

Microstructure and corrosion resistance of the duplex steel wide-gap one-side fluxcored wire welded joints

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ABSTRACT

Purpose: this paper was to determine the impact of the wide-gap welding, with increased root face gap, on structure and corrosion properties of the welded joints executed on duplex steel by one-side welding on ceramic backings.

Design/methodology/approach: In the described work, experiments were conducted to welding tests for selected joints, visual examinations, non-destructive testing of welded joints, X-ray examinations, and metallographic testing of welded joints.

Findings: As a result of the performed inspection, decreasing of the ferrite content with the increase of the root face gap (increase of welding heat input) was observed. The minimum measured ferrite content was not lower than 28 %, and the maximum value did not exceed 69% (the permissible range being from 25 to 70 %).

Research limitations/implications: Further studies on the impact of the wide-gap welding, with increased root face gap, on structure and corrosion properties of the welded joints are required.

Practical implications: The performed tests and examinations of welded joints with root face gap ranging from 6 to 10 mm were intended for extending the standard range from 2 to 6 mm.

Originality/value: The experimental program verified the testing methodology, and techniques of welding of the duplex steel with the wide-gap.

Keywords: Welding; Microstructure of welded joints; Testing of welded joints

1. Introduction

When analysing in recent years the world industry dealing in building of large - size constructions, including chemical cargo carriers, the growing tendency to use duplex stainless steel grades can be observed. Building of large - size constructions (of duplex steel) is of multi-stage character. At different building stages there occurs necessity to execute welded joints in fixed positions. These positions as a rule enforce using maximum welding heat input which results first of all from limited possibility to increase the speed of welding in these positions. Publications relating to duplex steel welding indicate that the recommended welding heat input should range from 0.5 to 2.5 KJ/mm [1-7].

The need to extend this range is associated with welding of 3D sections at assembly in fixed positions (mainly in vertical position). When building constructions of this type for butt joints usually mechanized welding is applied using automatic welding equipment (e.g. of Bug-o matic type), fluxcored wires, with active gas shield (Fig. 1).

The automatic welding equipment moves along a guide rail which is fixed to plate by means of magnets. When joining sections, one-side welding on ceramic backings is used. The root run of the weld penetration layer is formed then by means of flat ceramic backing which is then placed inside the section.

After the weld execution the backing is removable. The obtained root run of the weld does not require execution of any auxiliary operations, e.g. grinding off (Fig. 2).

Plate edges in such a welding method are bevelled at „1/2V”, which results in weld groove of „V” geometry (shape). One-side welding with preparation of weld groove at „V” is usually applied for plates of thickness ranging from 8 to 18 mm.

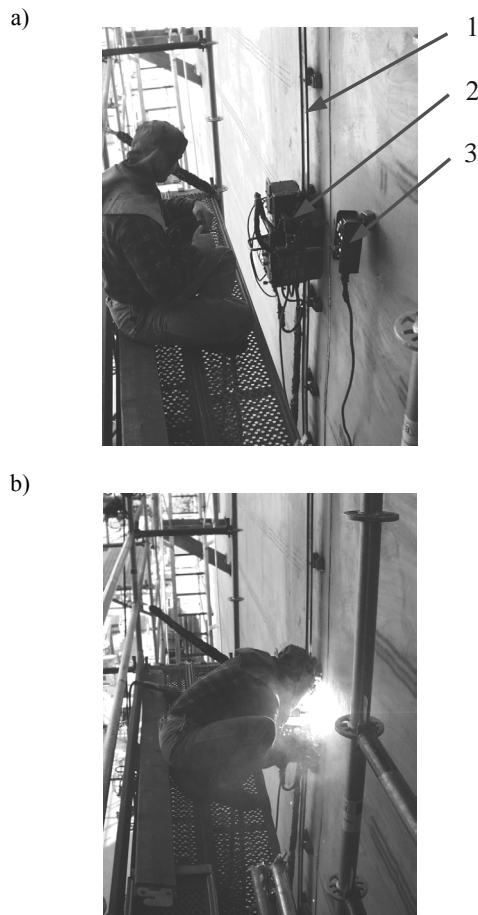


Fig. 1. Welding of butt type joints of large-size constructions, where: 1 – guide rail, 2 - automatic welding machine, 3 – control desk

One-side welding of plates up to 20 mm thickness in large-size (bulky) constructions has an advantage over both-sides welding due to:

- easy access only from one side (from the other side there is fitted the whole supporting structure consisting usually of stiffening of I and II type,
- possibility of automated execution of all weld layers,
- advantageous shape of the obtained weld penetration layer, preventing occurrence of hot cracks,
- reducing of labour demand for welded joint execution,
- reducing of labour demand necessary for edge treatment,
- improvement of conditions in welder-operator's working environment.

The drawback is a possibility of occurrence of angle distortions of the welded joint. However, this problem can be solved by using appropriate welding technology, consisting mainly in proper welding sequence and special stiffening of the welded joint.

It is the root face gap that is the basic parameter characterizing the weld groove geometry, influencing the quantity

of heat input, and as a result – the properties of the welded joints. For a butt type welded joint at one-side welding the root face gap (distance) ranging from 4 to 6 mm is assumed [8 - 12]. The limits values given result directly from experience in execution of similar welded joints. They make a compromise between obtaining correct strength and microstructural properties and the optimum performance of the welding process (optimization in terms of economic profitability - cost-effectiveness).

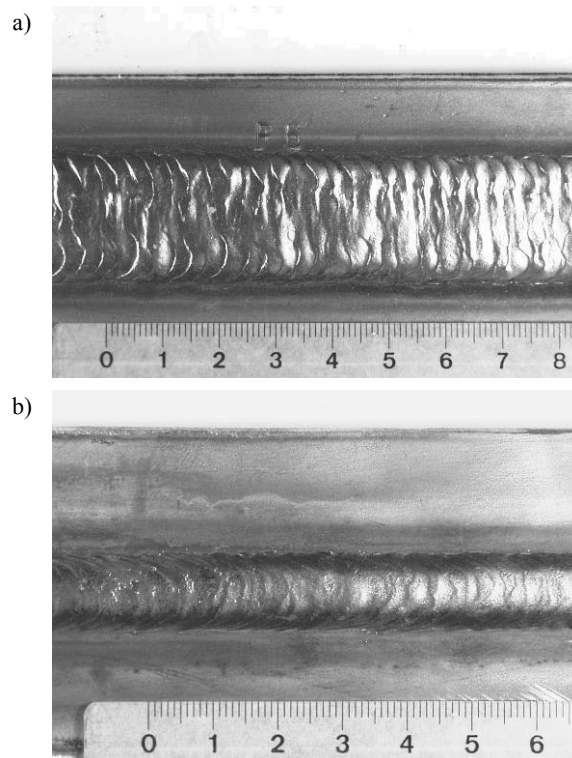


Fig. 2. View of weld executed by one side welding in PF (vertical - up) position (the weld penetration layer is formed on ceramic backing): a) the weld face, b) the root run of the weld

In case of reducing the root face gap to a less than 4 mm size for one-side welding on ceramic backings there appear some difficulties (problems) with execution of the weld penetration layer. The root run of this layer does not comply with requirements of the B quality level as per PN-EN 25817 standard and DNV rules relating to the shape and surface welding defects and imperfections. Execution (welding) of this layer in PF (vertical - up) position is made difficult (hindered) due to accumulation of heat in a small area. It may result in occurrence of local imperfections in form of sagging puddles, lack of fusion caused by a great number of connections (areas of welding operation starting and ending) of the weld penetration layer. Then the tendency of increased welds defectiveness occurs. Usually it results in increase of the total cost of the construction execution by extending the inspection scope (both interoperational and final ones). The aim is that the obtained minimum value of the root face gap before and during welding is not less than 4 mm.

The maximum value (6 mm) results mainly from experience gained by welding materials producers as regards obtaining of strength and microstructural parameters of welded joints. Due to scarcity of available literature relating to welding of large-size

constructions, where the main problem is maintaining of appropriate execution tolerances, in case of exceeding the maximum value of the root face gap being equal to 6 mm it is recommended to repair the weld groove prior to welding.

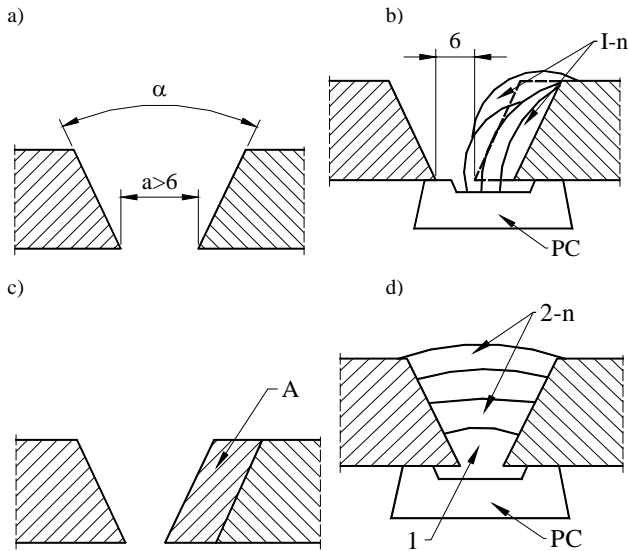


Fig. 3. Scheme of one-side welding combined with repair (reconstruction) of the plate edge by surfacing, where: a - root face gap, α -groove angle, PC-ceramic backing, b - repairing the weld groove prior to welding, c -padding welds, A - surfaced area after performed grinding off, d - weld, 1 - the weld root layer, 2-n- filler passes and face layer

This repair may be performed in two ways. The first one consists in replacement of part of the plate. However, in this case we are dealing with an additional weld joining the new fragment with the old one. Therefore this way is applied only as the last resort. The second step consists in reconstruction of the plate edge by surfacing (Fig. 3).

The process of preparation of weld groove with the plate edges surfacing is a complicated and multistage process. It comprises not only reconstruction of the plate edge but also its proper preparation for welding. Due to necessity to use minimum parameters, surfacing is characterized by high defectiveness rate. The following defects occur very frequently: lack of fusion and non - metallic solid inclusions. Execution of correct padding weld of the plate edge requires very high skills. It is a long-lasting and cost-intensive process. After the stage of the plate edges surfacing (Fig. 4) the executed padding weld cannot be inspected.

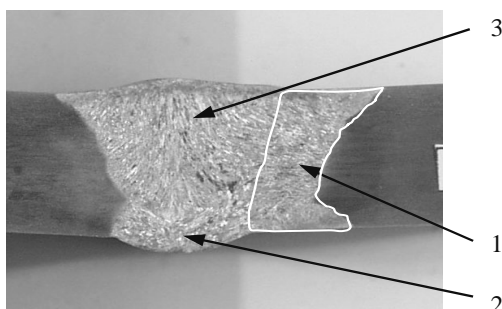


Fig. 4. Macro - image of the welded joint macrostructure with visible repair of the plate edge by surfacing, where: 1 – surfaced layer, 2 - weld root layer, 3 - filler passes and face layer

The only available methods are visual examinations and dye penetrant examinations, but they are applicable only to examination of surface welding defects and imperfections. There is no possibility to check the padding weld inside. The stage of the padding weld inside examination can be performed only on completion of the process of grinding off and welding of the whole joint (Fig. 5), which in case of large-size constructions is unacceptable.

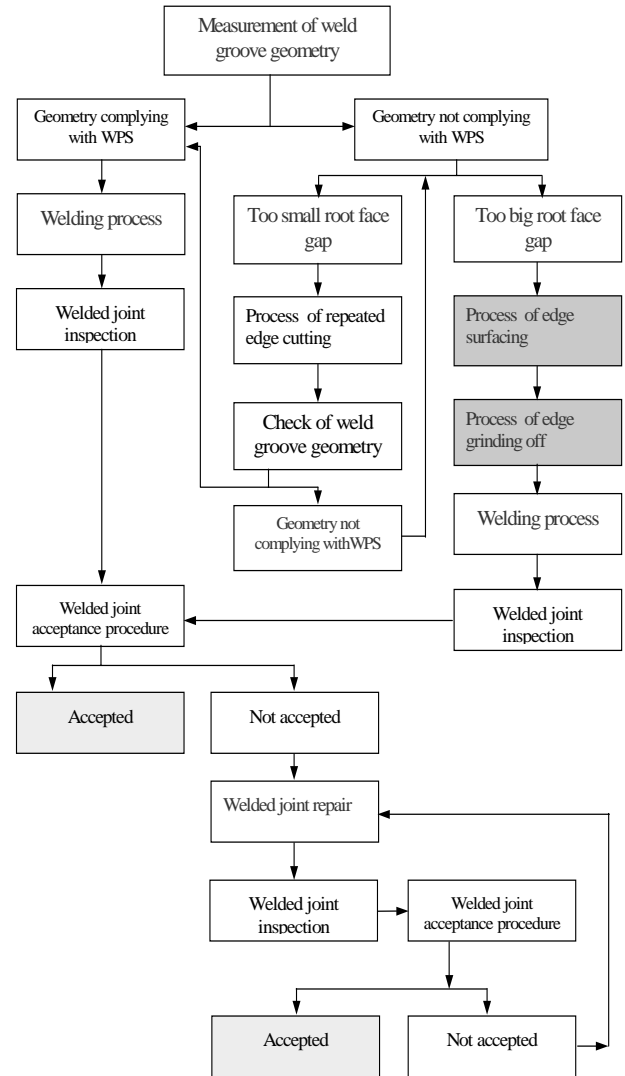


Fig. 5. Schematic presentation of stages of the welded joint execution – from the moment of the weld root geometry measurement to acceptance inspection of the welded joint [15].

The 2 mm range of root face gap tolerances, giving the dimension ranging from 4 to 6 mm, is too narrow in case of welding joints of total length exceeding 5 m. For execution of such a large-size construction, maintaining such a narrow tolerance range of the basic parameter of the weld groove is practically impossible and in many cases these dimensions are exceeded. It results most often from tolerances assumed (accepted) for particular operations. So e.g. the line marking-off tolerance range is ± 1 mm.

The plasma arc cutting tolerance range is ± 2 mm. Measuring errors resulting from measuring instruments are contained in ± 1 mm tolerance (allowance). In some cases values of tolerances for particular operations are summed up (tolerance stack-up) and the obtained dimension of the root face gap is exceeded. Most often the plus tolerances are extended, i.e. the dimension of the root face gap is higher than 6 mm (within 6 -10 mm limits).

Thus the surfacing process is consciously introduced into the process of basic execution of the welded joint. Generally in welding procedures in case of gaps >6 mm the surfacing of plate edges prior to welding is applied [13 - 15].

In order to execute one-side welded joints without using the edge surfacing process it is necessary to extend the range of root face gap tolerances.

The research and tests conducted at the Technical University of Szczecin in cooperation with the Szczecin New Shipyard permitted to determine the impact of the wide-gap welding, with increased root face gap, on structure and corrosion properties of the welded joints executed on duplex steel by one-side welding on ceramic backings.

2. Welding tests of selected joints

Welding tests were performed based on the elaborated experiment plan. 9 welded joints of 1.000 mm length each were executed.

Three-plate thickness was assumed. For each of them welding with root face gap of the weld groove, equal to 6, 8 and 10 mm, was performed. Table 1 presents characteristics of welded joints [15].

Particular joints were executed using FCAW – Flux Cored Arc Welding – 136 - one-side welding with the weld penetration layer on ceramic backing on plates (g [thickness] = 16.5mm) made of duplex steel UNS S31803 using filler metal DW329AP/C1 (100%CO₂). The following examinations were performed:

3. Non-destructive testing of welded joints

They were intended for the evaluation of quality of welded joints. The requirements specified for the B quality level as per PN-EN 25817 standard were assumed as a criterion.

Table 1.
Characteristics of executed welded joints.

No. of the weld	Plate thickness mm	Root face gap mm	Groove angle deg	Welding position	Welding heat input range
1	9	6	45	PF	2.02÷2.35
2	9	8	45	PF	2.34÷2.80
3	9	10	45	PF	1.58÷2.58
4	14.5	6	45	PF	1.80÷2.94
5	14.5	8	45	PF	1.94÷3.51
6	14.5	10	45	PF	1.94÷3.94
7	18.5	6	45	PF	1.63÷3.55
8	18.5	8	45	PF	2.13÷3.82
9	18.5	10	45	PF	2.37÷3.93

4. Visual examinations

They were performed based on the PN-EN 970 standard. All the welded joints covered by the analysis complied with the

requirements for the B quality level. Table 2 presents appearance of the weld faces and the root runs of particular welded joints with characteristic dimensions given.

On the basis of the performed visual examinations the following was found out:

- increase of the root run reinforcement width (maximum by 2.5 mm) with increase of the root face gap,
- increase of the root run reinforcement width (maximum by 4.5 mm) with increase of the root face gap,
- occurrence of undercutting of the root run of the weld on welded test plates on both sides, with root face gap exceeding 8 mm. Permanent character of these undercuts shows that it is necessary to modify the construction of ceramic backing (due to insufficient working area). These undercuts are easily removable because of small depth (less than 0.3 mm). All the test plates complied with the requirements for the B quality level as per PN-EN 25817 standard.

5. Tests of the ferrite content

The measurements were performed with ferritescope (Fig. 6). This instrument, for measuring the ferrite content, makes use of phenomenon of magnetic induction. The examinations covered measurement of the ferrite content (share) at the side of weld face, heat affected zone (HAZ) and base material. The width of heat affected zone (HAZ) was assumed experimentally, i.e. it was specified as the area from the fusion penetration line to 2 mm deep into base material. 20 measurements were performed in each of the zones. Examination results were listed in Table 3 and in Fig. 7.

6. X - ray non destructive examination

All test pieces underwent X-ray examinations which were performed based on the PN-EN 1435:2001 standard. The B quality level as per PN-EN 25817 standard was assumed as a criterion.

On the basis of the performed measurements of the ferrite content the following was found out:

- correct ferrite content in all examined test plates (acc. to relevant requirements of DNV rules),
- the lowest ferrite content (share) for test plates welded with 10 mm root face gap for three examined test plates,
- decrease in ferrite content together with increase of the root face gap (welding heat input increase),
- considerable stability of individual measurements results, especially for measurements performed in the weld face area,
- all the tested welded joints comply with the required quality level – stringent requirements, B quality level. Increasing of the root face gap to 10 mm in butt welded joints does not have an adverse effect on quality level,
- in each of the cases covered by the analysis the basic detected imperfections were single gas pores of size much smaller than the limit values for B quality level,
- no defects in form of cracks or lack of fusion were found.

On the basis of the performed analysis of the examination results there is no relation between the root face gap (range of its value changes) and the obtained quality of the joint.

Table 2. Dimensions of weld faces and the root runs of executed welded joints


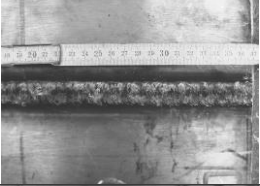




No and dimension of the weld mm	Macro - image of the weld face
No 1 weld face width 18 weld face height 1 root run width 12.5 root height 2	
No 2 the weld face width 19.5 weld face height 1.5 root run width 13 root height 1.5	
No 3 the weld face width 21 weld face height 1.5 root run width 15 root height 2	
No 5 the weld face width 23 weld face height 0.7 root run width 12.5 root height 2	
No 6 the weld face width 24.1 weld face height 1 root run width 14.5 root height 1.5	
No 8 the weld face width 25.5 weld face height 2 root run width 13 root height 2	



Fig. 6. Complete equipment for measuring the ferrite content, 1. calibration standards, 2. measuring probes, 3. ferritescope.

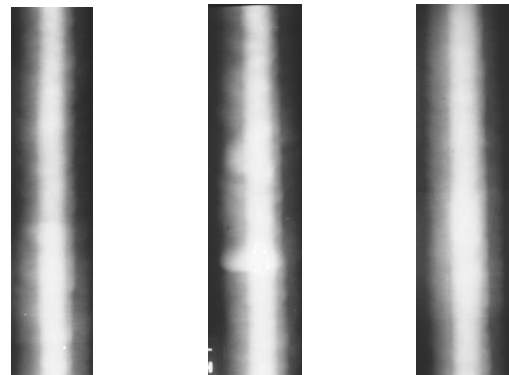


Fig. 7. Correct X – ray images of the sample No. 9 in different areas, done by Technic - Control Sp. z o.o. Szczecin

Table 3. Examples of the tests of ferrite content results of investigated welding joints

No. of the sample	Area of the test	Approximate ferrite content, %
1	Parent material	39
	HAZ	62
	Weld	49
2	Parent material	44
	HAZ	59
	Weld	45
3	Parent material	40
	HAZ	56
	Weld	38
4	Parent material	46
	HAZ	64
	Weld	47
5	Parent material	41
	HAZ	55
	Weld	41
6	Parent material	59
	HAZ	40
	Weld	55
7	Parent material	57
	HAZ	39
	Weld	46
8	Parent material	40
	HAZ	52
	Weld	39
9	Parent material	45
	HAZ	61
	Weld	39

7. Metallographic examination of welded joints

The testing was intended for specifying the welded joints microstructure. As a result of the metallographic analysis, the microstructure of areas (zones) of welded joints, executed depending on welding parameters, was determined. In order to reveal the microstructure of areas (zones) of duplex steel welded joints, chemical and electrolytic etching of microsections (metallographic specimens) was applied.

Specimens for testing were cut out mechanically and then they were subjected to the grinding and polishing process(es). The microsections (metallographic specimens) were subjected to macroetching in Murakami reagent of the following composition:

- potassium hydroxide KOH -10g
- potassium ferricyanide $K_3Fe(CN)_6$ -10g
- distilled water H_2O -100ml

This reagent dyes ferrite dark brown, whereas austenite remains undyed. Metallographic examination was performed using light microscope at x 400 enlargement, according to recommendations of DNV rules Pt.2 Ch.3 Sec.2 D203.

Ferrite volumetric share was determined with net counting method, according to ASTM E562 standard and as per guidelines in DNV Rules Pt.2 Ch.3 Sec.2 D203.

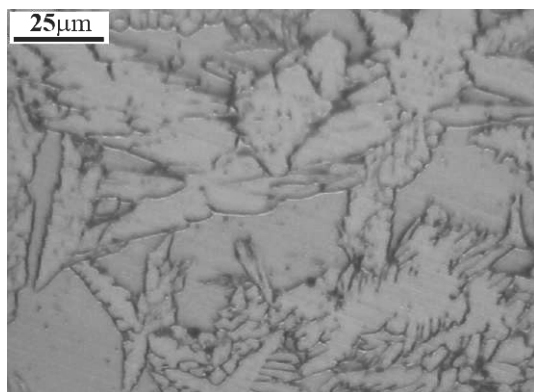


Fig. 8. Typical microstructure of examined weld exemplified by specimen No. 3, face side, x 400 magnification, ferritic – austenitic structure, average value of ferrite share 54%

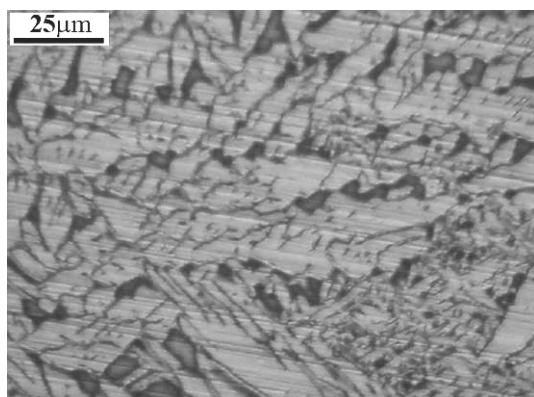


Fig. 9. Typical microstructure of examined of the weld exemplified by specimen No. 9, face side, x 400 magnification, ferritic – austenitic structure, average value of ferrite share 44%

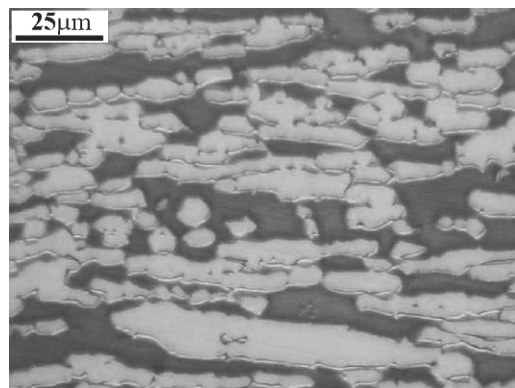


Fig. 10. Typical microstructure of examined of the HAZ exemplified by specimen No. 3, root side, x 400 magnification, ferritic – austenitic structure, average value of ferrite share 43%

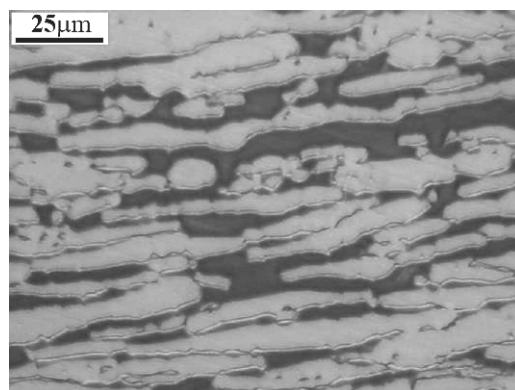


Fig. 11. Typical microstructure of examined of the HAZ exemplified by specimen No. 9, root side, x 400 magnification, ferritic – austenitic structure, average value of ferrite share 35%

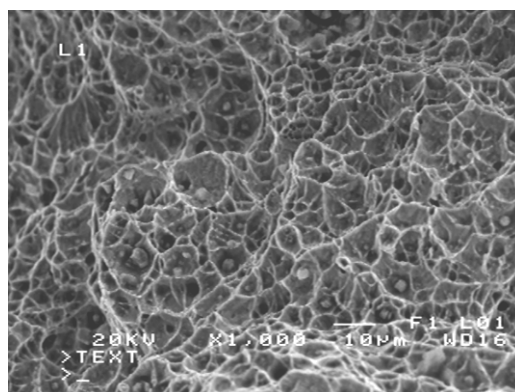


Fig. 12. Ductile fracture of the sample No. 9 weld

8. X-ray structural analysis

The X-ray structural analysis was conducted on modernized diffractometer DRON-3 equipped with counting and control unit Dronek-3. The filtered CoK_{α} radiation was used, of the wave

length $\lambda = 179.021$ pm, at the lamp voltage 40kV and intensity 23 mA. Deflected radiation intensity was measured using scintillation counter. The 5-second impulse counting time was used. Recording was carried out in angular range $2\Theta = 30 \div 105^\circ$ with 0.1° and 0.02° steps. The X-ray impulses supplied to DRONEK-3 from the detection track were counted in 20-bit counter and stored in the internal data memory. The measurement results were periodically transferred via a series connection to the host computer IBM PC. In all the examined test pieces only presence of ferrite and austenite was identified.

In the diagrams (graphs) only selected examination / test results are presented which are typical of all the test pieces.

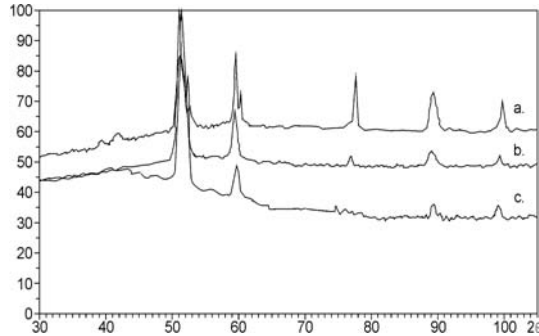


Fig. 13. Specification of diffraction patterns of welds of the samples: a - No. 1, b - No. 5, c - No.9, ferrite and austenite

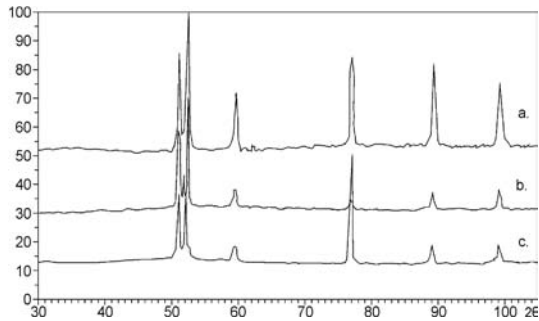


Fig. 14. Specification of diffraction patterns of welds of the samples: a - No. 1, b - No. 5, c - No.9 after grinding off the weld face to 2 mm depth, ferrite and austenite

9. Welded joints hardness and microhardness examination

The testing is intended for determining of hardness and microhardness of duplex steel welded joints.

Specimens for testing were cut out mechanically and then they were subjected to the grinding off and polishing process. The microsections (metallographic specimens) were subjected to macroetching in Murakami reagent.

The HV10 hardness measurements were performed according to the guidelines in the PN-EN 288 – 3, p. 7.4.5. standard. The microhardness measurements were performed using Vickers method at 25g loading.

Value of hardness of all test pieces did not exceed 350 HV, hardness of austenite and ferrite in the tested areas of welded joints was similar, and hardness of austenite was slightly higher than that of ferrite (Table 4 and 5).

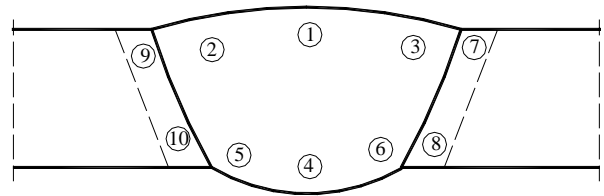


Fig. 15. Diagram of indents distribution in the HV10 hardness testing

Table. 4. HV0.025 microhardness exemplified by sample No. 9

Area on Fig. 15	Ferrite			Austenite		
	Test No.			Test No.		
	1	2	3	1	2	3
1	341	334	304	351	346	347
2	332	328	325	354	356	362
3	301	308	296	357	356	328
4	327	318	328	345	383	347
5	284	349	331	345	353	344
6	296	317	315	341	347	394
7	303	331	325	346	376	287
8	343	346	345	351	359	361
9	313	325	329	353	382	329
10	247	290	327	343	336	275

Tab. 5. HV10 hardness exemplified by sample No. 9

Area on Fig. 15	Test No.		
	1	2	3
1	305	309	313
2	306	308	315
3	318	321	321
4	323	343	325
5	329	334	327
6	324	338	329
7	338	342	328
8	332	353	316
9	335	349	317
10	323	331	324

10. Corrosion resistance examination

The tests were intended for obtaining qualitative and quantitative corrosion resistance of the tested welded joints.

The corrosion resistance tests were performed according to ASTM G48 - 76 standard using method A.

The test pieces were collected from the welded joints mechanically (cut with bandsawing machine). Then they were subjected to grinding off treatment (using abrasive disks of granularity 120) and to polishing with polish disks. The test pieces, prior to undergoing corrosion resistance tests, were subjected to 2 hour passivation using the pickling and passivating paste - Avesta Pickling Paste-101.

The test solution was prepared from: ferric chloride (III) $\text{FeCl}_3 \cdot 6\text{H}_2\text{O}$ (100g) and distilled water (900 ml). The test pieces were immersed in test solution for 24 hours. After the performed tests visual examination of the test pieces surfaces and weighing were carried out.

In none of the examined test pieces corrosion pits were detected. The highest mass decrement (loss) equal to 3.5 mg (the permissible level being 20 mg) was found out on test piece No. 2. Negligible loss (decrement) in mass was observed in all test pieces with high corrosion resistance of the passive layer.

11. Conclusions

- The performed tests and examinations of welded joints with root face gap ranging from 6 to 10 mm were intended for extending the standard range from 2 to 6 mm. Thus increased range is optimum, considering assembly and welding of large-size constructions where the technology permits for example cutting off the assembly allowances. Increase of the root face gap above 10 mm unjustified economically and it may cause considerable deformations of welded constructions.
- The performed non-destructive testing indicate the possibility to obtain welded joints of the required high quality, even in case of welded test pieces with the root face gap 10 mm. As a result of the performed inspection, decreasing of the ferrite content (share) with the increase of the root face gap (increase of welding heat input) was observed. The minimum measured ferrite content (share) was not lower than 28 % and the maximum value did not exceed 69% (the permissible range being from 25 to 70 %).
- The structural tests and examinations carried out confirm occurrence of only two phases: that of austenite and that of ferrite. In none of the tested and examined areas occurrence of micro-cracks, intermetallic phases or releases was detected.
- Corrosion resistance tests performed with three methods indicate occurrence of the passive layer on the examined test pieces, characterized by considerable resistance to aggressive factors exposure.
- Results of visual examinations of welded joints indicate necessity to change the construction of ceramic backings in case of welding with gaps exceeding 8 mm (increasing of the ceramic backing width and groove shape). Use of commonly available ceramic backings (like those used during the conducted tests of welding of PS-11/1.9 type backing made by IMO Gliwice) involves necessity of removal of undercutting of the root run occurring in the weld on both sides.
- So as to sum up, one can conclude that the wide-gap welding (with root face gap up to 10 mm) of duplex steel joints in vertical position does not have an adverse effect on structural and corrosion-resistance properties. When the technological process is carried out in an appropriate way, the welded construction can be executed (without the necessity to repair the welded joints geometry) using the extended range of the root face gap.

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