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INFLUENCE OF COVERED ELECTRODE TYPE ON UNDERWATER PAD WELD QUALITY IN HIGH-STRENGTH LOW-ALLOY STEEL

ABSTRACT

Water as a welding environment generates significant challenges affecting the quality of welded structures. The purpose of this study was to investigate the effect of the type of covered electrode (three for underwater works and three for air welding) on the quality of the padding welds made on high-strength low-alloy steel in wet welding conditions. The S355J2C+N structural steel was selected for tests. As filler materials six different covered electrodes were chosen. Tests were conducted in similar conditions – fresh tap water (temperature 20°C) at 150 mm depth. After surfacing, the specimens were subjected to visual testing. Subsequently, macroscopic examinations and Vickers HV10 hardness measurements were performed. It was proved that the grade of covered electrode has a significant influence on the quality and hardness of pad welded structures. Underwater electrodes, which are covered with different hydrophobic coatings, can reduce the occurrence of welding imperfections. It was shown that hardness of underwater welded structures with covered electrodes for air welding may be similar to structures made with the use of electrodes for underwater works. Moreover, it was stated that type of covered electrode may generate 130-140 HV10 lower hardness in heat-affected zone (HAZ).

Keywords: *Underwater welding; covered electrodes; wet welding*

INTRODUCTION

Underwater joining processes are widely used for the fabrication, maintenance, and repair of metallic structures in water environments. They can also be applied to improve the mechanical and functional properties of metal joints, particularly for the Friction Stir Welding (FSW) process [1,2]. However, the most often used is the conventional welding process. The method is used especially for underwater repairs, where there is necessity to save time [3]. Underwater welding is also used for joining metals directly in the seas and oceans, e.g. pipelines, oil platforms. The number of underwater welded structures increases year to the year. The process is treated as one of the special welding processes. In underwater welding, three main methods can be described. The first of them, named local dry cavity welding, allows to isolate the welding area from surrounding water. The welding pool and newly created weld metal are isolated from water by a small chamber. The water is pushed from this chamber by a high flow of protective gas. It allows the creation of a quasi-dry area of welding. During the process, the welder is located directly in the water. This method does not

allow us to observe processes in real-time [4,5]. The welder is not able to control the geometry of the welding pool and the face of the weld. Due to this aspect, the method is treated more like a laboratory method, and is not widely used in commercial applications. The second underwater welding method is dry welding. Dry welding is commonly used in real applications, but it has limitations. This method allows the welder and the welding area from the surrounding water by protective chambers, which allow it to remove water from the environment, even at higher depths [6]. The method allows to create conditions similar to air welding. The welder and welding area are inside the mentioned chamber, and the process can be performed without direct contact with the water environment. However, it requires building a chamber. In many cases, it makes a method uneconomical to be used due to limited costs. The cheapest and the fastest method of underwater welding is wet welding. The method is carried out directly in the water environment [7-9]. There is no isolation between water, welding arc and welding area. Also, the welder is in direct contact with the environment. Water as a welding environment may generate some important problems that affect the quality of underwater welded structures. It strongly increases the tendency of steel to cold cracking [10] due to increased cooling rate. These cracks are crucial for the quality of the underwater welded joints. They may appear in the weld metal and in the heat-affected zone (HAZ) even 72 h after completing the process. Another common problem is the instability of the welding arc [11]. It resulted from the welding depth and the hydrostatic pressure. The stability may be improved by using the special ultrasonic induction supporting system, but it requires the use of additional devices. Another problem for underwater welders is limited visibility of the welding area due to underwater gas bubbles created during the welding process [12]. Mentioned aspects decrease the quality of underwater welded structures compared to structures made in the air. Water as a welding environment also resulted in increasing the diffusible hydrogen content in deposited metal [13]. During the process, the filler materials can cumulate hydrogen, which quickly diffuses to the welded area. The conventional methods of preventing this phenomenon as drying the electrodes are impossible to be used for underwater welding. Additional problems in the water environment that decrease the quality of underwater welded structures are high residual stresses [14], which are observed after the welding process.

The most commonly welded material in water environments are different steel grades. It resulted from high usage of steel for offshore structures [15]. These structures may undergo failures, which also increase the usage of underwater welding processes in case of necessity to their repairs. One of the most important materials in the offshore industry are high-strength low-alloy steels. Many of these steels are characterized by high susceptibility to cold cracking. This tendency increased in the case of underwater welding, by the influence of water as a welding environment [16-18].

Due to mentioned reasons, there is a need to investigate aspects of underwater welding of HSLA steels. For presented investigations, the structural S355J2C+N steel was selected as a base material (BM). This steel is characterized by high-susceptibility to cold cracking in wet welding conditions. Tomków and Janeczek [19] proved that the quality of S355J2C+N welded joints may be improved by applying the additional stitches to the surface of multipass butt joints. The limitation of laying additional stitches is the difficulty of this process. Moreover, butt joints are not commonly used in the case of wet welding. In this paper, the aspect of pad welding on the S355J2C+N steel is presented. As a way to improve the quality of welded structures, a different selection of filler material was proposed, which may be significantly less expensive than other methods. This paper compares the properties between welds made with electrodes for underwater works and for air welding.

EXPERIMENTAL PROCEDURE

Pad welds were laid on the surface of S355J2C+N steel. Samples were welded on plates with 120 mm length, 30 mm width and 16 mm thickness. Prior to testing, the chemical composition of the steel was determined by spark emission spectrometry (Table 1). Carbon equivalent (C_{eq}) was calculated with a formula suggested by the International Institute of Welding [17]:

$$C_{eq} = C + Mn/6 + (Ni + Cu)/15 + (Cr + Mo + V)/5 \quad (1)$$

where:

- C, Mn, Ni, Cu, Cr, Mo, V is the chemical element content in the alloy [%].

The mechanical properties of S355J2C+N steel are listed in Table 2 in accordance with manufacturer data.

Table 1. Chemical composition of S355J2C+N steel (wt. %)

	C	Si	Mn	P	Cr	Mo	Ni	Cu	V	C_{eq}
S355J2C+N	0.2	0.5	1.1	0.02	0.02	0.001	0.001	0.02	0.005	0.386

Table 2. Mechanical properties of S355J2C+N

	Yield point, R_{eH} , MPa	Tensile strength, R_m , MPa	Elongation, A, %
S355J2C+N	min. 355	470-630	17-22

As filler materials, six commercial covered electrodes with Ø4 mm diameter were selected. Three of them are designed for underwater works, while the remaining three are used for welding in air. In the tests, the results between different types and groups may be compared. Their chemical compositions and description in accordance to manufacturers data is listed in Table 3. Their mechanical properties are shown in Table 4.

Table 3. Chemical composition of used covered electrodes (wt. %)

	Type	Usage	C	Mn	Si	P	S	Ni
U1	not stated	underwater works	0.06	0.47	0.33	0.01	0.016	0.07
U2	rutile coated with polymer coating		0.05	0.5	0.45	0.03	0.025	0.30
U3	rutile coated		0.1	0.5	0.43	0.02	0.008	-
A1	rutile and cellulose coated	air welding	0.08	0.5	0.20	-	-	-
A2	rutile coated		0.06	0.5	0.45	-	-	-
A3	rutile coated		0.05-0.11	0.4-0.7	0.2-0.4	<0.03	<0.02	-

Table 4. *Mechanical properties of used covered electrodes*

	Yield point Re MPa	Tensile strength, Rm MPa	Elongation, A %
U1	459.4	522.3	11
U2	not stated	564	12-13.5
U3	460	520	17
A1	380	480-570	22
A2	380	470-600	20
A3	min. 430	490-550	min. 24

Welding was performed manually in a special underwater stand (Fig. 1) at similar conditions - fresh tap water (temperature 20°C) at 150 mm depth.



Fig. 1. View of the underwater welding stand used in the experiments: 1 – welding power source, 2 – tank with water, 3 – welding table

All samples were welded with the same welding current 180 A (DC-). This value is relatively small for underwater works compared to the papers previously published by scientists from Gdańsk University of Technology [10,15,20]. As it was stated by Cisquini et al. [21] lower welding current may decrease the tendency for corrosion, so it may be helpful for obtaining greater quality of underwater welded structures. In presented investigations, the current was the same, but due to different behavior of electrodes in the water, there were differences in arc voltage. Moreover, welders had to use different welding speeds to make the welding arc stable. It resulted with small differences in welding heat input. In real underwater welding, the current is set on welding devices, and the rest parameters are set automatically with highest synergy, as in presented investigations. All welding parameters are presented in Table 5. Welding speed was determined by measuring the time and length of each weld. Specimens were named the same as covered electrodes, which were used for their performance.

During the process, the welding arc was stable, and no serious differences were observed. After welding, each sample was cleaned, and the slag layer was removed. In the next step (48 h after welding) the visual test (VT) was performed in accordance with EN ISO 17637:2017 standard.

Table 5. Welding parameters

Sample no.	Welding current, I A	Voltage, U V	Welding speed, Vsp mm/s	Heat input, ql kJ/mm
U1	180	27.7	4.65	1.07
U2		26.7	4.90	0.98
U3		33.7	5.83	1.04
A1		31.5	5.13	1.11
A2		23.2	4.26	0.98
A3		22.2	4.45	0.90

The macroscopic test was performed following EN ISO 17639:2022 standard. From each specimen, the cross-section was taken in the middle of the weld length. Then, the grinding, polishing and Nital 4% etching were performed. To show the differences in weld geometry and the amount of melted area of BM the dilution coefficient was calculated following formula [22]:

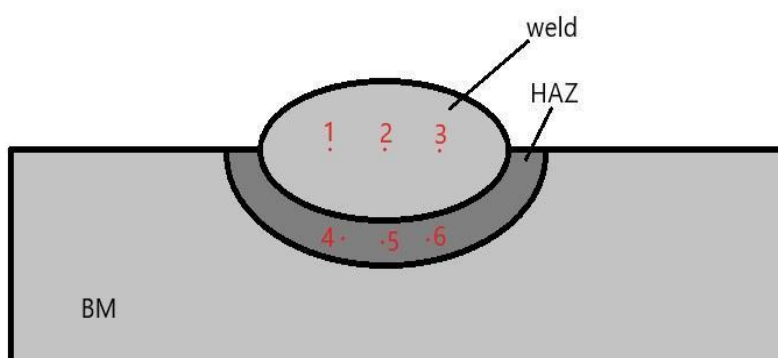
$$D = A_{\text{base}} / A \quad (2)$$

where:

- D – dilution, %,
- A_{base} – molten area of BM, mm²,
- A – total molten area, mm².

For area measurement the AutoCAD software was used.

Then, the Vickers HV10 hardness measurements (EN ISO 9015–1:2011) were performed in accordance with the schematic draw presented in Fig. 2. For the test the Sinowon V-10 stand equipped with an optical microscope was used.

**Fig. 2.** Hardness measurement points distribution

RESULTS AND DISCUSSION

The results of VT (Fig. 3) showed some typical problem of welded structures made in the water environment with covered electrodes. The most often observed was slag on the surface of the weld, which was detected in all specimens. Such inclusions are commonly observed in wet-welded structures produced with covered electrodes [20,23]. The lowest number of slags

were observed in specimens U2 (Fig. 3b) and A3 (Fig 3f). The biggest differences observed between specimens made with electrodes for underwater works (Figs 3a-3c) and air welding was the amount of spatters. The specimens made with filler material for air welding (Figs 3d-3f) are characterized by greater number of spatters. Moreover, their size was greater. The amount of spatters may be treated as an operability in a range of parameters for underwater welding [24]. Some differences in geometry of welds made with different electrodes were observed, which resulted in additional dilution calculations performed in the next step of performed studies.

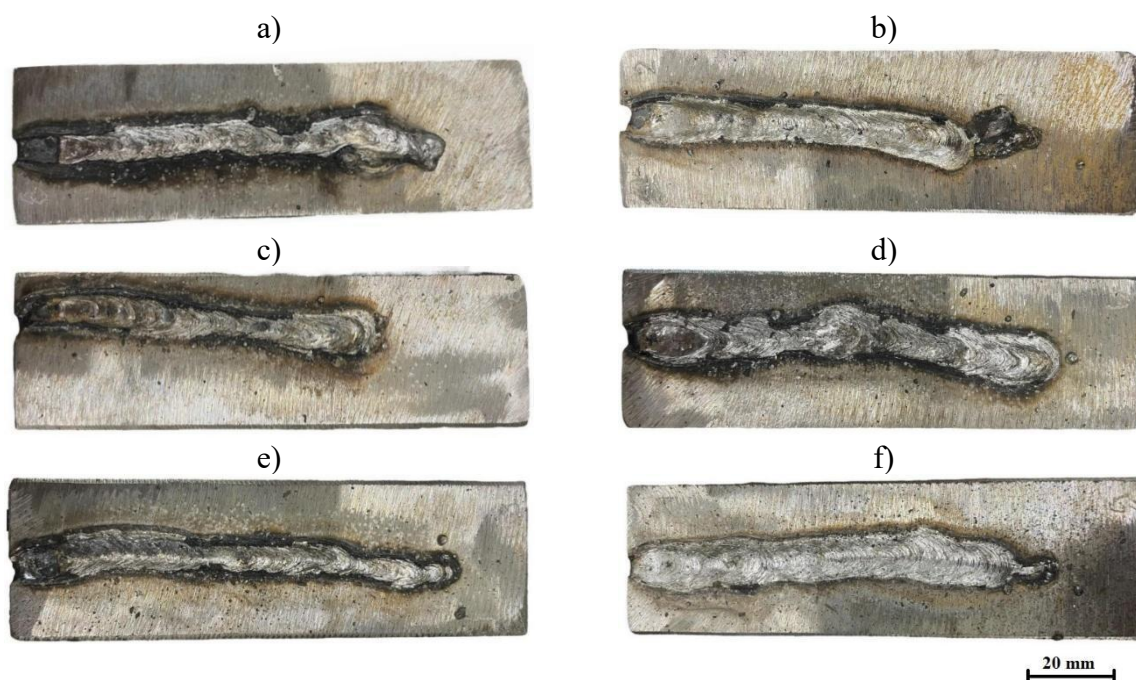


Fig. 3. Top views of specimens: a) U1, b) U2, c) U3, d) A1, e) A2, f) A3

In the next step, the macroscopic test was performed (Fig. 4). In all specimens the HAZ and welds were clearly visible. A macroscopic test confirmed different geometry of the weld, especially in depth of penetration into BM. Welds in specimens U1-U3 are characterized by more regular shape than in specimens A1-A3. Some imperfections like undercuts were detected in specimen A2 (Fig. 4e). None inside slag inclusions or porosity were observed the same as cracks.

In the next step the Vickers HV10 hardness measurements were performed. Firstly, the BM hardness was assessed as 209 ± 4 HV10. For all specimens, the weld and HAZ were measured. The hardness at level 380 HV10 was set as a criterion of acceptance following EN ISO 15614-1:2017 standard. Measurements showed significant differences for performed specimens. Only for sample U2 the hardness did not exceed 380 HV10 in HAZ. The hardness in weld for this specimen was the lowest. The highest welds hardness was measured in specimen U1, also made by underwater electrodes. Most specimens were welded by rutile-coated electrodes, which are commonly used for underwater welding [25]. However, there were no serious differences (except specimen U2) between specimens for air and underwater works. The most important factor is hardness. Specimens with hardness greater than 380

HV10 may undergo cold cracking. The results are presented in Table 6 and in Fig. 5.

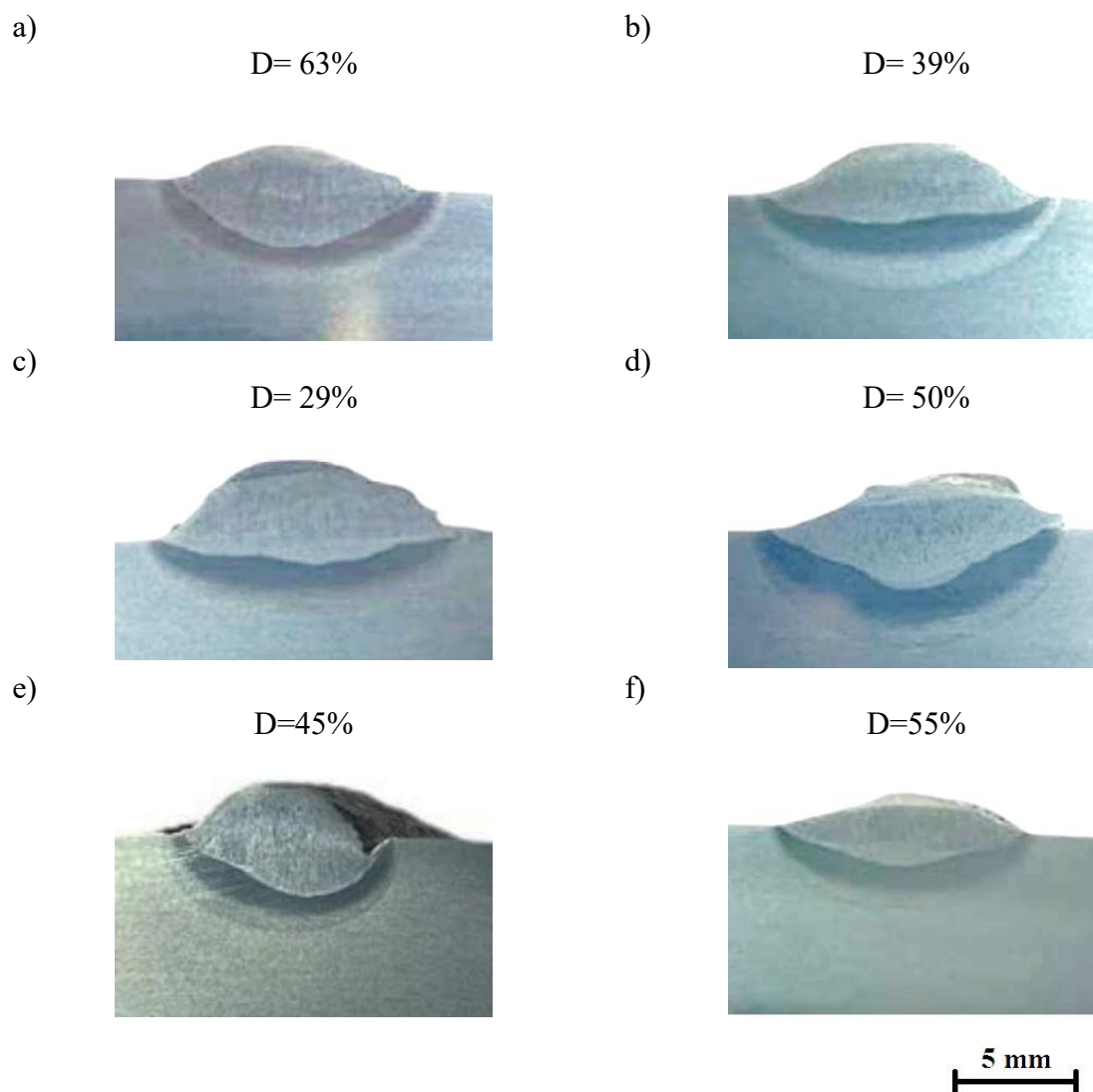


Fig. 4. Macrographs of specimens no: a) U1, b) U2, c) U3, d) A1, e) A2, f) A3

Table 6. Vickers HV10 hardness measurement results

Sample no.	Weld				HAZ			
				average				average
U1	332	348	352	344	484	480	452	472
U2	290	286	260	279	374	350	378	367
U3	229	294	331	306	502	499	495	499
A1	320	295	323	307	492	511	485	496
A2	345	302	366	338	502	516	482	500
A3	296	305	285	295	482	494	503	493

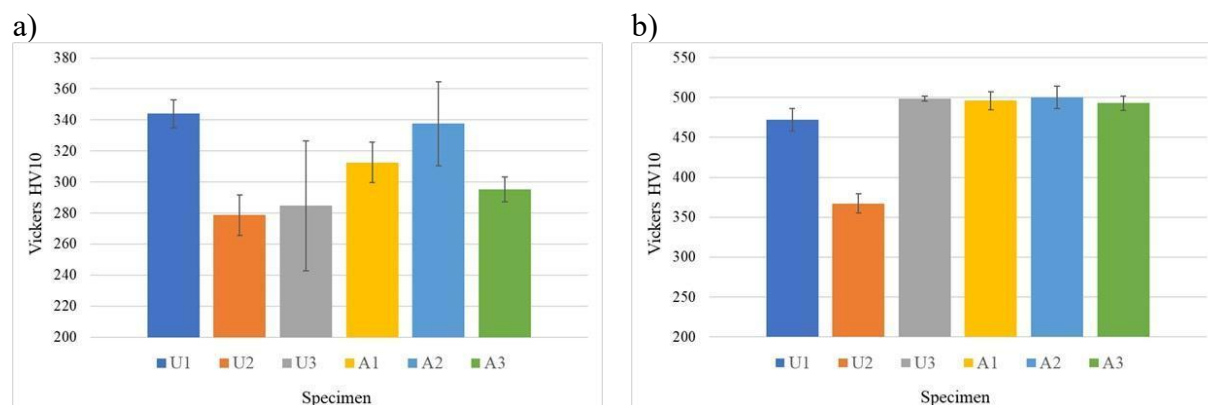


Fig. 5. Vickers HV10 hardness in: a) weld metal, b) HAZ; bars represent standard deviation

The hardness stand is equipped with an optical microscope. During measurements cracks were detected only in specimen A1, which was welded with rutile-cellulose covered electrodes (Fig. 6). In specimens welded with rutile-coated electrodes, no cracks were observed. The formation of these cracks is caused by high residual stresses, martensitic transformation (confirmed by high hardness values), and high diffusible hydrogen content, which is ~40 ml/100 g for rutile-coated electrodes [26].

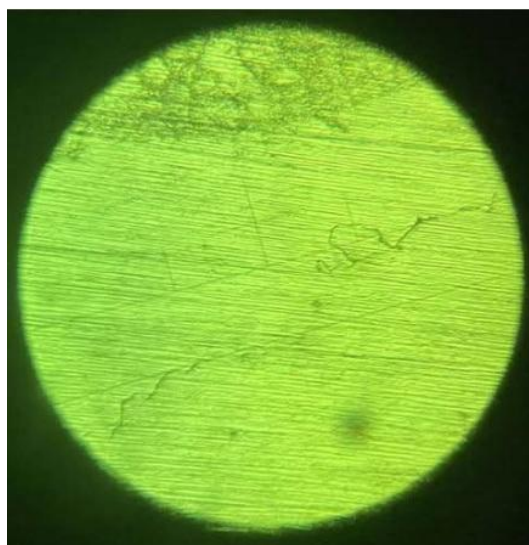


Fig. 6. Cracks observed in the HAZ of specimen A1

CONCLUSIONS

This work presents investigations on properties and quality of underwater pad welded structures made in wet welding conditions. As a filler material six different grades of covered electrodes were used: three for underwater works and three for air welding.

Performed tests allow to draw following conclusions:

1. The grade of covered electrode significantly affects the hardness of different areas of wet welded structures. No influence of the purpose of filler material on the hardness was observed.

2. The lowest hardness was measured for electrode U2 with average values 279 HV10 in weld and 367 HV10 in the HAZ. For the rest of used covered electrodes the HAZ hardness exceeds maximum values of 380 HV10 in accordance with EN ISO 15614-1:2017 standard for S355J2C+N steel.
3. The rutile-cellulose electrode used in wet welding conditions increases the HAZ hardness, and may contribute to cold cracking, which is a crucial problem in underwater welding. In specimens welded with rutile-coated electrodes, no cracks were detected.

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Ethical Standards

This research was conducted in full compliance with ethical standards. The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. Jacek Tomków serves as an Associate Editor of Advances in Materials Science. He has been excluded from the publication process.

Statement of Research and Publication Ethics

The authors declare that all procedures followed the principles of research integrity and publication ethics.

Conflicts of Interest

The authors declare no competing financial interests or personal relationships that could have influenced the work reported in this paper.

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