applications include pipelines, oil rigs, vessels, berth and breakwater elements as well as harbour infrastructure. Recent years have seen a considerably growing interest in underwater welding, which is reflected, among others, by an increase in the number of publications concerned with basic research and application reports [7-16].

The objective of this study is to present problems related to underwater welding, particularly as regards increasingly popular higher-strength steels and to presents practicable methods for improving the quality of joints welded under water.

Classification of Underwater Welding Methods

Underwater welding techniques are usually classified as two separate areas, i.e. wet and dry welding [1-4,17-19]. Wet welding is performed in the water environment where the welder, workpiece and electrode are in the direct contact with water, whereas dry welding requires the use of a chamber separating the welding area from water [3-4,12,17-19]. Another method, or sub-method, is local dry chamber welding. This method requires the use of a small volume chamber, the purpose of which is to temporarily separate an electric arc and workpieces

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from the water environment [11,20-24]. Figure 1 presents the schematic division of underwater welding methods.

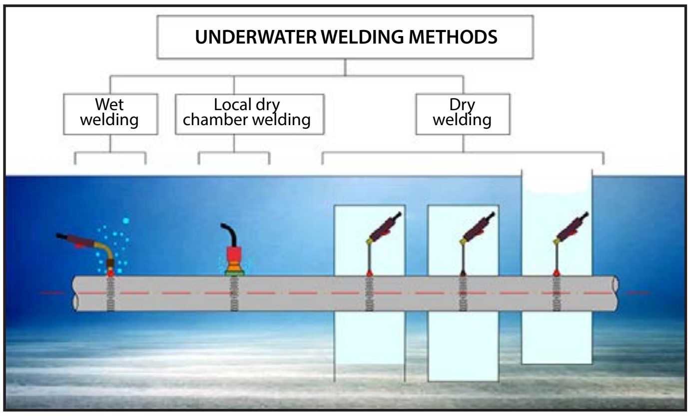

Fig. 1. Classification of underwater welding methods [19]

Each of the methods presented above, apart from advantages and disadvantages determining their application areas, provides different possibilities of welding process applications. Wet welding usually utilises MMA (111) and FCAW (136) methods, including self-shielded tubular cored arc welding (114) [1-9]. Dry welding can be performed using the MMA (111), TIG (141), MIG/MAG (131/135) FCAW (136) processes [3,4,12,25]. Local dry chamber welding is carried out primarily using MIG/MAG and FCAW (131/135/136) processes [21-23].

Underwater Welding Problems

Underwater welded joints tend to have lower quality and mechanical properties in comparison with joints welded in the air. There is a high likelihood of the following [1-6,16,18,19,27-35]:

- weld porosity,
- hot and cold cracks,
- slag confined in welds,
- change of weld deposit chemical composition (loss of alloying elements, increased content of carbon and oxygen).

The reason for these disadvantageous phenomena is the cooling effect of water affecting the kinetics of structural transformations in steels, significant amount of diffusion hydrogen in joints, increased pressure of the welding environment and impaired visibility during welding [1,3,4,18]. Figure 2 presents the surface of typical joints made under water with imperfections resulting from lower electric arc stability and limited visibility.

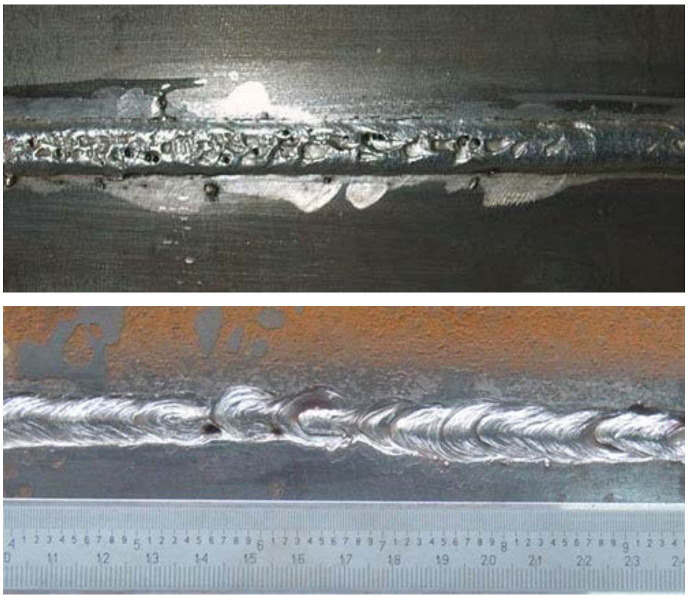

Fig. 2. Joints welded under water: a) S355J2G3 steel, flux-cored arc welding using the local dry chamber method, visible numerous gas pores; b) S420G2+M steel, wet MMA welding, visible undercuts and gas pores

Weld Porosity

The primary reason for the formation of gas pores is the saturation of the weld pool with gases, particularly with hydrogen. The chemical composition of the gas responsible for the formation of pores in underwater welded joints is presented in Table 1. Due to the fact that in comparison with the air water constitutes a significantly greater source of potential hydrogen, the amount of diffusion hydrogen in the weld deposit fails to meet the criteria set for traditional welding processes [1,3,16,18,19,21,28,32,33,36]. Table 2 presents typical amounts of diffusion hydrogen in the weld deposit during underwater welding with selected processes. All the processes enumerated are high-hydrogen processes (levels A and B according to PN-EN 1011-2). In addition to the welding method, weld metal hydriding is also affected by the depth of welding, current polarity, water salinity and welding linear energy (heat input) [1,2,18,19]. According to the author's own research [16,21,28] in the case of wet MMA welding, water salinity as well as the intensity and polarity of welding current have a statistically significant effect on the amount of diffusion hydrogen. In turn, while the local dry chamber method is used, in addition to the factors mentioned above, also the shielding gas flow rate, the length of exposed electrode wire and elastic band dimensions affect the amount of diffusion hydrogen.

The porosity of welds increases along with the depth of welding [36] and depends on electrode coating composition and welding parameters. It is possible to reduce weld porosity by providing coatings with approximately 12% $CaCO_3$ [1].

Underwater Welding Thermal Cycles

The worsened properties of underwater welded joints can be ascribed to, among others, more intense heat offtake from the welding area, which as a result leads to a shorter cooling time. The increased cooling rate favours the formation of hardening structures in the HAZ area and of remaining stresses in the joint [37]. The water environment is the decisive factor for heat offtake from the welding area for steel plates having thicknesses of up to 20 mm [18].

Figures 3 and 4 present the real thermal cycles measured during underwater welding using the local dry chamber method and during MAG welding in the air (135). The analysis of the underwater welding thermal cycles using the local dry chamber method has revealed that heat offtake intensity can be adjusted, among others, by means of heat input and plate thickness. In this way it is possible to obtain similar values of cooling time $t_{8/5}$ in the water environment and in the air. However, the possibility of such welding thermal cycle adjustment and modification is limited by the relatively narrow range of parameters ensuring arc stability.

Table 1. Chemical composition of gas present in the pores located in the welds made under water (% per weight) [1]

Source	H_2	CO	CO_2	Others
Suga and Hasui	96	0,4	0,04	-
Silva	62/82	11/24	4/6	-
Gooch	45	8	4	4

Table 2. Typical amounts of diffusion hydrogen in the weld deposit during underwater welding (determination by means of the glycerine method) [7,18,21,28,32]]

No.	Welding process	Amount of diffusion hydrogen in the weld deposit [ml/100 g]
1	Wet MMA welding with rutile electrodes	45÷87
2	Wet MMA welding with oxidising electrodes	13
3	Wet MMA welding with low-hydrogen electrodes	35÷45
4	Wet MAG welding	below 30
5	Wet self-shielded flux-cored arc welding	25÷44
6	Wet SAW welding	50
7	MAG welding using the local dry chamber method (C1)	10÷20

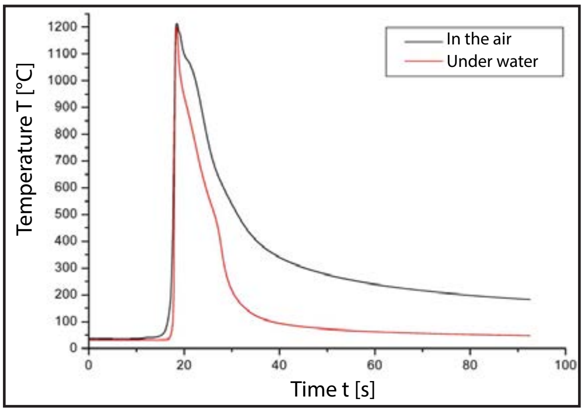

Fig. 3. Comparison of thermal cycles for overlay welding of 12 mm thick plate in the air and under water using the local dry chamber method; welding linear energy eL=0.9 kJ/mm

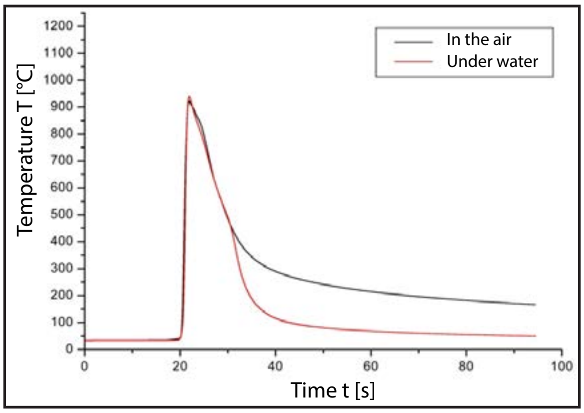

Fig. 4. Comparison of thermal cycles for overlay welding of 16 mm thick plate in the air and under water using the local dry chamber method; welding linear energy e_L=1.3 kJ/mm

Cold Cracking of Joints

The physicochemical properties of water as the welding environment are responsible for the fact that the most significant restriction of higher-strength steel weldability is the increased cold crack formation tendency [1,3,16,18,19,30-33,38].

Most of the available weldability test results are concerned with steels having a yield point of 355 MPa. However, increasingly frequently ocean technical structures (e.g. oil rigs and pipelines) are made of higher-strength steels obtained by thermomechanical control process (TMCP) and quenching and tempering. The publications [16,35,39] demonstrate that the wet MMA-welded (rutile electrode) S420G2+M and S500MC thermomechanical control processed higher-strength steels tend to develop cold cracks in butt joint welds (Tekken test pieces) and joints with fillet welds (CTS test pieces) in spite of low carbon equivalent values (S420G2+M: C_{eIIW}=0.37; S500MC: C_{eIIW}=0,30). Figures 5 and 6 present the microstructures of the underwater-welded joints made of S420G2+M steel containing cracks in the HAZ. Figure 7 presents the coarse acicular hardening structure in the HAZ of the joint made of S355J2G3 steel. Also the wet MMA welded joints made of S690Q steel are characterised by high cold crack formation susceptibility (Fig. 8). In this case the cold crack formation tendency is higher due to a high carbon equivalent (C_{eIIW}=0.52%).

Fig. 5. Microstructure of the wet MMA welded joint made of S420G2+M steel; visible extensive crack on the boundary between the weld and HAZ. Mag. 50×.

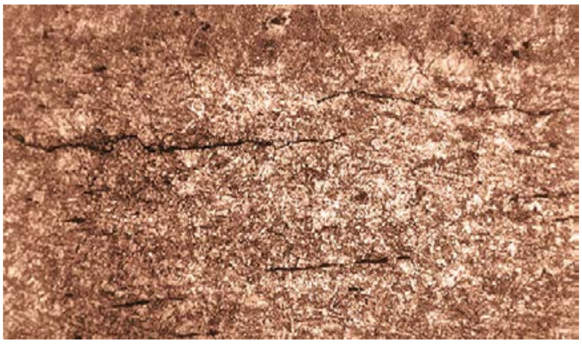

Fig. 6. Microstructure of the joint made of S420G2+M steel using the local dry chamber method and arc welding with solid wire electrode; numerous cracks in the joint HAZ. Mag. 200 ×.

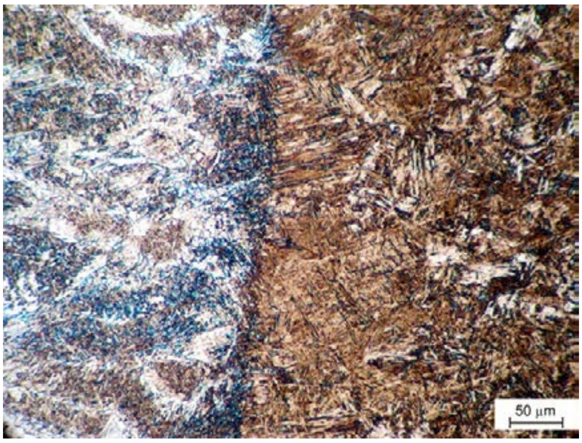

Fig. 7. Microstructure of the joint made of S355J2G3 steel using the local dry chamber method and arc welding with solid wire electrode; the view of the weld, fusion line and HAZ.

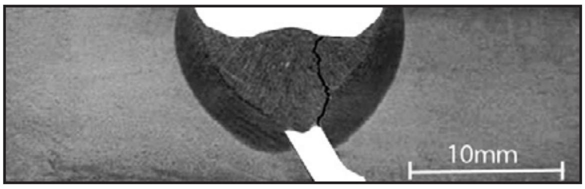

Fig. 8. Cross-section of the wet MMA welded Tekken test piece made of S690Q steel; visible crack initiated in the weld root

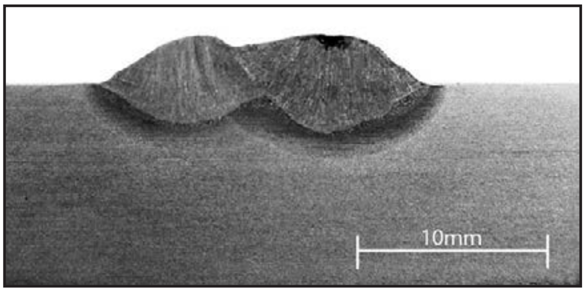

Fig. 9. Cross-section of the test piece made of S420G2+M steel with the test overlay weld and the temper bead made using the local dry chamber method and a solid wire. Overlap 40%.

The prevention of cold cracking in underwater welding, and wet welding in particular, is more difficult than in welding in air. There is no practical possibility of reducing the amount of diffusion hydrogen in the joint. Drying and providing covered electrodes with coatings (apart from hyperbaric welding) does not produce desirable results. Preheating workpieces before welding, commonly used in welding in air, is not possible in underwater conditions. Attempts at reducing cold crack susceptibility involve the use of electrodes having cores containing nickel and molybdenum and using the temper bead technique. This technique consists in making beads in a specific sequence in order to perform the heat treatment of previously made weld beads [1,38-41]. The heat emitted by a temper bead causes the accelerated diffusion of hydrogen, reduces the values of remaining stresses and increases the plasticity of structure in the lower area of the joint. The hardness of the weld HAZ decreases significantly. Figure 9 presents the cross-section of the test piece made of S420G2+M steel using the local dry chamber method and intended for examining the efficiency of the temper bead technique. The efficiency of this procedure depends on the overlap (distance between the longitudinal axes of the beads), welding parameters, time elapsing between making successive beads as well as on the strict compliance with the technological regime [38,40].

Another method enabling the improvement of steel weldability in water consists in using thermal insulation, which extends cooling time $t_{8/5}$ and decreases the maximum HAZ hardness [25,27]. The tests of the joints made of higher-strength EH36 steel performed in isobaric conditions (one-sided sheet contact with water) revealed that the use of EPS insulation causes the average decrease in HAZ maximum hardness by 60 HV10 [25]. In the case under discussion this change has enabled meeting hardness-related requirements specified in the PN-EN ISO 15614-1 standard. Limiting the cold crack formation susceptibility in HAZ can also be achieved through the use of Cr-Ni covered electrodes of austenitic structure. However, in this case hot crack development in the weld should be taken into consideration [1,18,19,32]. Figure 10 presents the microstructure of the weld of the joint made of S420G2+M steel using an austenitic filler; the joint revealed the presence of solidification cracks.

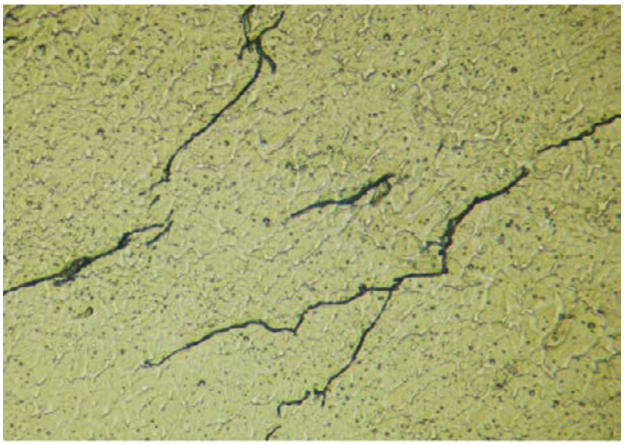

Fig. 10. Microstructure of the weld of the joint made of S420G2+M steel using a wet austenitic electrode; numerous branched cracks visible. Mag. 400×.

Pressure Effect

The value of pressure, which under water is practically always higher than atmospheric, significantly affects the character of a welding process. The value of pressure is decisive for the following [1,18,19,36]:

- underwater welding stability (an increase in pressure narrows the range of parameters ensuring process stability),
- size of losses caused by weld deposit spatters,
- arc diameter (an increase in pressure decreases the arc diameter),
- method of metal transfer in the arc (an increase in pressure increases the number of short circuits),
- electrode melting efficiency (an increase in pressure decreases melting efficiency),
- weld deposit chemical composition,
- amount of diffusion hydrogen in the weld deposit (an increase in pressure decreases weld deposit hydriding).

Technological Development and Research Trends

Among present research trends focused on welding in different conditions, the primary importance is attributed to tests on the effect of welding parameters (linear energy value) on the possibility of making joints having required properties and appropriate geometry [42-43]. The adverse effect of water on a joint being formed is best visible in wet welding [1,18,19]. The major developmental trends related to covered electrodes for wet welding are concerned with the chemical composition modification in electrode coating and core. Changes in coating chemical compositions aim to improve the coating ionisation properties in order to decrease the depth effect (water pressure) on arc stability and to minimise the amount of diffusion hydrogen in the joint [7,14,28]. Providing the electrode core with appropriate amounts of alloying agents (Ni, Mo) allows limiting the weld solidification cracking and brittle cracking susceptibility.

The reduction of joint cooling rates is attempted using materials separating the surface of workpieces from water [25,27].

The use of technologies utilising multi-run welding combined with the modification of the coating chemical composition enabled making joints of unalloyed steel in wet conditions; the joints met class A requirements according to AWS D3.6 [17] in relation to visual testing, radiographic examination and shear strength of a fillet weld, tensile tests, hardness measurements and toughness tests, i.e. the requirements set for joints made in air.

Wet self-shielded tubular cored arc welding is developed having in view the automation and pulsed current utilisation for run geometry control [26].

In dry welding, the direct effect of water on joint quality is significantly lower. However, adverse effects ascribed to this kind of welding include the disadvantageous influence of pressure on arc stability and increased amount of potential hydrogen in the arc area. The ongoing research is focused on the use of automated welding, which imposes the development of workpiece preparation methods (maintaining a proper distance between the elements). Research works are also concentrated on the development of visual systems which could enable welding process control, joint quality control and thermal process tests [44]. Another topical issue is the development of hyperbaric chamber designs due to the necessity of making joints of various shapes and dimensions [45].

In relation to local dry chamber welding methods the research trends are the following [3,11,20-24]:

- quantitative assessment of higher-strength steel susceptibility to hot crack formation,
- assessment of the effect of welding conditions and parameters on the amount of diffusion hydrogen in the weld deposit,
- tests of heat processes in plates welded at shallow depths,
- laser welding applications,
- testing conditions inside a local chamber.

In addition to carbon steels, also corrosion-resistant duplex steels, martensitic low-carbon steels, plated steels, titanium alloys and nickel alloys are used in the production of structures operating in a water environment. The latest reports refer to the hyperbaric MIG (131) welding of vessels made of aluminium alloys [45].

The remaining and topical issues connected with underwater welding include the following: [14,29]:

- Health and Safety at Work and welding personnel training,
- welding environment protection,
- planning and management,
- normalisation,
- joint quality control (NDT).

Summary

Moving welding processes under water leads to an increase in the content of hydrogen diffusion in the weld deposit and to an increase in the joint cooling rate. The increase in the cooling rate gives rise to the formation of brittle structures in the heat affected zone (HAZ) and to an increase in the value of remaining stresses. Joints made in such conditions are usually characterised by significant porosity. Underwater welding is performed in the conditions of impaired visibility, elevated pressure and deteriorated arc burning stability, which also contributes to the formation of welding imperfections. These phenomena reduce the underwater weldability of higher-strength steels, yet the demand for underwater welding services extorts the multidirectional development of underwater welding techniques worldwide, which is reflected by the growing number of publications. The state of the art related to underwater welding is incomplete in many areas and requires supplementation through systematic research. This particularly concerns applications related to high- and higher-strength structures operated in a water environment.

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