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Mechanical properties of duplex steel welded joints in large-size constructions

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Materials

ABSTRACT

Purpose: On the basis of sources and own experiments, the analysis of mechanical properties, applications as well as material and technological problems of ferritic-austenitic steel welding were carried out. It was shown the area of welding applications, particularly welding of large-size structures, on the basis of example of the FCAW method of welding of the UNS S3 1803 duplex steel in construction of chemical cargo ships.
Design/methodology/approach: Welding tests were carried out for duplex UNS S31803 steel plates, 9.5, 14.5 and 18.5 mm thick, with flux-cored wire The effect of welding with increased threshold space on mechanical properties of welded joints was determined when compared to those obtained in result of welding with 6 mm threshold space as well as to recommendations of DNV regulations and rules
Findings: It was shown that widening of threshold space tolerance and wide-gap welding of duplex steel is possible, i.e. completion of welded joints by one-side vertical bottom-top welding (PF) with no need for applying the process of edge pad welding in case of weld groove geometry with the threshold space ranging 6 to 10 mm, from the point of view of meeting requirements with respect to mechanical properties by welded joints
Research limitations/implications: The welding heat input exceeding the recommended values might influence 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; Materials; Welding; Welding joints properties

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1. Introduction

Duplex stainless steel welded joints have to be characterised by very high quality in case of large size constructions (with the length of welded joints above 5000 mm) intended for transportation of liquid chemical products, i.e. to meet at least the requirements of quality level B according to PN-EN ISO 5817 standard. At the same time, fusion weld surface should be smooth to counteract deposition of load residues. The proper structure of fusion weld for duplex steel welded joint is characterised by controlled content of ferrite and can not contain noxious phases such as carbides ($Cr_{23}C_6$) or sigma phases (FeCr). Due to two-phase structure, high quality criteria and complex character of microstructural changes, welding of duplex steels used in large-size constructions was successful in result of the influence of complex thermal cycle only in case of few production plants worldwide.

2. The state of the problem

Factors deciding about the structural and operational properties of butt welded joint formed from homonymous duplex steel materials using flux-cored wire can be systemised into the following sets:

- metallurgical parameters of duplex construction steels,
- metallurgical parameters of steel strips forming the core of flux-cored wire,
- parameters characterising components of the flux of flux-cored wires,
- parameters characterising the geometry of weld groove,
- parameters characterising the process of active gas-arc welding with flux-cored wire [1-5].

Out of the aforesaid parameter sets, the least examined (i.e. described in literature) is the one characterising welded joint geometry. Effect of respective parameters representing the weld groove on the parameters of welded joints seems to be important. Based on the analysis of literature, it is possible to state that from among parameters characterising welded joint geometry and affecting the properties of welded joints a significant importance may have the threshold space. Leading manufactures of the fillers for duplex steel welding recommend optimum ranges for the values of respective weld groove parameters in their published materials. In general, they are based on a limited number of welding tests and usually do not include the specific character of constructions with large dimensions. Under real conditions, completion of large-size duplex steel welded constructions can be connected (with many other parameters) with large variability in preparation of the edge for welding, making at the same time production problems. There can occur then sections of welded joints with parameters exceeding literature-recommended values. In such cases, reproduction of the geometry of weld groove is used before completing welded joint through pad welding of one or both edges. Due to completion reasons and taking technological and economic aspects as well as qualitative criteria into consideration, the repair process of welded joints should be significantly reduced or completely excluded. Achieving these conditions should be a two-step process. The first step is to aim at making a construction being characterised by preservation of assumed tolerances, without using and removing assemble allowances at the stage of integration on constructions on their assembly. The second step, which can be carried out parallel, is to expand the range of tolerances for the threshold space in such a way so that, on the one hand, requirements with respect to appropriate standards and regulations are being met by it and, on the other hand, it includes technological possibilities of a given production plant.

Literature insufficiently describes the process of gas-shielded welding of welded joints with flux-cored wire (FCAW) with a threshold space larger than recommended one. Enlargement of the threshold space is directly connected with an increase in the quantity of introduced heat (Q) when making a weld penetration layer. In case of the filling and facing layers, Q may increase or a division of respective layers into single welding runs with smaller unit quantity if introduced heat can be made, depending on welding position. In both cases, this will have effect on enlargement of total thermal cycle of welding. Under conditions of the multi-run welding of duplex steel, with the assumed thermal cycle, respective zones of welded joint are exposed to microstructural changes being not fully examined, which may critically affect welded joint mechanical properties. The objective of this paper is to analyse the effect of threshold space with values larger than literature-recommended ones on mechanical properties of welded joints [6-10].

When observing the world building industry of large-size constructions intended for transportation and storage of chemical products at the turn of last years, an upward trend is visible in using duplex stainless steels. Two-phase ferrite-austenitic structure of these steels ensures higher operation values in relation to traditionally used stainless steels with one-phase austenitic structure. Duplex steels are characterised by higher mechanical properties with increased corrosion resistance. In order to achieve these properties, microstructure has to be characterised by a proper ferrite to austenite ratio. The developed quality criteria for welded joints refer to macro- and microstructure, phase composition, mechanical properties and corrosion resistance. The character of thermal cycle (first of all the quantity of introduced heat) during the welding process has a critical effect on meeting these criteria. At different construction stages, starting with prefabrication and finishing with assembly, there is a need of completing welded joints in different forced positions. As a rule, these positions force using maximum Q, of course within a range allowed by technology. High quantities of introduced heat result first of all from a limited possibility of increasing the linear velocity of welding in these positions. Publications referring to duplex steel welding show that range of the recommended quantity of introduced heat should amount to 0.5 to 2.0 (2.5) KJ/mm. However, there is no explicit view on possibility of enlarging this range. Such an expansion is mainly required due to completion reasons.

When building large-size constructions, there are welded joints which are welded vertically bottom-top (PF). In such cases, mechanised welding is usually used with application of automatic welding machines, welding being made with flux-cored wires in the atmosphere of active shielding gas. Such an automatic welding machine moves on a guide rail which is fastened by means of neodymium magnets to duplex sheet metal plate [11-15].

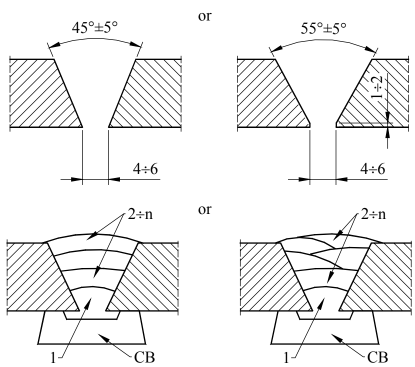


Fig. 1. Scheme of one-side welding on ceramic backings; CB- ceramic backing, 1- root run, 2-n- filling layers and face of weld

When welding the welded joints of this type, one-side welding on ceramic backing strips is used. The root of weld penetration layer is formed then by means of a ceramic backing strip (Fig. 1), which is being placed from the side of backstays. After completion of fusion weld, this backing strip is being removed. The obtained fusion weld root does not require making additional supportive operations, e.g. gouging and pre-welding or grinding.

When using this type of welding, metal plate edges are bevelled at “1/2V”, which gives in result a weld groove with “V-symmetric” geometry. One-side welding with “V”-prepared weld groove is usually used for metal plate thickness ranging 8 to 18 mm. The use of other type bevelling, e.g. „X”-shaped with two-side welding, can not be achieved since there is usually no possibility to fasten automatic welding machine from another welding side due to one-sided backstay system. One-side welding of metal plates with a thickness to 20 mm in large-size constructions is superior to two-side welding (double-sided welding) due to:

- possibility of automating the completion of all fusion weld layers,
- favourable shape of the obtained weld penetration layer protecting against development of crystallisation cracks,
- reduction of labour consumption in the completion of welded joint,
- reduction of labour consumption needed for edging,
- improvement of welder-operator work ergonomics.

A shortcoming is possibility to develop angular strains of welded joint. This problem can be solved by using appropriate welding technology, consisting mainly in proper welding sequence and special stiffening of welded joint. One of the key issues during the welding of such a welded joint is to preserve proper geometry of weld groove during the carried out process. Basic parameter characterising the geometry of weld groove, affecting the value of introduced heat quantity and in consequence the properties of welded joints, is the threshold space. In case of welded joints welded one-side in large-size constructions, a value of threshold space ranging 4 to 6 mm is being generally adopted. The given boundary values result directly from the experience of completing similar welded joints. They constitute a compromise between obtaining proper mechanical and microstructure properties and economic profitability of the carried out welding process. In case of reducing the threshold space below 4 mm for one-side welding on ceramic backing strips, difficulties show up in completing the weld penetration layer. The root of this layer does not meet requirements of the quality level B (according to PN-EN ISO 5817 standard) with respect to the geometry of weld reinforcement and the occurring surface unconformities. Making a layer in vertical welding position (PF) is hampered due to heat accumulation on a small area. This may cause development of local unconformities in the form of excess penetration beads, incomplete fusions induced by large number of joints (welding end and start sites) between respective sections of the weld penetration layer. Then, a trend for increased defectiveness of weld fusions is being observed. This results in the necessity of increasing repair range. In consequence, this can bring about a decrease in customer confidence in the aspect of completing welded joints. This can also contribute to enlargement of total construction completion costs through increasing the scope of inspection (both inter-operation and final one). It is being aimed at that the minimum value of threshold space before and during the welding is not smaller than 4 mm. The maximum value of threshold space (6 mm) results mainly from the experience of manufactures of welding materials with respect to obtaining welded joint mechanical and microstructure parameters. Due to poor available literature on the welding of large-size constructions where the main problem is to preserve proper completion tolerances, it is recommended to repair the weld groove before welding in case of exceeding the maximum value of threshold space (being 6 mm). This repair can be performed in two ways. The first method is to replace and insert a new fragment of metal plate. In this case, however, we deal with additional fusion weld connecting a “new” fragment with the “old” one. This method is used only as a last resort. The second method is to re-build the edge of metal plate through its pad welding (Fig. 2, Fig. 3).

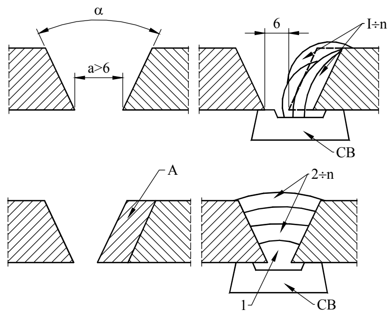


Fig. 2. Scheme of one-side welding with edge repairing before welding with the aid of building up; a- root gap, α- groove angle, CB- ceramic backing, I-n- padding welds, A- building’s up area after grinding, 1- root run, 2-n- filling layers and face of weld

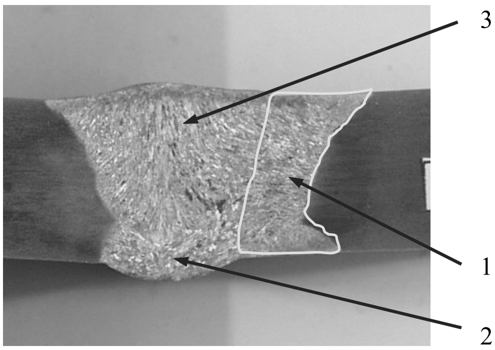


Fig. 3. Macrostructure of welded joint with visible edge repairing with the aid of building up; 1- padding welds, 2- root run, 3- filling layers and face of weld

The process of preparing weld groove using the pad welding of metal plate edges is a complicated and milt-step process. It includes not only edge re-building but also its proper preparation for welding. Due to the need of „moving” within the area of minimum parameters, the pad welding is characterised by unusually high degree of defectiveness. Very frequently, defects occur in the form of incomplete fusions or non-metallic inclusions. Completion of the proper padding weld of metal plate edge requires very high skills. It is a long-lasting and extremely labour consuming process.

The range of dimensional tolerance for the threshold space of 2 mm giving a gap dimension ranging 4 to 6 mm, resulting from literature recommendations, is too small in case of welding the welded joint of total length above 5 m. For completion of large-size construction (length of welded joints >5 m), preservation of such a narrow tolerance for the basic parameter of weld groove is practically impossible and in many cases these dimensions are being exceeded. This results most frequently from tolerances adopted for respective operations since the marking-out tolerance, for instance, is within a range of ±1 mm, while that for plasma arc cutting amounts to ±2 mm. Measuring errors are within a tolerance range of ±1 mm. In certain cases, there is a tolerance stack-up for respective operations and violation of the obtained dimension of threshold space. Most frequently, there is an in plus expansion of tolerances, i.e. dimensions of threshold space are larger than 6 mm (within a range of 6-10 mm). This way, the process of weld padding is being knowingly introduced into the basic process of completing a welded joint. In the procedures adopted as generalities, edge pad welding is applied before welding in case of gap larger than 6 mm

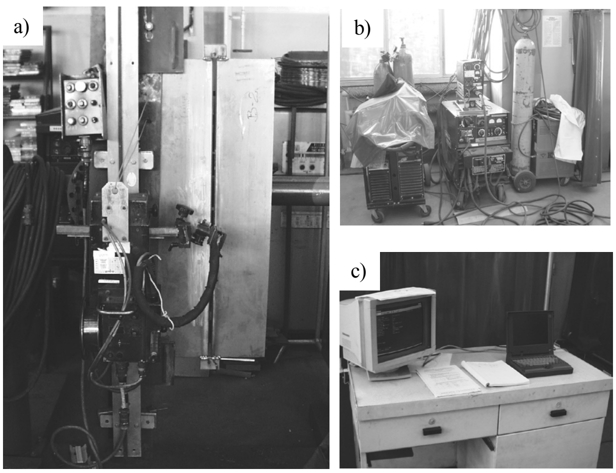


Fig. 4. View of stand for mechanized butt welding of tested joints: a) automatic welding machine with installed tested joint, b) welding rectifier, gas bottle with preheater, gas regulator and electric wirings, c) welding parameters registration equipment

The process of pad welding, as mentioned above, is a specific process, very difficult for completion and labour consuming. Widening of the tolerance of threshold space and wide-gap welding of duplex steel, i.e. completion of welded joints by one-side vertical bottom-top welding (PF) with no need for applying the process of edge pad welding is therefore a primary objective in case of weld groove geometry with the threshold space ranging 6 to 10 mm, bringing about reduction of the costs of welded construction production. The range of threshold space (6-10 mm) adopted for welding tests and carried out research was determined based on:

- analysis of weld groove technological and economic parameters,
- analysis of the ability to preserve adopted geometry tolerances during assembly of large-size construction in the open space allowing for unfavourable effect of surrounding conditions (e.g. thermal expansion due to temperature difference, non-uniform heating of construction with sunbeams).

3. Formation of welded joints

Welded joints were made by means of mechanised welding using a Bugo-matic automatic welding machine (Fig. 4) and applying the following materials:

- flux-cored wire Cromacore DW329AP (with rutile powdered flux), 1.2 mm in diameter, manufactured by Elga (Tab. 1),
- shielding gas in the form of 100%CO_2,
- duplex steel UNS S31803, 9.5, 14.5 and 18.5 mm thick, manufactured by INDUSTEEL Groupe Arcelor (Tab. 2),
- V-shape bevelling, one-side welding with the geometry of welded joints presented in Figure 5,
- flat ceramic backing strips, manufactured by IMO Gliwice, in two types: PS-11/1.9 and PS-14.

The method of stiffening welded joints, protecting against excessive transverse angular strain, was selected experimentally - by applying one-piece run-on and sectional run-off straps (Fig. 6) as well as five assembly clamps fastened from the side of ceramic strip. Figure 7 presents distribution of layers in respective welded joints. In Figure 8 is presented the arrangement of samples for testing of mechanical properties, whereas in Table 3 are presented types of samples used in respective tests. In Figures 9 and 10 are presented diagrams showing the arrangement of impressions in HV10 and HV0.25 hardness tests. The result of welding tests was production of nine welded joints (Tab. 4).

Table 1.
Chemical analysis of flux cored wire CROMACORE DW329 AP produced by Elga [% by weight]

C	Si	Mn	P	S	Cr	Ni	Mo	N	Cu	V	Nb
0.02	0.8	1.3	0.025	0.007	22.9	9.2	3.0	0.10	0.02	0.1	0.08

Table 2.
Chemical analysis of plate grade UNS S31803 [% by weight]

Thickness	C	Si	Mn	P	S	Cr	Ni	Mo	N	PREN *
9.5 mm	0.018	0.41	1.61	0.029	0.0002	22.41	5.36	2.82	0.17	34.4
14.5 mm	0.021	0.39	1.64	0.027	0.0003	22.62	5.36	2.81	0.18	34.7
18.5 mm	0.016	0.41	1.64	0.026	0.0002	22.59	5.37	2.84	0.18	34.8

* PREN- Pitting resistant equivalent number

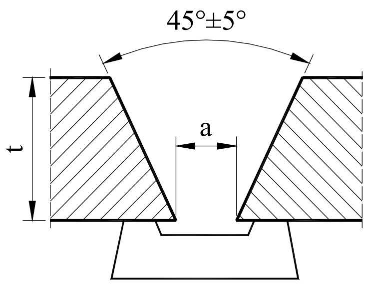


Fig. 5. Welded joints geometry; a- root gap (6; 8 i 10 mm), t - plate thickness (9.5; 14.5 i 18.5 mm)

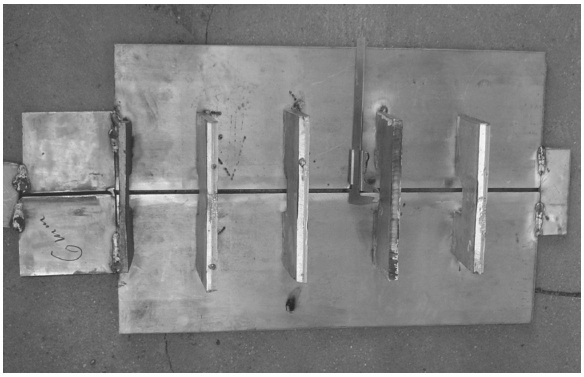


Fig. 6. View of welded joints protection before transverse angular distortion

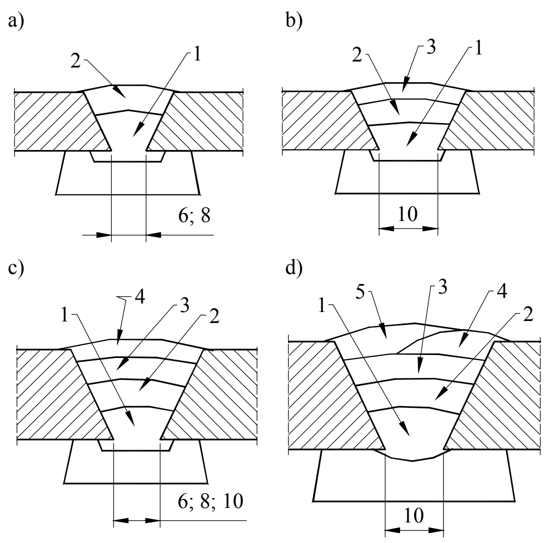


Fig. 7. Layers arrangement for particular welded joints: a) plate thickness 9.5 mm, root gap 6 and 8 mm, b) thickness 9.5 mm, root gap 10 mm, c) thickness 14.5 mm, root gap 6; 8; 10 mm, and for plate thickness 18.5 mm for root gap 6 i 8 mm, d) thickness 18.5 mm, root gap 10 mm

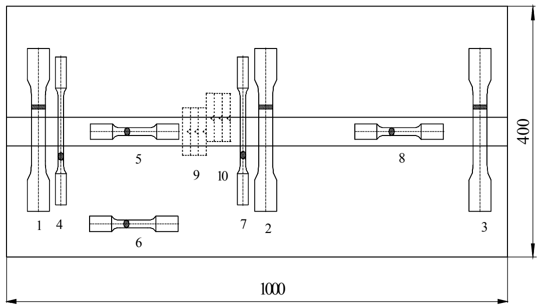


Fig. 8. Specimens arrangement for destructive testing; *1, 2, 3* - flat specimens, located perpendicular to weld axis, cut from the beginning, middle and the end of weld; *4, 7* - round specimens, located perpendicular to weld axis; *5, 8* - round specimens, located in the weld axis; *6* - round specimens, located parallel to the weld, within the distance of 100 mm from the weld axis; *9* - specimens for measure impact strength, notch in the weld axis (3 pcs.); *10* - specimens for measure impact strength, notch in the fusion line (3 pcs.)

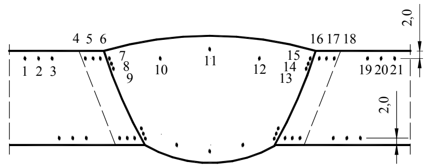


Fig. 9. Lay-out of indentations in hardness test HV10

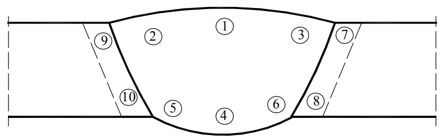


Fig. 10. Lay-out of indentations in hardness test HV0.025

4. Tensile strength of flat samples

In welded joints of metal plates with the least thickness analysed (9.5 mm), an increase in mean values of tensile strength (R_m) and tear stress (R_u) was observed together with an increase of the quantity of introduced heat (Q) - Fig. 11. In welded joint with a maximum space (10 mm) being characterised by the least range and standard deviation of obtained results, a favourable effect of the introduction of additional filling layer (resulting from technological reasons of welded joint completion) on the obtained values R_m is visible. In case of one sample collected from welded joint with a space of 8 mm, a crack occurred in weld fusion. This sample is also characterised by the least narrowing (Z).

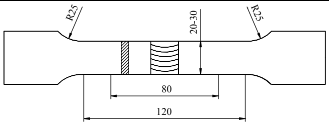
The phenomenon of increasing R_m and R_u together with an increase in the threshold space from a minimum value (6 mm) the maximum one (10 mm) is also observed in welded joints of metal plates with thicknesses of 14.5 mm and 18.5 mm. The size of this increase depends on the applied mean quantity of introduced heat

($\overline{Q}$). It is clearly visible for metal plates with a thickness of 18.5 mm welded with the following spaces: 6 mm ($\overline{Q}$=2.66 KJ/mm) and 8 mm ($\overline{Q}$=3.11 KJ/mm). On the other hand, a decrease in R_m and R_u is observed for a 10 mm gap due to introduction of an additional run into the facing layer, despite a slightly higher quantity of introduced heat ($\overline{Q}$=3,22 KJ/mm). As far as the narrowing of analysed samples is concerned, there is a small decrease in the narrowing value (Z) with an increase in the gap size between welded elements, irrespective of the thickness of welded elements.

Table 3.
Types of samples used in mechanical properties research

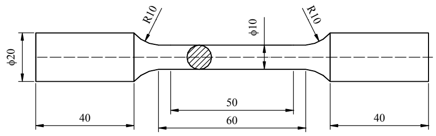
Samples dimensions and criterion realization conditions

Flat samples

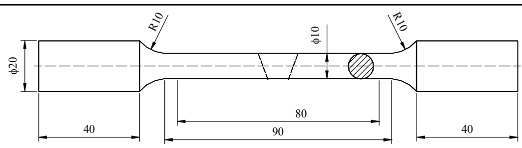


- R_m > 620 MPa,
- testing temperature +22°C

Round specimens located in the weld axis

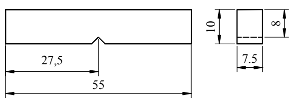


Round specimens, located parallel to the weld

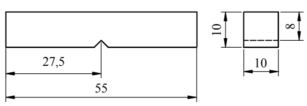


- $R_{e0.2}$ > 450 MPa
- R_m > 620 MPa,
- A_t > 20%
- E > 180 GPa
- testing temperature +20°C

Specimens for measure impact strength
Joints of thickness 9.5 mm



Joints of thicknesses: 14.5 and 18.5 mm



- IE^{-20} > 27 J
- KV^{-20} > 34 J/cm^2
- testing temperature -20°C

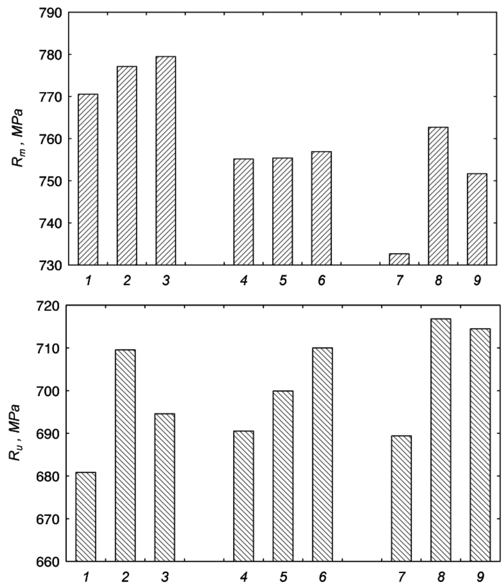


Fig. 11. Average tensile strength (R_m), average true tensile stress (R_u) of flat specimens; *1, 2, 3*- samples cut from joints of thickness 9.5 mm welded with the root gap: 6, 8 and 10 mm; *4, 5, 6*- samples cut from joints of thickness 14.5 mm welded with the root gap: 6, 8 and 10 mm; *7, 8, 9*- samples cut from joints of thickness 18.5 mm welded with the root gap: 6, 8 and 10 mm

Table 4.
Welded joints characteristics

Joint no	Plate thickness [1] [mm]	Root gap [mm]	No of layers	Q_{min} [2] [KJ/mm]	Q_{max} [2] [KJ/mm]	$\overline{Q}$ [2] [KJ/mm]
1	9.5	6	2	2.12	2.27	2.20
2	9.5	8	2	2.52	2.61	2.56
3	9.5	10	3	1.63	2.46	2.12
4	14.5	6	4	1.94	2.74	2.20
5	14.5	8	4	2.03	3.36	2.44
6	14.5	10	4	2.06	3.81	2.85
7	18.5	6	4	1.69	3.37	2.66
8	18.5	8	4	2.30	3.59	3.11
9	18.5	10	5	2.53	3.76	3.23

[1] real plate thickness

[2] Q_{min}, Q_{max}, $\overline{Q}$ - minimal, maximum and middle value of heat input, calculated acc to PN-EN 1011-1 in accordance with formula: $Q = k* ((I*U)/V)*10^{-3}$ [KJ/mm], where: k- thermal efficiency factor, I- current intensity [A], U- arc voltage [V], V- welding speed [mm/s]

5. Tensile strength of cylindrical samples

During determination of the tensile strength of cylindrical samples collected perpendicular to fusion weld, i.e. including both the fusion weld and heat-affected zone and the basic material, no physical yield point was found. Analysis of the test results showed a small increase in the proof stress ($R_{e0.2}$) for samples collected from the vicinity of welded joint start with increasing the threshold space to a maximum value.

The extreme in this case occurs in welded joint with a gap of 10 mm (Fig. 12). The central area of welded joints is characterised by the occurrence of minimum value $R_{e0.2}$ for a sample welded with an average gap (8 mm) and is being distinguished by very similar proof stress values for welded joints with a minimum gap (6 mm) and a maximum one (10 mm).

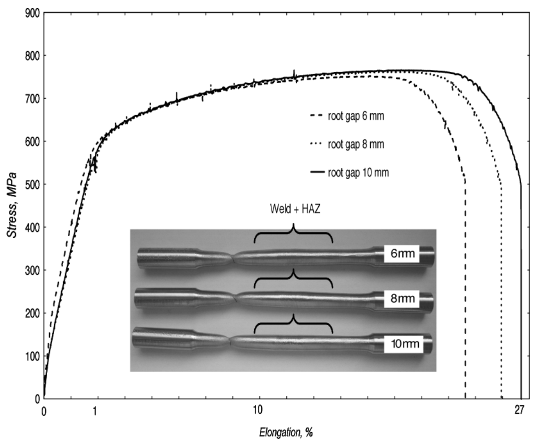


Fig. 12. Stress-strain curve in tension of round samples situated perpendicular to weld axis, within the distance of ~75 mm from the beginning of the weld

During the test, the least obtained value $R_{e0.2}$ was ~510 MPa, whereas the requirements (DNV regulations) mention a minimum value of 450 MPa. Welded joints, irrespective of the size of gap between welded edges, are characterised by similar stress patterns up to R_m (Fig. 12). Effect of the tested areas on the percentage elongation (A_t) was found.

The start of welded joints is characterised by the occurrence of the extreme for welded joints with maximum space. In the central part of welded joint, $A_{t\ max}$ was found for a 8 mm gap. In both areas, increase of the threshold space does not cause a decrease in A_t when compared to the values obtained with minimum space. Increase of the threshold space affects an increase in the tensile strength (R_m), irrespective of the area where samples for tests have been collected. Maximum values R_m are typical for a welded joint with the largest threshold space (10 mm).

The largest value of the longitudinal modulus of elasticity (E) for samples situated in the vicinity of welding start point was obtained for a welded joint with the threshold space of 10 mm and for samples cut-out from the central part of welded joint in case of the threshold space of 6 mm. In each of the analysed areas, E_{min} occurs for welded joints with a gap being 8 mm.

Basing on the analysis of the results of mechanical tests for cylindrical samples cut-out from the fusion weld axis and the basic material parallel to fusion weld at a distance of 100 mm from its axis, $R_{e0.2\ min}$ was found in samples collected from a welded joint with average space (8 mm). The welded joint with maximum space (10 mm) is characterised by the largest values $R_{e0.2}$, whereas the extreme occurs for a welded joint with minimum space (6 mm) both for samples cut-out from the central part and those from the start site of welded joint (Fig. 13).

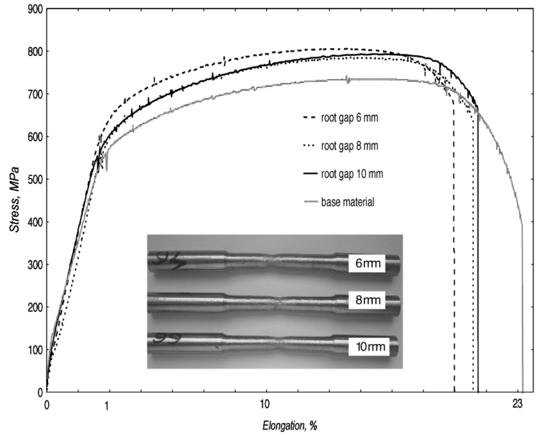


Fig. 13. Stress-strain curve in tension of round samples situated in the weld axis within the distance of ~125 mm from the begging of the weld and in the base material

Samples collected from the basic material are characterised by $A_{t\ max}$. In case of measurements for samples situated in the longitudinal axis of fusion weld, the largest single value A_t was obtained for a welded joint with the threshold space of 10 mm. The least scatter of test results is typical for a welded joint with an 8 mm gap. For a welded joint with a gap of 6 mm, $R_{m\ max}$ occurs. Increase of the threshold space induces a small decrease in the R_m value but these values are higher in each analysed area than those observed in the basic material (Fig. 13). As far as the obtained results of the longitudinal modulus of elasticity (E) are concerned, the value extreme occurs in a welded joint with the threshold space of 10 mm, irrespective of the tested area (vicinity of fusion weld start or end site). In case of the same number of runs in welded joint, an increment in the threshold space inducing a rise in the mean quantity of introduced heat leads to an increase in the mean content of austenite in welded joint. This in turn contributes to a small decrease in the proof stress and the tensile strength, with a simultaneous increase of the mean value of percentage elongation and longitudinal modulus of elasticity.

6. Impact resistance

Samples were cut-out from welded joints from the side of the weld root at a distance of ~2 mm from metal plate surface. Basing on the results of impact resistance tests (at -20°C) for samples situated in the fusion weld axis and the fusion lines of welded joints of 9.5 mm thick metal plates, an increment in the mean value of impact resistance (KV^{-20}) was found as the threshold space increased (Fig. 14). The maximum $KV^{-20\ avg}$ occurs with the threshold space of 8 mm. This welded joint is also distinguished by the least range and standard deviation. In case of welded joints of a 14.5 mm thick metal plate, a clear increase of $KV^{-20\ avg}$ is being observed. The value extreme occurs in welded joints with maximum space (10 mm), both in samples with a notch situated in the axis and the fusion line. Welded joints of metal plates with the largest thickness (18.5 mm) are characterised by a small increase of KV^{-20} after increasing the threshold space to 8 mm. For welded joints with a gap equal to 10 mm, there is a decrease in KV^{-20}

below the values obtained for welded joints with the threshold space of 6 mm (Fig. 14). On the other hand, the extreme of KV^{-20}_{avg} value in the fusion line occurs in a welded joint with a gap of 10 mm. It was found that increase of the number of welded joint runs (increase of the number of thermal cycles) brings about a drop in impact resistance in the fusion weld axis (e.g. at a metal plate thickness of 9.5 mm for the threshold space of 10 mm). The observed scatters of test results in the fusion line may result from the shape of fusion weld line and the location of notch, which should theoretically include in equal parts the fusion weld and the heat-affected zone.

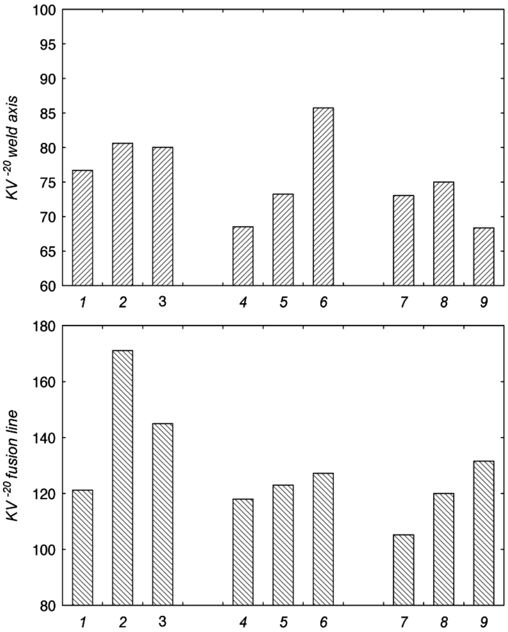


Fig. 14. Average impact strength of samples cut from welded joints; *1, 2, 3*- samples cut from joints of thickness 9.5 mm welded with the root gap: 6, 8 and 10 mm; *4, 5, 6*- samples cut from joints of thickness 14.5 mm welded with the root gap:6, 8 and 10 mm; *7, 8, 9*- samples cut from joints of thickness 18.5 mm welded with the root gap: 6, 8 and 10 mm

The factographic analysis was carried out of the fractures of impact resistance test samples (being characterised by the least values of breaking work) from the area of the fusion weld axis and the fusion line of welded joints with metal plate thicknesses of 9.5, 14.5 and 18.5 mm welded with the threshold spaces of 6, 8 and 10 mm. Trans-crystalline sample fractures were found having a plastic character, with fibrous fractures and visible inclusions of slag originating in the welding process (Fig. 15). Welded joints with a maximum threshold space are being distinguished by the least number of non-metallic inclusions. All analysed fractures of the samples from impact resistance tests are characterised by a honeycomb structure. These fractures have a ductile character in result of plastic strain. On the pit bottoms, micro-caverns are visible. Randomness of the inclusion distribution as well as a non-uniform picture of pits is observed. On all examined fractures, damaged crystallites of slag inclusions occur on the bottom of larger pits. No grains growth was observed in the samples welded with increased threshold space.

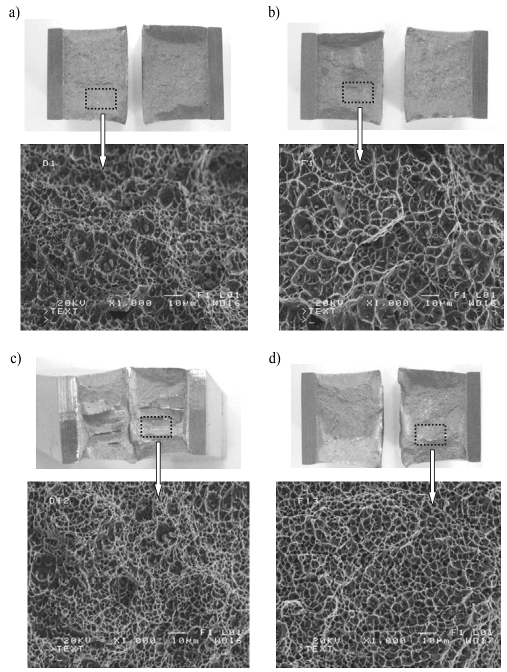


Fig. 15. Samples fractures after impact strength researches (base material thickness: 14.5 mm): a) welded joint with the root gap of 6 mm - notch in the weld axis, b) welded joint with the root gap of 10 mm - notch in the weld axis, c) welded joint with the root gap of 6 mm - notch in the fusion line, d) welded joint with the root gap of 10 mm - notch in the fusion line. SEM magnification 1000x

7. Welded joint hardness HV10

For metal plate thickness of 9.5 mm, a drop in hardness is observed from the side of the weld root in the weld penetration layer for the same number of runs (in case of gaps of 6 and 8 mm) together with an increase in Q value (Fig. 16). This is caused by thermal influence of a successive placed layer, i.e. of the facing layer in this case. The weld face, at a space of 8 mm, is being characterised by a larger quantity of introduced heat (Q=2.61 KJ/mm) in relation to a space of 6 mm (Q=2.27 KJ/mm).

When comparing the obtained values of hardness (HV10) in the fusion weld root for spaces of 6 and 10 mm, an increase in this value is being observed for a space of 10 mm, which is visible in particular in the area of weld penetration layer, despite the higher quantity of introduced welding heat. This is explained by the fact that an additional run was completed at a space of 10 mm due to technological reasons, applying Q at a level of 1.63 KJ/mm.

Basing in the test results, it is possible to state that an increase in the quantity of thermal “charge” of a successive placed layer brings about a decrease in the hardness of previous layer, i.e. of the weld penetration layer on this case. When analysing the results of HV10 measurements from the side of the fusion weld face for threshold spaces of 6 and 8 mm, it is possible to state that increase of Q brings about an increase in hardness. This phenomenon can be also observed in the heat-affected zone at a space of 10 mm.

On the other hand, in case of the fusion penetration line and the fusion weld face for a space of 10 mm the facing layer was completed with a higher current strength and a higher welding speed but with a slightly smaller quantity of introduced heat due to additional filling run. The higher values found, in particular within the weld face area, when compared to a space of 8 mm result directly from different cooling conditions (larger cooling speed).

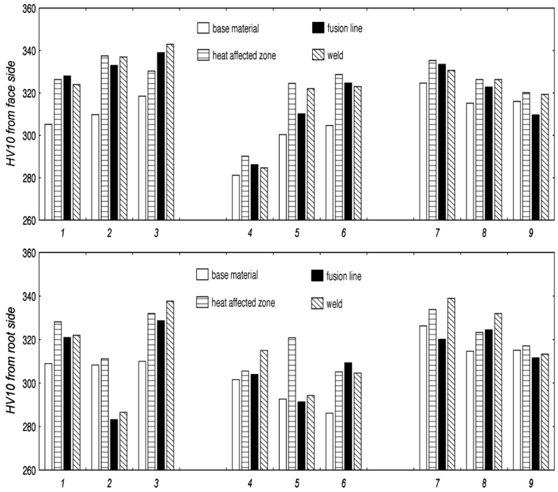


Fig. 16. Vickers hardness (HV10) of welded joints; *1, 2, 3*- samples cut from joints of thickness 9.5 mm welded with the root gap: 6, 8 and 10 mm; *4, 5 ,6*- samples cut from joints of thickness 14.5 mm welded with the root gap: 6, 8 and 10 mm; *7, 8 ,9*- samples cut from joints of thickness 18.5 mm welded with the root gap: 6, 8 and 10

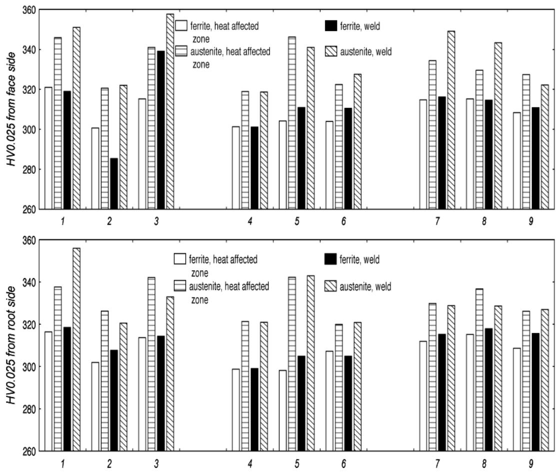


Fig. 17. Vickers hardness (HV0.025) of welded joints; *1, 2, 3*- samples cut from joints of thickness 9.5 mm welded with the root gap: 6, 8 and 10 mm; *4, 5, 6*- samples cut from joints of thickness 14.5 mm welded with the root gap: 6, 8 and 10 mm; *7, 8, 9*- samples cut from joints of thickness 18.5 mm welded with the root gap: 6, 8 and 10 mm

In case of hardness measurements in welded joints of 14.5 thick metal plates from the side of fusion weld root, a decrease in hardness is being observed within the area of weld penetration and fusion weld lines together with an increase in welding linear energy. From the side of fusion weld face for this metal plate thickness, increase of the quantity of introduced heat brings about an increase in hardness, like with 9.5 mm thickness. However, it is possible to observe that for threshold spaces of 8 and 10 mm welded at extremely high Q (>3.3 KJ/mm) and with large difference between respective values of introduced heat the differences between mean hardness values in the heat-affected zone and the fusion weld are small. The phenomenon of decreasing hardness in all areas of the weld penetration layer, despite applying a higher quantity of introduced heat, is clearly visible in case of measurements in welded joints of 18.5 mm thick metal plates. Like with thicknesses being discussed above, a degree of this decrease depends on the quantity of introduced heat when welding the first filling layer. Measurements from the side of fusion weld face for this thickness of metal plates for a space of 6 and 8 mm are characterised by a small increase in hardness with rises in the quantity of introduced heat. Slightly smaller hardness values observed in a welded joint with a 10 mm space, when compared to a space of 8 mm, may result from division of the facing layer into two runs, despite application of higher Q. The second run of the facing layer brings about another influence of the heat cycle on a part of the first run of the weld face.

8. Welded joint hardness HV0.025

In result of HV0.025 hardness tests in 9.5 thick welded joints, $HV0.025^{min}$ is being found for austenite and ferrite grains, from the weld face side, in a welded joint with average threshold space. On the other hand, $HV0.025^{max}$ was obtained in case of a welded joint with maximum space. The analysis of HV0.025 hardness distribution in the measurement line from the side of fusion weld root shows that a welded joint with a 6 mm space is characterised by the largest values. All analysed welded joints are being distinguished by larger values of HV0.025 hardness for austenite grains (Fig. 17).

The most favourable distribution of HV0.025 values from the root side are being found for ferrite grains for a welded joint with maximum space. The analysed mean metal plate thickness (14.5 mm) is being distinguished by another hardness distribution. The least HV0.025 value for austenite and ferrite grains, from the sided o fusion weld face, occurs in a welded joint with minimum space. On the other hand, the least values of HV0.025 for austenite and ferrite grains from the side of fusion weld root are being observed for welded joints with a space of 6 and 10 mm (Fig. 17). The welded joint of maximum metal plate thickness (18.5 mm), welded with the threshold space of 10 mm, is being characterised by the least values of HV0.025, both in case of measurements in austenite grains and the ferrite ones as well as in measurement lines from the weld face side and the fusion weld root.

9. Conclusions

Basing on the carried out tests, the effect of one-side welding on ceramic backing strips with increased threshold spaces on the mechanical properties of UNS S31803 steel welded joints was determined when compared to those obtained in result of welding with a 6 mm threshold space and DNV regulations.

- Increase of the threshold space to a maximum value of 10 mm has a positive effect, bringing about a small increase of R_m, with respect to all tested thicknesses, in relation to minimum space.

- Welded joints, irrespective of the gap applied between connected edges, are being characterised by high proof stress with relatively long elongation. Tensile resistance values for cylindrical samples collected from the fusion weld axis exceeded in each of the analysed cased the values obtained from samples cut-out from the basic material, which is evidence both of no negative effect of the large quantity of introduced heat and no effect of increased threshold space. It is similar in case of the proof stress for samples collected from the fusion weld axis and perpendicular to it. The $Re_{0.2}$ value from these areas is higher in all analysed welded joints than those obtained for samples collected from the native material. The Young's modulus (E) for samples collected across the fusion weld axis were characterised by larger values than those for samples collected from the fusion weld axis. For samples collected from the fusion weld axis for welded joints with the threshold space of 6 and 10 mm, the E values are larger than for those collected from the native material. All tested samples met, with a sizeable surplus, the requirements specified by DNV regulations, irrespective of the threshold space of weld groove.
- Metal plate thickness affects the impact resistance of welded joints. For welded joints of 9.5 thick metal plates, an optimum welding is that with the threshold space equal to 8 mm. The most clear-cut results appear to be those obtained for metal plates with a thickness of 14.5 mm. A clear upward trend in the results for the breaking work and the impact resistance is visible here when increasing the threshold space. In case of this metal plate thickness, the most favourable completion of welded joints is that with maximum threshold space (10 mm). When analysing the results for the breaking work and the impact resistance of samples collected from metal plates with a thickness of 18.5 mm, two trends are being observed. For samples with the notch incised in the fusion weld axis, there is a decreasing trend as the threshold space increases to maximum value (10 mm). In case of samples collected in the fusion penetration line, an opposite trend is being observed, i.e. an increasing one. All samples exceeded, with a sizeable surplus, the required criterion (least obtained value was by over 50% larger from the required minimum). Considerable increase is being observed in the value of the breaking work and the impact resistance of samples situated in the fusion penetration line.
- There is a strong influence of the thickness of metal plate and the threshold space on the HV10 hardness of welded joints, in particular within the area of the weld face and the weld root. Within the area of the fusion weld face, an increase in hardness occurs together with the increase of threshold space. Within the area of the fusion weld root, a small decreasing trend in hardness is being observed together with the increase of threshold space.
- There is an influence of the thickness of metal plate and the threshold space on the HV0.025 hardness of austenite and ferrite grains. The lowest hardness values are characteristic of welded joints with the largest gaps.

It was shown that widening of threshold space tolerance and wide-gap welding of duplex steel is possible, i.e. completion of welded joints by one-side vertical bottom-top welding (PF) with no need for applying the process of edge pad welding in case of weld groove geometry with the threshold space ranging 6 to 10 mm, from the point of view of meeting requirements with respect to mechanical properties by welded joints.

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