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FEATURES OF WELDING DUPLEX STAINLESS STEELS IN WET UNDERWATER WELDING IN COMPARISON WITH WELDING IN AIR (REVIEW)

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ABSTRACT

The presented review shows that the main task in welding duplex stainless steels (DSS) is ensuring the conditions which should promote reduction of the negative impact of the welding thermal cycle on the microstructure and change of the initial balance of the phase components, particularly in the high-temperature region of the HAZ. In welding duplex stainless steels the required ratio of ferrite and austenite in the weld metal is provided by changing the chemical composition, and in the HAZ it is achieved due to lowering of the cooling rate. Depending on cooling rate $w_{13/8}$ or time of staying predominantly in the temperature range of phase transformations, the respective microstructure of metal of the weld and HAZ is formed with the specified ratio of phase components of austenite and ferrite, which, in its turn, affects the mechanical properties and corrosion resistance of duplex steel welded joints. A clear correlation of the mechanical properties is observed, depending on austenite and ferrite content in the weld metal. With increase of the cooling rate, the quantity of precipitates of excess phases, Cr_2N chromium nitrides, becomes greater. It was found that in view of intensive cooling impact of the water environment, the volume fraction of austenitic phase is lower in the metal of the weld and in the HAZ high-temperature region in wet underwater welding, compared with volume fraction of the austenitic component in welding in air at the same heat input values. With increase of the energy input, a significant increase of volume fraction of austenitic phase is observed, particularly in wet underwater welding. Considering the features, characteristic for wet underwater welding, the energy input levels and chemical composition of weld metal require correction as regards the recommendations, which were developed for welding in air.

KEYWORDS: duplex steels, wet underwater welding, energy input, cooling rate, phase composition, austenite, ferrite, microstructure, welding thermal cycle

INTRODUCTION

The idea of creation of duplex stainless steels arose in 1920s, and the first melt was done in 1930 in Avesta, Sweden. Duplex stainless steels were introduced and have been actively developed by European companies since 1935 [1]. New generation ferritic-austenitic steels feature a lower carbon content, usually, not higher than 0.02–0.03 %, and additional alloying by nitrogen in the amount of 0.10–0.27 % for standard duplex stainless steel (DSS). Nitrogen content in super duplex stainless steels (SDSS) is in the range of 0.24–0.32 [2, 3]. A noticeable increase in the share of duplex steel application has occurred only in the last 30 years due to improvement of the production technology, particularly of the processes of controlling nitrogen content in steels [4].

The main fields of application of duplex stainless steels are oil and gas, petrochemical, pulp and paper industries. At present the areas of their application have extended to metal structures, operated in water environment, in particular, at construction of marine and nuclear power plants, pipelines for transportation of sulphurous gas, oil and sea water, due to a favourable combination of high mechanical strength and general and local corrosion resistance, as well as re-

sistance to cracking caused by interaction of stresses and hydrogen, the source of which is an acidic medium of liquid carbohydrates [5]. In the presence of hydrogen sulphide and chlorides the risk of stress corrosion cracking becomes greater. Such media can be present, for instance, in oil and gas producing wells, including in sea water [6].

An optimal combination of high characteristics of strength and resistance against, in particular, pitting corrosion, as well as stress corrosion cracking is ensured at 1:1 ratio of the ferritic and austenitic phases in the metal structure, i.e. at 50 % content of each of the components. Such characteristics are achieved by annealing at the temperature of 1020–1100 °C for 5 min with subsequent quenching in water for DSS 2205 standard steel [2], and for SDSS 2507 super duplex steel the hardening annealing temperature is equal to 1040–1120 °C [2, 6]. The higher the annealing temperature, the higher is the ferritic component content [6]. Thus, solid solution annealing is the as-delivered condition of duplex steels. Annealing temperature depends on the alloy chemical composition, as well as on the steel making technology accepted in production.

Duplex steels usually have good weldability, and they can be welded by most of the welding methods, applied for austenitic stainless steel. Under the influence of the welding thermal cycle (WTC) the

austenitic-ferritic phase balance is disturbed, as a result of the impact of high heating and cooling rates, characteristic for different welding methods. One of the main tasks in welding duplex stainless steels is ensuring the conditions, which would promote reduction of the negative influence of the high heating and cooling rates and preservation of the initial balance of the microstructure to varying degrees, which ensures the main technological characteristics of the welded joints, such as mechanical and corrosion properties.

CONTROLLING THE STRUCTURE OF THE WELDED JOINT METAL

Preservation of the required austenite-ferrite balance can be achieved in two ways: change of the chemical composition and lowering of the cooling rate in welding. The first variant is usually realized at selection of filler material for weld metal of the welded joint. The type of weld metal alloying is chosen with a greater austeniticity margin due to increase of nickel content, as well as with additional alloying by nitrogen. Thus, the Cr_{eq}/Ni_{eq} ratio is reduced, which corresponds to an increase towards austeniticity. If Cr_{eq}/Ni_{eq} ratio, for instance for 2205 steel is in the range of 2.25–3.50 within the admissible values by EN 1.4462 standard (Figure 1) [4, 7], then for filler metal Cr_{eq}/Ni_{eq} ratio will be much smaller. For manual arc welding of 2205 steel in keeping with DSTU EN ISO 3581:2021, it is recommended to use electrodes with 2209 alloying type, which correspond to nominal composition of 22 9 3 NL [8].

Application of filler material with the composition, equivalent to that of the base metal, would shift the balance towards ferrite, because of a high cooling rate.

A measure of the cooling rate is the welding energy input, which is inversely proportional to it. Recommendations and standards on duplex steel welding were developed, which specify application of energy input in the range of 0.5–2.5 kJ/mm for welding standard duplex steel of 2205 type with 22–23 % chromium and 0.5–1.5 kJ/mm for super duplex stainless steel of 2507 type with 25 % chromium [9–13]. Moreover, reference publications give different values of energy input, which is a measure of general heat input per a unit of weld length. IIW recommends keeping the energy input in the range of 1.2–2.0 kJ/mm for welding 2205 steel, BOHLER and Sandvik manufacturers of consumables recommend 1.0–3.0 kJ/mm [14–16]. There are no universal recommendations, because of a large number of welding parameters, so that selection and optimization of the welding parameters, including energy input values, are done in each concrete case.

It is generally accepted that the lower limit of energy input of 0.5 kJ/mm to some extent promotes pres-

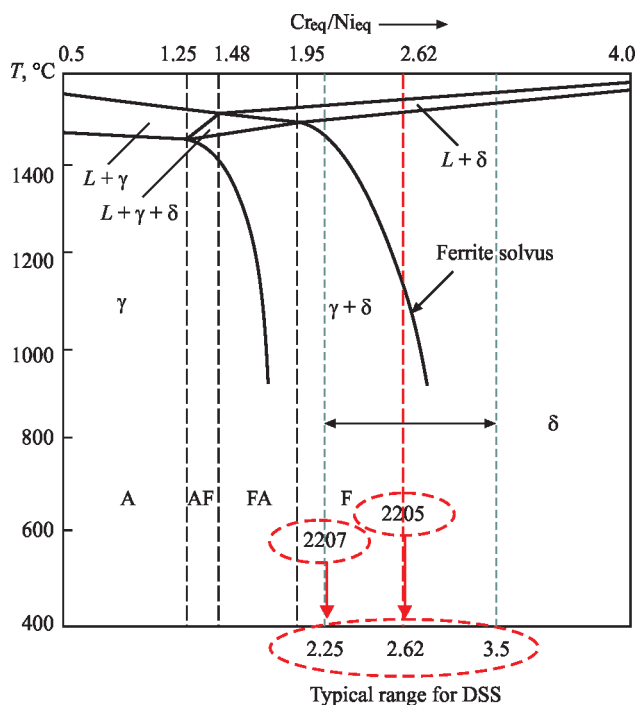


Figure 1. Pseudobinary (Fe–Cr–Ni) diagram plotted using Cr_{eq}/Ni_{eq} equivalent ratio

ervation of microstructure balance within the admissible limits, namely formation of a sufficient quantity of austenite to ensure the required mechanical properties of the metal of the weld and welded joint. The upper value of energy input is limited to reduce the volume of precipitation of the secondary phases, which lower the corrosion resistance.

Increase of energy input from 0.7 to 1.2–1.3 kJ/mm in welding SDSS 2507 super duplex stainless steel promoted an increase of weld metal impact toughness. Impact energy at Charpy V-notch was equal to 45 J at testing at -40 °C temperature, which is much higher than the required value of 27 J [17]. Studies have also appeared, which show that the energy input limitation to 1.5 kJ/mm is not justified in welding SDSS 2507 super duplex stainless steel, particularly when joining large thicknesses (20 mm and greater), and which recommend widening the range of admissible energy input. Good properties of the weld metal were achieved in welding with energy input of 2.1–2.2 kJ/mm [18]. In work [19] the influence of the removed heat on the microstructure, mechanical properties and corrosion resistance of welded joints of SDSS UNS S32750 super duplex steel was studied. Welding was conducted with different energy inputs of 0.54 and 1.1 kJ/mm. Investigations led to the conclusion, that application of a low heat input may be better, as there is no great difference in the weld properties, depending on the used heat input.

The influence of the heat input level in the range from 0.45 to 0.60 kJ/mm was studied in welding dis-

similar joints of DSS 2205 duplex stainless steel with ASS 316 L austenitic stainless steel. Low heat input demonstrated a higher hardness and tensile strength, as a result of a higher content of ferrite and higher cooling rate. The higher energy input improved the corrosion resistance [20].

The given data demonstrate that there is no common approach to determination of the heat input level and that the energy input is not the only factor responsible for formation of the microstructure in the weld metal and in the HAZ to ensure the required balance of phase components of austenite and ferrite.

The energy input levels recommended in instructions and standards, should promote formation of a microstructure with the required content of the austenitic and ferritic components in different regions of the welded joint. Ferrite content in the weld metal and in the HAZ should be in the range of 25–70 %, in order to ensure the optimal mechanical properties and corrosion resistance [21]. The following ferrite levels are believed to the generally accepted:

- base metal (BM) — 35–55 %;
- weld metal (WM) — below 60 %;
- HAZ — below 65 %. Sometimes, up to 70 % are allowed in the HAZ.

Some industry standards limit the ferrite component content even more. The requirements pertaining to oil and gas industry are given in Table 1.

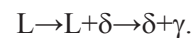
The rate of cooling of metal of the weld and HAZ depends on a totality of such factors, as welded metal thickness, welding technology (welding process efficiency), energy input, welding mode, welding environment, and many others.

Welding energy input is just a guiding parameter, which to a certain extent can determine the cooling rate, and, thus, the time of metal staying in the region, where the polymorphous transformation of ferrite (δ) into austenite (γ) takes place. In keeping with the pseudobinary Fe–Cr–Ni state diagram the start of $\delta \rightarrow \gamma$ transformation depends on the alloy chemical composition, and the transformation completeness depends on the time of staying in this two-phase region (Figure 1) [4, 7]. Therefore, the cooling rate, alongside the alloy chemical composition, determines

the time of staying in the two-phase region. Austenite transformation from ferrite takes place in the solid state, as this is a diffusion process. The transformation completeness depends on the time of staying in this range of the two-phase state.

The model of metal crystallization can be determined by Cr_{eq}/Ni_{eq} ratio. For 2205 duplex steel of certain chemical composition it corresponds to the value of 2.62 (Figure 1). The range of Cr_{eq}/Ni_{eq} ratio within the tolerances by chemical composition for 2205 steel (EN 1.4462) is equal from 2.25 to 3.5, i.e. it is quite wide.

With such a ratio the crystallization model is as follows:



The temperature range of $\delta \rightarrow \gamma$ phase transformations is 1200 °C (1300)–800 °C, and it depends on the metal chemical composition. This is a diffusion process, it involves temperature and time. That is, the completeness of $\delta \rightarrow \gamma$ phase transformations depends on the metal chemical composition, cooling rate and time of staying in the temperature range of 1200 (1300)–800 °C, which also depends on the cooling rate. In the opinion of authors of [24], the metal chemical composition has a greater influence on the final ferrite/austenite ratio than does the cooling rate. It is shown that the change of chemical composition of 2205 duplex steel in the range of tolerances for steel, towards increase of austenite-forming element content, namely nickel, up to 6.0 % on the upper level, as well as nitrogen up to 0.18–0.19 %, ensured producing less than 70 % ferrite in the HAZ metal at all the cooling rates from 20 to 100 °C/s at the temperature of 700 °C. In a similar way, much higher values were obtained at impact testing at a low temperature (–46 °C). This steel was called Arctic 2205 [25].

In work [18] the weld metal cooling rate was calculated in welding 20 mm SDSS 2507 super duplex steel by experimental data with recording of the welding thermal cycles. Two welding technologies were used: mechanized gas-shielded welding with 1.2 mm solid wire (GR experiment) and with 1.2 mm flux-cored wire (FR experiment). Different cooling rates were obtained at the same energy input in GR (1.2–1.3 kJ/mm) and FR (1.1–1.3 kJ/mm) (Figure 2). In flux-cored wire welding the cooling rate is much lower than in solid wire welding: by almost 10 °C/s and more in the temperature range of 1200–800 °C. So, in the fifth layer the cooling rate in FR is 50 °C/s, and in GR it is 60 °C/s.

It was also noted that the cooling rate increased with the number of layers. The lowest cooling rate was recorded in solid wire welding at greater energy input (GH) = 2.2 kJ/mm. In this study also a conclusion was made that it is exactly the cooling rate,

Table 1. Ferrite content in the welded joint according to standards

Standard name	Ferrite content, %		
	BM	HAZ	WM
API RP 582 (API A 938C) [22]	30–65	30–65	30–65
NORSOK M630 D45 [23]	35–55	30–70	–
Specification for oil and gas industry	35–55	<60–65	<60

and not the time of staying in the critical temperature range of 1200–800 °C, which is the key factor of nitride formation.

Conducted analysis of the influence of welding technology on phase composition and internal stresses of welded joints of austenitic and duplex steels showed that such highly-productive and promising types of welding, as electron beam (EBW) and laser (LW) have a negative influence on phase composition of two-phase (duplex) steels and single-phase steels, because of high cooling rates of the welded joints [26]. At EBW of 2205 duplex steel variation of the electron beam power and focal distance allowed lowering the cooling rates and ensuring satisfactory ferrite content (~70%). In this case, the time scheme was used, i.e. the time of staying in the critical temperature range of 1200–800 °C. At cooling rate, which ensured cooling during 4.5 s, 84–87 % ferrite formed, at cooling rate resulting in cooling within 7.4 s it was 79–84 % ferrite, and at cooling rate ensuring the time of 17.7 s the amount of ferrite was 69–70 % [27].

The data given in [18, 25–27] demonstrate how the different factors, namely welding process, energy input, metal chemical composition, and cooling rate can be responsible for the impact on formation of the microstructure, phase composition and amount of excess phase precipitates, including nitrides.

In addition to recommendations on the specific heat input, there is also the concept, in which $\tau_{12/8}$ time scheme is used (time required for cooling from 1200 to 800 °C), which describes the cooling conditions. Such a procedure for determination of the cooling conditions, involves certain difficulties, as it requires placing the thermocouples in the weld pool [2]. In keeping with this concept, it is recommended to conduct cooling of the welded joint in this temperature range for 10 s. In such a case, optimal microstructure and properties of the metal being welded are achieved [28].

Microstructure (HAZ) of duplex stainless steel undergoes more complex transformations and is the result of two mutually opposite processes. First, the process of transformation of the initial austenite fraction into ferrite $\gamma \rightarrow \delta$ takes place under the influence of welding thermal cycle at heating and at achievement of temperature above the ferrite solvus region ($T = 1250\text{--}1300$ °C), which depends on the metal chemical composition, and then, at further cooling, the reverse transformation $\delta \rightarrow \gamma$ occurs when the ferrite solvus temperature has been reached.

HAZ microstructure evolution depends on certain factors, namely base metal initial microstructure, maximal temperature in a specific region of the HAZ, time of staying at the maximal temperature and heating and cooling rate, i.e. on the actual WTC.

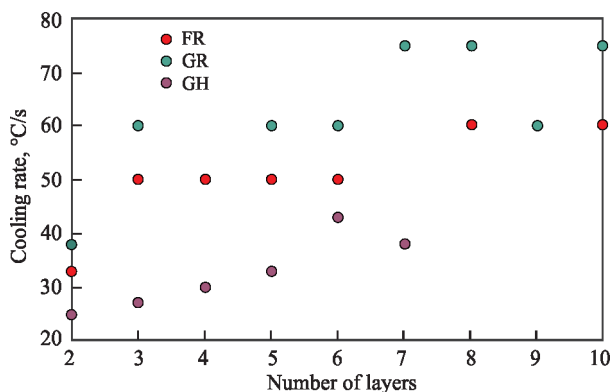


Figure 2. Average rate of cooling from 1200 to 800 °C, depending on the number of welding passes and welding procedure, where FR and GR is flux-cored wire and solid wire welding in the recommended energy input modes, respectively, GH — at higher energy input

The majority of studies currently presented in publications, mostly confirm the influence of the cooling rate on the microstructure and phase composition of HAZ and weld metal, which, in its turn affects the mechanical properties and corrosion resistance of the welded joints. Somewhat contradictory are the data on the temperature range and time parameter, which should be selected as the criteria, which are determinant for formation of the microstructure and phase composition of the metal of the weld and HAZ.

In study [29] the author emphasizes that as the temperature range of ferrite transformation into austenite, which usually is from 1200 to 800 °C, depends on the steel chemical composition, the parameter of cooling time between 1200 and 800 °C ($\tau_{12/8}$) should be used for characterization of temperature cycles of duplex steel welding. That is, this is exactly the range, which is the criterion of duplex steel weldability, and not the one between 800 and 500 °C, i.e. ($\tau_{8/5}$), as it is usually accepted for structural steels. The cooling rate in this range will determine the quantity of ferrite produced in the final microstructure. If the cooling time ($\tau_{12/8}$) is the criterion for determination of the HAZ final microstructure and phase composition, then the cooling rate in the temperature range from 1200 to 800 °C also is the determinant value, i.e. $w_{12/8}$, and not $w_{8/5}$.

When developing the model characterizing the content of ferrite, depending on the cooling rate, the authors of work [25] used the rate of cooling at 700 °C as the criterion. Other criteria were tested in a similar way, such as the rate of cooling at 1000 °C, or time of cooling from 800 to 500 °C, or from 1100 to 900 °C. Even if the ferrite-austenite transformation takes place at a high temperature of 1200 °C, the rate of cooling at 700 °C turned out to be the most accurate for prediction of duplex steel HAZ microstructure, compared to other criteria [30].

INFLUENCE OF WATER ENVIRONMENT ON WELDED JOINT STRUCTURE AND PROPERTIES

Despite the wide application of duplex steels, the influence of water environment on welded joint structure and properties has been little studied. Results of extensive research or reports on the behaviour of duplex steels in underwater welding and properties of the produced joints are found in publications. The majority of available results of the conducted experiments were derived at application of manual welding by commercial electrode materials, developed for application in air, as specialized electrode materials for wet underwater welding still have not been developed [31, 32].

At present there exist several technologies: wet underwater welding and dry underwater welding. Wet underwater welding is performed directly in the water environment. Dry underwater welding, in its turn, is subdivided into local dry welding, when only the arc burning zone is protected from the water environment, and welding in the chamber, completely protected from the water environment. The latter is, as a rule used in welding critical structures.

An example of application of electrodes developed for welding in air, in wet underwater welding of duplex steels is given in work [32]. It is noted that the arc was unstable, and internal welding defects such as pores, gas cavities and cracks in the weld root were also found. Welding stability improved at voltage increase up to 62.3 V. Ferrite content in the metal of the welds and HAZ increased slightly in wet underwater welding, compared to welding in air, although it is difficult to make any conclusions, as welding in air and under the water was conducted at application of different technologies and with different energy inputs. Welding in air was conducted with 1.2 mm solid wire for gas-shielded welding (Casto MAG 45505 S), and in wet underwater welding 4 mm diameter electrodes

of BOHLER FOXCN 22/9N/EN 1600 – EN 22 9 3 N LR 32 brand were used.

In dry hyperbaric flux-cored wire welding of sparsely-alloyed UNS S 32101 duplex steel [33–36] in the hydrostatic pressure range from 0 to 0.75 MPa the most well-balanced microstructure is demonstrated by weld metal produced at the pressure of 0.45 MPa with average austenite content of 53.3 %. The balanced ferrite-austenite microstructure of the weld metal prevented precipitation of excess phases, namely Cr₂N chromium nitrides, while in the HAZ precipitation of Cr₂N chromium nitrides was observed at austenite content of 36 %. Weld metal met the requirements of ASTM A923 (2014), which allows limit value of absorbed energy of 34 J [34]. A higher total energy input $q = 3.16$ kJ/mm at the same depth provided more time for austenite transformation in the weld metal, which is one of the causes for its higher content in the weld metal. In welding at the pressure of 0.75 MPa, the total energy input was equal to 2.97 kJ/mm, and in welding without pressure and at the pressure of 0.15 MPa it was 2.38 kJ/mm (Table 2). Thus, a clear correlation between austenite content in the weld metal and energy input in welding is observed [33].

Weld metal, produced in welding at the pressure of 0.45 MPa, also had higher resistance against pitting corrosion and mechanical properties [35, 36].

Analysis of the conducted research [33–36] led to the conclusion that the largest quantity of austenite in the weld metal is achieved in welding with the highest total energy input $q = 3.16$ kJ/mm, which ensures better integrated characteristics of resistance to pitting corrosion and mechanical properties of welded joints.

Work [37] is a study of water environment influence in welding S32101 duplex steel by 1.6 mm self-shielded E 2209-T-0-4 flux-cored wire, developed for welding in air. Unstable arc burning and unsatisfactory formation of weld metal were observed in

Table 2. Parameters of dry hyperbaric flux-cored wire multilayer welding

Ambient pressure, MPa	Number of layers	Current, A	Voltage, V	Welding speed, mm/s	Heat input, J/mm
0 — normal	1 — root	170	28	4	1190
	2 — finish	180	29	4.4	1186
0.15	1 — root	170	28	4	1190
	2 — finish	180	29	4.4	1186
0.45	1 — root	160	27	4	1080
	2 — fillingя	170	28	4.8	992
	3 — finish	180	29	4.8	1088
0.75	1 — root	150	26	4.4	886
	2 — fillingя	170	28	4.8	992
	3 — finish	180	29	4.8	1088

Table 3. Values of welding parameters and heat input

Sample number	Welding speed, V_{wp} , mm/s	Welding depth, m	Welding current I_w , A	Voltage U_a , V	Heat input q , J/mm
UDW 1	8	20	220	26.4	726
UWW 1	8	20	220	26.4	726
UDW 2	7.2	20	260	30	1083.3
UWW 2	7.2	20	260	30	1083.3
UDW 3	7.2	20	300	33.2	1383.3
UWW 3	7.2	20	300	33.2	1383.3

Note. UDW — dry underwater welding; UWW — wet underwater welding.

welding. With welding depth increase from 0.1 to 40 and 80 m metal porosity becomes greater and is equal to 1.51, 9.08 and 11.17 %, respectively. The same is observed with increase of depth: weld metal microstructure is refined, and HAZ width is reduced, contrarily, and it is equal to 0.15 mm (150 μ m) at 0.1 m depth; 0.1 mm (100 μ m) at 40 m depth, and 0.08 mm (80 μ m) at 80 m depth. Lowering of ferrite content

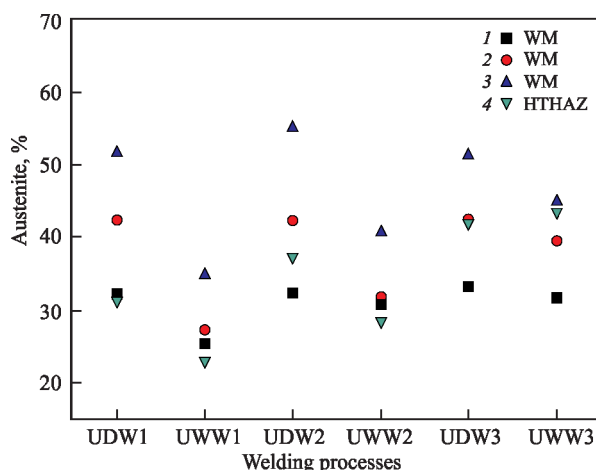


Figure 3. Volume fraction of γ -phase austenite at different welding methods and modes in different welded joint regions: 1 — weld surface; 2 — weld center; 3 — weld region, adjacent to the fusion line; 4 — HTHAZ — high temperature heat-affected zone in the weld center was also found: 21.1, 24.3 and 15.5 %, respectively. Austenite content in the weld metal is higher in welding at 80 m than at 40 m.

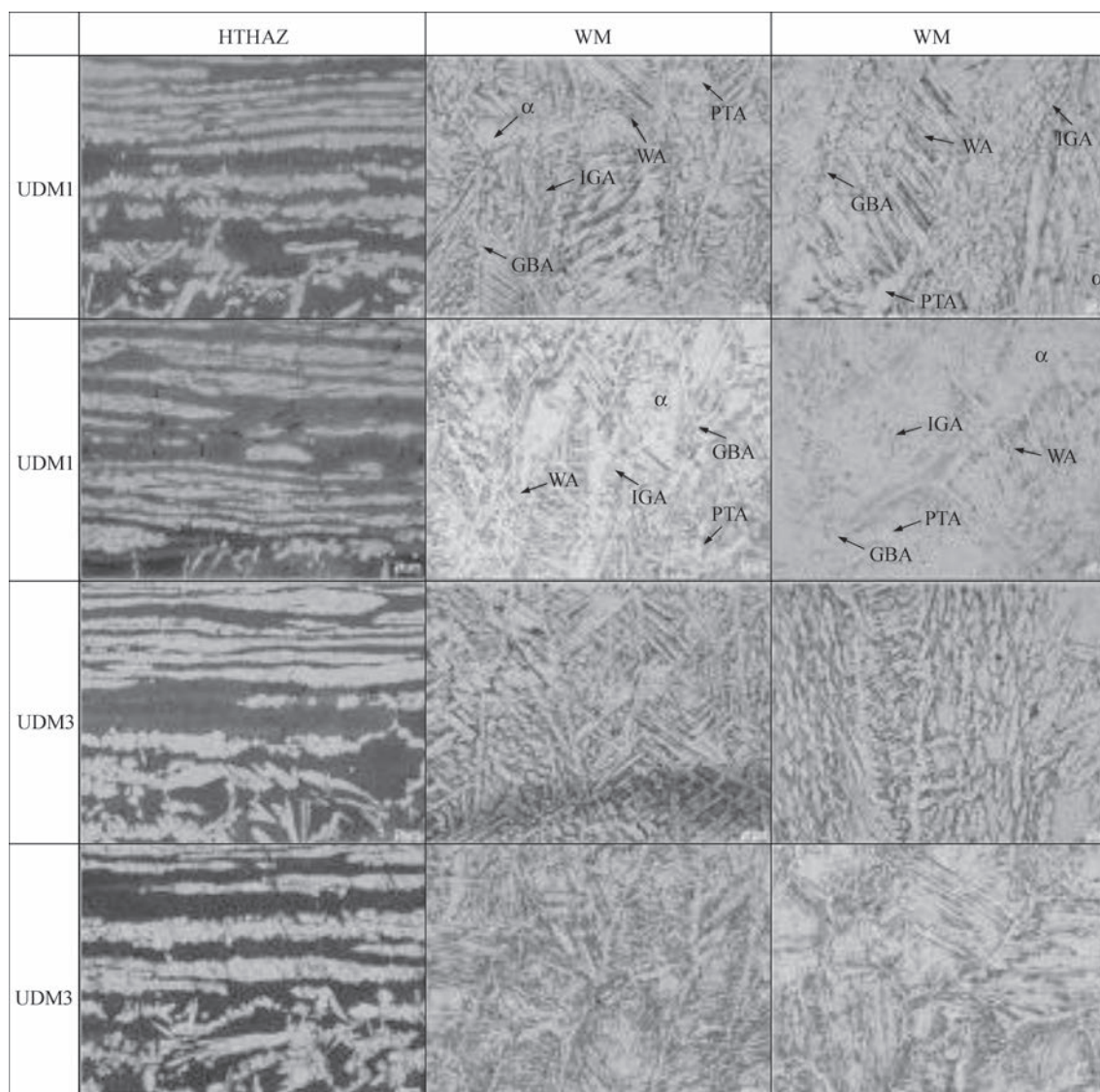


Figure 4. Microstructure of different regions of welded samples made by welding in air and by wet underwater welding

Comparative studies of the microstructure of the metal of the weld and HAZ in dry welding of UNS S32101 duplex steel with 1.2 mm flux-cored wire in CO₂ shielding gas in the pressure chamber and directly in the water environment were conducted in [38]. Table 3 gives welding and heat input parameters.

Figure 3 shows the volume fraction of γ -phase austenite at different welding methods and modes in different regions of the welded joint.

Analysis of the data given in Figure 3, leads to the following conclusions:

- volume fraction of γ -phase in wet underwater welding is much lower in all the weld metal regions and in the high-temperature subzone of the HAZ (HTHAZ), compared to γ -phase volume fraction in dry welding at the same heat input values;

- with increase of energy input value from 0.726 to 1.383 kJ/mm the γ -phase volume fraction increases in wet underwater welding from 27.3 % — UWW 1 to 39.4 % — UWW 3, i.e. 1.5 times, while in dry underwater welding it changes only slightly, remaining almost constant (~42 %) — weld center;

- at all the energy input levels the same regularity of γ -phase content in different welded joint regions is found in the case of wet and dry underwater welding. The largest volume fraction of γ -phase is observed in the weld metal adjacent to the fusion line, and the smallest γ -phase fraction is in HTHAZ;

- γ/α values increased greatly in wet underwater welding for weld metal, adjacent to the fusion line: from 35.01 % for UWW 1 up to 44.9 % for UWW 3.

Increase of γ -phase content in wet underwater welding is less intensive in weld regions adjacent to the fusion line: UWW 1 — 35.01 %; UWW 3 — 44.9 %, i.e. almost 1.3 times increase.

The most intensive increase of γ -phase content in wet underwater welding occurs in HTHAZ from UWW 1 — 23 % to UWW 3 — 43.55 %, by almost 1.9 times. In dry welding increase of γ -phase content in HTHAZ is less pronounced — from UDW 1 — 31.34 % to UDW 3 — 41.55 %, i.e. by more than 1.3 times.

Figure 4 gives the microstructure in different regions of welded joints.

Authors of [38] note that the volume fraction of nitrides is decreased with increase of energy input. It is also noted that HTHAZ cooling rate in wet underwater welding is higher than in dry welding.

HTHAZ for UDW 3 showed optimal local corrosion resistance, and the lowest local corrosion resistance was found in UWW 1.

Data given in Table 3 and in Figure 3 demonstrate that the cooling rate decreases with increase of energy input, and the austenitic component fraction is increased. The probability of chromium nitride formation in wet underwater welding rises, compared to dry

welding, as a result of increase of the cooling rate and lowering of austenitic component volume fraction.

It is shown in the presented review that the cooling rate is one of the main factors, having the strongest influence on the HAZ microstructure and phase composition in all the welding processes at the same chemical composition. The appropriate HAZ microstructure with the respective ratio of austenitic and ferritic phase components is formed depending on the cooling rate.

CONCLUSIONS

1. It is desirable to adjust the energy input ranges, which are recommended for welding duplex steels by different technologies, during technology optimization, depending on chemical composition of the metal being welded.

2. Investigations confirm the influence of the cooling rate on the microstructure and phase composition of the metal of the weld and HAZ, which, in its turn, influences the mechanical properties and corrosion resistance of the welded joints.

3. Completeness of $\delta \rightarrow \gamma$ phase transformations depends on the metal chemical composition, cooling rate and time of staying in the temperature range of 1200 (1300)–800 °C, which also depends on the cooling rate.

4. Due to the cooling impact of water environment, the cooling rate in wet underwater welding, particularly in HTHAZ, is higher than in welding in air.

5. Austenite content in the metal of the weld and in the HAZ is directly proportional to the energy input and inversely proportional to the cooling rate.

6. Increase of energy input promotes an increase of the austenitic component in wet underwater welding to a greater degree, particularly in HTHAZ, than in welding in air.

7. With increase of energy input, the volume fraction of precipitation of excess phases, Cr₂N chromium nitrides, becomes smaller.

8. Considering the peculiarities inherent to wet underwater welding, the levels of energy input and weld metal chemical composition require correction, as regards the recommendations developed for welding in air.

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CONFLICT OF INTEREST

The Authors declare no conflict of interest

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