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Mechanical Properties of Welded Joints in Steel S1100QL after Multiple Repair Welding

Abstract: The article presents the use of high-strength toughened steels in various industries and the chronological development of various grades of the above-named steels. In addition, the article discusses the repair of defective fragments of welded joints by means of grinding, grooving or machine cutting followed by the making of a repair weld. Occasionally, the repair process must be repeated or performed many times. An issue of particular importance is the repair welding of steels having a yield point of above 700 MPa. Typically, in structures made of high-strength steels the process of repair consist in the removing of an imperfection (primarily having the form of cracks or porosity) followed by the making of another joint in the area of the previously removed imperfection. The tests described in the article were concerned with flat butt joints made of 18 mm thick toughened steel S1100QL using the MAG method and metallic flux-cored wire grade Stein-Megafil 1100 M (process 138). The tests involved the making of three welded joints, i.e. one production joint and two joints subsequently subjected to three and four-fold repair welding. In addition, the article presents the methodology and results of transverse tensile tests, transverse bend tests, impact strength tests and hardness tests.

Keywords: high-strength toughened steels, steel S1100QL, repair welding of steels

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Introduction

Presently, the fabrication of steel structures is based on the use of steels having a yield point of up to 1000 MPa. Regardless of the foregoing, increasingly many production companies predict that in the near future it will be necessary to make structures in steels having a yield point of more than 1000 MPa. High yield point toughened steels are currently some of the most popular materials when making welded structures of critical importance and exposed to significant loads, e.g. chassis frames of cranes and vehicles, poles and supports, lifting equipment, elements of drilling rigs, special bridge

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structures etc. According to reference publications [1] and information obtained from companies manufacturing elements of crane structures and other large-sized load-bearing elements, the use of steels having a yield point exceeding 1000 MPa is near [2].

The making of structures in high-strength steels leads to a decrease in the thickness of walls, resulting in the reduction of production costs through decreasing the weight of a structure, reducing the consumption of welding consumables and lowering the laboriousness of the welding process. Figure 1 presents an example demonstrating how the use of steel S1100QL instead of S355J2+N enables the reduction of the thickness of a plate by approximately 65% [3].

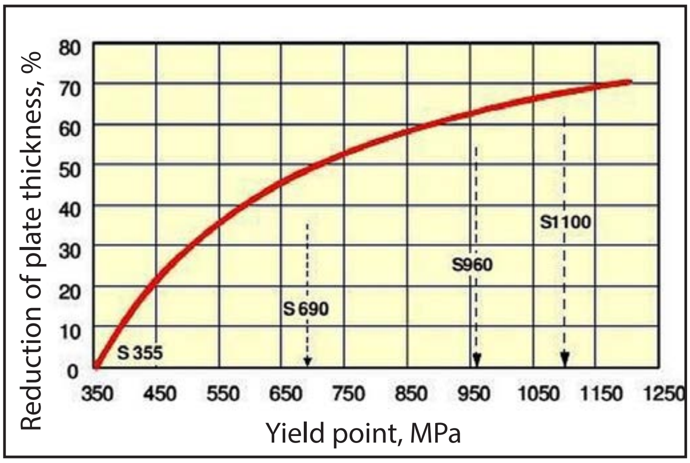

Fig. 1. Reduction of required plate thickness using high--strength steels in comparison with structures made of steel S355J2+N [3]

The year 2000 saw the launch of advanced structural steels characterised by a yield point of above 1000 MPa. The chronological development of high-strength steels is presented in Figure 2.

The proper repair of defective fragments of welded joints involves their removal through grinding, grooving or machine cutting followed by the making of a repair weld. Occasionally, it is necessary to repeat a repair or perform it several times.

Reference publications address the effect of repair welding on the mechanical properties and the microstructure of joints made in various steels. The aforesaid publications also refer to a number of repairs not reducing the properties of welded joints. For instance, the tests involving the butt joints made in 12 mm thick steel S355J2+N and P460NL1, connected with the removal of a fragment of the weld using mechanical treatment revealed that *when analysing the mean values of the results obtained in individual experiments, the fourfold repair of the welds performed in accordance with the presented procedure did not reduce the mechanical properties of the joints in the scope subjected to assessment* [5].

The tests concerning the effect of the MAG welding thermal cycles (modelling of 1, 2 and 3 repairs) on the mechanical properties and the toughness of welded joints made in 20 mm thick steel S960QL (V-type join, wire SG 960) revealed that:

- repair welding performed three times, involving the removal of the "defective" weld using an angle grinder and mechanical treatment did not reduce the tensile strength of the joints;
- unacceptable reduction of tensile strength *Rm* was observed in the joints subjected to 3 repairs involving the use of arc-air gouging [6].

Tests concerning the repair welding of butts joints made of 10 mm thick steel S690 TM (MAG, wire Union NiMoCr) revealed that the repeated repairs of welds (1, 2 and 3) involving the removal of a fragment of the weld and the use of arc-air gouging did not significantly affect the

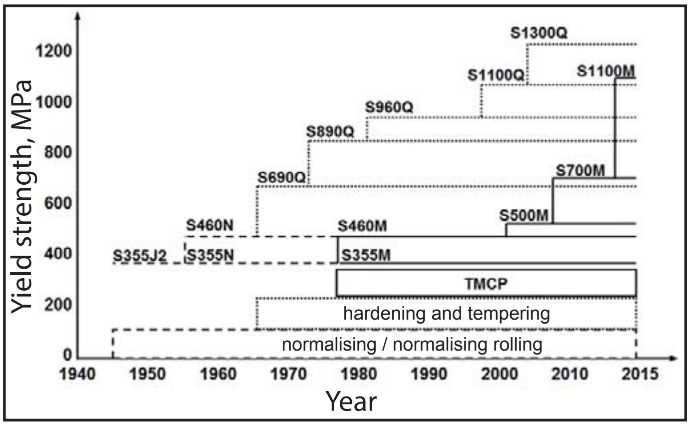

Fig. 2. Development of structural steels (TCMP – Thermo-Mechanical Control Process) [4]

tensile strength of joints made of the above-named steel [7]. The bend angle amounted to 130° (positive result). The weld face only ruptured in the joint repaired three times. However, it was also noticed that the repair welding was followed by a significant decrease in the toughness of the joints, particularly of the heat affected zone (HAZ).

In certain cases the procedure of repair welding is covered by regulations or standards. For instance, according to the requirements of Norsok Standard M-101 [8, 9], concerning the structure of off-shore drilling rigs, repair welding can be performed in the same area only two times. It is necessary to entirely remove the primary weld along with the heat affected zone (HAZ) and to perform welding in accordance with the procedures and welding procedure specifications applied when making the primary joint [8]. Similarly, according to Offshore Standard DNV-OS-C401 related to the making and testing of structures of off-shore drilling rigs, repair welding of the same area can be performed only two times, where subsequent repairs, if any, should be approached individually [10].

A significant issue is the repair welding of steels having a yield point of above 700 MPa. In structures made of high-strength steels the necessity of repair involving the removal of an imperfection and the making of a new joint in the area of the previously detected imperfection is primarily triggered by the presence of cracks (Fig. 3) or porosity.

A study involving the manufacturers of structures made of high strength steels revealed that repair welding is performed just once. If the repair welding process performed once fails to remove imperfections, the fragment containing a defective joint is cut out and a new fragment containing a proper joint is welded in the place of the defective one. As a rule, repeated repairs of the same joint are not performed or repairs of the same joint are performed many times without recording the fact in the documentation related to the fabrication of a given structure. As can be seen, reference publications do not contain information concerning the permissible number of repairs based on test results concerning the mechanical properties of joints as well as the microstructure of the base material and that of the HAZ during successive repairs of welded joints made in high yield point steels.

This article presents mechanical test results concerning steel S1100QL after several repair welding operations.

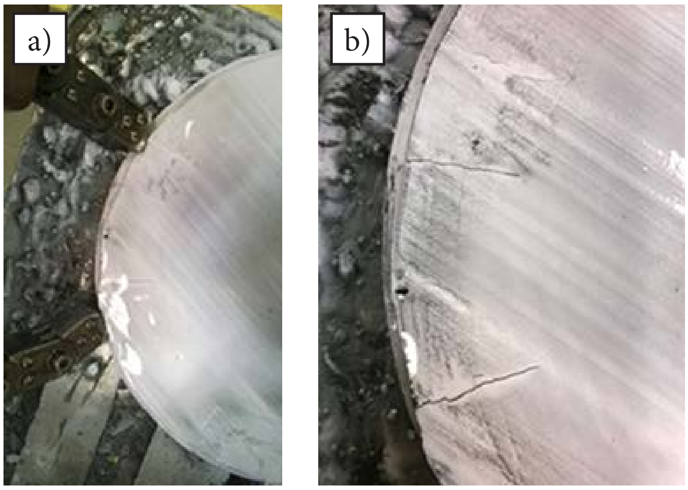

Fig. 3. Cracks visible in the area of the element subjected the magnetic-particle test; the test element being made of steel S1100QL using contact electrodes for magnetisation (a) and discontinuity indication (b)

Table 1. Chemical composition of steel S1100QL

Chemical element content, % by weight									
C	Si	Mn	P	S	Cr	Cu	Ni	Mo	B
0.192	0.220	0.855	0.014	0.0034	0.606	0.012	1.858	0.636	0.0017
Chemical element content, % by weight according to the producer [1]									
C	Si	Mn	P	S	Cr	Cu	Ni	Mo	B
max 0.21	max 0.50	max 1.40	max 0.020	max 0.005	max 0.80	max 0.30	max 3.00	max 0.70	max 0.005

Test materials

Materials used in the tests were flat butt welded joints made of 18 mm thick high yield point (above 900 MPa) toughened steel S1100QL. The chemical composition of the above-named steel was identified using an Q4 TASMAN spark emission spectrometer. The results of the chemical composition identification are presented in Table 1.

Welded joints

Welded joints were made using flux-cored wire grade Stein-Megafil 1100 M (classification En ISO 18277 A: T 89 4 Z M M 1 H5) providing a weld deposit having a yield point of above 960 MPa, tensile strength restricted within the range of 980 MPa to 1180 MPa, elongation A above 8% and a Charpy V impact energy of above 47 J at a temperature of -20°C. According to the information provided by the manufacturer, the above named wire is used for the welding of steel S960QL1 and S1100 having a thickness of up to 12 mm [11]. In turn, according to publication [12] the Megafil 1100 M wire is used for the welding of steels S890 through S1100QL1.

The joints of test plates (18 × 150 × 400 mm) were made using the MAG method and the above-presented metallic flux-cored wire (process 138) having a diameter of 1.2 mm. The shielding gas used in the tests was the ISO 14175-M21-ArC-18 mixture. The welding of the root run was performed using a Lincoln Power Wave 455 STT semi-automatic welding machine, whereas filling layers were made using a Multi Surfacer D2 mechanised welding machine (Welding Alloys).

The tests involved the making of three welded joints, i.e. a production joint (joint no. 1), a joint subjected to three repairs (joint no. 2) and a joint subjected to four repairs (joint no. 3). The repair welding was performed on grooves modelling the removal of defective metal across the entire V-type cross-section of the weld, except for the root layer having an approximate thickness of 4 mm. The removal of the above-named part of the production weld was performed using arc-air gouging. Previously performed tests did not reveal the effect of the arc-air gouging process on the microstructure of the steel subjected to welding or that of the HAZ in comparison with the production joint, where the imperfection-modelling groove was made using mechanical treatment. The technological parameters used when welding joints nos. 1, 2 and 3 are presented in Table 2.

The production joint (no. 1) was prepared for welding as presented in Figure 4a. The preparation of the joint was followed by the making of a penetration run and filling runs in the flat position (Fig. 4b).

The production joints as well as the joint after three and the one after four repairs were subjected to visual, penetrant and radiographic tests (non-destructive tests). The tests revealed that the joints represented quality level B according to Pn-EN ISO 5817:2014-05. The above-presented non-destructive tests were followed by tests of mechanical properties.

Table 2. Technological parameters used in the welding of joints nos. 1, 2 and 3

Joint no.	Run	Current A	Arc voltage V	Welding rate cm/min	Interpass temperature °C	Heat input kJ/cm
1 (production joint)	1	90-100	14.5	13	-	4.81÷5.35
	2-12	200-210	26	45	150	5.55÷5.82
2 (joint repaired 3 times)	1	145	17.1	14.5	-	8.21
	2-21	210-225	26.0-26.2	45	150	5.82÷6.29
3 (joint repaired 4 times)	1	130	16.7	15	-	6.95
	2-22	210-225	26.0-26.2	45	150	5.82÷6.29

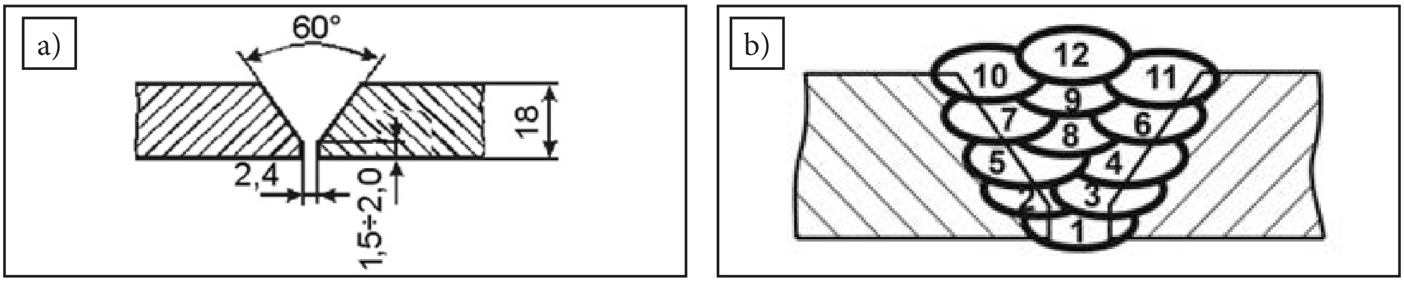

Fig. 4. Shape of the weld groove (a) and the welding sequence (b) of production joint no. 1

Methodology in tests of mechanical properties

In relation to each welding variant, the tests concerning the effect of the repeated thermal cycle of repair welding on the properties of the test joints included transverse tensile tests, transverse bend tests, impact strength tests and hardness measurements.

The static transverse tensile test of the specimens sampled from the welded joints were performed following the requirements of the PN-EN ISO 4136 standard [13] using an Instron 4200 testing machine featuring the computer-aided recording of test results.

The face bend test of the butt welds (FBB) as well as the root bend test of the butt welds (RBB) were performed following the requirements of PN-EN ISO 5173+A1 [14] using an MTS Criterion C-60 testing machine. During the RBB of the specimens of joints no. 1 and 2 it was noticed that the specimens were moving away from the bending mandrel, leading to the bending of the specimens over a significantly shorter radius than the nominal one. This, in turn resulted in the cracking of the specimens before reaching an angle of 1800. For this reason, the bending of the specimens of welded joint no. 3 was performed using a beam enabling the bending of the specimen over the entire diameter of the bending mandrel (in cases of the yield point of the weld being lower than that of the base material). The bending device is presented in Figure 5.

Impact energy was determined in impact tests performed (following the requirements of PN-EN ISO 9016 [15]) at a temperature of -40°C, using standard specimens (10 × 10 × 55 mm) with the Charpy V notch and an RKP 300 pendulum machine (AMSLER).

The hardness measurements of the welded joints were performed following the requirements of the PN-EN ISO 9015-1 standard [16], using the Vickers hardness test under an intender load of 98.1 N (HV10) and a KB50BVZ-FA hardness tester (KB Prüftechnik) in accordance with the schematic diagram presented in Figure 6.

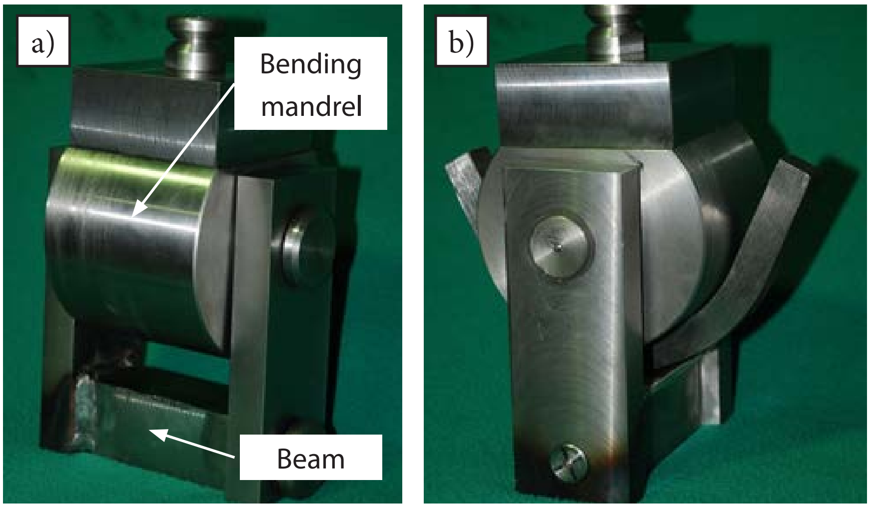

Fig. 5. Bending device with the beam: a) main view of the bending device with the beam below the bending mandrel, b) welded joint specimen in the device after the bend test

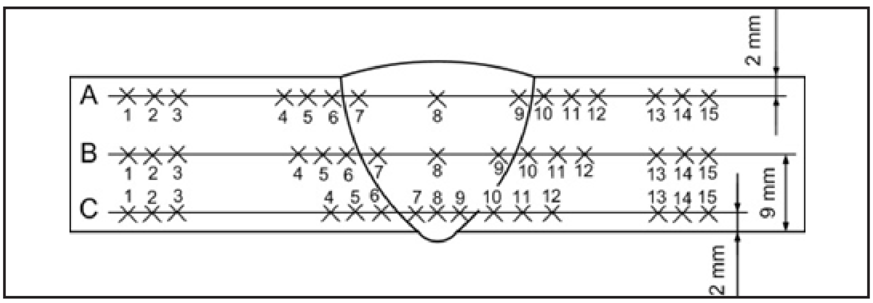

Fig. 6. Schematic diagram of hardness measurements in the test joints

Table 3. Mechanical properties of steel S1100QL

Basis	$R_{0.2}$, MPa	R_m, MPa	A, %	KV^{-40}, J
Equist weld[1)]	≥1100	1250÷ 1550	≥10	27
Inspection certificate	1196	1465	11	no data

1) Equist – computer database of normalised steels

Table 4. Results of the static tensile tests in relation to production joint no. 1 and repair joints nos. 2 and 3

Specimen designation	R_m, MPa	Area of rupture, remarks
1/R/1	1004	weld
1/R/2	1004	weld
2/R/1	927	weld
2/R/2	944	weld
3/R/1	973	HAZ
3/R/2	980	weld

Criterion: $R_m \geq 1100$ MPa

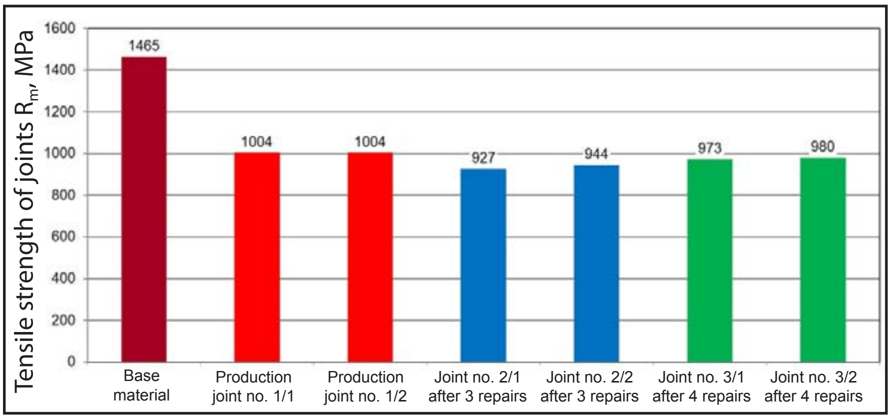

Fig. 7. Results of the tensile tests (Rm) in relation to production joint no. 1 and repair joints nos. 2 and 3 compared with the tensile strength of the base material of steel S1100QL

Table 5. Results of the bend tests in relation to production joint no. 1 and repair joints nos. 2 and 3

Specimen designation	Bend angle	Remarks
1/FBB/1	180°	without scratches and cracks
1/FBB/2	180°	without scratches and cracks
1/RBB/1	25°	cracks in the weld
1/RBB/2	20°	cracks in the weld
2/FBB/1	180°	without scratches and cracks
2/FBB/2	180°	without scratches and cracks
2/RBB/1	10°	cracks in the weld
2/RBB/2	10°	cracks in the weld
3/FBB/1	180°	without scratches and cracks
3/FBB/2	180°	without scratches and cracks
3/RBB/1	180°	without scratches and cracks
3/RBB/2	180°	without scratches and cracks

Key: FBB – face bend test of the butt weld, RBB – root bend test of the butt weld
Bending mandrel diameter: 120 mm
Criterion: bend angle of 180°

Test results of mechanical properties

The mechanical properties of the base material of steel S1100QL are presented in Table 3, whereas the results concerning the mechanical properties of welded joints nos. 1, 2 and 3 are presented in Tables 4-7 and in Figures 7-9.

The HAZ hardness in joint no. 1, 2 and 3 amounted to 456 HV10, 447 HV10 and 416 HV10 respectively. The above-presented values did not exceed the hardness of the base material amounting to 467 HV10 in joint no. 1, 452 HV10 in joint no. 2 and 430 HV10 in joint no. 3.

Conclusions

The tests performed within the research work led to the formulation of the following conclusions:

1. The above-presented technology enables the MAG welding of butt joints made in 18 mm thick steel S1100QL, representing quality level B, confirmed by non-destructive tests.

2. The tensile strength of the test joints was restricted within the range of approximately 927 MPa to approximately 1004 MPa.

3. Production joint no. 1 and repair joint no. 2 (after three repairs) satisfied the requirement related to a bend angle of 1800 when performing the face bend test (of the butt weld). During the free bending test, i.e. without the use of the beam, the specimens of the above-named joints subjected to the root bend test failed to satisfy related requirements.

4. The requirement related to a bend angle of 1800 was satisfied by the 18 mm thick joint subjected to a bend test involving the use of the beam. The above-named joint was repaired four times, where successive grooves were made using the arc-air gouging process.

5. The requirements related to the toughness of the weld and the HAZ were satisfied in cases of the production joint and both repair joints. In the HAZ area, the average value of impact energy at a temperature of -40°C amounted to 165 J in terms of the production joint (no. 1), 130 J in relation to the joint subjected to three repairs (no. 2) and 144 J as regards the joint repaired four times (no. 3). The average impact energy values concerning the weld area tested at a temperature of -40°C amounted to 95 J in relation to joint no. 1, 74 J in relation to joint no. 2 and 84 J as regards joint no. 3.

6. The hardness in the HAZ of production joint no. 1 amounted up to 456 HV10, where the hardness of the base material was restricted within the range of 423 HV10 to 483 HV10. As regards the joint subjected to three repairs

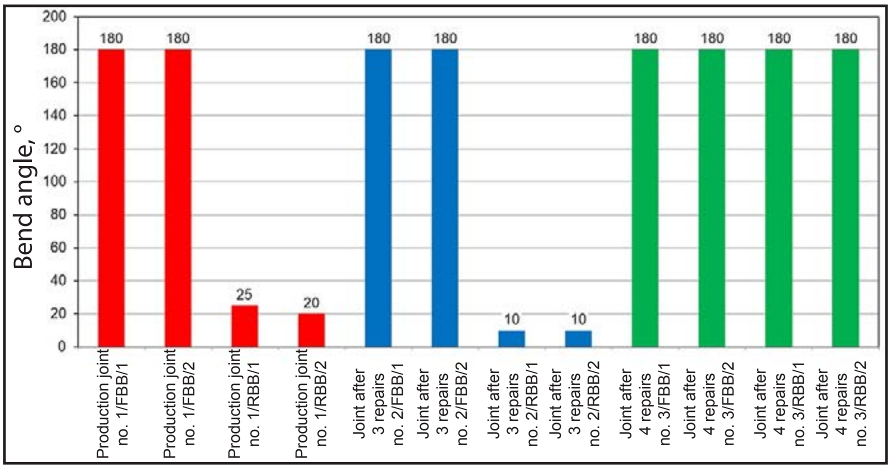

Fig. 8. Results of the bend tests in relation to production joint no. 1 and repair joints nos. 2 and 3

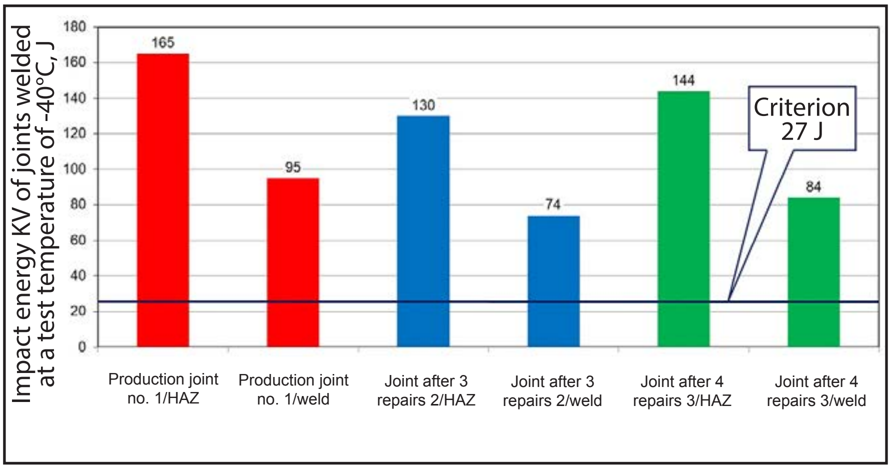

Fig. 9. Results of the impact energy tests performed at a temperature of -40°C in relation to production joint no. 1 and repair joints nos. 2 and 3

Table 6. Results of the impact energy tests in relation to production joint no. 1 and repair joints nos. 2 and 3

Joint no.	Notch location, specimen designation	Test temperature °C	Impact energy KV, J			Mean value, J
			1	2	3	
1	HAZ, 1/KV/VHT	-40	157.5	162.5	175.0	165.0
	Weld, 1/KV/VWT	-40	87.5	100.0	97.5	95.0
2	HAZ, 2/KV/VHT	-40	134	132	124	130
	Weld, 2/KV/VWT	-40	68	82	72	74
3	HAZ, 3/KV/VHT	-40	202	160	70	144
	Weld, 3/KV/VWT	-40	84	82	86	84

VHT – specimen with the V-notch in the HAZ area
VWT – specimen with the V-notch in the weld area
Criterion: ≥ 27 J at a temperature of -40°C

Table 7. Results of the hardness measurements related to production joint no. 1 and repair joints nos. 2 and 3

Joint no.	Measurement line according to Fig 6	Measurement area and hardness HV10														
		BM			HAZ 1			Weld			HAZ 2			BM		
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	A	442	437	436	456	437	434	326	322	309	405	419	430	432	432	434
	B	467	483	466	380	366	360	324	322	320	395	410	421	434	435	432
	C	437	438	436	363	379	345	313	329	324	363	327	351	424	426	423
2	A	444	441	432	447	412	404	330	306	304	398	422	432	431	444	442
	B	452	449	440	372	394	377	333	292	300	331	355	378	429	439	447
	C	450	445	441	355	354	352	292	276	274	311	355	351	426	435	437
3	A	430	421	418	416	405	341	302	315	317	340	366	405	406	417	412
	B	428	425	420	336	359	377	317	307	319	333	332	367	419	420	429
	C	427	421	413	313	318	305	268	277	276	365	362	349	414	415	419

Remarks: BM – base material, HAZ – heat affected zone
Requirements according to PN-EN ISO 15614-1:2017-08, Table 3: ≤ 450 HV10 in relation to steels of group 3 according to ISO/TR 15608, where special values should be determined in relation to steel having R_e > 890 MPa.

(no. 2), the maximum hardness in the HAZ area amounted to 447 HV10, where the hardness of the base material was restricted within the range of 426 HV10 to 452 HV10. In turn, as regards the joint repaired four times (no. 3), the maximum hardness in the HAZ area amounted to 416 HV10 where the hardness of the base material was restricted within the range of 406 HV10 to 430 HV10.

7. In terms of the welding procedure qualification related to steel S1100QL it is recommended that the maximum value of the base material hardness be adopted as the criterion of the maximum value of the hardness of joints made in steel S1100QL.

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