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Corrosion resistance of SAW duplex joints welded with high heat input

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Materials

ABSTRACT

Purpose: test if the welding heat input exceeding the recommended values has negative impact on strength properties and corrosion resistance of the executed welded joints as well as description of influence of the heat input of submerged arc welding (SAW) of duplex steel UNS S31803 (0.032%C, 23.17%Cr, 9.29%Ni, 3.48%Mo, 0.95%Mn, 0.7%Si, 0.16%N, 0.017P, 0.006%S, 0.11%Cu) on welded joints microstructure, particularly average values of ferrite volume fraction, mechanical properties, and corrosion resistance.
Design/methodology/approach: analysis of welding heat input influence on mechanical properties, value of ferrite share, and corrosion of test joints has been done. Non-destructive and destructive testing, e. g. visual examinations, microstructure examination, corrosion resistance tests according to ASTM G48 Method A, HV5 hardness tests, impact and tensile test were carried out. For analysis of welding heat input influence on creation of welding imperfections, there were executed welding of sheet of thickness 9, 14, 28 mm. Butt joints on plates of different thickness were made where the applied heat input of welding exceeded the 2.5 kJ/mm value. Maximum heat input level was HI ≤ 3.0; HI ≤ 3.5; HI ≤ 4.0; HI ≤ 4.5; HI ≤ 5.0.
Findings: based on the performed tests the conclusion is that according to DNV Rules the welding heat input exceeding the recommended values has no negative impact on strength properties and corrosion resistance of the executed welded joints. It was shown that submerged arc welding of duplex steel with the heat input from 2.5 kJ/mm up to 5.0 kJ/mm has no negative influence on properties of the joints.
Research limitations/implications: the welding heat input exceeding the recommended values may influenced the precipitation processes in the HAZ, what need further experiments.
Practical implications: application of high value of the welding heat input will be profitable in terms of the welding costs.
Originality/value: an original value of the paper is to prove that a usage of high value welding heat input provides the best joints quality.
Keywords: Metallic alloys; Corrosion; Metallography; Technological design; Welding

1. Introduction

The application of duplex steels in the construction of chemical tankers has led to the elaboration of the quality criteria for steel and welded joints in the ships construction that concern to the macro and microstructure, mechanical properties and corrosion resistance. Special attention was paid to the ferrite to austenite fraction ratio, the presence of carbides on the grain boundaries and intermediate phases precipitations in the weld metal and the heat-affected zone (HAZ). The completion of these criteria requires appropriate control over the procedure of carrying of structure transformation processes, which are essentially subjected to the character of the heat cycle during the welding process. So far the utilize quality assessment criteria do not refer to the secondary austenite presence in the weld and the HAZ.

The data concerning to the influence of thermal cycle on the transformation of the ferrite to secondary austenite ratio in HAZ has been explained fragmentarily. Short durations of the high temperature impact and high temperature gradients in the HAZ determine the specificity of the diffusion processes and the ferrite (α) to the austenite (γ) and secondary austenite (γ_2) transformation. The γ_2 secondary austenite in duplex steel is formed as the result of $\alpha + \gamma \rightarrow \alpha + \gamma + \gamma_2$ transformation in the austenitic-ferritic structure after heating to the temperatures below the A - B solvus line in the phase equilibrium diagram of Fe-Cr-Ni (Figure 1). In the result of cooling down from the temperatures above the solvus line the γ primary austenite creates as a product of $\alpha \rightarrow \gamma$ transformation.

2. Thermal cycle of welding and post weld treatment of welds

The decomposition of the primary phases (α, γ) in the duplex steel weld joint HAZ on the example of UNS S31803 (0.032%C, 23.17%Cr, 9.29%Ni, 3.48%Mo, 0.95%Mn, 0.7%Si, 0.16%N, 0.017%P, 0.006%S, 0.11%Cu) steel as welded, and after post weld treatment was analysed in [1]. Avesta Sheffield FCW 2205-H flux cored wire was used as a filler material.

Thermal the past of HAZ has a substantial influence on its structure and properties.

The HAZ structure after heat treatment consisted of primary ferrite grains with primary austenite precipitated on the grain boundaries, and with secondary austenite growing as a Widmanstätten type from the grain boundary austenite into the ferrite grains. The differences of HAZ microstructures of the duplex steel weld HAZ, as welded, heat input HI 1.6 kJ/mm, welding process 136, shielding gas CO_2 and after post weld annealing 1273K/30 are presented on Figures 2 and 3. The differences of HAZ properties and phase composition after welding with heat input HI 1.6 kJ/mm and 2.2 kJ/mm and after post weld annealing are presented in Tables 1 - 4.

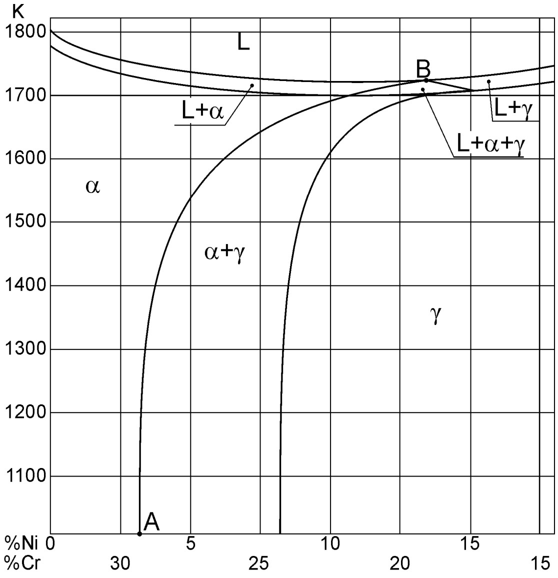

Fig. 1. Fe-Cr-Ni equilibrium system for 68% Fe [1]

Table 1.
Properties and phase composition of HAZ after welding, heat input HI 1.6 kJ/mm, welding process 136, shielding gas CO2, welding position PA, weld type - butt weld, number of runs - 4 [1]

Area of the weld	Face of the weld	Root of the weld
Hardness HV5	305 ±7	316 ±3
Ferrite hardness HV0.02	214 ±4.5	213 ±10.35
Austenite hardness HV0.02	163 ±6.43	205 ±7.65
Loss of weight corrosion after ASTMG48A test [mg]	1.0	
Ferrite fraction [%]	72.07 ±2.67	71.81 ±2.85

Table 2.
Properties and phase composition of HAZ after welding, heat input HI 2.2 kJ/mm, welding process 136, shielding gas CO2, welding position PA, weld type - butt weld, number of runs - 4 [1]

Area of the weld	Face of the weld	Root of the weld
Hardness HV5	309 ±5	304 ±6
Ferrite hardness HV0.02	199 ±10.04	194 ±8.73
Austenite hardness HV0.02	171 ±7.72	17v5.174
Loss of weight corrosion after ASTMG48A test [mg]	1.0	
Ferrite fraction [%]	71.85 ±1.18	74.71 ±1.45

The secondary austenite formation in the duplex steels is the outcome of thermodynamic equilibrium breach of the alloy during heat treatment, or an effect of the welding heat impact, whose magnitude depends on the value of the heat input [2 -5]. Precipitates of γ2 formed as a result of post weld aging have a most important influence on HAZ hardness. Pitting corrosion resistance of the welds is strongly influenced by thermal cycle parameters. The secondary austenite in the duplex steel may emerge as a result of the following transformations: eutectoid: $\alpha \rightarrow \sigma + \gamma 2$ in the temperatures 973 – 1173K, diffusion transformation in the temperatures above 923K which results the Widmanstätten structures, and the isothermal conversion in the temperatures below 923K that proceeds similarly to the martensite transformation. The nucleation and growth of the γ2 phase may occur on the α - γ phase grain boundaries, or inside the ferrite grains.

Table 3.
Chemical composition of HAZ after welding [% by weight], heat input HI 1.6 kJ/mm, welding process 136, shielding gas CO2, welding position PA, weld type - butt weld, number of runs - 4 [1]

Area of the weld		Face	Root
Ferrite	Cr	23.61 ±0.42	23.64 ±0.36
	Ni	5.03 ±0.37	5.11 ±0.29
	Si	0.36 ±0.04	0.36 ±0.04
	Mn	1.86 ±0.12	1.98 ±0.17
	Mo	2.76 ±0.13	2.76 ±0.24
Austenite	Cr	21.62 ±0.28	21.91±0.39
	Ni	6.6 ±0.2	6.83 ±0.54
	Si	0.34 ±0.02	0.35 ±0.03
	Mn	2.07 ±0.13	2.01 ±0.06
	Mo	2.05 ±0.11	1.95 ±0.13

Table 4.
Chemical composition of HAZ after welding [% by weight], heat input HI 2.2 kJ/mm, welding process 136, shielding gas CO2, welding position PA, weld type - butt weld, number of runs - 4 [1]

Area of the weld		Face	Root
Ferrite	Cr	23.52 ±0.43	23.48 ±0.29
	Ni	5.13 ±0.27	4.91 ±0.29
	Si	0.38 ±0.04	0.39 ±0.04
	Mn	1.77 ±0.15	1.76 ±0.11
	Mo	2.77 ±0.2	2.51 ±0.15
Austenite	Cr	22.41 ±0.14	22.7 ±0.18
	Ni	6.06 ±0.2	6.28 ±0.47
	Si	0.35 ±0.07	0.4 ±0.04
	Mn	1.85 ±0.11	1.78 ±0.2
	Mo	2.25 ±0.09	2.32 ±0.3

The presence of the secondary austenite in duplex steels, in respect of the chemical composition, distribution, location, and morphology of the phase, causes the loss of chemical balance between ferrite and austenite, and the local decline of corrosion resistance of the alloy, particularly of the pitting corrosion [1 -5]. The influence of the welding heat cycle and postweld treatment on the HAZ properties is the subject of this paper.

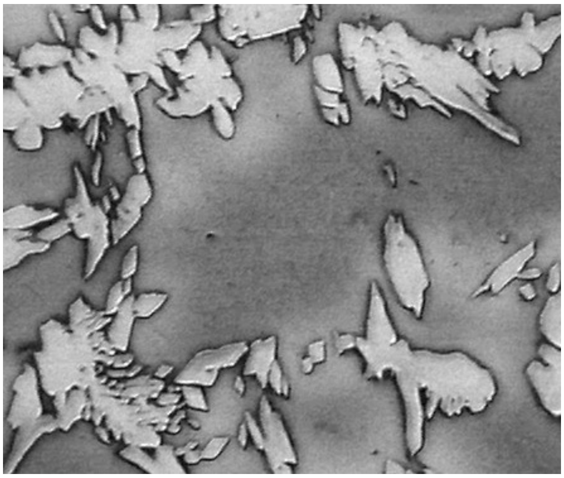

Fig. 2. Microstructures of the duplx steel weld HAZ, as welded, heat input HI 1.6 kJ/mm, welding process 136, shielding gas CO_2, welding position PA, weld type - butt weld, number of runs – 4, dark phase – ferrite, white phase - austenite [1]

3. Heat input

The heat input of submerged arc welding of steels is usually limited. High-strength steels, austenitic steels, austenitic-ferritic steels require such selection of the welding limited heat, which is a compromise between welding efficiency and joint quality [1 - 5].

Basic parameters of submerged arc welding are: arc current kind, intensity, voltage, speed of welding, wire diameter, length of wire extension, thickness and width of welding flux layer and inclination angle of an electrode or a welded joint. Welded joints of duplex austenitic-ferritic steel grades as per the Det Norske Veritas rules have to comply with such strength criteria as bend test, impact test, tensile test, hardness test, macroscopic and microscopic examination of the executed welded joint structure, specifying percentage index of ferrite content (ferrite share), as well as performing of the welded joint corrosion resistance test.

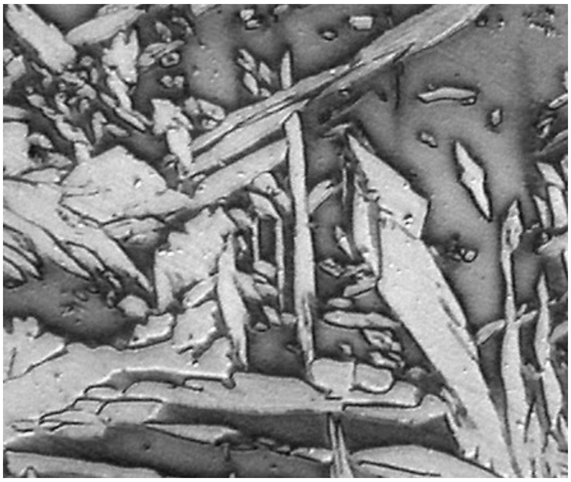

Fig. 3. Microstructures of the duplx steel weld HAZ, heat input HI 1.6 kJ/mm, welding process 136, shielding gas CO_2, welding position PA, weld type - butt weld, number of runs – 4, post weld annealing 1273K/30 s, dark phase – ferrite, white phase – austenite, small white needles - Widmanstätten type secondary austenite [1]

Submerged Arc Welding (SAW) of steel grades demanding use of limited welding heat input, inclusive of high-strength steel, austenitic steels and duplex type austenitic-ferritic steels requires such selection of parameters which fulfil technological requirement, mechanical properties and corrosion resistance of welded joints [6 - 9].

When executing welded joints with a concrete kind of edge preparation for welding such optimum parameters of submerged arc welding are specified as arc current kind, intensity, and voltage as well as speed of welding for a selected flux cored wire diameter.

The quality of the weld bead is evaluated on the basis of the weld face appearance and the character of slag removal. Selection of welding parameters is intended for ensuring high operating properties of the joint, low filler metal consumption and repeatability of quality of the welds at an acceptable level.

Heat input of welding is the resultant parameter that, apart from impact on technological characteristics of the welded joint has also a considerable influence on the extent of welding technology acceptance. The value of welding heat input calculated as per formula (1) may vary within ±15% range of the welding heat input value applied at performing welding technology acceptance tests, observing constant parameters of the welded joint geometry [10 - 15].

$$HI[kJ/mm] = \eta * \frac{I[A]*U[V]}{Vsp[mm/s]*1000} \qquad (1)$$

where:

- HI – welding heat input
- η – coefficient of welding efficiency
- I – welding current intensity

- U – welding voltage
- Vsp - speed of welding

The aspect of limiting the welding heat input when executing duplex steel UNS S31803 joints, frequently emphasized, keeps giving raise to controversy as regards its permissible value limit. For this purpose an attempt was made to specify the maximum heat input (HI) value of welding at which it is possible to execute the welded joint and to analyse the obtained mechanical (strength) parameters according to Det Norske Veritas Rules.

4. Welding tests and joints investigation

In order to compare requirements applicable to welded joint specified in the Det Norske Veritas Rules and the impact of the welding heat input occurring at SAW welding of duplex steel UNS S31803 on the corrosion resistance of welded joints, a number of tests were performed for specifying maximum value of the welding heat input at which the welded joint loses its corrosion resistance or strength (mechanical) properties.

In joints with the above mentioned a series of butt joints on plates of 30 mm thickness were executed where the applied heat input of welding exceeded the 2,5 kJ/mm value. Beads of butt joints with butt weld were made using maximum value of welding heat input, starting from 3.0 kJ/mm and increasing every 0.5 kJ/mm up to value 5kJ / mm, in flat welding position. All welds were tested for corrosion resistance and the weld metal microstructure analysis was performed, as well as ferrite fraction was determined.

Table 5.
Results of the test of chemical composition and mechanical properties of the parent material used in the experiment

Chemical composition of the steel UNS S31803, average values [%]									
C	Si	Mn	P	S	Cr	Ni	Mo	N	PREN*
0.03	0.9	1.8	0.025	0.015	22.1	5.2	2.9	0.17	≥ 34

Mechanical properties, average values		
Re [N/mm^2]	Rm [N/mm^2]	KV -20°C [J]
590	780	170

*PREN: Pitting Resistance Equivalent Number; PREN = 3.3 Cr [%] + Mo [%] + 16 N [%]; PREN minimal value, required according to international standards for planned constructions of chemical tankers is 34.

In addition, destructive and non-destructive testing of butt joints with butt-welded was performed, with heat input of welding exceeding the recommended value HI 2.5kJ/mm. In order to determine the influence of the multiple-pass welding/bead welding on the ferrite fraction, and on the corrosion resistance, welded joints of various thicknesses bevel pate thickness 9, 14, 28 mm and with constant value of welding heat input on level 1.35kJ/mm were executed, in which filler pass and final layers were made by submerged arc welding in horizontal-vertical position. All butt weld joints were tested for corrosion resistance and the weld metal microstructure analysis was performed, as well as ferrite fraction t was determined.

Table 6.
Catalogue chemical composition and mechanical properties of the filler materials - welding wire2205/flux 805

Chemical composition, average values [%]					
C	Si	Mn	Cr	Ni	Mo
0.02	0.6	1.1	23.0	8.5	3.0

Mechanical properties, average values				
Re [N/mm^2]	Rm N/mm^2]	A5 [%]	KV +20°C [J]	KV -40°C [J]
590	800	28	90	70

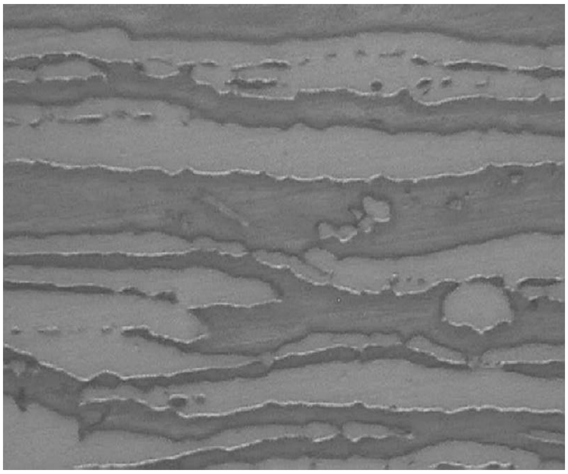

Fig. 4. Microstructure of the parent material, steel UNS S31803 used in the experiment; ferrite - dark phase, austenite - bright phase; ferrite (α) volume fraction 48%

The duplex steel UNS S31803 used for testing was characterized by similar chemical composition and strength parameters as given in Table 5 and the structure as on Fig. 4. Filler metal used for welding of test joints: flux cored wire of 3.2 mm diameter, grade 2205, made by Avesta Company, with the flux 805, whose strength parameters and chemical composition are given in Table 6.

All butt joints with butt weld were subjected to the following non-destructive testing:

- visual examinations according to the required quality level B acc. to the Polish – European Standards PN-EN 25817,
- X-Ray examinations acc. to the Polish – European Standard PN-EN 12062 with the required quality level B as per the Polish – European Standard PN-EN 25817.

The following destructive testing of joints were done too:

- macroscopic examination,
- bend test of face from the first and second side of welding at a criterion in specified bend angle 120º; mandrel diameter 5 x thickness of the test plate,

- impact test- min KV = 27J w -20 °C,
- tensile test, – min Rm = 620 MPa,
- corrosion resistance tests were carried out according to ASTM G48 Method A test and guidelines of Det Norske Veritas and American Bureau of Shipping. The specimens (76×24×16.5) were dipped in ferric chloride reagent (100g $FeCl_3 \cdot 6H_2O$ in 900 ml H_2O). Etching was performed at temperature 295 ± 2 K. The test duration was 24 hours. According to guidelines of Det Norske Veritas and American Bureau of Shipping the specimen mass loss smaller than 20 mg is acceptable,
- microstructure examination and ferrite share determination were performed using optical microscopy. Colour etching by Murakami's reagent (KOH – 10g; $K_3Fe(CN)_6$ – 10g; H_2O – 100ml) was used to produce contrast between the primary phases (ferrite and austenite) and to reveal the presence of secondary phases precipitates. A programme for analysing digital images VISILOG 4 determined the ferrite and secondary phases content. Hardness tests HV5 were performed according to EN 288 in the cross section of the welded joints in the heat-affected zone area. Six measurement points have been chosen in the face of the weld line, and the root of weld line. More detailed studies of the hardness alternation were performed using Vickers HV0.02 method. Thirty measurements of each phase in different the heat-affected zone areas (face, root) of the samples, and in different aging conditions were performed.

5. Joints microstructure, chemical phase composition and properties

Butt joints with butt weld of test plates were welded using maximum heat input at a level of HI ≤ 3.0; HI ≤ 3.5; HI ≤ 4.0; HI ≤ 4.5; HI ≤ 5.0. The X-Ray examinations of butt welded joints were performed acc. to the European standard EN12062 with the required quality level B as per EN 25817 standard (positive test results).

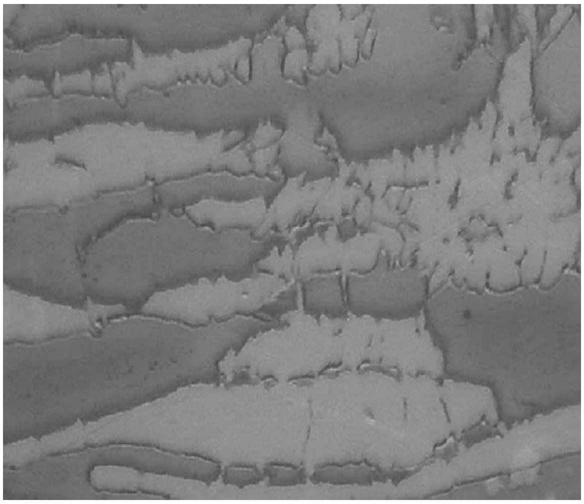

Fig. 5. Microstructure of the HAZ; heat input HI = 4.5; ferrite - dark phase, austenite - bright phase; ferrite (α) volume fraction 59%

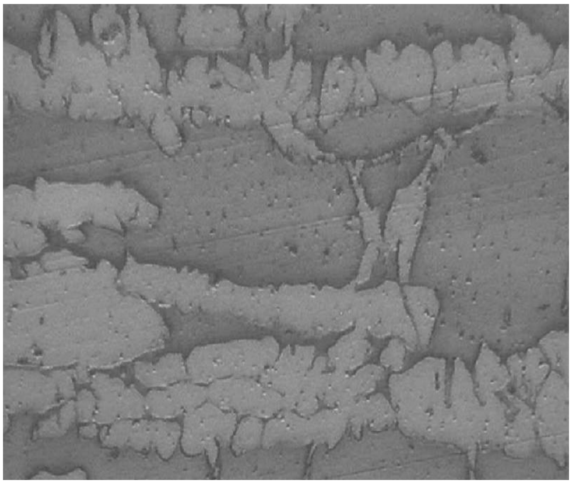

Fig. 6. Microstructure of the HAZ; heat input HI = 4.5; ferrite - dark phase, austenite - bright phase; ferrite (α) volume fraction 57%

The destructive testing were performed as per DNV Rules. The performed bend test of face from the first and second side of welding: (min specified bend angle 120°; mandrel diameter 5 x thickness of the test plate, were positive. The metallographic examination shown ferritic – austenitic structure of the welds and HAZ and an appearance of secondary austenite in some tested joints (Fig. 5 – 10).

The result of ferrite fraction tests, shown on Fig. 11 - 12 corresponded the acceptance level acc. to DNV rules. A tensile test of the joints was in all cases higher, than 620 MPa - required minimum value. Charpy V-notch specimens and hardness tests Vickers method – results were presented on the Fig. 13 – 14 (all tests results were positive) and the fracture images of welds and HAZ were ductile Fig. 15 – 16. Results of the corrosion resistance tests are presented in Tab. 7 and 8. Test samples subjected to corrosion resistance testing were free of any corrosion traces (Fig. 17– 18).

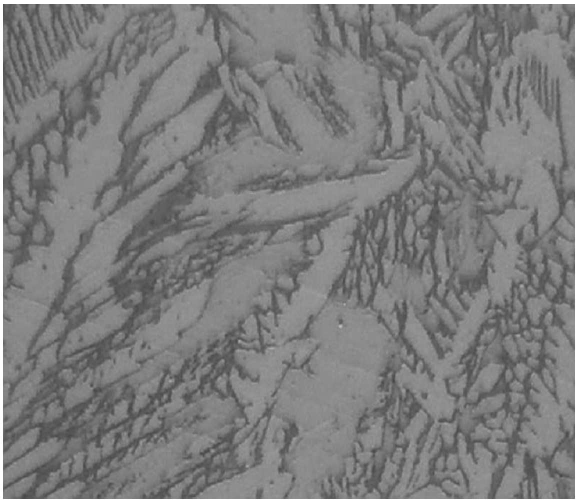

Fig. 7. Microstructure of the weld; heat input HI = 4.5; ferrite - dark phase, austenite - bright phase; ferrite (α) volume fraction 47%

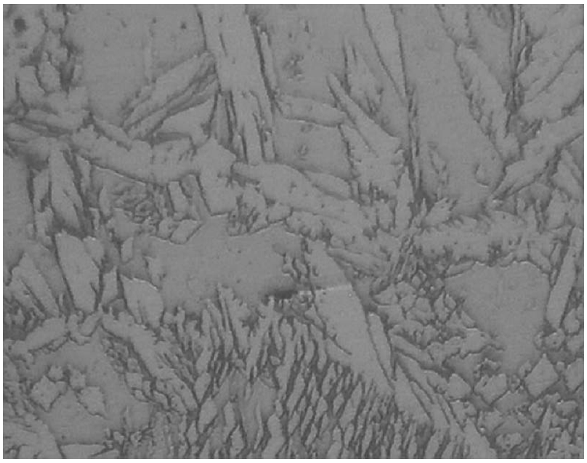

Fig. 8. Microstructure of the weld; heat input HI = 4.5; ferrite - dark phase, austenite - bright phase, needles of secondary austenite; ferrite (α) volume fraction 54%

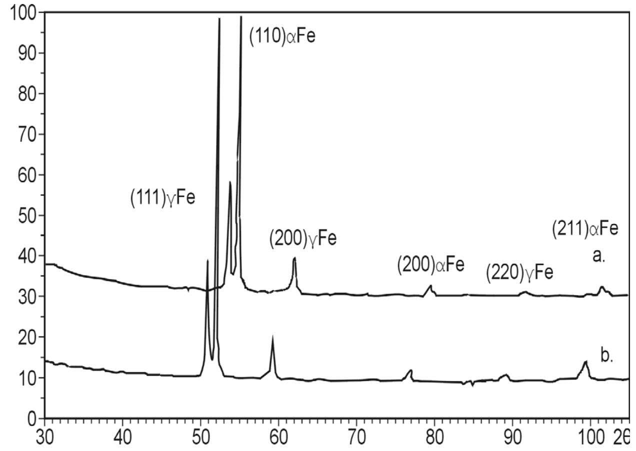

Fig. 9. Diffraction image of the weld, heat input: a - HI = 3.0; kJ/mm, b - HI = 4.5; kJ/mm; αFe – ferrite, γFe - austenite

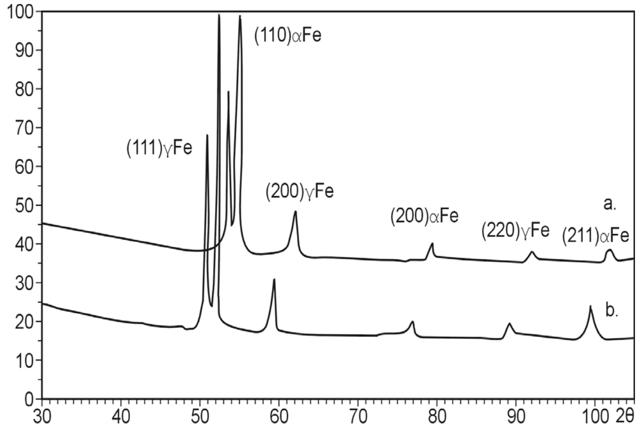

Fig. 10. Diffraction image of the HAZ, heat input: a - HI = 3.0 kJ/mm, b - HI = 4.5; kJ/mm; αFe – ferrite, γFe - austenite

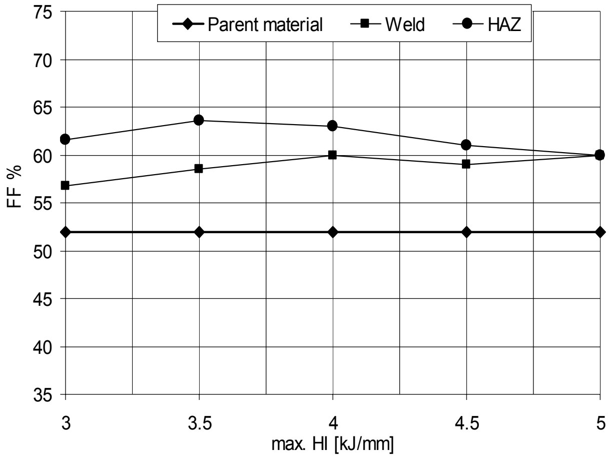

Fig. 11. Average values of ferrite volume fraction FF% in butt joints with butt welds [%]

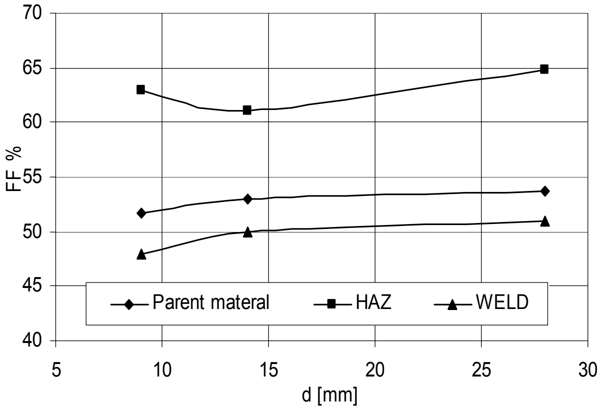

Fig. 12. Average value of ferrite volume fraction FF% in butt joints with butt weld in the plate thickness - d function, heat input HI = 4.5 kJ/mm

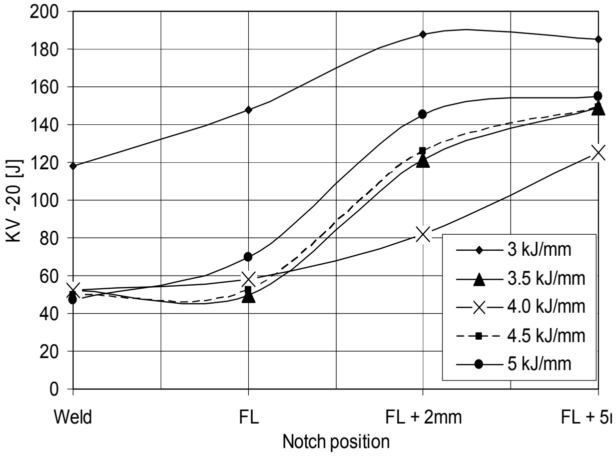

Fig. 13. Average value of KV J of butt joints with butt welds (min KV = 27J at -20 °C)

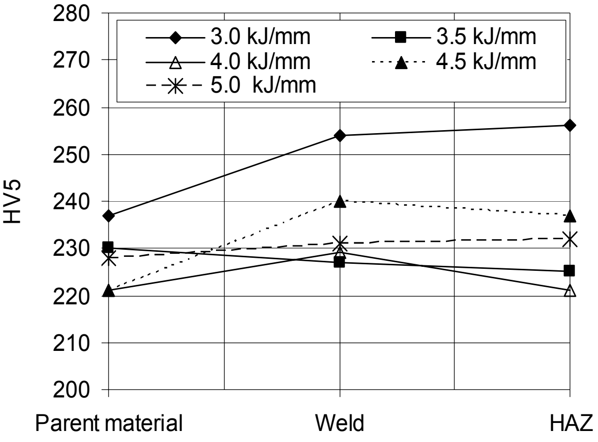

Fig. 14. Average values of HV5 hardness of butt joints with butt welds

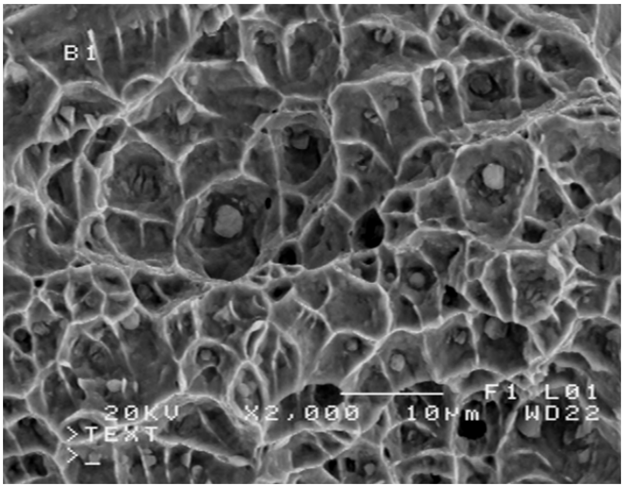

Fig. 15. Ductile fracture image of the HAZ, heat input HI = 4.5 kJ/mm

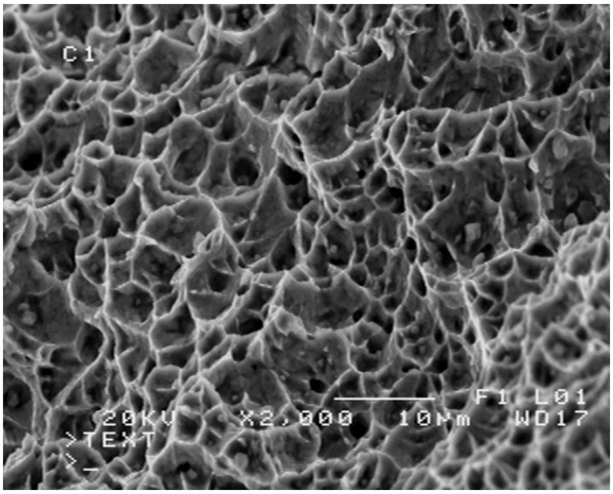

Fig. 16. Ductile fracture image of the weld, heat input heat input HI = 3.0 kJ/mm

Table 7.
Average value of mass loss of butt-welded joints after corrosion resistance testing, plate thickness 14 mm

Max. hit input [kJ/mm]	Average value of mass loss of butt-welded joints after corrosion resistance testing [mg]
3.0	1.15
3.5	1.12
4.0	1.10
4.5	1.07
5.0	1.05

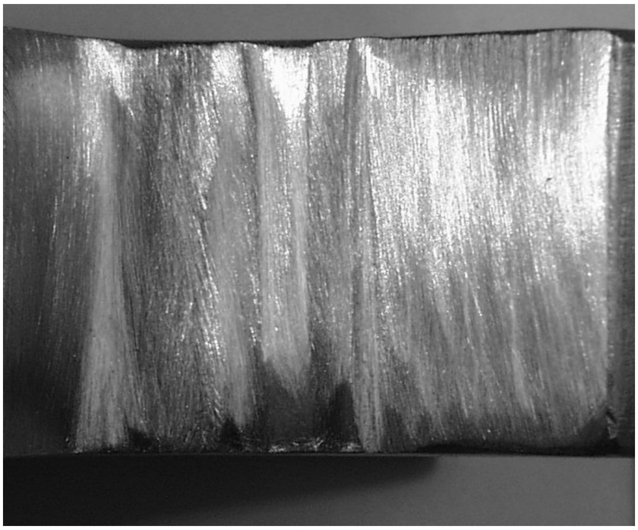

Fig. 17. Macrostructure of the weld after corrosion test; heat input 3.0 kJ/mm; no pitting corrosion

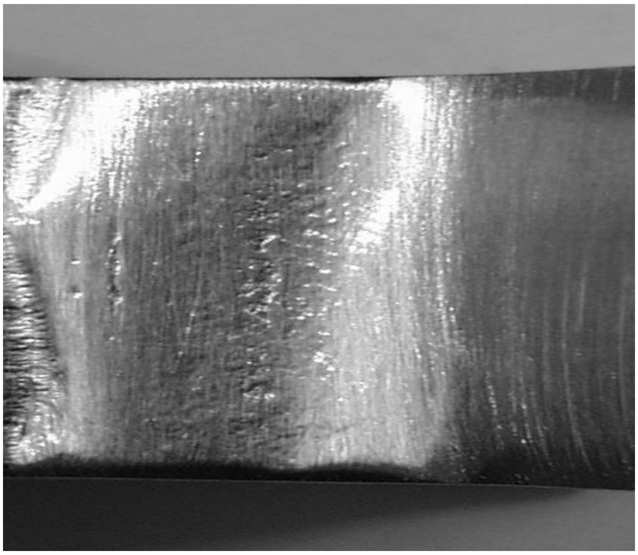

Fig. 18. Macrostructure of the HAZ after corrosion test; heat input 4,5 kJ/mm; no pitting corrosion

Table 8.
Average value of mass loss of butt-welded joints after corrosion resistance testing, Max. hit input 3.5 kJ/mm

Plate thickness [mm]	Average value of mass loss of butt-welded joints after corrosion resistance testing [mg]
9	1.02
14	1.12
28	1.25

6. Conclusions

Based on the performed tests it was proved that the welding heat input exceeding the recommended values had no negative impact on strength properties and corrosion resistance of the executed welded joints, as:

- the obtained results of strength testing of butt-welded joints, with applied heat input ranging from 3 to 5 kJ/mm are at an acceptable level with considerable strength margin,
- the performed microstructure butt joints with butt weld examination at x 400 enlargement proved that there were no intermetalic and carbides phase release, including sigma phase,
- the performed microstructure tee joints with butt weld examination at x 400 magnification whereas at multiple-pass welding of joints with constant heat input applied in some test pieces appeared release of secondary austenite in the weld area,
- the corrosion resistance test of the test butt joints with butt weld yielded positive result without any corrosion pits, and the tested joints mass decrement is at a level 1.25 mg, according to guidelines of Det Norske Veritas and American Bureau of Shipping the specimen mass loss smaller than 20 mg is acceptable
- the performed corrosion resistance tests tee joints with butt weld did not show any corrosion traces (pits), whereas loss in mass was lower in 28 mm thick tested plate than in case of tested thinner plates using the same hat input of welding.
- average value of ferrite share, especially in heat affected zone (HAZ) of the welded joint was smaller than 70% level what in each of the variants complies with criteria specified both in the DNV rules, and in the references,
- welding of butt joints, using constant heat input, of both 9, 14 and 28 mm thick plates gives comparable values of ferrite share in the executed welded joints,

The weld and heat - affected zone structure consisted of primary ferrite grains with primary austenite precipitated on the grain boundaries, and with secondary austenite growing as a Widmanstätten type from the grain boundary austenite into the ferrite grains. Secondary austenite formed in the ferrite and at ferrite/austenite phase boundaries. Volume fraction of ferrite (α) austenite (γ) and secondary austenite (γ_2) are strongly influenced by welding.

Thermal the past of heat - affected zone has a substantial influence on its structure and properties. Precipitates of γ_2 formed as a result of post weld aging have a most important influence on HAZ hardness.

Pitting corrosion resistance of the welds is strongly influenced by thermal cycle parameters. A different level of Chromium and nickel constitution in the α, γ, and γ_2 phases, as well as a phase volume fraction have a significant influence on corrosion resistance. Generally post weld heat treatment decreases the pitting corrosion resistance.

Primary austenite has a bigger hardness compared with ferrite for the every post weld conditions. The secondary austenite hardness is influenced by chemical composition changes of the phase.

The presence of the intermediate phases, carbides, and nitrides precipitates in a heat-affected zone of a welded joint of duplex steels were not observed.

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