DOI: 10.1515/adms-2015-0015

D. Fydrych*, J. Łabanowski, J. Tomków, G. Rogalski

Gdansk University of Technology, Department of Materials Science and Welding Engineering,
Narutowicza 11/12, 80-233 Gdańsk, Poland
**darfydry@pg.gda.pl*

COLD CRACKING OF UNDERWATER WET WELDED S355G10+N HIGH STRENGTH STEEL

ABSTRACT

Water as the welding environment determines some essential problems influencing steel weldability. Underwater welding of high strength steel joints causes increase susceptibility to cold cracking, which is an effect of much faster heat transfer from the weld area and presence of diffusible hydrogen causing increased metal fragility. The paper evaluates the susceptibility to cold cracking of the high strength S355G10+N steel used, among others, for ocean engineering and hydrotechnical structures, which require underwater welding. It has been found from the CTS test results that the investigated steel is susceptible to cold cracking in the wet welding process.

Keywords: *Underwater welding, wet welding, high strength steel, weldability, cold cracking*

INTRODUCTION

The most often used form of underwater welding is wet welding, during which the welding arc and the created welded joint have direct contact with water. The process is carried out with the use of covered electrodes (process 111) or flux corded wires (process 114) [1-6]. The water environment intensifies the welding process problems. The following aspects may be considered the most important steel weldability limiting factors in wet welding [1,2,7-11]:

- rapid cooling rate caused by accelerated heat abstraction from the arc external zone and the weld area. This leads to formation of brittle hardened structures.
- increased diffusible hydrogen content, which is an effect of presence of water vapour surrounding the electric arc. This results in increased susceptibility to cold cracking, weld porosity and spatter.
- presence of residual stresses, which also increases the joint susceptibility to cracking.
- increased pressure in the welding area, which causes instability of the electric arc burning.
- limited visibility of the welding area due to presence of solid particles and gas bubbles in the water.

Operation conditions of the hydrotechnical and ocean engineering structures require the high strength steels with the yield point R_e about 350 MPa and over 420 MPa to be generally used for structural elements, with share of the latter limited to 10% [12]. Weldability of high strength steel in air environment is well investigated and described. In the case of underwater welding, investigations show that its weldability is limited and in the wet welded joints cold cracking appears the most serious problem [7-10,13-15]. Therefore, forming of microstructures susceptible to hydrogen embrittlement should be avoided with particular care [16].

Evaluation of steel weldability in water environment may be carried out both by self-restraint tests (Tekken and CTS) and externally loaded tests (eg. implant) [7-10, 14,15]. As the underwater welding works, particularly during repair of failures and damage, require making joints with fillet welds, the CTS [17] test should be used for evaluation of steel susceptibility to cold cracking. First of all it allows to perform [18,19]:

a) evaluation of cracking occurrence and intensity (evaluation of relative susceptibility to cracking),
b) determination of minimum preheating temperature,
c) determination of the correct welding parameter range (heat input).

Schematic illustration of the CTS test principle is shown in Figure 1.

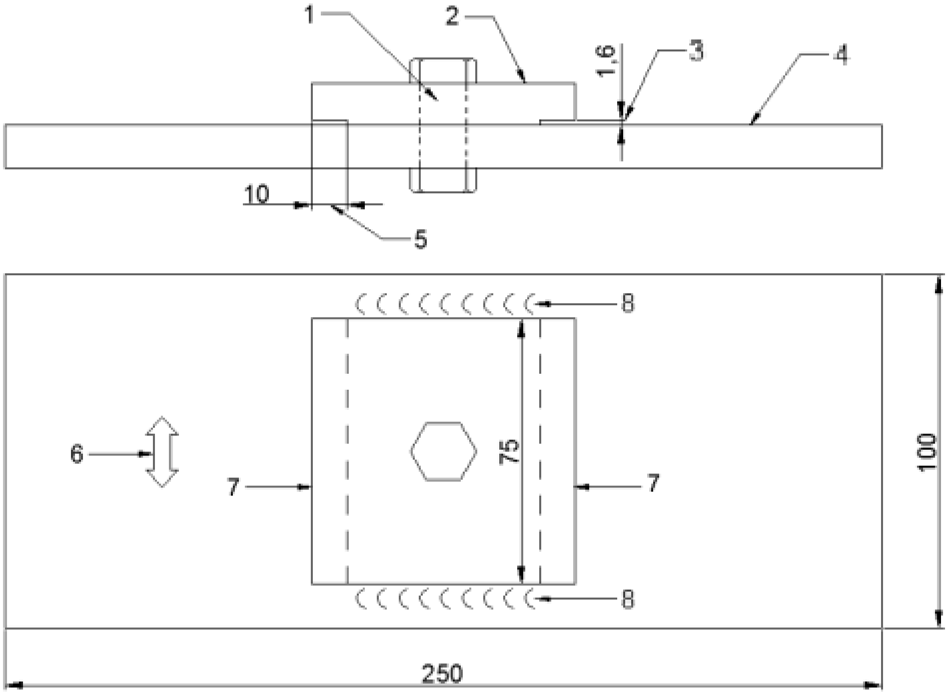

Fig. 1. Schematic illustration of the CTS test principle; 1- clearance hole, 13 mm diameter; 2- top plate; 3- root notch gap; 4- bottom plate; 5- root notch length; 6- preferred principal rolling direction; 7- test welds; 8- anchor welds [17]

In order to carry out the test in accordance with the PN-EN ISO 17642-2 standard requirements [17], the following procedure should be maintained:

- cut out the test piece in accordance with dimensions (Fig. 1), taking the rolling direction into account,
- perform the test piece edge machining,
- drill the fastening holes and mill the groves,
- mount the test piece elements by means of an M12 screw, with 100 Nm tightening torque,
- make the anchor welds depending on plate thickness:
    a) below 15 mm, weld dimension a=6 ± 1 mm,
    b) above 15 mm, weld dimension a=13 ± 1 mm,
- make a single-bead test weld in the PA position after 12 hours of completing the anchor welds,

- after 48 hours of completing the first side welding, the second weld on the opposite side should be made,
- after further 48 hours, the test pieces should be subjected to the NDT and DT examination,
- cut out more test pieces for further tests,
- prepare metallographic specimens,
- carry out Vickers hardness measurements.

EXPERIMENTAL

The aim of investigation was evaluation of the S355G10+N steel susceptibility to cold cracking during wet welding with the use of covered electrodes (111). The investigation plan assumed carrying out 6 test joints of 18 mm thickness with fillet welds (CTS test).

In order to verify the plate inspection certificate data, the chemical composition analysis was performed by the emission spectrometry method. Table 1 presents the steel chemical composition and Table 2 its mechanical properties. The tested steel is characterised by a relatively low carbon equivalent value (below 0.45%), which indicates good weldability in air environment with the use of low hydrogen processes.

Table 1. *Chemical composition of S355G10+N steel*

Element content, wt.%											
	C	Si	Mn	P	S	Cr	Mo	Ni	Al	Cu	Ce_{MIS}
Acc. to certificate 3.1	0.09	0.35	1.58	0.01	0.002	0.03	0.02	0.29	0.032	0.26	0.400
Acc. to control analysis	0.11	0.35	1.39	0.01	0.005	0.02	0.02	0.25	0.039	0.27	0.384

Ce_{MIS}=C+Mn/6+(Cr+Mo+V)/5+(Cu+Ni)/15

Table 2. *Mechanical properties of S355G10+N steel acc. to PN-EN 10225 standard [20]*

Yield point R_e, MPa	Tensile strength R_m, MPa	Elongation A, %
>355	470 ÷ 630	>22

Welding was carried out on an underwater welding stand at 20 cm depth. The anchor welds and test welds were made with general purpose OMNIA (ISO 2560-A: E 38 0 R 11) rutile electrodes of 4.0 mm diameter, with reversed polarity (DC-), for welding in all positions. Table 3 presents chemical composition and mechanical properties of the electrodes used. Welding parameters are given in Table 4. The CTS test pieces are designated by the test symbol and consecutive numbers.

Table 3. *Chemical composition and mechanical properties of Omnia electrodes*

Chemical composition, %			Mechanical properties		
C	Mn	Si	R_e, MPa	R_m, MPa	A, %
0.07	0.5	0.5	430	480	26

Table 4. *Welding parameters of the CTS tests*

	Weld I				Weld II			
Test piece no.	Welding current I, A	Arc voltage U, V	Welding time t, s	Welding heat input q, kJ/mm	Welding current I, A	Arc voltage U, V	Welding time t, s	Welding heat input q, kJ/mm
CTS 1	188	25.0	16.67	1.50	188	24.3	19.04	1.66
CTS 2	184	25.3	14.86	1.32	188	24.3	19.50	1.70
CTS 3	184	26.3	14.13	1.31	192	23.3	16.81	1.44
CTS 4	192	23.2	22.81	1.94	188	25.0	19.96	1.79
CTS 5	184	26.8	16.74	1.58	188	24.3	17.32	1.51
CTS 6	184	25.3	17.00	1.51	188	24.0	18.34	1.58

The test joints were subjected to non-destructive tests after 72 hours of welding completion. Visual tests (VT) and penetration tests (PT) were carried out in accordance with the respective standard recommendations [21,22]. Many welding imperfections were found in the test pieces. The most frequent ones were undercuts, ununiformed weld faces and metal spattering. None of the test pieces showed cracks. In the visual tests distinct welding imperfections were found in test piece CTS5 (both welds) as well as in test pieces CTS1 and CTS3 (welds carried out as the second), therefore they were rejected and not used in further tests. The other welds were subjected to penetration tests, which were classified at the quality level B in accordance with the PN-EN ISO 5817 standard.

METALLOGRAPHIC MACROSCOPIC TESTS

The metallographic macroscopic tests were carried out in accordance with the respective standard recommendations [23]. The macroscopic test pieces were cut out according to the following pattern:
- test piece CTS 1 – test pieces CTS 1.1, CTS 1.2,
- test piece CTS 2 – test pieces CTS 2.1, CTS 2.2,
- test piece CTS 3 – test pieces CTS 3.1, CTS 3.2,
- test piece CTS 4 – test pieces CTS 4.1, CTS 4.2, CTS 4.3, CTS 4.4,
- test piece CTS 5 – test pieces CTS 5.1, CTS 5.2,
- test piece CTS 6 – test pieces CTS 6.1, CTS 6.2, CTS 6.3, CTS 6.4.

Examples of macroscopic polished cross sections are shown in Fig. 2. At that stage, no imperfections of the crack type were identified in any of the test pieces. In the CTS 2 test piece (Fig. 2d) a loss of weld material was found at the fusion bottom.

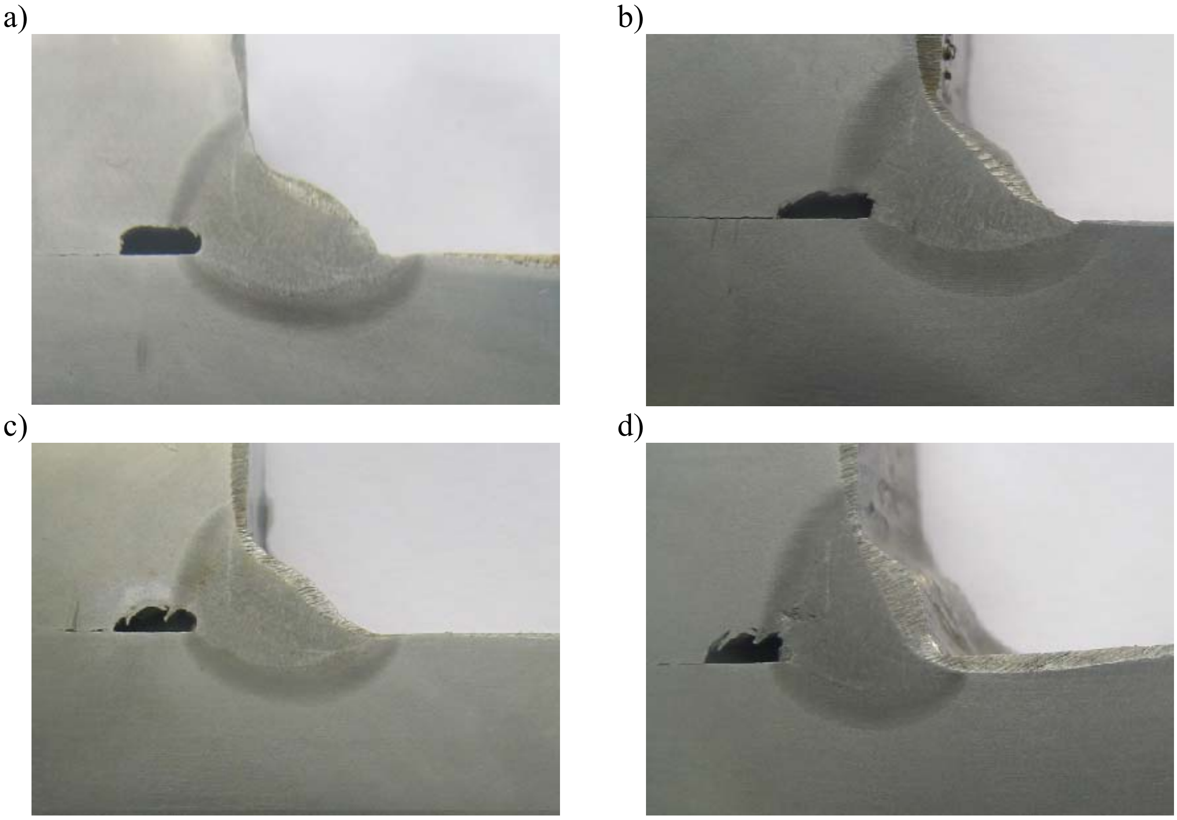

Fig. 2. Cross sections of test joints made under water – first welds - a) CTS 3.1. No imperfections; b) CTS 6.1. No imperfections; - second welds; c) CTS 4.2. No imperfections; d) CTS 2.1. Visible loss of material at the notch. Etch. Nital

METALLOGRAPHIC MICROSCOPIC TESTS

The microscopic tests showed microstructure of the base material that contains fine grained ferrite and pearlite. A dendritic structure was identified in the weld metal area. In test pieces CTS2, CTS4 and CTS6 cracks were found in the weld. Presence of a acicular, martensitic structure was found in the HAZ area of each test piece (Fig. 3). Such structure is a consequence of rapid cooling in the water environment. Welding imperfections of crack type were found in the HAZ area of each tested piece (Fig. 3). These are cold cracks caused by simultaneous action of hardened microstructure, residual stresses and high diffusible hydrogen content. Based on previous research [9], the content of diffusible hydrogen in welded joints performed under water at described conditions was evaluated at – 55 ml/100g.

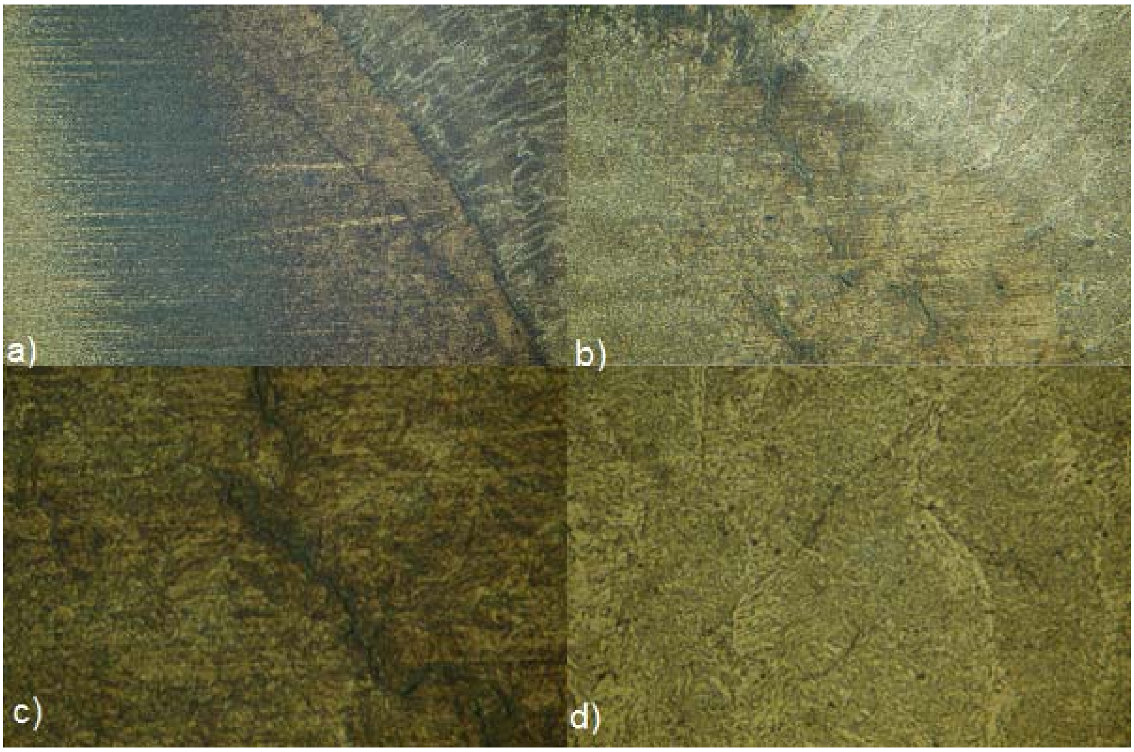

Fig. 3. Microstructure of S420G2+M steel joints welded under water with cracks;a) crack in HAZ. Magn. 50×; b) crack in HAZ. Magn. 200×; c) crack in HAZ. Magn. 500×; d) crack in weld. Magn. 500×

HARDNESS MEASUREMENTS

Vickers hardness measurements were carried out in a measurement line situated 2 mm below the weld faces, with 98N (HV10) load in accordance with the respective standard requirements [24]. Schematic layout of hardness test and examples of hardness distribution are presented in Fig. 4 and 5. Maximum hardness values in HAZ of the CTS test joints exceeded the assumed, in accordance with the PN-EN ISO 15614-1 standard requirements, acceptance criterion of 380HV10 [25]. The obtained values reached 459 HV10, which indicates formation of hardened structures (martensite) in that area. Hardness tests confirm the metallographic microscopic tests (Fig. 3). Table 5 presents results of hardness measurements in the form of maximum values in HAZ area.

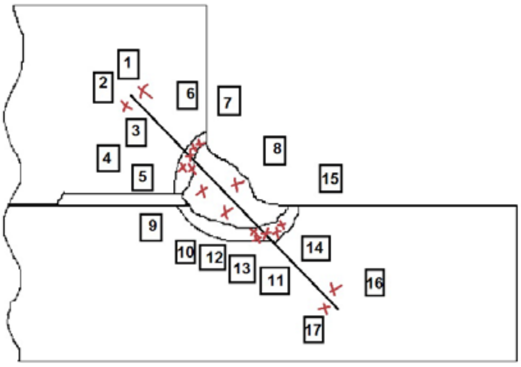

Fig. 4. Schematic illustration of the places of hardness measurements upon welded joint cross section

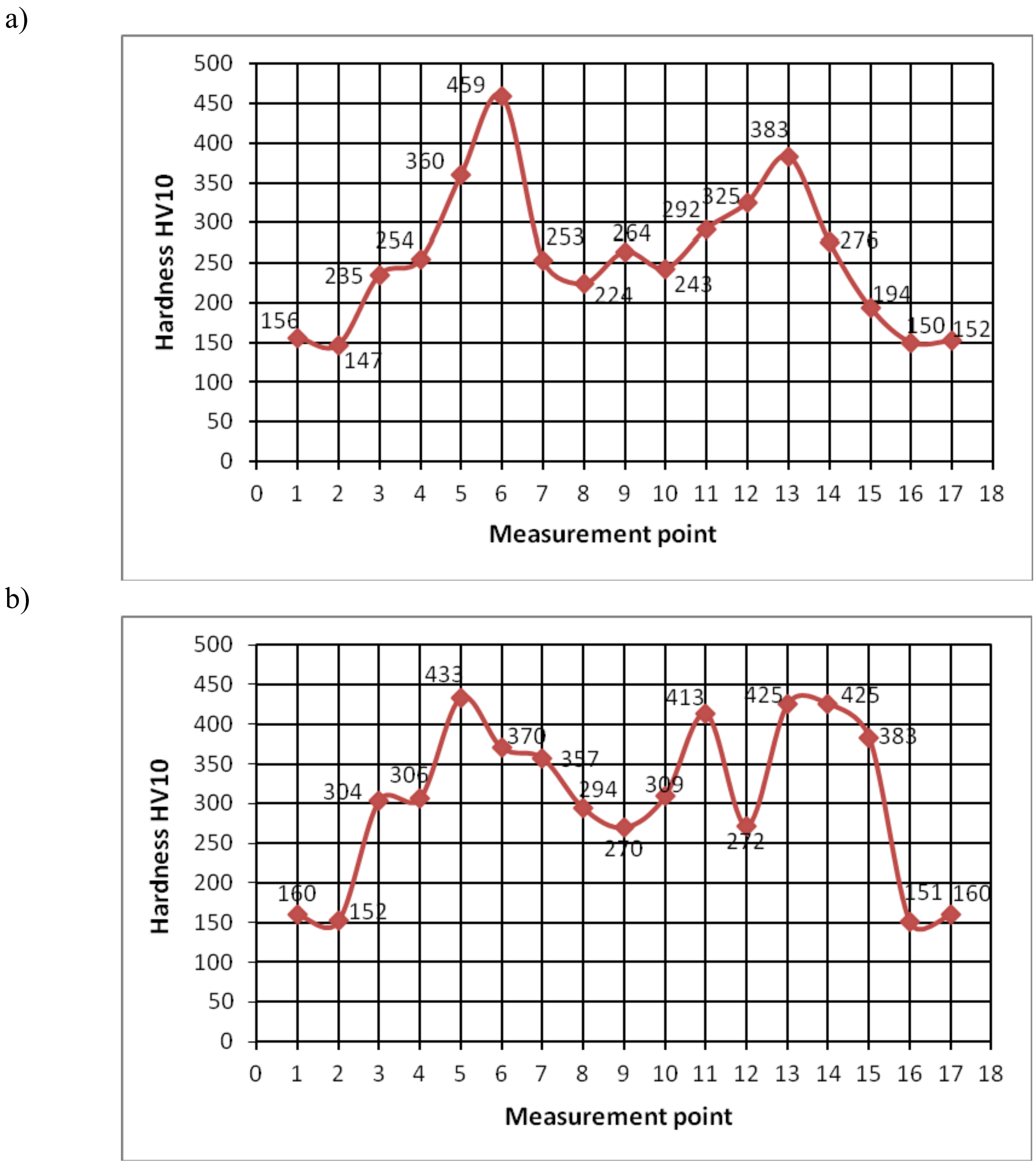

Fig. 5. Hardness distribution; a) across CTS2 (first weld) joint welded under the water, HV10max=459; b) across CTS4 (second weld) joint welded under the water, HV10max=433

Table 5. *Results of hardness tests*

Test piece	1	2	3	4	5	6
Maximum hardness HV10	437	459	366	433	Joint rejected	383

SUMMARY

The work presents an experimental evaluation of the high strength S355G10+N steel weldability on an 18 mm thick test piece in underwater wet welding with covered electrodes (111). Based on test results of joints with fillet welds (CTS), it was found that in the conditions of the performed experiment the investigated steel had limited weldability. Cold cracks were found in HAZ of the joints and in weld metal. The occurrence of cracks was a consequence of high diffusible hydrogen content in deposited metal, welding stresses and brittle hardened structures (Fig. 3). In the HAZ structural changes took place resulting in an increase of hardness from the 150-160 HV10 level (for base material) up to 366-459 HV10. Only the CTS3 sample meets the assumed acceptance criterion (380 HV10) according to the PN-EN ISO 15614-1 standard. Investigations will be continued with orientation towards quantitative evaluation of the S355G10+N steel weldability in the case of carrying out joints of different thermal severity number (Tekken and implant tests).

CONCLUSIONS

- Investigated S355G10+N high strength steel showed limited weldability at underwater conditions. CTS samples showed many cold cracks located in weld metal and HAZ of the joints.
- Wet welding of the S355G10+N steel caused considerable increase of joint hardness (up to 459 HV10). In most cases the test joints do not meet the assumed acceptance criterion (380 HV10) in accordance with the PN-EN ISO 15614-1 standard.
- In order to verify the obtained results, tests should be carried out on butt welded joints (Tekken) as well as quantitative method investigations should be performed, eg. the implant test.

BIBLIOGRAPHY

1. Fydrych D., Łabanowski J., Rogalski G.: Weldability of high strength steels in wet welding conditions. Polish Maritime Research, 2 (2013).
2. 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).
3. 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).
4. Guo N., Du Y., Feng J., Guo W., Deng Z.: Study of underwater wet welding stability using an X-ray transmission method. Journal of Materials Processing Technology, 225 (2015).
5. Guo N., Guo W., Du Y., Fu Y., Feng J.: Effect of boric acid on metal transfer mode of underwater flux-cored wire wet welding. Journal of Materials Processing Technology, 223 (2015).
6. 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).

7. Maksimov S.Y.: Prevention of cold cracks in heat affected zone in underwater welding of low-alloyed high-strength steels. Збірник Наукових Праць НУК, 4 (2014).
8. Silva L.F., dos Santos V.R., Paciornik S., Mertens J.C.E., Chawla N.: Multiscale 3D characterization of discontinuities in underwater wet welds. Materials Characterization, 107 (2015).
9. Fydrych D., Rogalski G., Tomków J., Łabanowski J.: The tendency to form cold cracks at the S420G2+M steel joints welded under water using wet method (in Polish). Przegląd Spawalnictwa (Welding Technology Review), 10 (2013).
10. Maksimov S.Y.: Underwater arc welding of higher strength low-alloy steels. Welding International, 6 (2010).
11. Omajene J.E., Martikainen J., Wu H., Kah P.: Optimization of underwater wet welding process parameters using neural network. International Journal of Mechanical and Materials Engineering, 1 (2014).
12. Ćwiek J.: Hydrogen degradation of weldable high strength steels (in Polish). Gdansk Univ. Of Technology, Gdańsk 2006.
13. Garašić I., Kralj S., Kožuh Z., Pacak M.: Analysis of underwater repair technology on the jack-up platform spud can. Brodogradnja, 2 (2010).
14. Fydrych D., Łabanowski J., Rogalski G., Haras J., Tomków J., Świerczyńska A., Jakóbczak P., Kostro Ł.: Weldability of S500MC steel in underwater conditions. Advances in Materials Science, 2 (2014).
15. Fydrych D., Kozak T.: Underwater welded joint properties investigation. Advances in Materials Science, 4 (2009).
16. Sharp J.V., Billingham J., Robinson M.J.: The risk management of high-strength steels in jack-ups in seawater. Marine Structures, 14 (2001)
17. PN-EN ISO 17642-2:2005 Destructive tests on welds in metallic materials - Cold cracking tests for weldments - Arc welding processes - Part 2: Self-restraint tests
18. 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).
19. Kannengiesser T., Boellinghaus T.: Cold cracking tests-an overview of present technologies and applications. Welding in the World, 1 (2013).
20. PN-EN 10225:2011 Weldable structural steels for fixed offshore structures - Technical delivery conditions.
21. PN-EN ISO 17637:2011 Non-destructive testing of welds. Visual testing of fusion-welded joints
22. PN-EN ISO 3452-1:2013-08 Non-destructive testing -- Penetrant testing -- Part 1: General principles
23. PN-EN ISO 17639:2013-12 Destructive tests on welds in metallic materials - Macroscopic and microscopic examination of welds
24. PN-EN ISO 9015-1:2011 Non-destructive testing of welds. Hardness testing. Part 1.
25. PN-EN ISO 15614-1:2008 Specification and qualification of welding procedures for metallic materials -Welding procedure test - Arc and gas welding of steels and arc welding of nickel and nickel alloys.