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Effect of Excessively Wide Welds on the Fatigue Service Life of Welded Joints

Abstract: Many a time, welded joints contain a welding imperfection having the form of an excessively wide butt weld with reference number 5212 in PN-EN ISO 6520-1. The fact that the effect of the above-named imperfection on the service life of welded joints had not been identified before inspired research aimed to fill the above-named gap. The study discusses the results of fatigue tests of welded joints having excessively wide welds and contains conclusions based on the test results. In general, the presence of welding imperfection 5212 in welded joints is highly undesirable.

Keywords: welding imperfection 5212, excessively wide welds, fatigue tests

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Introduction

Welding imperfections present in metal welded joints have been classified in six groups in PN-EN ISO 6520-1. A large group of such imperfections includes those concerning shapes and sizes of joints (categorised in group 5). Among other things, group 5 includes an excessively wide butt weld (or a butt weld having an excessive width) frequently encountered in welding practice and designated using reference number 5212 (Fig. 1) [1].

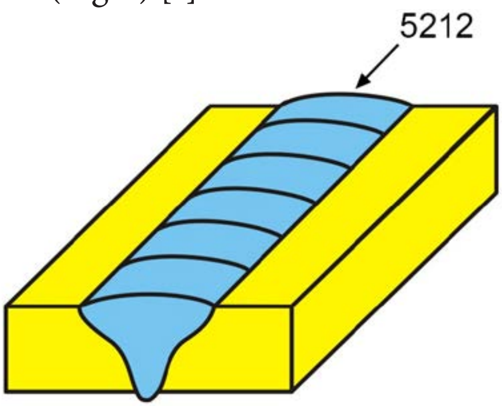

Fig. 1. Excessive weld width

As can be seen in Figure 1, the excessive weld width is an external imperfection detected using visual tests [2, 3]. However, the PN-EN ISO 5817 standard, the requirements of which are applied when performing visual test-based assessments of the quality of metal welded joints, does not contain information about the boundary values of this imperfection as they have not been determined until today. Therefore, the above-named imperfection does not affect the final assessment of a welded joint. However, it should be noted that the geometry of an excessively wide weld significantly differs from expected and can considerably influence the distribution of stresses in joints decreasing their operational usability. In addition, an increase in the weld volume is accompanied by the increased likelihood of the formation of other undesirable welding imperfections, usually having an adverse effect on welded joints. For this reason, the effect of the excessive width of a weld on

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the operational usability of welded joint became the subject of related tests. The above-named effect was identified using the strictest possible, i.e. fatigue-related, criterion.

Test Materials

The fatigue tests were performed using 12 mm thick normalised steel S355J2 + N in the as-delivered state. According to Inspection Certificate 3.1 consistent with PN-EN 10204, the chemical composition of the above-named steel is as presented in Table 1, whereas the mechanical properties of the steel are as those presented in Table 2.

Steel S355J2 + N was welded using process 135 and filler metal wire SpG4S (ISO 14341 – A:G50 5 M21 4Si1) having a diameter of 1.2 mm. The chemical composition and mechanical properties of the above-named wire, according to Certificate 2.2 consistent with PN-EN 10204, are presented in Tables 3 and 4 respectively.

The analysis of Table 1-4 revealed that wire SpG4S enabled the obtainment of a weld deposit having a yield point similar to that of the base material. The MAG welding method used in the tests was performed using a typical shielding gas mixture containing 80% of argon and 20% of carbon dioxide (mixture ISO 14175 – M21 – ArC – 20).

Shapes and Dimensions of Specimens

Steel S355J2 (12 mm thick) was used to make 4 test joints (Y-type) (500 × 500 mm) on ceramic strip PS-52F20; the joints were characterised by variable widths of the weld faces (Fig. 2).

The test joints were made in the flat position using the MAG method, straight polarity DC and a Multi Surfacer D2

Table 1. Chemical composition of steel S355J2 according to heat analysis

C%	Mn%	Si%	P%	S%	Cu%	Cr%	Ni%	Al%
0.09	0.78	0.33	0.069	0.002	0.26	0.74	0.22	0.040

Table 2. Mechanical properties of steel S355J2

R_e; MPa	R_m; MPa	A_5;%	KV(-20°C) J/cm²	Remarks
374	523	27.6	153.75	Normalised material

Table 3. Chemical composition of wire SpG4S

C%	Mn%	Si%	P%	S%	Al%	Cr%
0.079	1.67	0.94	0.011	0.020	0.030	0.04

Table 4. Mechanical properties of wire SpG4S

R_{eL}; MPa	R_m; MPa	A_5;%	KV(-50°C) J/cm²
538	595	27	105

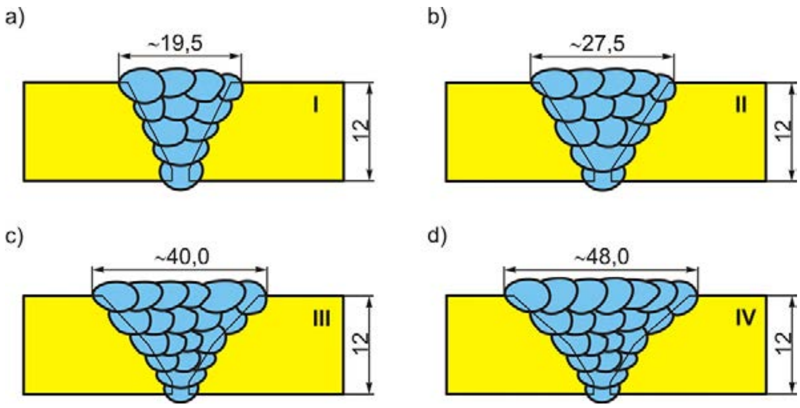

Fig. 2. Test joints containing weld faces having various widths

Table 5. Welding parameters related to the test joints made of 12 mm thick steel S355J2

Parameters \ Type of joint	I	II	III	IV
Number of layers and runs	7	7	10	12
Welding current; A	230-260	208-251	230-260	232-240
Arc voltage; V	19.8-26.5	20.0-26.0	21.0-27.5	21.0-27.5
Filler metal (wire) feeding rate; m/min	6.5-7.5	6.5-7.5	6.5-7.5	6.5-7.5
Electrode extension; mm	14-16	14-16	14-16	14-16
Shielding gas flow rate; l/min	12-14	12-14	12-14	12-14
Welding rate; cm/min	20-55	20-40	20-55	20-50
Interpass temperature; °C	220	220	220	220

station (Welding Alloys). The number of layers and runs depended on the width of a weld being made. The welding parameters related to individual types of the joints are presented in Table 5.

The test joints were sampled for the specimens used in the fatigue tests; the shape and dimensions of the test specimens are presented in Figure 3.

The minimisation of the angular strains of the test plates required the use of counterstrain involving the use of the ceramic strip (10 mm in height).

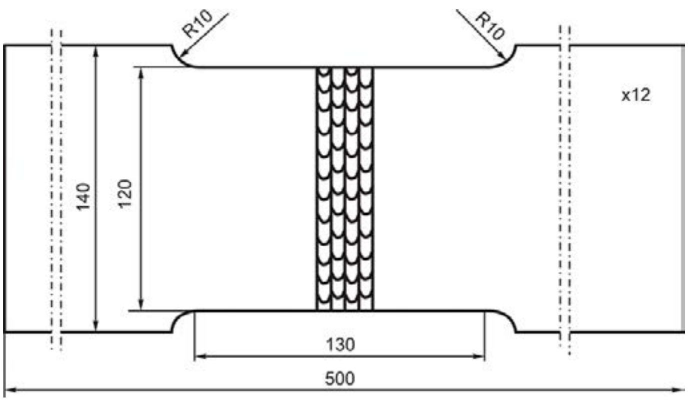

Fig. 3. Shape and dimensions of the specimens used in the fatigue tests

The elements of the test plates were matched using tack welds. The tack welds were made within the weld groove (where the weld was made). Each plate was sampled (using a band saw) for 3 elements which after machine cutting were used as specimens in the fatigue tests.

Tests of Specimens

The welded joints used in the fatigue tests were subjected to visual, penetrant and radiographic tests.

The visual tests of the test 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. Taking into consideration the subject of the fatigue tests, particular attention was paid to the visual inspection of excessively wide welds (welding imperfection). The measurement results concerning the widths of the weld faces, the heights of their excess weld metal and the classification of quality are presented in Table 6.

Table 6. Measurement results concerning the face width and excess weld metal height of the butt welds in the specimens used in the fatigue tests.

No.	Specimen number	Specimen (weld) face width b; mm	Average value $\bar{b}$; mm	Excess weld metal height *h*; mm	Average height $\bar{h}$; mm	Quality level according to PN-EN ISO 5817
SERIES I						
1	1	19.6; 19.4; 19.4;	19.47	2.9; 2.8; 2.9;	2.87	B
2	2	19.2; 19.3; 19.3;	19.27	2.9; 2.9; 2.9;	2.90	B
3	3	19.5; 19.4; 19.4;	19.43	2.8; 2.9; 2.9;	2.87	B
SERIES II						
4	1	27.8; 27.8; 27.8;	27.80	2.9; 3.1; 3.2;	3.07	B
5	2	27.4; 27.7; 27.4;	27.50	3.1; 3.0; 3.1;	3.07	B
6	3	27.5; 27.7; 27.8;	27.67	3.0; 3.3; 3.4;	3.23	B
SERIES III						
7	1	40.0; 39.3; 40.0	39.77	3.5; 3.6; 3.6;	3.57	B
8	2	40.3; 39.5; 40.3;	40.03	3.6; 3.7; 3.6;	3.63	B
9	3	39.5; 40.0; 39.8;	39.77	3.5; 3.6; 3.7;	3.60	B
SERIES IV						
10	1	48.1; 48.3; 48.7;	48.37	3.1; 3.3; 3.3;	3.23	B
11	2	47.3; 48.4; 48.2;	47.97	3.3; 3.0; 3.3;	3.20	B
12	3	48.0; 47.4; 47.6;	47.67	3.0; 3.3; 3.1;	3.13	B

Because of the number and sizes of welding imperfections present in the specimens, all of the test joints used in the fatigue tests were classified as meeting the requirements of quality level B.

The penetrant tests of the test joints were performed in accordance with the requirements of PN-EN ISO 3452-1 and assessed in accordance with the requirements of PN-EN ISO 23277. The tests did not reveal the presence of linear or non-linear indications on the surfaces subjected to the tests. In accordance with the correlation referred to in PN-EN ISO 17635, the test joints were classified as meeting the requirements of quality level B. The penetrant test results confirmed the results obtained in the visual tests.

The radiographic tests of the specimens (joints) used in the fatigue tests were performed in accordance with the requirements of PN-EN ISO 5579 and those of PN-EN ISO 17636-1. The quality of the joints revealed during the radiographic tests was assessed in accordance with the requirements of PN-EN ISO 10675-1. The radiographic tests revealed the presence of scattered pores (in the welds), the number and sizes of which made it possible to classify the joints as satisfying the requirements of acceptance level 1, equivalent to quality level B. The joints (specimens) used in the fatigue tests (subjected to non-destructive tests) were characterised by high workmanship, as a result of which, in each case, they were classified as satisfying the requirements of quality level B according to PN-EN ISO 5817.

Tests and Results

The fatigue tests of the specimens containing butt welds having various face weld widths were performed using an MTS 810 testing machine (YSA), one level of stress σ_{max} = 225 MPa and load asymmetry factor $R = \sigma_{min}/\sigma_{max} = +0.2$. Therefore, during the tests the specimens were under load σ_{max} = 225 MPa and σ_{min} = 45 MPa. The fatigue test results are presented in Table 7.

The test results were subjected to statistical analysis. The Student's t-distribution [4, 5, 6] was used to determine 90% confidence intervals containing grand means m of the test results and 90% confidence intervals containing individual results of n-tests. The confidence limits for grand means were determined using the following dependence:

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

Table 7. Fatigue test results concerning the butt welded joints made of steel S355J2, having various face weld widths, tested under load σ_{max} = 225 MPa and σ_{min} = 45 MPa

No.	Designation of specimen series	Designation of specimen	Number of transferred load cycles, N	Average number of transferred load cycles, N	Remarks
1	I	1	456 939	523 105	Fracture was initiated in the interface between the weld root and the base material
2		2	644 144		
3		3	468 233		
4	II	1	754 924	798 697	Fracture was initiated in the interface between the weld root and the base material
5		2	894 178		
6		3	746 988		
7	III	1	312 752	385 791	Fracture was initiated in the interface between the weld face and the base material
8		2	424 613		
9		3	420 007		
10	IV	1	313 214	330 004	Fracture was initiated in the interface between the weld face and the base material
11		2	359 920		
12		3	316 877		

where:

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

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

N_i – values of individual measurements,

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

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

In turn, confidence limits for individual results were determined using the following dependence:

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

where $\zeta_N = t_\alpha \cdot s$ – accuracy of a test. The statistical analysis results are presented in the graphic form in Figure 4.

The analysis of Table 7 and Figure 4 revealed that, as regards the fracture initiation area, the welded joints could be divided into two groups. The first group was composed of the joints of series I and II, where the fracture was initiated in the interface between the weld root and the base material (Fig. 5). The second group was composed of the joints of series III and IV, where the fracture was initiated in the interface between the weld face and the base material (Fig. 6).

The foregoing led to the conclusion that the test results concerning both groups of the joints should be considered separately as entirely different sets of numbers. The conclusion was also confirmed when analysing Figure 4. The confidence intervals concerning the mean values of the lives of the test specimens overlapped both in cases of the specimens of series I and II and III and IV. The overlapping of the confidence intervals of the specimens of series I with the confidence intervals of the specimens of series III and IV could not be taken into consideration as they belonged to different sets of results.

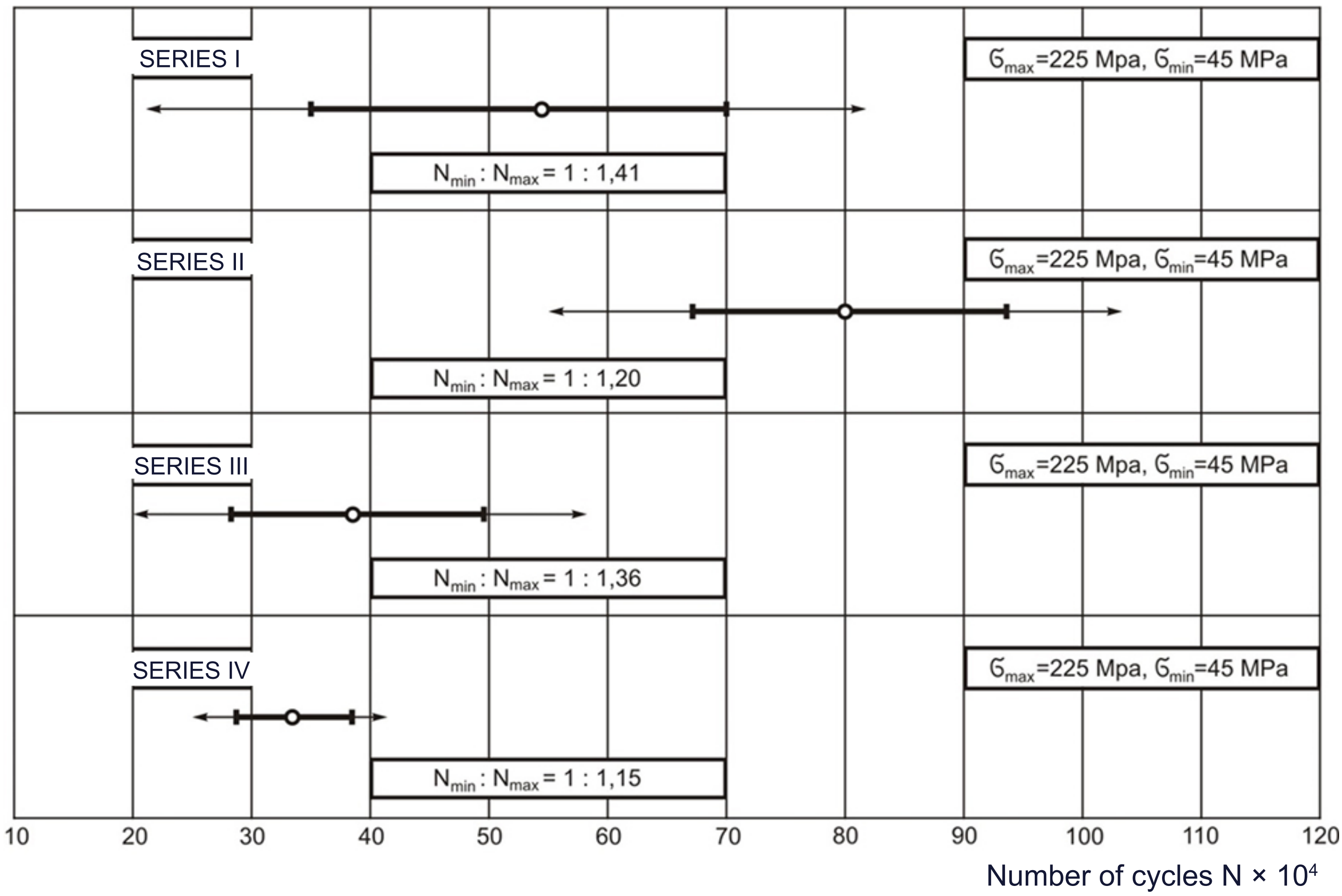

Fig. 4. Confidence intervals related to the average values of lives and to the results of the lives of the specimens containing the joints having excessively wide welds: ——— – 90% confidence interval related to the average value; ⟷ – 90% confidence interval related to the test results; **O** – average value

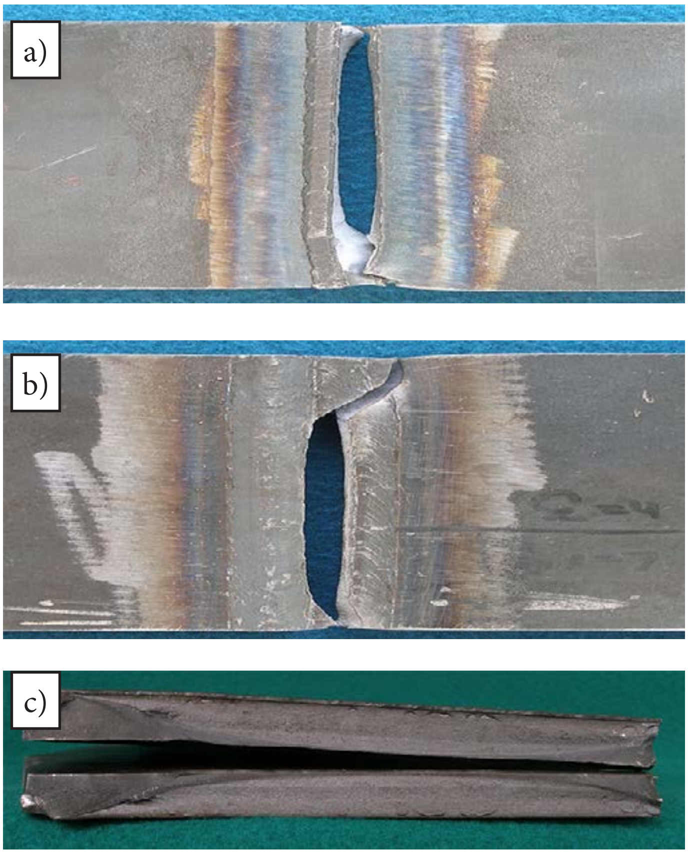

Fig. 5. Exemplary fatigue fracture initiation in the interface between the butt weld root and the base material (specimen no. 3 of series I): a) view from the root side, b) view from the face side, c) fatigue fracture

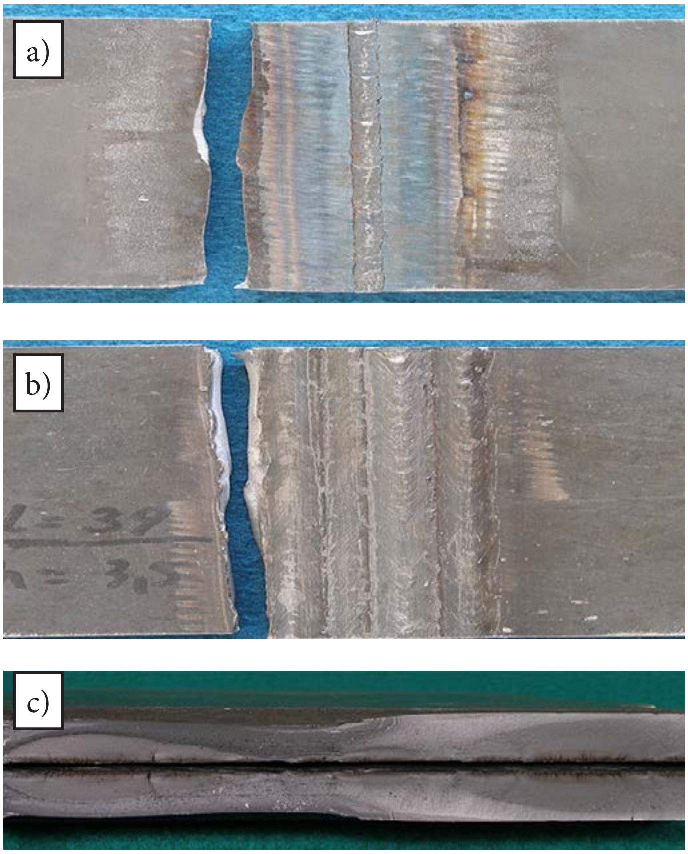

Fig. 6. Exemplary fatigue fracture initiation in the interface between the butt weld face and the base material (specimen no. 3 of series III): a) view from the root side, b) view from the face side, c) fatigue fracture

The analysis of the mean values of the life of the tested specimen series (Table 7, Fig. 4) revealed unequivocally that the fatigue service life of the specimens of series I and II was significantly higher than that of the specimens of series III and IV. This fact could be ascribed to the significant change in the cross-sectional weld geometry (series III and IV) caused by the excessive width of the weld. The presence of the above-named imperfection (excessively wide weld) was responsible for the fact that the notch determining the initiation and development of the fatigue crack was the interface between the weld face and the base material (Fig. 6b). For this reason, the difference between the mean life values of the specimens of series III and IV was insignificant. Entirely different was the fatigue service life of the specimens of series I and II. Their higher fatigue service life (in comparison with that of the specimens of series III and IV) resulted from the compensating effect of the excess weld metal height in the plane of the notch, i.e. the interface between the root and the base material as well as from the higher strength of the weld deposit in comparison with that of the base material. In multi-run welding, the above-named effect could be weakened by the presence of the "grooves" (surface irregularities) in the weld face; the formation of the grooves could be attributed to the overlapping of the individual runs of the weld (Fig. 5b). The presence of the grooves could also justify the significant difference between the mean life-related values related to the specimens of series I and II.

Summary and Concluding Remarks

The joints of critically important steels structures revealed the presence of disturbingly many excessively wide butt welds (welding imperfections). The PN-EN ISO 5817 acceptance standard does not specify the effect of the above-named imperfection on the quality of the joints and on their operational usability. For this reason, it was necessary to perform the fatigue tests of the specimen in order to clarify the above-presented issue.

The test joints were subjected to non-destructive tests including visual, penetrant and radiographic tests. Neither the visual nor the penetrant tests revealed the presence of cracks on the surfaces subjected to the tests. In accordance with the requirements of PN-EN ISO 5817, the joints were classified as representing quality level B. The identical test result was obtained in the radiographic tests. The radiographs revealed the presence of insignificant scattered pores, the number and sizes of which satisfied the requirements of quality level B. As can be seen, the test results demonstrated that the technology used for the welding of the test joints was appropriate and that the joints made using the above-named technology represented high workmanship.

The fatigue tests of the specimens containing the excessively wide welds were performed using one level of stress σ_{max} = 225 MPa and the same load asymmetry factor R = +0.2. The test results were subjected to statistical analysis involving the determination of 90% confidence intervals containing grand means of the test results and 90% confidence intervals containing individual test results. The rest results in the graphic form are presented in Figure 4. The analysis of Figure 4 and Table 7 revealed that the specimens of series I and II constituted one set of results, whereas the specimens of series III and IV constituted another (second) set. The overlapping of the confidence intervals of the mean values of the service lives of both specimen groups could imply the insignificance of the differences between the above-named groups. As a result of the above-presented dependences it could be stated that the presence of the excessively wide welds (imperfection) in the welded joints significantly decreased their fatigue service life. As regards the test joints, the above named decrease was restricted within the range of approximately 26% to approximately 59%. The averaging decrease stood at approximately 42.5%. As can be seen, the above-named decrease significantly reduced the fatigue service life and, consequently, the operational properties of the welded joints. In terms of the safety of welded structures, the above-presented phenomenon is unallowed.

The above-presented tests and their results justified the formulation of the following conclusions:

1. The welded joints having excessively wide welds and used in the fatigue tests were characterised by high workmanship satisfying the requirements of quality level B according to PN-EN ISO 5817.
2. Excessively wide welds (welding imperfections) in the welded joints significantly reduced their fatigue service life and, consequently, their operational properties.
3. As regards the test joints, the decrease in the fatigue service life of the specimens with excessively wide welds was restricted within the range of approximately 26% to 59%, where the averaging value of the decrease amounted to approximately 42.5%.
4. In terms of the safety of welded structures during operation, the presence of excessively wide welds (welding imperfections) should be regarded as unallowed.
5. The test results can constitute an additional indicator when determining acceptance criteria for structures exposed to variable loads.

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Standards

- PN-EN ISO 6520-1: *Welding and allied processes – Classification of geometric imperfections in metallic materials – Part 1: Fusion welding*
- PN-EN ISO 5817: *Welding – Fusion-welded joints in steel, nickel, titanium and their alloys (beam welding excluded) – Quality levels for imperfections*
- 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 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 14175: *Welding consumables – Gases and gas mixtures for fusion welding and allied processes*
- PN-EN ISO 17637: *Non-destructive testing of welds -- Visual testing of fusion-welded joints*
- 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*