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Mechanical and Microstructural Properties of A36 Marine Steel Subjected to Underwater Wet Welding

Eko Surojo *, Raka Pungkas Aji, Triyono Triyono * , Eko Prasetya Budiana and Aditya Rio Prabowo *

Department of Mechanical Engineering, Universitas Sebelas Maret, Surakarta 57126, Indonesia; rakapungkas24@student.uns.ac.id (R.P.A.); ekoprasetya@staff.uns.ac.id (E.P.B.)

* Correspondence: esurojo@ft.uns.ac.id (E.S.); triyono74@staff.uns.ac.id (T.T.); aditya@ft.uns.ac.id (A.R.P.)

Abstract: Underwater wet welding (UWW) is applied to repair basic offshore structures, underwater pipelines, water transportation, docks, and port equipment. The underwater wet welding method used in the current research was shield metal arc welding (SMAW), and this was conducted on an A36 steel plate. We investigated the effect of a water temperature of 10 ± 5 °C and different types of water flow (without flow, non-uniform flow with baffle bulkhead, and non-uniform flow without baffle bulkhead). The defects found on the specimen included spattering, irregular surfaces, porosity, and undercutting. A high cooling rate led to the formation of more acicular ferrite (AF) phases in the weld metal area than a slow cooling rate. The microstructure of the heat affected zone (HAZ) area led to the formation of finer and small grains. Values of tensile, impact, and hardness strength were greater with higher cooling rates. The highest tensile strength value was 585.09 MPa, and this occurred with non-uniform flow without a baffle bulkhead. The highest values of absorbed energy and impact strength were 41.9 J and 2.05 J/mm², respectively, and these occurred with a non-uniform flow without a baffle bulkhead. The greatest hardness values were found with a non-uniform flow without a baffle bulkhead in the weld metal area.

Keywords: underwater wet welding (UWW); A36 steel plate; E7018 electrode; types of water flow; water temperature

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1. Introduction

To meet its potential, the maritime industry requires supportive infrastructure such as cargo transportation using ships, offshore systems, submarine cables, and underwater piping systems. Periodic repair of defective components is required in the maritime industry. Underwater welding involves the direct repair of infrastructure in water [1]. Underwater welding is divided into two methods: wet welding (wet underwater welding) and dry welding (dry underwater welding). Wet underwater welding is cheaper, simpler, and suitable for repairing most geometrically complex structures, because it does not require additional tools, such as hyperbaric vessels, in the working process [2]. Some countries in the world have four seasons in one year, causing the characteristics of the water temperature to change. Structural platform repair in the North Sea is done at a temperature of 40 °F or 4.4 °C [3]. Therefore, underwater wet welding must be carried out under these water conditions.

Underwater wet welding is more difficult to perform than underwater dry welding or welding in the open air. Several factors that make underwater welding more difficult are a low water temperature, high pressure, water flow, and the presence of hydrogen in the weld. The presence of certain conditions in the welding process, especially in underwater welding, cause fast cooling rates, arc stability, droplet weld transition, and defects on the material. During the welding process, hydrogen can be absorbed by the melted weld pool and dissolved in the metal lattice. The diffusible atomic hydrogen is of particular importance. The high cooling rate in underwater wet welding gives hydrogen significantly

less time to leave the weld area by diffusion [4]. The best welding results can be obtained with the use of rutile electrodes which allow easy arc initiation and stability during the process. Such electrodes provide greater weld ductility, but the weld is less resistant to hot cracking during the crystallization process [5]. Temper bead welding can produce similar results through local heat treatment of the joint. Some studies have shown that welding with temper beads can be an effective way to improve the weldability of steel in water environments. Tomków et al. showed that temper bead welding is associated with a significant decrease in HAZ hardness in S460N steel welded with covered electrodes under wet welding conditions [6].

Chen et al. studied the effect of the water flow velocity on the arc stability and metal transfer in underwater wet welding. Increasing the flow rate increases heat dissipation during welding, resulting in a decrease in the arc temperature, arc shrinkage, an increase in the current density, and deeper penetration [7]. Zhang et al. demonstrated that welds carried out in water contained lower concentrations of acicular ferrite (AF) in the weld area and a low pro eutectoid ferrite (PF) content in the HAZ area. These characteristics were promoted by a fast cooling rate and low ambient temperature [8]. Pessoa et al. studied underwater bead-on-plate welding at various depths and with different types of electrodes. An increased underwater welding depth results in a decreased tensile strength and bead area porosity [9]. Omajene et al. explained the effects of welding parameters on the weld bead shape of underwater welds. The greater convective heat transfer coefficient in water compared to air was shown to result in rapid cooling during underwater welding. A low water temperature can result in more inclusions and a higher diffusible hydrogen level in the coarse grain heat-affected zone, which leads to a greater cracking tendency [10].

Çolak et al. studied the mechanical performance and morphology of marine structural underwater welding. The study determined that defects significantly influence the mechanical properties and width of the weld zone [11]. Di et al. analyzed the effect of the cooling rate on the microstructure, inclusions, and mechanical properties of weld metal during local dry underwater welding. The presence of acicular ferrite in weld metal with a rapid cooling rate is associated with high strength and toughness values [12]. Guo et al. characterized spatter during underwater wet welding using the X-ray transmission method. Three types of spatter—droplet repelled spatter, explosive spatter, and molten pool shock patter—were observed during underwater wet welding [13]. Wang et al. characterized arc bubbles during underwater welding through a visual sensing method. Underwater wet welding led to a more brittle specimen than onshore welding [14]. Gao et al. studied the microstructural and mechanical performance of underwater wet welded S355 steel. A low heat input is associated with the production of weld metal with the best mechanical properties as the presence of more weld passes is associated with the largest fine reheated zone [15]. Based on these reviews, it can be stated that there is a need for further assessment and observation of marine steel under UWW treatment to widen the body of knowledge on material characteristics and properties and enlarge the body of experimental data to allow future advanced analyses and simulation using computational methods.

This work aimed to physically and mechanically characterize several marine steel specimens represented by an A36 plate. The subject was welded under idealized UWW conditions where the water flow, welding depth, and environment temperature were carefully considered. After the specimens had been made under such conditions, macroscopic and microscopic photos were taken to assess their physical characteristic. A series of destructive tests were done to measure their mechanical properties, i.e., tensile, hardness, and bending. The experimental results are in the discussion and concluding remarks.

2. Materials and Methods

2.1. Material Preparation and Welding Process

The material used in this study was ASTM A36 low carbon steel with dimensions of 300 mm × 400 mm × 4 mm. The chemical composition was tested in a steel laboratory in Cepur (Klaten, Indonesia) using the spectrometer shown in Table 1. Specimens that

were cut were marked and centered using a marker to sign the welding direction. The welding method used was Shield Metal Arc Welding (SMAW). The type of welding used was bead-on-plate without a groove, and this was conducted at a depth of 0.35 m. The water flow rate was 0.67 mm/s. The water temperature used was 10 ± 5 °C. The welding parameter that was varied was the water flow (without flow, non-uniform flow with a baffle bulkhead, and non-uniform flow without a baffle bulkhead). Underwater and air welding were performed with an E7018 electrode with a diameter of 4 mm, a travelling speed of 3–4 mm/s, a voltage of 24 V, and a nominal current of 120 A.

Table 1. Chemical composition ASTM A36.

Chemical Composition (wt %)	C	Mn	P	S	Si	Ni	Cr	Mo	Cu	Fe
ASTM A36	0.19	0.472	0.018	<0.01	0.129	0.014	0.025	0.036	0.01	Bal.

In order to research the effects of water flow and temperature, a control system was designed, as shown in Figure 1. The parts of the system were a circulating system consisting of a valve, pump, reservoir, thermometer, pipes, water tank, and welding jig. The pump was assembled with pipes and a valve connected to the water tank. The reservoir was used to stream similar water with the same temperature. Different methods were used to vary the type of water flow. The equipment used is shown in Figure 2. The without flow condition was created by turning off the water pump, so there was no water stream in the water tank. The non-uniform flow with a baffle bulkhead condition was created by turning on the pump and adding a baffle bulkhead to the side inlet and outlet water tank between welding specimens. Non-uniform flow without a baffle bulkhead condition was created by removing the bulkhead. The baffle bulkhead was made by punching holes in the glass according to the size of the side water tank with vertical and horizontal distances between holes of 10 mm.

Figure 1. The experimental platform of the water flow control system.

Figure 2. The s control system using: (a) jig specimen welding, (b) pipe water flow system, (c) reservoir system, and (d) baffle bulkhead installation.

2.2. Underwater Bead-On-Plate Testing Properties

Microstructural and macrostructural observations were carried out using optical microscopy (Euromex Microscopen bv, Arnhem, The Netherlands). The microstructure observation procedure included polishing and etching based on the ASTM E407-07 standard. The etchant was 5 mL HNO_3 and 100 mL alcohol [16]. The hardness of the bead-on-plate was measured using a Highwood Micro Vickers tester (TTS Unlimited, Inc., Osaka, Japan) with a load of 200 gf [17]. The measured distance at the middle of the weld zone was zero that between weld metal and base metal was 0.2 mm, while that in the heat affected zone (HAZ) was 0.1 mm. The tensile strength test began by cutting the specimen based on JIS Z 2201 [18]. A SANS Universal testing machine with a capacity of 10 tons was used to perform the tensile test. The velocity used in the tensile test was 11.25 mm/s based on the related standard. The bending test was carried out on a plate size based on the AWS D1.1 standard. The type of bending test performed was the face bend. The impact value was determined with the Charpy impact tester machine. The test was carried out using a swing load of 0.5 kg and an arm length of 0.85 m. The starting angle (α) of the swing was 90° [19]. Impact testing was carried out in the heat affected zone (HAZ) area. All sample specimens are shown in Figure 3.

Figure 3. Sample specimens of (a) the bending test, (b) the impact test, and (c) the tensile test in (mm).

3. Results and Discussion

3.1. Physical Properties

3.1.1. Visual Defect Observation

Visual observation of bead defects can be done without damaging the material before or after testing its physical or chemical properties. The results showed that the water environment with a temperature of 10 ± 5 °C and various types of water flow resulted in defects appearing on the surface and weld area. Images of specimens exposed to each water flow variation are shown in Figure 4. Defects were found through visual observation without the use of tools. The defects that occurred with different water flow variations were compared.

Welding defects are largely influenced by environmental factors, such as the temperature, water flow, and water content. Defects found during the welding process were spatter (S), irregular surface (I), undercut (U), and porosity (P). Visual observations (see Table 2) showed that air welding leads to lots of spatter defects (84 occurrences) caused by the temperature of the molten metal, which is too high. Spatter defects occur due to the large arc length generated during welding [20]. There were fewer irregular surfaces following air welding compared with underwater welding. The visual observations showed 12 porosity defects that occurred in the without flow condition. Underwater welding under the non-uniform flow condition with and without a baffle bulkhead led to 15 and 18 porosity defects, respectively.

Underwater welding in water with a temperature of 10 ± 5 °C causes the welding metal to crystallize very quickly, so that a significant amount of air is trapped in the weld metal [7]. The visual observations showed 12 areas of porosity defects that occurred in the without flow condition. Underwater welding conducted under the non-uniform flow

conditions with and without a baffle bulkhead led to 15 and 18 porosity defects, respectively. A higher water flow rate led to an increase in porosity defects [9]. Undercuts occurred when the metal solidified too fast, causing a puddle to form from the electrodes to the end of the weld metal [21]. Underwater wet welding in water with a low temperature was associated with fewer undercut defects due to the high cooling rate of the bead and electrode melted together with the base metal. There was no groove. Irregular surface defects increase welding heat dissipation due to a decreased temperature and shrinkage with the water flow [20]. Heat dissipation is the loss of heat energy due to contact of the water flow with the molten pool during welding. Irregular surface defects can be identified by uneven weld surfaces. Instability of the electric arc causes this type of defect due to the flow of water.

Figure 4. Results for specimens exposed to: (a) air welding, (b) flowless welding, (c) non-uniform flow welding with a baffle bulkhead, and (d) non-uniform welding without a baffle bulkhead.

Table 2. Defects identified by visual observations.

No	Variation	Parameter Temperature (°C)	Type of Flow	Defects	Amount
1	A0	35	Air	Undercut (U)	6
				Spatter (S)	84
				Irregular Surface (I)	1
2	A1	10 ± 5	Without Flow	Porosity (P)	12
				Undercut (U)	8
				Spatter (S)	10
				Irregular Surface (I)	3
3	A2	10 ± 5	Non-uniform with baffle bulkhead	Porosity (P)	15
				Undercut (U)	5
				Spatter (S)	2
				Irregular Surface (I)	4
4	A3	10 ± 5	Non-uniform without baffle bulkhead	Porosity (P)	18
				Undercut (U)	4
				Spatter (S)	3
				Irregular Surface (I)	4

3.1.2. Macrostructure and Microstructure

Macroscopic testing showed differences in the penetration depth and porosity based on the type of flow in cold water. Water flow during underwater welding causes forced convection heat transfer. Non-uniform flow without a baffle bulkhead was associated with a higher cooling rate than non-uniform flow with a baffle bulkhead. Figure 5 shows that air welding was associated with deeper penetration than underwater welding without flow. The depth of penetration in air welding was 1.81 mm on average. Meanwhile, the average penetration depth in underwater welding without flow was 1.4 mm. The penetration depth is also affected by hydrostatic pressure. A high level of pressure increases the boiling point of water and leads to compressed arc welding [22]. Non-uniform flow with a baffle bulkhead and non-uniform flow without a baffle bulkhead were associated with higher penetration depths than the condition without flow. The penetration depth is affected by droplets in the metal transfer process, which are pushed by the opposing flow of water (upstream). The penetration depth was 1.653 mm in the non-uniform flow condition with a baffle bulkhead and 1.87 mm without a baffle bulkhead. The high level of heat loss due to forced convection caused a decreased heat input, leading to a decrease in the volume of melted metal and a reduced penetration depth [7].

Figure 5. Observation results for air welding, flowless welding, non-uniform flow with a baffle bulkhead, and non-uniform flow without a baffle bulkhead.

The water flow variations were associated with porosity defects in the weld metal area. Welding with a non-uniform flow without a baffle bulkhead led to the greatest amount and

largest porosity defects, as shown in Figure 6. A high level of heat loss increases the cooling rate so that the gas contained in the liquid weld beads does not have time to escape [7,12]. In all specimens, the HAZ area had no defects, including porosity defects, in the weld metal area. The HAZ condition influences the welding process as it does not change form into liquid metal. Changes that occur in the HAZ area concern the shape or grain size of the ferrite and pearlite phases. The smaller or finer the grain, the greater the hardness of a material [23]. The shape transformation of grain is affected by the cooling rate of each variation. Air welding has a slow cooling rate, resulting in the formation of a wider HAZ area. A fast cooling rate occurred under the non-uniform condition without a bulkhead. This caused the HAZ area to be smaller.

Figure 6. Macroscopic structural view of a welding specimen exposed to welding under the following conditions: (a) air, (b) flowless welding, (c) non-uniform flow with a baffle bulkhead, and (d) non-uniform flow without a baffle bulkhead.

The microscopic tests used to determine the phase composition and grain size of the beaded metal, HAZ, and base metal areas are shown in Table 3. Changes in the microstructure phase leads to changes in the mechanical properties of the steel. In the carbon steel welding process, the ferrite structure changes into several phases, namely grain boundary ferrite (GBF), ferrite with the second phase (FSP), acicular ferrite (AF), and polygonal ferrite (PF) [15]. A low water temperature of 10 ± 5 °C and an uneven cooling rate resulted in the production of weld metal with a less uniform microstructure and less PF [8]. AF has relatively high levels of hardness and tensile strength and better impact values than PF and GBF [14]. The weld cooling process takes place continuously, that is, the process of decreasing the temperature does not involve a sudden drop in temperature. Overall, the ferrite structure in the weld metal formed from underwater welding is smaller than that formed from air welding—underwater welding in the presence of flow results in an increased welding cooling rate. The heat affected zone (HAZ) leads to the formation of a microstructure consisting of ferrite and pearlite [24]. The higher the flow rate and the lower the ambient temperature, the smaller the grain size structure in the HAZ area. Thus, the smallest grain size was formed in the non-uniform flow condition without a baffle bulkhead.

Table 3. Microscopic structures of specimens exposed to different conditions (scale bars for each figure is 60 μm).

Variation	Base Metal	Heat-Affected Zone	Weld Metal
Air Condition
Without Flow Condition
Non-uniform flow without bulkhead
Non-uniform with bulkhead

3.2. Mechanical Properties

3.2.1. Tensile Strength

The results of the tensile test from specimens exposed to underwater and air welding showed the occurrence of heat affected zone (HAZ) fracturing. Heat affected zone fracture occurred because the reinforcement on the weld metal had not been removed, so the area in the middle of the specimen was wider than other areas. The maximum tensile strength obtained occurred in the HAZ area. The process of heat transfer in the HAZ area affected the magnitude of the phase change, even though the metal did not melt.

As shown in Figure 7, the tensile strength in the air welding specimen was 416.16 MPa and the elongation was 4%. The specimen in cold water without flow had values of 481.08 MPa and 6.137%. The tensile strength and elongation were greater in specimens exposed to underwater welding due to changes in the number and size of the microstructural elements. The grain size formed in the HAZ affects the tensile strength of the joint. The tighter and finer the grain size, the greater the mechanical strength [12]. Data from the test

of non-uniform flow without a baffle bulkhead showed a tensile strength of 585.09 MPa and an elongation of 6.93%. The tensile strength of specimens exposed to underwater welding without flow or with a non-uniform flow with a baffle bulkhead increased by 58.15 MPa. Meanwhile, elongation increased by 0.23%.

Figure 7. Results of the tensile strength and elongation tests.

The level of penetration that occurs during welding also affects the tensile strength of the bead on the plate weld. Deeper penetration will increase the mechanical strength properties of the weld. Low penetration results in a low tensile strength and increased brittleness of the weld [25]. The material's mechanical strength will increase with smaller and finer grains [26]. A rapid cooling rate is also associated with the formation of the HAZ area: the higher the cooling rate, the smaller the HAZ area around the weld. The mechanical strength will increase with deep penetration and a small HAZ area.

3.2.2. Hardness Test

Hardness testing was carried out to determine the level of hardness to determine whether the material was ductile or brittle. The highest hardness values were obtained in the HAZ area, because the peak temperature of the HAZ area is the highest and fast welding cooling occurs there due to fast heat transfer. The welding cooling rate was higher in a water environment with a temperature of 10 ± 5 °C. Cold underwater specimens had an average hardness of 305.6 HVN in the highest HAZ area without a baffle bulkhead. The underwater specimens produced with a baffle bulkhead and without flow had average hardness values of 282.6 and 228.3 HVN in the HAZ area. At the same time, the hardness value in the lowest HAZ area was found in the specimens exposed to air welding (197.4 HAZ). In the weld metal area, the highest hardness value was also associated with the cold underwater specimen produced without a baffle bulkhead (225.2 HVN). The weld metal area with the lowest hardness occurred in the air welding specimen (163.06 HVN), as shown in Figure 8. Meanwhile, specimens exposed to welding without flow and to flow with a baffle bulkhead had slight differences in the weld metal area: 196.06 and 197.36 HVN, respectively. The formation of acicular ferrite (AF) and ferrite with second phase (FSP) structures in the weld metal area resulted in higher levels of hardness [27].

Figure 8. Hardness test results for the proposed specimen.

3.2.3. Impact Test

Figure 9 shows a comparison of the toughness of under cold water weld specimens produced with various water flow and air welding processes in the HAZ area. In this graph, the lowest impact strength was associated with the air welding condition (20.48 joules and 1.37 J/mm²). Underwater cold welding without flow led to an absorbed energy value and impact strength of 32.18 joules and 1.58 J/mm², respectively.

Figure 9. Graphical summary of the impact test results.

The highest absorption energy and impact strength values were found in the underwater welding specimens exposed to non-uniform flow without a baffle bulkhead: 41.90 joules and 2.05 J/mm², respectively. The specimens exposed to non-uniform cold water underwater welding with a baffle bulkhead had impact test values between those of the specimens exposed to the without flow condition and those exposed to the non-uniform flow without baffle bulkhead conditions: 39.08 joules of absorbed energy and an impact strength of 1.96 J/mm².

The cooling rate during welding affects the toughness of the specimen: the greater the cooling rate, the less heat input into the welding process. In addition, the weld penetration of each specimen was shown to affect the impact strength. Less penetration was associated with a smaller HAZ area. The impact test results for specimens exposed to a fast cooling rate showed cracks in the base metal area, which were identified as ductile fractures, as shown in Figure 10. A ductile fracture is a fracture caused by the application of a static

load to the material. Ductile fractures are characterized by energy absorption accompanied by significant deformation around the fracture, so it looks rough, fibrous, and grey. An increase in the ferrite phase percentage in the HAZ area affects the impact strength [28].

Figure 10. Fracture identified in the impact test on specimens welded under the following conditions: (a) air, (b) flowless underwater, (c) non-uniform flow with a bulkhead, (d) non-uniform flow without a bulkhead.

3.2.4. Bending Test

The type of bending test performed was face bending. Face bending caused the position of the punch to be at the base of the plate or root. The purpose of this test was to determine the quality of the specimens from the welding results. The definition of toughness in the bending test is the amount of bending the plate can withstand in terms of the angle. Testing on the bending specimen was carried out by the bending test, and the test results are shown in Figure 11. A 2.6 mm crack occurred in the specimen exposed to non-uniform flow welding with a baffle bulkhead. The size of the crack was included in the accepted category because it was not more than 3 mm. Rapid cooling is a major factor in the formation of fine grains: the tighter and finer the grain size, the greater the mechanical strength [12]. The presence of the welding bead on the plate without a groove led to the content of the bead being a combination of the electrode content and the base metal. With the joining of the two metals, the surface structure became strong.

Figure 11. Results of the bending test on specimens welded under the following conditions: (a) air, (b) flowless underwater, (c) non-uniform flow with a bulkhead, (d) non-uniform flow without a bulkhead.

4. Discussion of the Experiments

Underwater welding at a temperature of 10 ± 5 °C causes the welding metal to crystallize very quickly, causing a significant amount of air to be trapped in the weld metal [7]. The visual observations identified showed 12 areas of porosity defects in the specimen exposed to the without flow condition. Underwater welding conducted under the conditions of a non-uniform flow with and without a baffle bulkhead was associated with 15 and 18 porosity defects, respectively. A higher water flow rate results in an increase

in the number of porosity defects [9]. Undercut defects occur when the metal solidifies too fast, causing a puddle to form from the electrodes to the end of the weld metal [21]. Underwater wet welding at a low temperature was associated with less undercut defects due to the high cooling rate of the bead and electrode melted together with the base metal. There was no groove. Irregular surface defects increase heat dissipation during welding due to a decreased temperature and shrinkage with the water flow [20]. Heat dissipation is the loss of heat energy due to contact of the water flow with the molten pool during welding. Irregular surface defects can be identified by uneven weld surfaces. The instability of the electric arc causes this type of defect due to the flow of water. The findings based on the defect characterization and mechanical testing can be summarized as follows: the increase of the defect during water flow is quantified by a certain property only, i.e., porosity. In terms of overall defects, air flow contributes more significant to the defect counts. These are the primary reasons why mechanical testing of the steel subjected to the underwater wet welding displays superiority compared to the welding using air flow.

This work may be continued with the consideration of complicated parameters in underwater wet welding. Recent work by Surojo et al. [29] discussed the influence of the water flow and depth/location on welding performance using mechanical testing. Another possibility for extension of this work could involve marine vessels, e.g., the hull structure of a ship [30–36]. The subject is no longer on the material specimen scale, but the use of a down-scaled hull prototype or weld could be used to represent parts of the ship structure, such as the frame and side hull. Additionally, material subjects could include ice-class steel and the results could be used to inform marine operations in polar regions, which have increased in the last decade following the opening of the Northern Sea Route (NSR) [37–41]. Performance evaluation may use impact testing and sensor applications in either quasi-static or free-fall tests [42].

5. Concluding Remarks

The effects of cold water flow on the bead-on-plate underwater wet welding of low carbon steel A36 were investigated. An increase in the water flow rate resulted in an increased cooling rate during welding. The following conclusions were obtained:

- In terms of the physical properties, more defects, such as porosity and undercut defects, occur in underwater welding than in air welding. The penetration depth is more dependent on the water flow than the cooling rate. A smaller grain size structure forms in the HAZ area due to the higher flow rate and lower ambient temperature there. Thus, the smallest grain size was found in the specimen exposed to the non-uniform flow condition without a baffle bulkhead.
- In terms of the mechanical properties, the tensile and impact strength values increased as the cooling rate increased. The highest hardness values were found in the HAZ area, and the highest average value occurred in the specimen exposed to the non-uniform flow without a baffle bulkhead. The impact strength was greater in the specimens welded under the following conditions: in the air, with a non-uniform flow with a baffle bulkhead, and with a non-uniform flow or without flow due to the HAZ area in the specimens. The bending test found no defects in any of the specimens because the electrode metal made the specimens stronger.

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