

COLD CRACKING OF S460N STEEL WELDED IN WATER ENVIRONMENT

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ABSTRACT

This paper shows results of weldability testing of fine-grained high -strength low- alloy S460N steel welded in water environment by covered electrodes. The tests were carried out by using the CTS test specimens with fillet welds. Four specimens were welded under water and one specimen in air. Welded joints were subjected to non-destructive visual and penetration tests. The accepted joints were then subjected to macroscopic and microscopic inspection and Vickers hardness measurements as well. The experiments showed that S460N steel welded in water environment is characterized by a high susceptibility to cold cracking.

Keywords: underwater welding, wet welding, high-strength low-alloy steel, cold cracking, CTS test

INTRODUCTION

Development of underwater welding is a result of increasing demand on mineral raw materials. Searching for hydrocarbons resources on sea and ocean bed caused in extensive progress of diving techniques as well as making use of divers in building marine structures. From several dozen years an issue of conducting repair of ocean-engineering and hydro-technical structures has been appeared more and more often. The developing offshore industry demands to make the repairs in water environment , without disassembling the elements and moving them into air [1,2]. The most widely used repair method is wet welding which, for economic reasons, is carried out generally with covered electrodes [3,4]. However in wet welding FCAW method is also common used [5]. Despite its common application the method leads to many problems [6,7]. For structural elements working under water high strength steels are more and more widely used. Weldability of these steels in the air is a well investigated issue but transferring the process into water environment still produces many problems [3,4]. The joints made by using

wet method show presence of welding imperfections such as gas porosity, shape failures and cracks [8,9]. The issue most often met is steel susceptibility to cold cracking [10-13]. Water environment significantly intensifies risk of producing such cracks due to the following factors appearing during welding process [1,14]:

- increased cooling rate resulting from fast transfer of heat from outer part of arc and welding area,
- hydrogen concentration resulting from presence of water vapour surrounding welding arc,
- presence of residual stresses,
- increased pressure values, leading to instability of welding arc.

The water environment makes it impossible or difficult to apply many traditional methods for preventing cold cracking, which are successfully used in making welded joints in the air. Out of the methods lowering risk of cold cracking in water environment, the following find application in practice [3,7,23]:

- the increasing of welding heat input,

- the application (for crucial elements only) of austenitic electrodes whose deposited metal is more ductile,
- the addition of calcium fluoride to electrode coating which binds hydrogen into a durable compound in welding temperature, decreasing its influence on generating cold cracks.

There is a common opinion that water practically eliminates possible application of preheating to welded joints as well as their further thermal treatment to be performed in a traditional way, that is able to minimize steel susceptibility to cracking. Fast cooling rate unfavourably influences structural transformations, that impairs joint properties [15,16]. Water environment makes the cooling rate faster. However, the latest investigations show that application of heating induction is possible [17]. Research tests on ultrasonic enhancement the underwater welding processes [18,22] or application of temper bead welding technique [19,24] are also carried out. The minimizing of steel susceptibility to cold cracking is especially important in case of higher strength steels. Water contributes to increasing number of imperfections, resulting also in decreasing mechanical properties of welded joints. It results a. o. from diffusion of hydrogen which creates favourable conditions for producing cracks and micro-cracks lowering the strength of joints [7,14,20]. The recent investigations show that even a change in chemical content of electrodes does not eliminate the problem of cold cracking which appear in the joints [12].

For assessment of steel weldability in water environment the self-restraint CTS tests and Tekken tests are used [1,2,6]. As underwater welding operations, especially those connected with failure repair, require making fillet joints, the CTS test was selected for the assessment of susceptibility to cold cracking of the S460N steel.

EXPERIMENTS AND RESULTS

The research was aimed at the assessment of weldability of S460N fine-grained steel during wet welding by means of MMA method (111 acc. to ISO 4063). The research program covered conducting CTS tests on five joints in accordance with guidelines of EN ISO 17642-2 standard, four out of which were welded in water environment and one in air. The CTS test belongs to technological self-restraint tests and makes it possible to assess susceptibility to cold cracking in all zones of overlapping joints with fillet welds. Fig. 1 presents the schematic diagram of the specimen in question.

The test specimen was produced of S460N fine-grained high strength steel plate of 12 mm in thickness. Tab.1 shows the chemical composition of the steel according to a control analysis performed by using spark emission spectrometry. The mechanical properties of the examined steel are presented in Tab. 2.

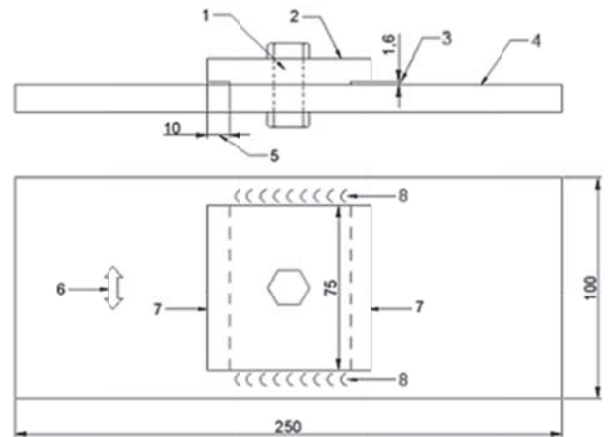


Fig. 1. The schematic diagram and dimensions of the CTS test specimen acc. EN ISO 17642-2 standard; 1- clearance hole of 13 mm diameter; 2- top plate; 3- root notch gap; 4- bottom plate; 5- root notch depth; 6- preferred principal rolling direction; 7- test welds; 8- anchor welds

Tab. 1. Chemical composition of S460N steel

Element content, %											
	C	Si	Mn	P	Cr	Mo	Ni	Al	Cu	V	Ce _{MIS}
Acc. control analysis	0.16	0.53	1.51	0.02	0.07	0.03	0.05	0.033	0.13	0.097	0.464

$$Ce_{MIS} = C + (Cr + Mo + V) / 5 + (Cu + Ni) / 15$$

Tab. 2. Mechanical properties of S460N steel

Yield point R _s , MPa	Ultimate tensile strength R _m , MPa	Elongation A, %
511	626	27.3

The welding operation was carried out in water environment at the water depth of 150 mm by using the underwater test stand (Fig. 2) of the Laboratory of Welding Engineering in Gdańsk University of Technology.

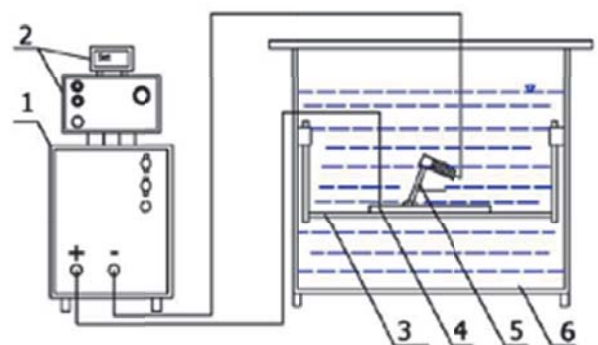


Fig. 2. The schematic diagram of the underwater welding at small depth: 1- power source, 2- control panel and wire feeder, 3- table, 4- welded plate, 5- covered electrode and electrode holder, 6- tank

The anchor welds and test welds were made with the use of OMNIA (ISO 2560-A: E 38 0 R 11) commercial rutile electrodes of 4 mm diameter, intended for welding in all positions. The electrodes were selected based on the fact that they ensure good plastic properties of deposited material in order to minimize possible generation of cracks. The chemical composition and mechanical properties of the applied electrodes are given in Tab. 3.

Tab. 3. Chemical composition (wt %) and mechanical properties of Omnia covered rutile electrodes [26]

Chemical composition, wt %			Mechanical properties of deposited material		
C	Mn	Si	Re, MPa	Rm, MPa	A, %
0.07	0.55	0.44	503	538	26

The CTS specimens were marked by using the test name and subsequent arabic digits. The welding was carried out with the constant DC- polarity in compliance with producer's recommendations. The welding process parameters are presented in Tab. 4.

Tab. 4. Welding parameters of CTS tests

No. of specimen	Weld I				Weld II			
	Welding current, I, A	Arc voltage, U, V	Welding time, t, s	Heat input, q, kJ/mm	Welding current, I, A	Arc voltage, U, V	Welding time, t, s	Heat input q, kJ/mm
Welded under water								
W1	192	25.8	18.7	1.04	196	24.5	17.2	1.10
W2	192	25.5	17.9	1.22	196	24.8	12.9	0.84
W3	184	25.8	20.1	1.27	188	25.0	16.6	0.98
W4	188	25.5	17.1	1.05	184	22.3	15.9	0.91
Welded in air								
P5	181	23.4	21.1	1.19	178	24.1	17.9	1.03

The prepared specimens were subjected to non-destructive tests after 72 h from the end of welding operation. The visual and penetration tests were conducted in compliance with the standards EN ISO 17637 (VT) and EN ISO 3452-1 (PT). In the case of the specimens welded under the water, weld imperfections were observed in one weld of the specimen 2 (insufficient weld thickness, incompletely filled groove, incomplete fusion) as well as in two welds of the specimen 4 (in the first - laid weld: insufficient weld thickness, lack of fusion; in the second-laid weld: undercuts, incomplete fusion, insufficient weld thickness, spattering). The joints were qualified unacceptable. In the case of the specimen welded in air, cracks were observed in crater pipe, which did not excluded the joints from further tests. In the visual tests (VT) the welds complying with the quality level B acc. EN ISO 7637 standard were acceptable. In the penetration tests the welds

complying with the quality level 2X acc. EN ISO 3452-1 standard were considered acceptable. Fig. 3 presents example results of the non-destructive tests in question.

a)



b)

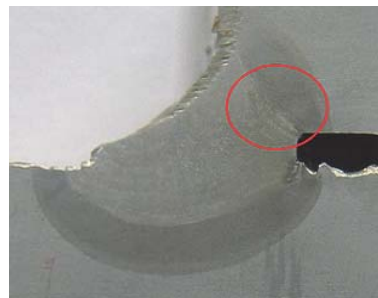


Fig. 3. Results of non-destructive testing of S460N steel joints; a) VT, the specimen W2, the first-laid weld: incompletely filled groove, incomplete fusion; b) PT, the specimen W1 : no imperfections.

MACROSCOPIC METALLOGRAPHIC TESTS

The metallographic tests were carried out in acc.to guidelines of EN ISO 17639 standard – after etching the specimens with 4 % Nital. The macroscopic tests of CTS specimens welded in water environment revealed imperfections such as gas pores and cracks. The welds made in air did not have imperfections. Fig. 4 presents example results of the macroscopic tests.

a)



b)

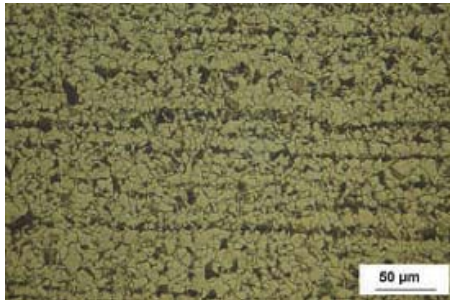


Fig. 4. Pictures illustrating results of the macroscopic testing of S460N steel; a) the specimen W3.1: cracks along fusion line and in HAZ; b) the specimen P5.1: no imperfections. Etching: Nital

MICROSCOPIC METALLOGRAPHIC TESTS

As a result of the performed microscopic tests it was stated that the structure of S460N steel is composed of fine-grained pearlite as well as fine-grained ferrite with layers. HAZ has brittle structures characteristic for joints made in fast cooling rate conditions. Cracks were revealed in all the specimens welded in the water. They were placed in the welds, HAZ as well as fusion line along 65-75% of its length. During examining the specimen welded in air no cracks were found. Fig. 5 presents the results of microscopic tests of S460N steel.

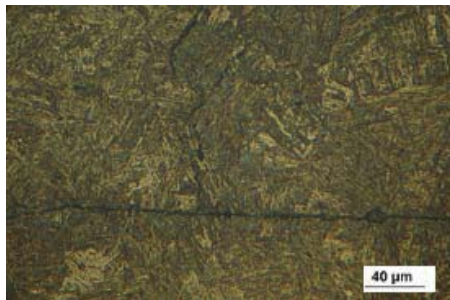
a)



b)



c)



d)

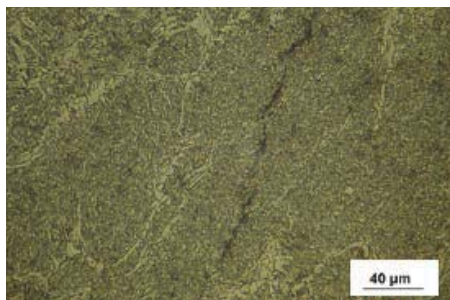


Fig. 5. Results of the microscopic testing of S460N steel joints welded under water; a) base material, magn. 400x; b) cracks in HAZ, magn. 50x; c) cracks in HAZ, magn. 500x; d) cracks in weld, magn. 500x. Etching: Nital

HARDNESS MEASUREMENTS

The Vickers hardness measurements under 98 N load (HV10) along the line placed 2 mm below weld face were made in compliance with the requirements of PN-EN ISO 9015-1:2011 standard. Fig. 6 presents the schematic layout diagram of measurement points. Fig. 7 shows example results of hardness measurements for the S460N steel specimens. The maximum values of hardness in HAZ of the tested CTS joints welded in water environment were equal to around 500 HV10, reaching its very maximum of 508 HV10 in the specimen W3. In the case of the specimen P5 welded in air the maximum hardness reached 468 HV10. For S460N steel the limit hardness value of 380 HV10 was assumed according to the PN-EN ISO 15614-1:2008 standard. Tab. 5 shows results of hardness measurements in the form of maximum values found in HAZ of particular joints.

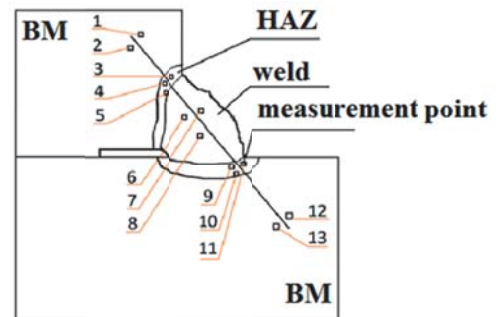
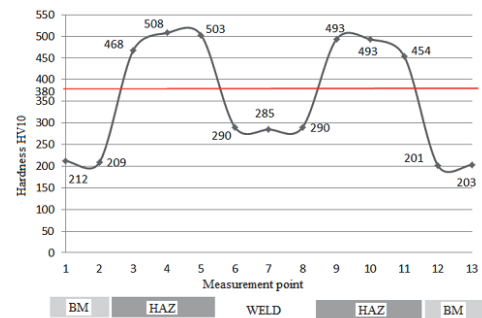


Fig. 6. Schematic layout of hardness testing points – CTS test

a)



b)

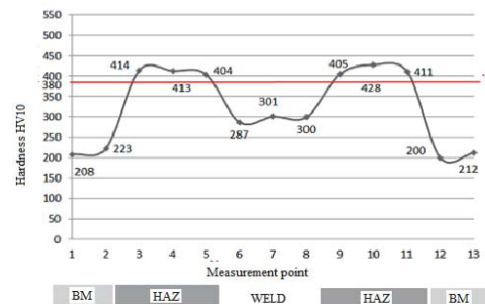


Fig. 7. Results of hardness measurements for S460N steel; a) hardness distribution across W3 (first-laid weld) joint welded underwater, HV10max=508; b) hardness distribution across P5 (first-laid weld) joint welded underwater, HV10max=414

Tab. 5. Results of hardness tests

No. of specimen	Maximum value of HV10
Specimens welded underwater	
W1	503
W2	500
W3	508
W4	525
The specimen welded in air	
P5	433

SUMMARY

Weldability tests of S460N high strength steel 12 mm plate specimens welded with covered electrodes in water environment using wet method and in air were performed. The welding process involved many problems - welding arc was burning instable that made forming correct welds difficult. In joints made of the tested steel many cracks located both in the weld and HAZ were found. The microscopic tests revealed that the cracks run along 65-75 % fusion line. In the case of joints welded in air environment no imperfections were found. Results of Vickers hardness measurements (HV10) demonstrated that all the specimens welded under water had the hardness value reaching 525 HV10. It contributes to forming cold cracks such as those found during the other tests. None of the tested joints will satisfy the assumed hardness criterion according to EN ISO 15614-1 standard (380 HV10) for the tested steel. One of the ways of lowering the hardness of welded joints made of a high strength steel in water environment may be application of the temper bead welding technique [25]. The other way to improve the quality of joints made in water environment is friction taper welding [27-29].

Haring regard to the value of S460N steel carbon equivalent, welding conditions favouring the increase of steel tendency to cold cracking and experience [3,4,8,19,24] it should be recognized, that presented results are justified

CONCLUSIONS

1. Based on the results of the technological weldability tests of S460N high strength steel it may be stated that CTS welded joints made under water by using covered electrodes (rutile) in wet conditions are characterized by a high susceptibility to cold cracking.
2. The underwater wet welding using covered electrodes resulted in a significant increase of hardness of the HAZ of welded joints up to 525 HV10 (in the specimen W4). All of the specimens made under water and made in air do not satisfy the acceptance criterion acc. EN ISO 15614-1 standard.
3. It is recommended to perform weldability tests of the butt-welded joints (Tekken test) as well as to conduct

a research aimed at the improvement of S460N steel weldability in water environment.

REFERENCES

1. Wang, J., Sun, Q., Jiang, Y., Zhang, T., Ma, J., & Feng, J.: *Analysis and improvement of underwater wet welding process stability with static mechanical constraint support*. Journal of Manufacturing Processes, 34 (2018), pp. 238-250.
2. Hu Y., Shi YH., Shen XQ., Wang ZM.: *Microstructure, pitting corrosion resistance and impact toughness of duplex stainless steel underwater dry hyperbaric Flux-Cored Arc*. Materials, 10 (12) (2018), pp. 1443.
3. Fydrych D., Łabanowski J., Tomków J., Rogalski G.: *Cold cracking of underwater wet welded S355G10+N high strength steel*. Advances in Materials Science, Vol. 16., iss. 3 (2015), pp. 48-56
4. Fydrych D., Łabanowski J., Rogalski G.: *Weldability of high strength steels in wet welding conditions*. Polish Maritime Research, 2 (2013), pp. 67-73.
5. Świerczyńska A., Fydrych D., Rogalski G.: *Diffusible hydrogen management in underwater wet self-shielded flux cored arc welding*. International Journal of Hydrogen Energy, 42(38) (2017), pp. 24532-24540.
6. Li HL., Liu D., Song YY., Yan YT., Guo N., Feng JC.: *Microstructure and mechanical properties of underwater wet welded high carbon-equivalent steel Q460 using austenitic consumables*. Journal of Materials Processing Technology, 249 (2017), pp. 149-157.
7. Santos V. R., Monteiro M. J., Rizzo F.C., Bracarense A. Q., Pessoa E. C. P., Marinho R. R., Vieira L. A.: *Development of an oxyrutile electrode for wet welding*. Welding Journal, 91(2012), pp. 319-328.
8. Garašić I., Krajl S., Kožuh S.: *Investigation into cold cracking in underwater wet welding of API5L X70 steel*. Transactions of FAMENA, 3 (2009), pp. 25-34.
9. Maksimov S. Yu.: *Underwater arc welding of higher strength low-alloy steels*. Welding International Vol. 24, Iss. 6 (2010), pp. 449-454.
10. Rogalski G., Łabanowski J., Fydrych D., Tomków J.: *Bead-on-plate welding on S235JR steel by underwater local dry chamber process*. Polish Maritime Research, 21 (2014), pp. 58-64.
11. Kannengiesser T., Boellinghaus T.: *Cold cracking tests- an overview of present technologies and applications*. Welding in the World, 1 (2013), pp. 3-37.

12. Kurji R., Coniglio N.: *Towards the establishment of weldability test standards for hydrogen-assisted cold cracking*. The International Journal of Advanced Manufacturing Technology, 77 (2015), pp. 1581-1597.
13. Chen H., Guo N., Shi X., Du Y., Feng J., Wang G.: *Effect of hydrostatic pressure on protective bubble characteristic and weld quality in underwater flux-cored wire wet welding*. Journal of Materials Processing Technology, 259 (2018), 159-168.
14. Guo N., Liu D., Guo W., Li H., Feng J.: *Effect of Ni on microstructure and mechanical properties of underwater wet welding joint*. Materials & Design, 77 (2015), pp. 25-31.
15. Sajek A., Nowacki J.: *Comparative evaluation of various experimental and numerical simulation methods for determination of t8/5 cooling times in HPAW process weldments*. Archives of Civil and Mechanical Engineering, 18(2) (2018), pp. 583-591.
16. Górka J.: *Microstructure and properties of high-temperature (HAZ) of thermos-mechanically treated S700MC high-yield-strength steel*. Materiali Tehnologije/Materials Technologies, 50 (4) (2016), pp. 617-621.
17. Gao W.B., Wang D.P., Cheng F.J., Deng C.Y., Xu W.: *Underwater wet welding for HSLA steels: chemical composition, defects, microstructures, and mechanical properties*. Acta Metallurgica Sinica (English Letters), 9 (2015), pp. 1097-1108.
18. Gao W., Wang D., Cheng F., Di X., Xu W.: *Micro-structural and mechanical performance of underwater wet welded S355 steel*. Journal of Materials Processing Technology, 238 (2016), pp. 333-340.
19. Fydrych D., Świerczyńska A., Rogalski G., Łabanowski J.: *Temper bead welding of S420G2+M steel in water environment*. Advances in Materials Science, Vol. 16, iss. 4 (2016), pp. 5-16.
20. Zhang H.T., Dai X.Y., Feng J.C., Hu L.L.: *Preliminary investigation on real-time induction heating-assisted underwater wet welding*. Welding Journal, 1 (2015), pp. 8-15.
21. Gao W., Wang D., Cheng F., Deng C., Liu Y., Xu W.: *Enhancement of the fatigue strength of underwater wet welds by grinding and ultrasonic impact treatment*. Journal of Materials Processing Technology, 223 (2015), pp. 305-312.
22. Sun Q.J., Cheng W.Q., Liu Y.B., Wang J.F., Cai C.W., Feng J.C.: *Microstructure and mechanical properties of ultrasonic assisted underwater wet welding joints*. Materials & Design, 103 (2016), pp. 63-70.
23. Fydrych D., Świerczyńska A., Rogalski G.: *Effect of underwater wet welding conditions on the diffusible hydrogen content in deposited metal*. Metallurgia Italiana, 11/12 (2015), pp. 47-52.
24. Tomków J., Rogalski G., Fydrych D., Łabanowski J.: *Improvement of S355G10+N steel weldability in water environment by Temper Bead Welding*. Journal of Materials Processing Technology, 262 (2018), pp. 375-381.
25. Tomków J., Fydrych D., Rogalski G., Łabanowski J.: *Temper bead welding of S460N steel in wet welding conditions*. Advances in materials science, 3 (2018), pp. 5-13.
26. [http://www.lincolnelectric.com/plpl/Consumables/Pages/product.aspx?product=Products_ConsumableEU_StickElectrodes-Omnia-Omnia\(LincolnElectric_EU_Base\)](http://www.lincolnelectric.com/plpl/Consumables/Pages/product.aspx?product=Products_ConsumableEU_StickElectrodes-Omnia-Omnia(LincolnElectric_EU_Base))
27. Xiong J., Yang X., Lin W., Liu K.: *Effects of welding parameters on microstructure and mechanical properties of underwater wet friction taper plug welded pipeline steel*. Welding in the World, (2018), pp. 1-12.
28. Xu Y.C., Jing H.Y., Han Y.D., Xu L.D.: *Microstructures and mechanical properties of friction tapered stud overlap welding for X65 pipeline steel under wet conditions*. Journal of Materials Engineering and Performance, 26(8) (2017), pp. 4092-4103.
29. Wang F., Yang X., Yin Y., Cui L.: *Thermal process influence on microstructure and mechanical behavior for friction taper plug welding in structural steel S355*. The International Journal of Advanced Manufacturing Technology, 88(9-12) (2017), pp. 3459-3466.

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