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Effect of a Gap between Elements Being Joined on the Fatigue Service Life of Joints Welded on a Steel Backing Strip

Abstract: In accordance with standard Pn-en iso 9692-1, when making welded joints using a backing strip, the maximum distance between elements being joined should amount to 15 mm. In certain cases, the use of a gap greater than the normative one could be technically justified. The above-presented issue inspired tests aimed to identify the influence of a gap between elements being joined on the operational service life of these joints. The tests involved the adoption of a fatigue criterion. The article describes results of fatigue tests along with related conclusions.

Keywords: non-destructive testing, fatigue tests, welded joints, welding using backing strip, distance between welded elements

DOI: 10.17729/ebis.2016.6/3

Introduction

In welding practice a steel strip is usually used when the obtainment of the proper shape of a weld root is difficult or when maintaining a required distance between elements to be joined poses a technical problem. Such a situation is relatively frequent in terms of large-sized structures or structures of complicated shapes, as was the case described in publication [1].

In accordance with the requirements of Pn-en iso 9692-1, the maximum gap between edges to be joined in a welding process performed using a steel strip should amount to 15 mm. If the gap distance is longer, the repair procedure requires that the surfacing of one edge, the non-destructive test concerning the quality of surfaced layers and their grinding (aimed to even them up) be performed. The above-presented activities are very expensive, particularly if welds need to be improved. It would be significantly easier and cheaper to adopt a greater gap than that specified in the related standard. However, it should be noted that a greater gap results in an increase in the weld volume which, in turn increases the probability of the formation of unallowed welding imperfections in the weld and, consequently, could reduce the service life of a joint. The above-named issues inspired tests aimed to determine the effect of a gap between elements (edges) to be welded on the fatigue service life of joints welded using a steel strip, without removing the strip after welding. The tests involved the preparation of test plates made of steel s355j2+n with butt welds on a steel strip. The welds were made using mag welding (process 135) and variously sized gaps between the edges being joined.

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Table 1. Chemical composition of steel S355J2 + N according to heat analysis in % by weight

C	Mn	Si	P	S	Cr	Ni	Mo	Cu	Al	N_2	V	Nb
0.17	1.55	0.20	0.013	0.008	0.022	0.012	0.002	0.017	0.030	0.004	0.005	0.0215

Table 2. Mechanical properties of steel S355J2 + N

R_{eH} MPa	R_m MPa	A_5 %	KV2/300 (-20°C) J/cm²	Note
473	598	27.9	177	Material in the normalised state

Table 4. Mechanical properties of the SpG4S wire

R_{eL} MPa	R_m MPa	A_5 %	kV/300 (-50°C) J
538	595	27	105

Table 3. Chemical composition of the SpG4S wire in % by weight

C	Mn	Si	P	S	Cr	Ni	Mo	Cu	V	Ti	Al	N_2
0.079	1.67	0.94	0.011	0.020	0.04	0.01	0.01	0.01	0.01	0.01	0.030	0.007

Test Materials

The tests involved the use of a 20 mm thick plate made of normalised steel S355J2+N in the as-delivered state. According to Inspection Certificate 3.1, consistent with PN-EN 10204, the chemical composition and mechanical properties of the steel were as presented in Table 1 and 2 respectively.

Steel S355J2+N was welded using process 135 and a SpG4S (ISO 14341 – A: G50 5 M21 4Si1) grade wire having a diameter of 1.2 mm. The chemical composition of the wire and its mechanical properties, according to Inspection Certificate 3.1 consistent with PN-EN 10204, are presented in Table 3 and 4.

The analysis of Tables 1 through 4 revealed that the SpG4S wire contained a weld deposit having a yield point like that of steel S355J2. The shielding gas used during MAG welding was a mixture containing 80% of argon and 20% of carbon dioxide (ISO 14175 – M21 – ArC – 20).

Shape, Dimensions and Preparation of the Specimens

Steel S355J2 having a thickness of 20 mm was used when making test joints made on a steel strip (500 mm × 500 mm) using variously-sized gap between the elements being joined (Fig. 1); the joints were next sampled for specimens used in fatigue tests (Fig. 2).

The test joints with the strip were made in the flat position using the MAG method (straight polarity DC) and a Multi Surfacer D2 mechanised station (Welding Alloys). The number of layers and runs depended on the gap (distance) between the edges being joined. Process parameters used when welding individual joints are presented in Table 5.

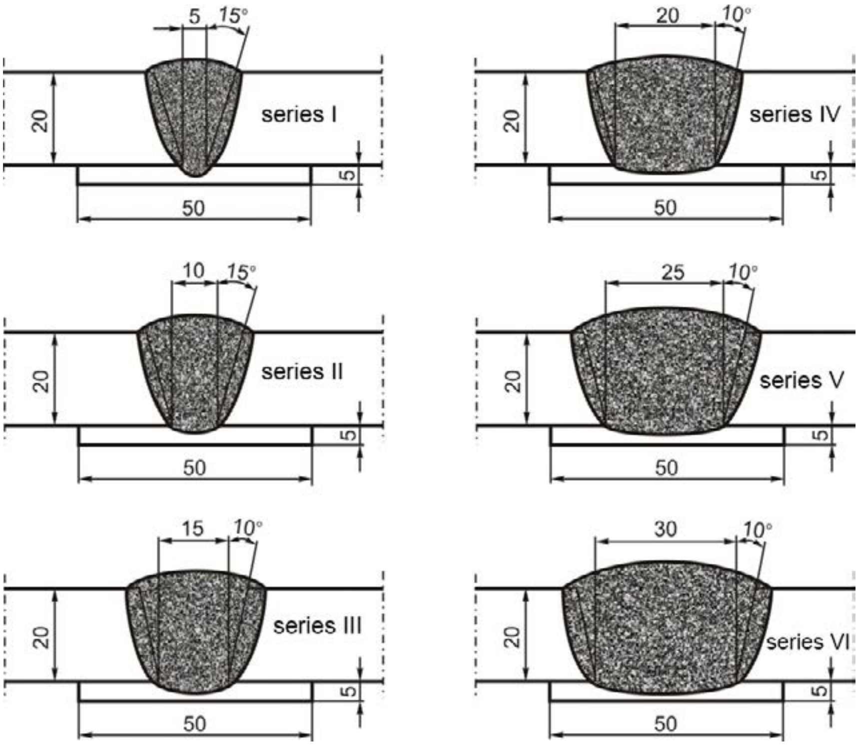

Fig. 1. Types of test joints; Note: the strip was a 5 mm thick and 50 mm wide flat bar made of steel S355J2

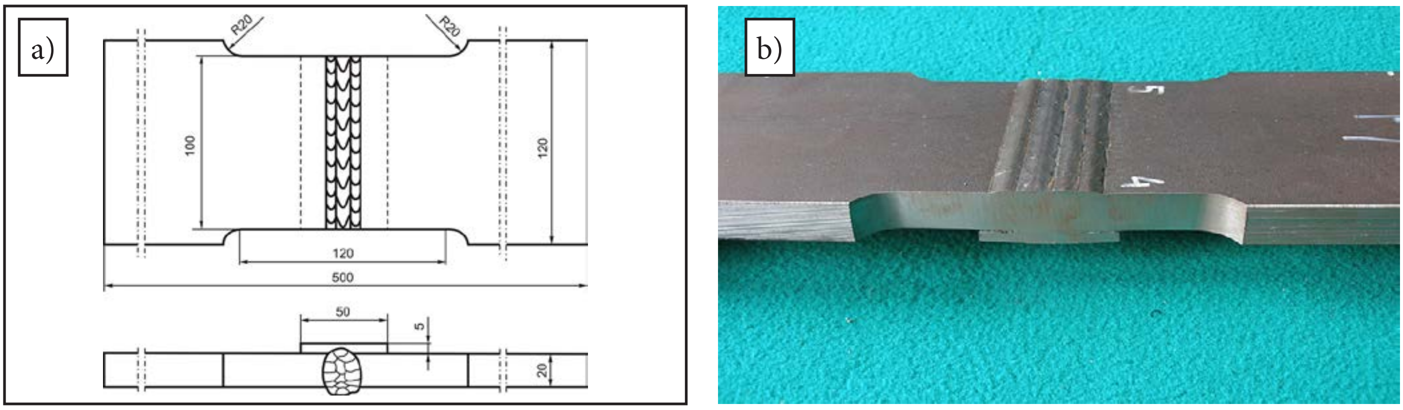

Fig. 2. Shape and dimensions of the specimens subjected to fatigue tests:
a) schemes of the specimens, b) view of the specimen

Table 5. Welding parameters used when making the test joints on the steel strip

Type of joint **Parameters**	I	II	III	IV	V	VI
Number of layers and runs	13	19	22	22	31	39
Current; A	220÷250	220÷240	220÷255	230÷245	230÷250	225÷275
Filler metal feeding rate; m/min	7.5	7.5	7.5	7.5	7.5	7.5
Arc voltage; V	25.5	25.5	25.5	25.5	25.5	25.5
Electrode extension; mm	18÷22	18÷22	17÷20	15÷18	15÷20	16÷20
Shielding gas flow rate; l/min	20	20	20	18÷22	18÷20	20
Layer or run welding rate; mm/min	350÷500	400÷450	400	400	400	400÷450
Interpass temperature; °C	200	200	200	200	200	200

In order to minimise the angular strains of the test plates it was necessary to apply counter-strains involving the use of a supporting strip of appropriate height (Fig. 3).

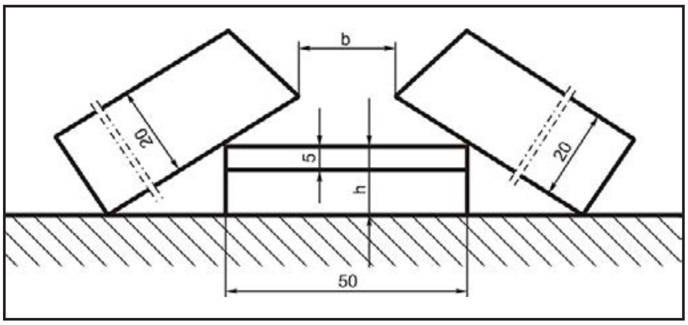

Fig. 3. Scheme of counter-strain minimising the angular strain of the test plate; h – support height, b – gap between the edges being joined

In the case of the joint designated with digit I, the support used was 16 mm high, in cases of joints II, III, IV and V the height of support amounted to 25 mm, whereas in the case of joint VI the support was 30 mm in height.

Before welding, the test plates were fixed using tack welds made within the weld groove. Each test plate was sampled (using a band saw) for 3 elements subjected to machine cutting to prepare specimens for fatigue tests.

Non-Destructive Tests of Specimens

The surfaces of the test joints were subjected to visual and penetrant tests whereas their volume was subjected to radiographic tests.

The visual tests of the joints were performed in accordance with the requirements of PN-EN ISO 17637 and assessed in accordance with the requirements of PN-EN ISO 5817. The tests did not reveal the presence of cracks on the surfaces subjected to the tests. Because of welding imperfections present on the surface, the joints were classified as representing quality level B.

The penetrant tests of the specimens, performed in accordance with the requirements of PN-EN ISO 3452-1 and assessed in accordance with the requirements of PN-EN ISO 23277, did not reveal the presence of any linear or non-linear indications on the surfaces subjected to the tests. In accordance with PN-EN ISO 17635, the test joints were classified as representing quality level B. As can be seen, the results of the penetrant tests confirmed the results of the visual tests concerning the joints subjected to the fatigue tests.

The radiographic tests of the joints were performed in accordance with the requirements of PN-EN ISO 5579 and in accordance with the requirements of PN-EN ISO 17636-1 as well as assessed in accordance with the requirements of PN-EN ISO 10675-1. The radiographic tests revealed the presence of scattered gas pores, the boundary size of which enabled the classification of the joints as representing acceptance level 1 equivalent to quality level B.

As can be seen, the joints of the specimens prepared for the fatigue tests and subjected to non-destructive tests were characterised by high quality confirmed by their classification as representing quality level B according to PN-EN ISO 5817.

The proper application of the layers and runs as well as the structures of the individual zones of the joints made using the steel strip were identified using metallographic tests [2]. The test joints were sampled for elements used for the preparation of macro (Fig. 4) and microscopic (Fig. 5) metallographic specimens.

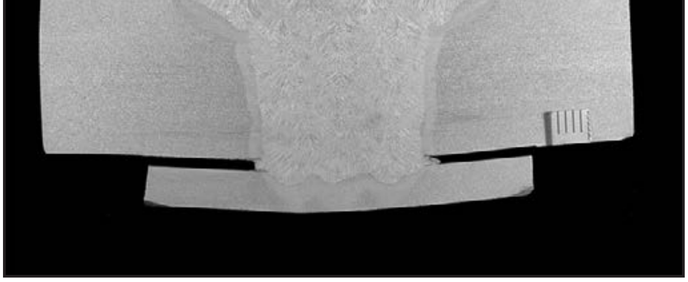

Fig. 4. Macroscopic metallographic specimen of the joint made using the steel trip and a gap of 20 mm between the edges being joined

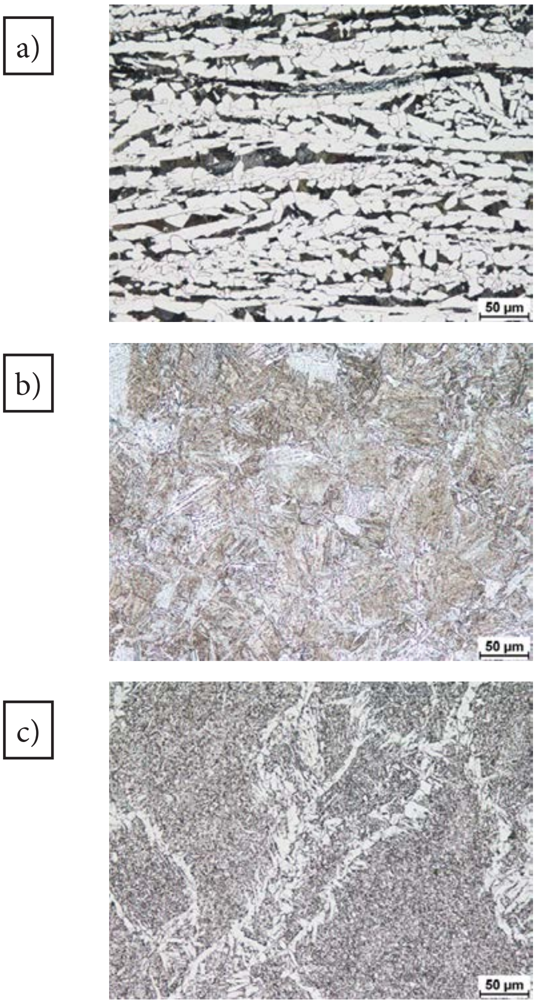

Fig. 5. Exemplary structures of the joint made using the steel trip and a gap of 20 mm between the edges being joined: a) structure of steel S355J2: ferrite + perlite; etchant: Nital, mag.: 200 x; b) structure of the HAZ: bainite, etchant: Nital, mag.: 200 x; c) structure of the weld: bainite in the lattice of ferrite, etchant: Nital: Nital, mag.: 200 x

The analysis of Figure 4 revealed that the joints were characterised by the proper application of individual layers and runs in the weld as well as by proper penetration into the strip and the weld groove edges. The structures presented in Figure 5 were consistent with expectations, which additionally confirmed the proper making of the specimens prepared for the fatigue tests.

Fatigue Tests and Results

The fatigue tests of the specimens containing the test joints made using the steel trip and various gaps between the elements were performed using an MTS 810 testing machine (USA) and one stress level σ_{max} amounting to 225 MPa. The tests involved the adoption of load asymmetry coefficient $R = \sigma_{min}/\sigma_{max} = +0.2$. Therefore, during the tests the specimens were exposed to the following loads σ_{max} = 225 MPa, σ_{min} = 45 MPa. The fatigue test results are presented in Table 6 and in Figure 6.

The fatigue test results were subjected to a statistical analysis. Student's t-distribution [3-5] was used to determine 90% confidence intervals containing the general means ("m") of test results and 90% confidence intervals containing individual results of "N" tests. The boundaries of the confidence intervals for the general means are identified using the following dependence:

$$\overline{N} - \varsigma < m < \overline{N} + \varsigma$$

where:

$\overline{N} = \sum_{i=1}^{n} Ni / n$ – test arithmetic mean,

$\zeta = t_\alpha \cdot s/\sqrt{n}$ – test accuracy,

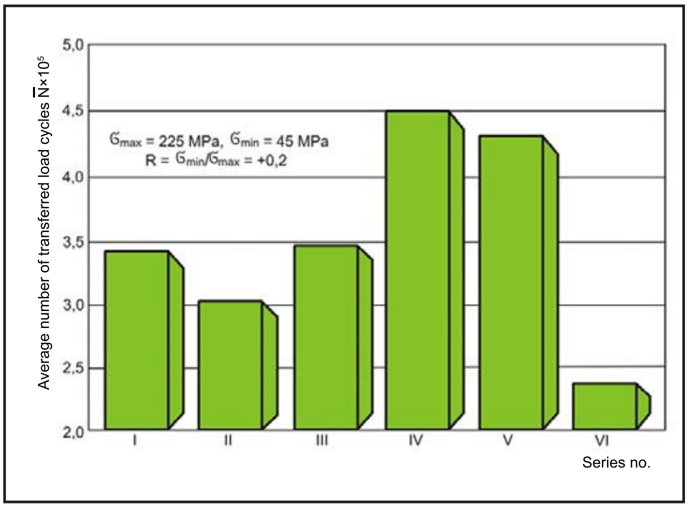

Fig. 6. Demonstration of service life mean values concerning the specimens containing the joints made using the strip and having various gaps between the elements

Ni – values of individual measurements,

t_α –Student's t-distribution value for the number of the degrees of freedom $k = n$ -1 and 90% confidence interval,

$s = \sqrt{1/(n-1)\sum_{i=1}^{n}(Ni - \overline{N})^2}$ – standard deviation.

Table 6. Fatigue tests results concerning the welded joints made using the strip, made of steel S355J2, with variously-sized gaps between the elements being joined

No.	Gap between elements, mm	Series no.	Specimen no.	Number of transferred load cycles, n	Mean number of transferred load cycles, $\overline{N}$	Remarks
1	5	I	1	330622	343845	Crack initiated in the transition zone between the butt weld and the base material and strip
2			2	310700		
3			3	390212		
4	10	II	1	239609	304267	Crack initiated in the transition zone between the butt weld and the base material and strip
5			2	358714		
6			3	314477		
7	15	III	1	339004	348171	Crack initiated in the transition zone between the butt weld and the base material and strip
8			2	332817		
9			3	372692		
10	20	IV	1	419639	451760	Crack initiated in the transition zone between the butt weld and the base material and strip
11			2	385417		
12			3	550223		
13	25	V	1	393936	433267	Crack initiated in the transition zone between the butt weld and the base material and strip
14			2	411308		
15			3	494557		
16	30	VI	1	282964	237939	Crack initiated in the transition zone between the butt weld and the base material and strip
17			2	254354		
18			3	176499		

In turn, the boundaries of the confidence intervals for individual results are identified using the following dependence:

$$\overline{N} - \zeta_N < m < \overline{N} + \zeta_N$$

where $\zeta_N = t_\alpha \cdot s$ – test accuracy.

The statistical analysis results, in the graphic form, are presented in Figure 7.

The analysis of Table 6 as well as Figures 6 and 7 revealed that the highest fatigue service life was that of the specimens of series IV (specimens with a gap of 20 mm between the elements being joined). In turn, the lowest fatigue service life was that of the specimens of series VI (specimens with a gap of 30 mm between the elements being joined). However, it should be noted that the calculated confidence intervals for the average service life values of the specimens of I, II, III, IV and V overlapped, which indicated the insignificance of differences between them. Therefore, the test results concerning the specimens of series I through V constituted the same set. In comparison with series V, the service life results concerning the specimens of series VI differed slightly (confidence intervals of these series did not overlap). The difference between them was small. However, the comparison of the service life results of the specimens of series VI with the remaining series indicated the insignificance of the differences as the confidence intervals overlapped. Consequently, it can be concluded that the service life results concerning the specimens of all series belonged to the same set. The conclusion

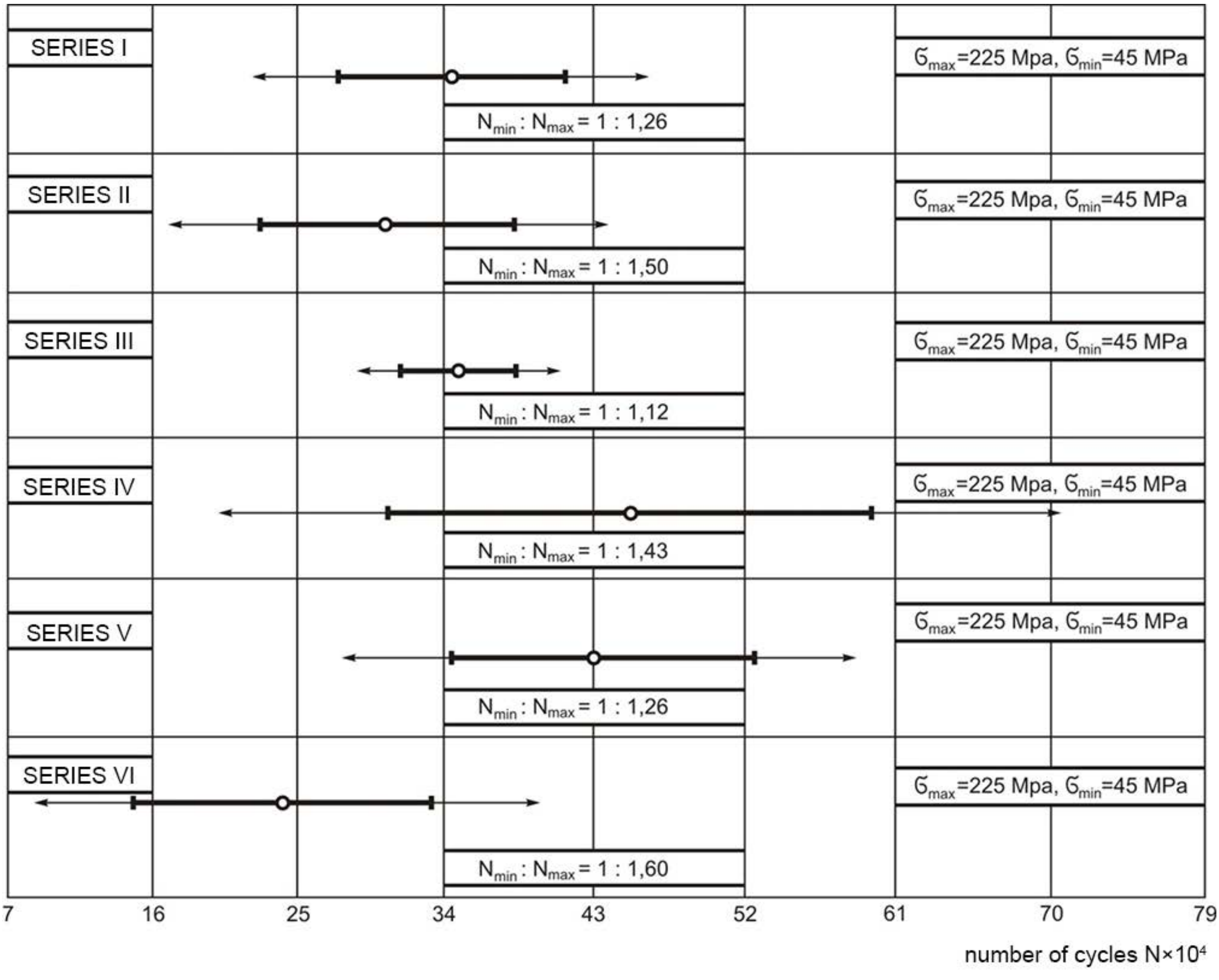

Fig. 7. Confidence intervals for the mean values of service life and service life results concerning the specimens containing the joints having the strip and various gaps between the elements being joined: 90% confidence interval for the test results, ↔90% confidence interval for the test results, ° – mean value

was confirmed by the analysis of the scatter of fatigue test results (N_{min}:N_{max}) concerning the specimens of various series (Fig. 7). The scatter was restricted within the range of 1:1.12 to 1:1.60. This slight scatter demonstrates that the test results were correct.

In all of the cases the fatigue cracks were initiated from the transition of the weld root to the welded material and the strip (Fig. 8).

The areas of crack initiation as well as the planes of crack development were consistent with expectations [6]. The transition of the weld root to the strip and the material being welded was characterised by the significantly higher concentrations of stresses that the concentration caused by the presence of small gas pores scattered in the weld volume (during the radiographic examination the joints were classified as representing quality level B); in the case under discussion the above named feature was dominant.

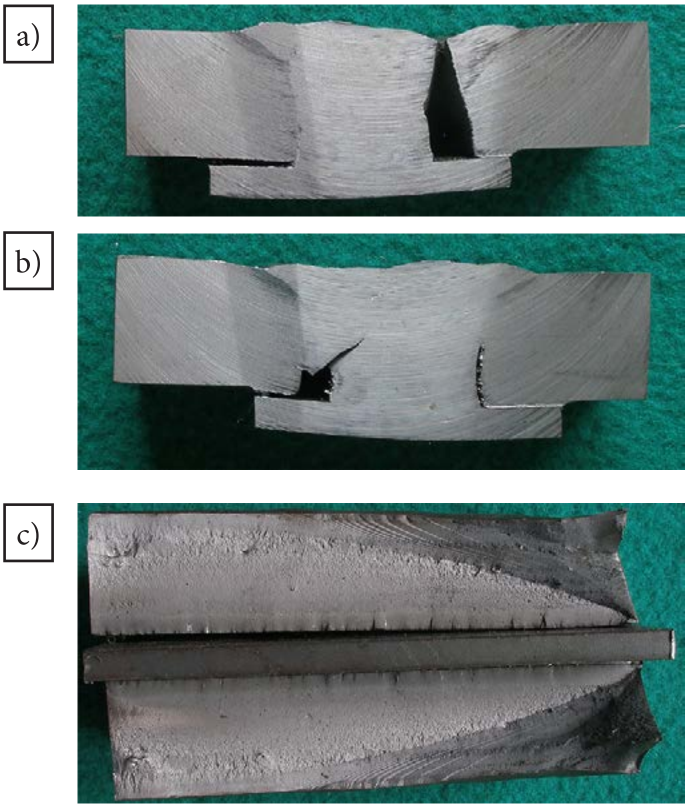

Fig. 8. Areas of fatigue crack initiation in the specimens: a), b) cracks on the cross-section of the joint, c) fatigue crack with the visible crack centre

Summary and Conclusions

In some cases of steel structures, particularly those having large dimensions and exposed to variable loads, it is necessary to weld the edges of structural elements using a steel strip, sometimes with a gap greater than that specified in application-related standards. However, an increase in the gap translates into the increased volume of the weld and the number of potential fatigue crack initiators as well as the statistical probability of crack initiation. The above-presented issue inspired the fatigue tests of the butt welds made using the steel strip and variable gaps (5-30 mm) between edges being joined. The tests aimed to obtain additional indicators facilitating the easier and cheaper making of welded structures exposed to variable loads without compromising safety during operation.

The tests joints were subjected to NDT including visual, penetrant and radiographic tests. Both the visual and penetrant tests did not reveal the presence of cracks on the surfaces. In accordance with the requirements of standard PN-EN ISO 5817, the joints were classified as representing quality level B. The identical results were obtained in the radiographic tests. The radiograms revealed the presence of small and scattered gas pores, the number and size of which satisfied the requirements related to quality level B. The test results confirmed that the welding technology used for the making of the test joints was selected properly and that the quality of the joints was high.

The conclusion was confirmed by the macroscopic tests of the test joints revealing the proper penetration of the first layer into the base material and the strip as well as the proper application of the layers filling the weld groove. The structures of the base material, HAZ and the weld of the test joints were identified using microscopic tests. The tests results were consistent with expectations, which additionally confirmed the proper selection of the technology used for the welding of the joints.

The fatigue tests of the specimens having various gaps between the elements were performed using one stress level $\sigma_{\max}$ = 225 MPa and load asymmetry coefficient $R=+0.2$. The test results were subjected to a statistical analysis involving the identification of 90% confidence intervals including the general means of the test results and 90% confidence intervals containing individual test results. The analysis results are presented in the graphical form in Figure 7 revealing that highest fatigue service life was found in the specimens having a gap of 20 mm between the elements being joined (series IV), whereas that lowest fatigue service life was found in the specimens having a gap of 30 mm (series VI). It can also be seen that the confidence intervals for the general means of the individual series of the specimens overlapped, which this indicated the insignificance of differences between them and led to the conclusion that the fatigue test results concerning all of the specimens belonged to the same set.

In cases of all specimens with a various gap between the elements being joined, fatigue cracks were initiated in the transition area between the weld root and the base material and the strip. The plane of the fractures was perpendicular to the longitudinal axis of the specimens, which was consistent with expectations as this transition area in the joint made using the steel strip was characterised by the highest concentration of stresses. In turn, the plane of the fatigue fractures was characteristic of elements subjected to one-side tension.

The above-presented tests led to the formulation of the following conclusions:

1. The welded joints made using the steel backing strip, utilised in the fatigue tests, were characterised by high workmanship representing quality level B according to the requirements of PN-EN ISO 5817.
2. The fatigue service life of the welded joints made using the steel backing strip with a gap in the weld root restricted within the range of 5 to 30 mm was the same.
3. When making welded joints using a backing strip it is possible to use a gap in the weld root restricted within the range of 5 to 30 mm.
4. The results of the tests can additionally aid the process of designing welded structures subjected to changing loads.

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Standards

- PN-EN ISO 9692-1: *Welding and allied processes – Types of joint preparation – Part 1: Manual metal arc welding, gas-shielded metal arc welding, gas welding, TIG welding and beam welding of steels*
- PN-EN 10204: *Certification for Steel Plates – Inspection documents*
- PN-EN 10025-2: *Hot rolled products of structural steels. Part 2: Technical delivery conditions for non-alloy structural steels*
- PN-EN ISO 14175: *Welding consumables – Gases and gas mixtures for fusion welding and allied processes*
- PN-EN ISO 14341: *Welding consumables – Wire electrodes and weld deposits for gas shielded metal arc welding of non alloy and fine grain steels – Classification*

- PN-EN ISO 17637: *Non-destructive testing of welds -- Visual testing of fusion-welded joints*
- PN-EN ISO 5817: *Welding – Fusion-welded joints in steel, nickel, titanium and their alloys (beam welding excluded) – Quality levels for imperfections*
- PN-EN ISO 3452-1: *Non-destructive testing – Penetrant testing – Part 1: General principles*
- PN-EN ISO 23277: *Non-destructive testing of welds – Penetrant testing – Acceptance levels*
- PN-EN ISO 17635: *Non-destructive testing of welds. General rules for metallic materials*
- PN-EN ISO 5579: *Non-destructive testing – Radiographic testing of metallic materials using film and X- or gamma rays – Basic rules*
- PN-EN ISO 17636-1: *Non-destructive testing of welds – Radiographic testing – Part 1: X- and gamma-ray techniques with film*
- PN-EN ISO 10675-1: *Non-destructive testing of welds. Acceptance levels for radiographic testing. Steel, nickel, titanium and their alloys*