A REVIEW ON UNDERWATER WELDING

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ABSTRACT

The paper describes principles of underwater welding and recent trends in research works undertaken for enhance welding technology and properties of underwater welds. Department of Materials Technology and Welding at Gdansk University of Technology (GUT) has been involved in underwater welding research for over 25 years. Investigations include technology of underwater welding, and weld properties examinations. All tests have been performed with the use of self designed stands allow to perform welds in shallow depths as well as the depths up to 1000 m. The main investigation directions performed at the Department of Materials Technology and Welding are presented:

- ➢ HSLA steel's weldability and the variables affecting welded joints' susceptibility to cold cracking
- ➢ How wet welding circumstances affect the amount of diffusible hydrogen in the welds.
- ➢ The impact of heat input, underwater welding depths, and shielding gas composition on the toughness of welds.

Key words: *underwater welding, wet welding, dry welding, local cavity, weldability of steel*

1. INTRODUCTION

The Department of Materials Technology and Welding at GUT has been researching underwater welding techniques for about thirty years. A few unique test stands were built in labs and used to determine welding settings and the characteristics of welded joints. Wet shielded metal arc welding and gas metal arc welding using the local cavity approach are the main research areas of the Underwater Welding Laboratory [1, 2]. Additional study is carried out using underwater cutting techniques [2, 3]. When it is not possible to place metal structure into a dry dock, welding operations must be performed in water environment [2, 4, 5, 6, 7]. The following categories apply to underwater welding processes [2,4,8]:

a) wet welding,
b) dry welding,
c) local cavity welding.

In the current work, an overview of contemporary underwater welding procedures is offered. Particular focus is given to local and wet cavity welding.The classification of underwater welding techniques is presented in Fig. 1.

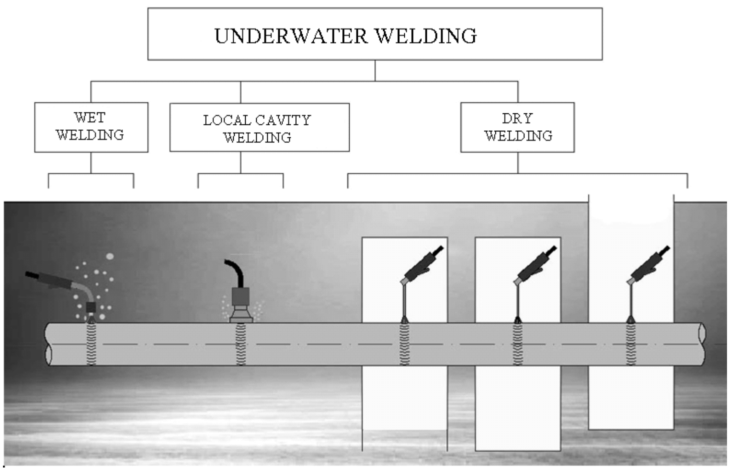

Fig. 1. Classification of underwater welding

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There is no mechanical separation between the water and the welding arc when wet welding is carried out under ambient pressure with the welder-diver submerged. Even the most geometrically complex structures can be welded because to the procedure' simplicity [5,6,9,10]. Shielded metal arc welding (SMAW) and flux cored arc welding (FCAW), including self shielded flux cored arc welding, are the two wet welding methods most frequently utilised. The most affordable and adaptable way of operations in an underwater environment is wet welding with coated electrodes [5,6,9,10]. Direct welds using covered electrodes or FCAW can be made down to a depth of 100 metres [10]. Wet welding produces substantially higher cooling rates than dry welding does in a water environment. It can fluctuate from 415 to 56 °C/s in the temperature range of 800 to 500 °C [11]. This results in the loss of ductility of the heat-affected zone and the weld metal (HAZ). High levels of porosity are also known to be present in underwater wet welds (Fig. 2). Molecular hydrogen, carbon monoxide, or water vapour can all create pores [12,13,14]. All wet welds contain some amount of pores. The three main variables influencing this phenomena are the water depth, electrode coverage, and arc stability [10,12,13,14].

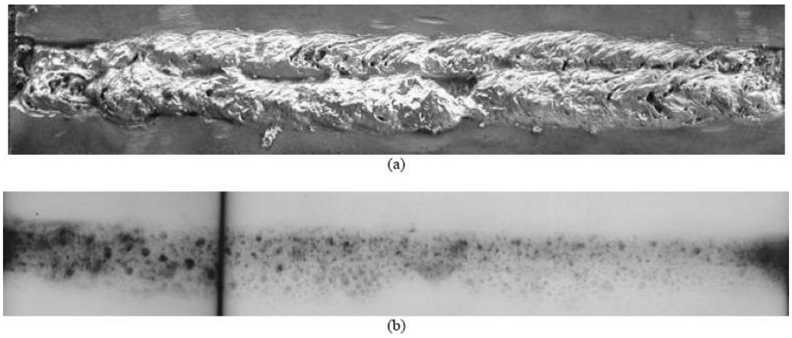

Fig. 2. V-groove wet weld deposited at 100 m depth (a) and its radiographic image (b) [15]

The quality of wet welds has increased during the past few years. Modern electrodes that are readily available on the open market and unique flux-cored wires guarantee high-quality welded junctions [6,16,17].

Welding by local cavity method is possible due to utilizing standard equipment for semiautomatic or automatic gas metal arc welding (GMAW) [18,19] instrumented additionally with special outer nozzle and elastic cover as it is shown in Fig. 3. In local cavity method cooling conditions are nearly the same as those existed during welding in the air [20]. Results of diffusible hydrogen determination tests indicate that amount of hydrogen in weld metal is in the range from 5 to 21 ml/100g Fe and depends on welding parameters, especially flow rate of shielding gas [18,19]. Properties of welds performed with the use of local dry chamber are much better than properties of wet welds and meet requirements of classification societies for depth up to 200 m [21,22].

Figure 4 shows a view of some sample weld beads produced by local cavity welding. The method's biggest drawback is the inability to observe the welding process. Application of a laser beam as a heat source can also be used to carry out local cavity processes [23].

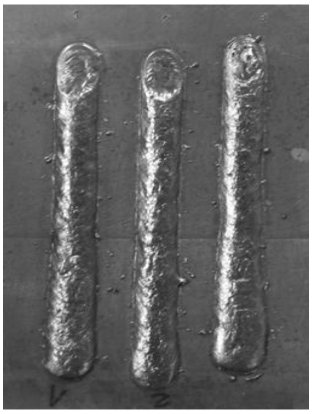

Fig. 4. Weld beads obtained by local cavity welding

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In In a chamber (Fig. 5) where water has been replaced with air or a gas combination, depending on depth, dry hyperbaric welding is done at atmospheric pressure. The quality of underwater dry welds is higher than that of wet welds, but significant support equipment is needed, and the associated expenses are quite high [4,7,24]. Dry welds frequently exhibit mechanical characteristics that are on par with those of comparable welds done above water. Dry welding repairs are expected to cost and take twice as long as wet welding repairs [5]. In dry conditions, nearly all conventional welding techniques are usable. The most popular welding methods are SMAW, GMAW, FCAW, and tungsten inert gas welding [4,7,25]. (TIG). 300 m is the highest depth at which manual hyperbaric welding may be done.

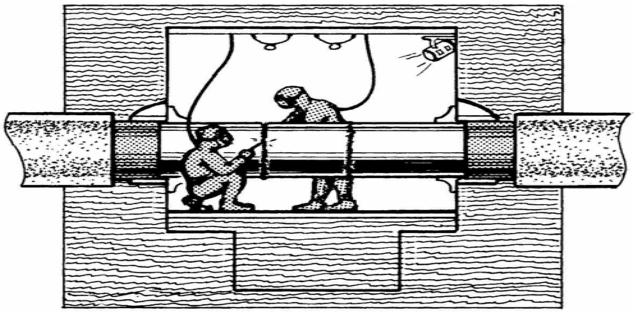

Fig. 5. Underwater welding in dry conditions

2. WELDABILITY OF STEEL IN WATER ENVIRONMENT

Due to increased pressure, hydrogen content in the welded metal, and faster cooling rates, underwater welding is more challenging than welding done outside [2,4,8,11,26]. The presence of diffusible hydrogen and brittle microstructures in the welds can be grounds for crack formation, and it has been demonstrated that increased pressure makes welding arcs unstable [4,8,10].

In the most cases underwater welding is used for joining carbon steels, low alloy steels, austenitic and duplex stainless steels [2,4,12]. Weldability of steel in water environment is governed by its cold or hot cracking tendency [28,29,27,30]. Susceptibility to cold cracking is main problem in welding of high strength low alloy steels (HSLA) (Fig. 6) and fabrication of dissimilar joints. Hot cracks in the most cases are observed in weld metal of fully austenitic stainless steels (Fig. 7). There are relatively numerous publications on this subject [4, 9, 18,27,28,31,13].

Fig. 6. Microphotograph of the cold crack in the bainite structure of heat affected zone [18]

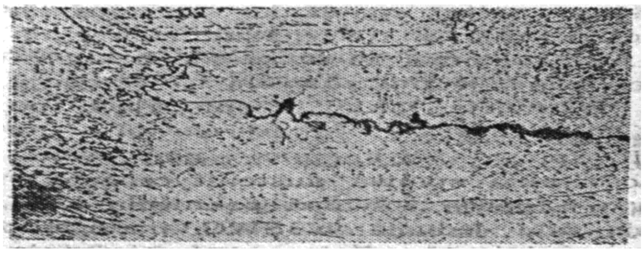

Fig. 7. Microphotograph of the hot crack in austenitic weld metal [30]

Welded joints of high strength steels performed in wet underwater conditions are very susceptible to cold cracking (hydrogen cracking) [27,28,30]. For eliminate tendency to cracking the effect of three factors: amount of diffusible hydrogen, hard microstructures in HAZ and high residual stresses in the weld joint should be minimized [33,34,35]. Reduction of the hydrogen content can be obtained with the use of consumables which give low amount of hydrogen in welds or by selecting welding parameters which minimize weld pool hydrogen pickup [19,36].

Unfavorable structure transformations in HAZ can be avoided by controlling of cooling rate of welded joint by the use of special insulation on surface of the welded plate and apply high heat inputs [11,36]. Welding practices that reduce residual stresses in the joints include: the use of small weld deposits and consumables with compatible coefficients of thermal expansion with base material and the selection of edge preparations which reduce weld deposit.

The strength of the steel used for the deep-water structures is very important factor, because high strength steel (yield strength over 350 MPa) is required at greater depths. High strength steels usually have carbon equivalents greater than 0.4% and show worse weld-ability. Although underwater welding by local cavity method ensures cooling conditions nearly the same as during welding in the air [2,8], cold cracks can occur in high strength steel welded joints. So the aim of undertaken research was determination of susceptibility to cold cracking of the joints performed in underwater conditions by local cavity method. For that purpose HSLA S355 (18G2A) steel was selected together with matching filler materials for GMAW process. There are only a few papers on this subject and the results reported by authors are not in full agreement [2,8,18,20]. Chemical composition of tested material is given in table 1.

Table 1. *Chemical composition of S355 (18G2A) steel, wt %*

C	Mn	Si	Cr	Ni	Cu	Al
0.17	1.44	0.35	0.04	0.077	0.30	0.027

Test welds were made at the stand for underwater welding (Fig. 8) employing GMAW process and with the use of IS-10S wire (Φ = 1.2 mm).

Susceptibility to cold cracking was carried out by implant method. Implant specimens were performed at the following conditions: heat input e_L=10□20 kJ/cm and shielding gas (CO_2) flow rate of Wg=20□50 l/min [18]. Cylindrical notched specimen of the test material was inserted into a borehole of backing plate and then welded to it by one bead. The specimen was subjected to a static tensile loading on “Implant 02” stand showed in Fig. 9. The time to fracture was recorded. The tensile load was maintained for 16 hours if the specimen had not failed before [18].

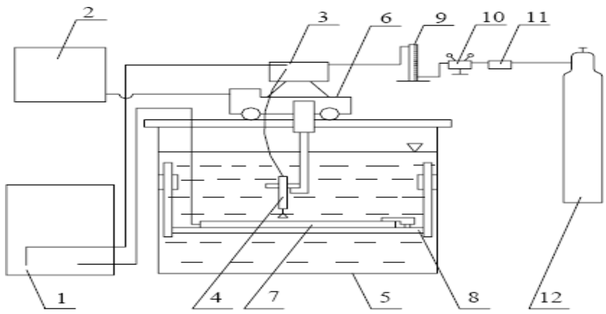

Fig. 8. Test stand for underwater welding

1 – power source, 2 – track feeder, 3 – engine, 4 – head, 5 – water container, 6 – welding track, 7 – specimen, 8 – work piece holder, 9 – flow meter, 10 – reducer, 11 – preheater, 12 – gas cylinder

Fig. 9. Test stand "Implant 02" [37]

Glycerin method was used for evaluation of diffusible hydrogen content in the weld metal. The amount of hydrogen was determined in the range from 10 to 21 ml/100g Fe. The hydrogen amount strongly depends on flow rate of shielding gas. Regression analysis for obtained results was performed with the aid of the Statistica software package. Using critical stress σ_{cr} as dependent variable, Wg and e_L as independent variables the following regression equation was obtained:

$$\sigma_{cr} = -184{,}81 + 14{,}59 \square Wg - 0{,}24 \square Wg^2 + 39{,}33 \square e_L - 1{,}33 \square e_L^2 + 0{,}13 \square Wg \square e_L,$$

where:

σ_{cr} – critical stress [MPa],

Wg – flow rate of shielding gas [l/min], e_L – heat input of welding [kJ/cm].

with R^2=0.995 (determination coefficient) and p=0,05 (level of significance). The relation can be presented graphically (Fig. 10).

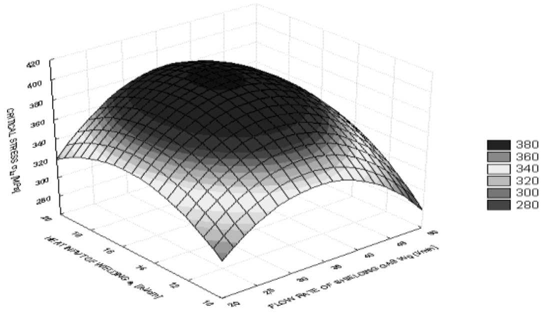

Fig. 10. Relationship between critical stress σ_{cr} and flow rate of shielding gas Wg and heat input e_L for underwater welds [18]

The obtained model allows optimization of welding parameters. The surface area shown in Fig. 10 reaches its maximum at following values: Wg=35 l/min and e_L=16 kJ/cm.

Other investigations were aimed at the determination of diffusible hydrogen content in weld metal after wet underwater welding using of covered electrodes [36]. Problem has been solved by the use of design of experiment method (Plackett-Burman design). Test welds (Fig. 11) were performed at the stand for welding on low depths (Fig. 8) with application of various welding conditions: welding current, painting of electrode, electrodes polarity, thickness of flux covering electrodes core, salinity of water, contamination of electrode (carbohydrates) and time of wetting of electrode in water. To evaluate the diffusible hydrogen content in the weld metal glycerin method was used [38]. The results of these

experiments are collected in table 2. The amount of hydrogen was determined in the range from 45.90 to 87.40 ml/100g Fe.

Fig. 11. Specimens with test beads obtained by wet underwater welding conditions with the use of covered electrodes

The results of analysis performed in Statistica software (fig. 12) show that the most relevant variables are: salinity of water, contamination of electrode, electrode polarity and welding current [36].

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Table 2. *Conditions and results of diffusible hydrogen measurements [36]*

No	Welding current [A]	Thickness of covering [mm]	State of electrode	Painting	Salinity of water [‰]	Polarity	Time in water [min]	Average hydrogen amount H_D [ml/100 g Fe]
1	240	0.90	pure	yes	10	+	5	45.90
2	292	0.90	pure	no	0	+	0	70.46
3	240	1.35	pure	no	10	-	0	47.27
4	292	1.35	pure	yes	0	-	5	74.17
5	240	0.90	oil	yes	0	-	0	87.40
6	292	0.90	oil	no	10	-	5	71.11
7	240	1.35	oil	no	0	+	5	83.98
8	292	1.35	oil	yes	10	+	0	63.95
9	240	1.35	oil	no	0	+	5	79.48

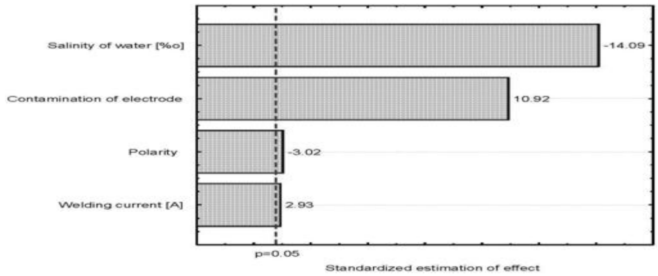

Fig. 12. Pareto chart of the standardized effects [36]

Following investigations aimed at determination of shielding gas and water depth on impact strength of joints made under water by local cavity method. Test welds were made on test stand for underwater welding on high depths (Fig. 13) using GMAW process with CO_2 and Ar+CO_2 shielding gases [39].

Fig. 13. Test facility for simulating underwater welding on high depths

Specimens were sampled from test joints made in following conditions: depth of water up to 200 m, heat input from 1.53 to 4.38 kJ/mm. Impact strength was measured on Charpy V specimens at room temperature. As it can be seen from fig. 14, up to 60 m water depth difference in values of impact strength is relatively low, but in the range 60□100 m for welding in mixed gas Ar+CO_2 the drop of impact strength is observed. The results of these experiments indicated that it is recommended to use only pure argon as a shielding gas when welding is performed on depths lower than 60 m [39].

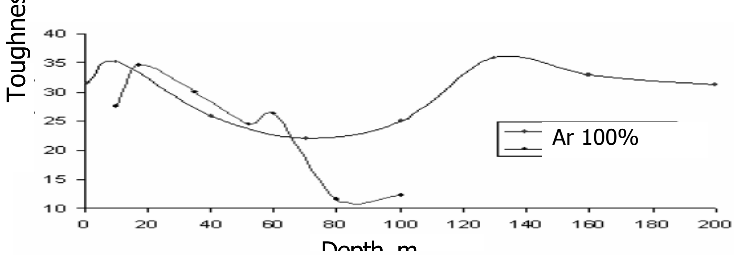

Fig. 14. The influence of underwater welding depth and shielded gas composition on welds toughness [39]

3. SUMMARY

Modern techniques of underwater welding give possibility of obtaining joints with sound welds that meets requirements of classification societies. Recent improvements in underwater welding have led to the increased use of wet and dry hyperbaric welding for marine applications. But more spread application of wet welding methods is limited due to common opinion of low quality of welds performed by this method [2,4,8,10,11,24]. The general acceptance of underwater welding processes has been further advanced by the standardization of methods, procedures, and certification requirements provided by the American National Standards Institute and American Welding Society[40].

In spite of many successful applications and results of investigations, underwater welding requires new research and development to achieve its full potential.

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