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Effect of the One-Time Repair of Welded Joints in Steel S690QL on the Properties of the HAZ

Abstract: An essential stage in the making of steel structures involves the removal of welding imperfections. Undoubtedly, an additional thermal cycle accompanying the remaking of a weld adversely affects the mechanical properties of the HAZ. The article presents the results of technological tests concerning repeated MAG-based arc repair welding on the properties of the HAZ in welded joints made of steel S690QL.

Keywords: welding imperfections, repair welding, joint properties, steel S690QL

DOI: *10.17729/ebis.2017.6/1*

Introduction

Various industries have recently seen a growth in applications of high-strength toughened steels and steels subjected to the thermo-mechanical control process (TMCP). The above-named steels are usually used in the shipbuilding industry, during the construction of roads and bridges, in water-power and nuclear power engineering, in off-shore structures (e.g. oil rigs) as well as in the construction of pipelines and production of construction equipment. The use of high-strength steels has enabled the making of significantly lighter and smaller structures without compromising their mechanical properties. The reduction of weight and dimensions have translated into lower costs of transport and welding works as amounts of filler metals and, consequently, laboriousness related to the making of welded joints have also decreased significantly [1-3].

In many sectors of the modern heavy industry (pipeline constructions, production of construction equipment and machinery), competition-driven needs for higher production efficiency and lower manufacturing costs also apply to high strength steels [4-6]. The foregoing inspires efforts aimed to quicken welding operations, including, e.g. higher welding rates or greater thicknesses of layers (in particular root layers).

The making of welded joints, particularly those made using manual welding techniques, entails inevitably the formation of various welding imperfections. The preliminary insight into welding imperfections usually formed when welding steels characterised by high yield points and requiring repair welding include transverse cracks, localised porosity, uniformly distributed porosity, lack of side-wall fusion and lacks of

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penetration. The above-named imperfections are usually removed by grinding or through arc-air gouging. Available reference publications did not contain information concerning the effect of thermal gouging and repair welding on properties of repaired welded joints.

The article presents the effect of repair welding on mechanical and structural properties of the HAZ during the MAG welding of 12 mm thick sheets made of steel S690QL.

Base Material and Filler Metal

The base material used in the tests had the form of a sheet made of steel S690QL according to PN-EN 10025-6:2009 and having the following dimensions: 350×200×12 mm. The minimum normative mechanical properties of the steel were the following: $R_m \geq 770$ MPa; $R_e \geq 690$ MPa; $A_5 \geq 14\%$; minimum impact energy at a temperature of -40°C ≥ 30 J. The chemical composition of the base material was subjected to analysis based on spark source optical emission spectrometry and performed using a Q4 TASMAN spectrometer (Bruker). The chemical composition analysis results are presented in Table 1.

The filer metal used in the tests was a Union X96 electrode wire (Böhler) having a diameter of 1.2 mm (classification: PN-EN ISO 16834-A-G 89 5 M21 Mn4Ni2.5CrMo). Mechanical properties of the weld deposit according to data provided by the manufacturer were as follows: $R_e \geq 930$ MPa; $R_m \geq 980$ MPa; impact energy ≥ 47 J at a temperature of -50°C. The selection of the filler metal was based on the requirement that the weld deposit should ensure the rupture of the joint outside the weld. This enabled the identification of the mechanical properties of the HAZ. The shielding gas used in the test was mixture PN-EN ISO 14175-M21-ArC-18.

Tests and Results

Two test joints were made using the MAG method. Directly after welding, one of the joints was subjected to mechanical tests. The second joint was cut precisely along the weld axis (using a band saw) and re-scarfed (through machining) to reach a depth enabling the removal of the weld without damaging the HAZ. The sheets prepared in the above-presented manner were welded again. It was only then that the joint welded for the second time was subjected to mechanical tests. The edges of the base material were prepared through mechanical scarfing (Fig. 1).

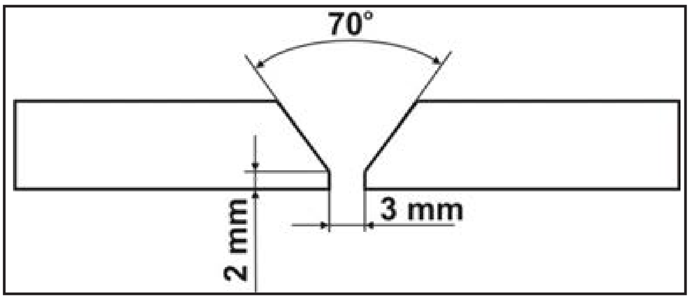

Fig. 1. Pre-weld preparation of the joint

Before tacking, the edges of the base material were degreased using acetone. Afterwards, three 5 mm long tack welds were made. Before welding, the tacked steel plates were fixed on the welding table using eccentric screws. The test joints were made using a MultiSurfacer D2 Weld automated welding station (Welding Alloys) equipped with a microprocessor-based control system enabling the adjustment of a required welding rate and ensuring the repeatable positioning of the welding torch fixed to the station support unit. The preheating temperature amounted to 100°C. The interpass temperature was below 250°C. Temperature measurements were performed using a contact thermometer. Both joints were made in the flat position (PA) using the parameters presented in Table 2.

Table 1. Chemical composition analysis results – steel S690QL

Chemical element content, % by weight													
C	Si	Mn	P	S	Cr	Mo	Ni	Cu	Al.	Ti	V	Zr	Fe
0.16	0.25	1.11	0.001	0.002	0.96	0.15	1.2	0.22	0.05	0.02	0.09	0.003	rest

Table 2. Welding parameters

Run no.	Welding current, A	Arc voltage, V	Filler metal feeding rate, m/min	Welding rate, cm/min	Heat input*, kJ/mm
1	155	18.4	4.4	22.0	0.62
2÷3	235	24.0	7.5	37.0	0.73
4÷6	265	24.0	8.4	40.0	0.76

*Heat input was calculated in accordance with PN-EN 1011-1:2009

The welded joints were numbered using Roman numerals, i.e. "I" marking the joint welded once and "II" marking the joint made for the second time.

Visual and Radiographic Tests

The test joints were subjected to visual tests performed in accordance with PN-EN ISO 17637:2017-02. The tests aimed to determine whether the welded joint contained welding imperfections disqualifying it as meeting the criteria of quality level B according to PN-EN ISO 5817:2014. In both cases, the joint did not reveal any welding imperfections and represented quality level B.

Afterwards, the joints were subjected to radiographic tests for the presence of such welding imperfections as incomplete fusions and porosity. The tests were performed in accordance with the PN-EN ISO 17636-1:2013 standard. The joints contained few internal gas pores which did not disqualify them as representing quality level B. As a result, the joints were subjected to further tests. The related radiographs are presented in Figure 2.

Tensile Tests

Tensile tests were performed following the requirements of the PN-EN ISO 4136:2013 standard using an Instron 4210 testing machine. Each joint was sampled for three specimens. In each case, and as expected, the specimens ruptured in the HAZ. The tensile test results are presented in Table 3.

Table 3. Tensile test results concerning the welded joints in steel S690QL

Joint no.	Test result, MPa			Mean value, MPa
	1	2	3	
I	847	852	850	849.7
II	848	841	842	843.7

The tensile strength of the welded joints was restricted within the range of 841 to 852 MPa. The mean value of three measurements involving joint I amounted to 849.7 MPa, whereas that concerning joint II was 843.7 MPa. In both cases, the tensile strength exceeded the normative strength related to steel S690QL, i.e. 770 MPa (according to PN-EN 10025-6:2009). The tensile strength-related difference between joint I and joint II amounted to 6 MPa. The

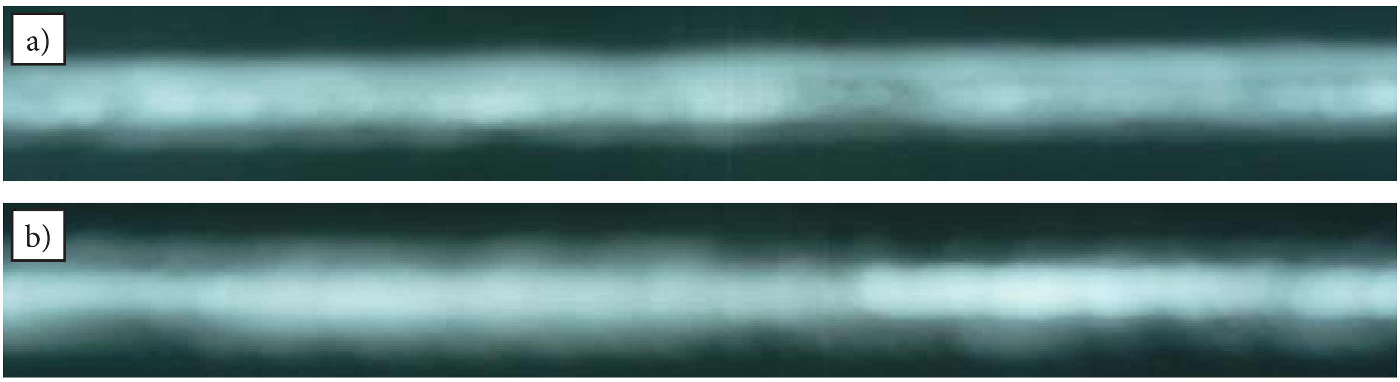

Fig. 2. Radiogram of joint I (a) and joint II (b)

above-presented negligibly small difference does not demonstrate the negative effect of a two-time welding thermal cycle on the tensile strength of the joint.

Impact Strength Test

The impact strength test was performed following the requirements of PN-EN ISO 5173:2010. Impact energy was determined in relation to specimens having the dimensions of 10×10×55 mm. The test involved 5 specimens with a notch made in the HAZ and 3 specimens with a notch made in the weld. The test was performed at a temperature of -40°C. The test results are presented in Table 4 and Figure 3.

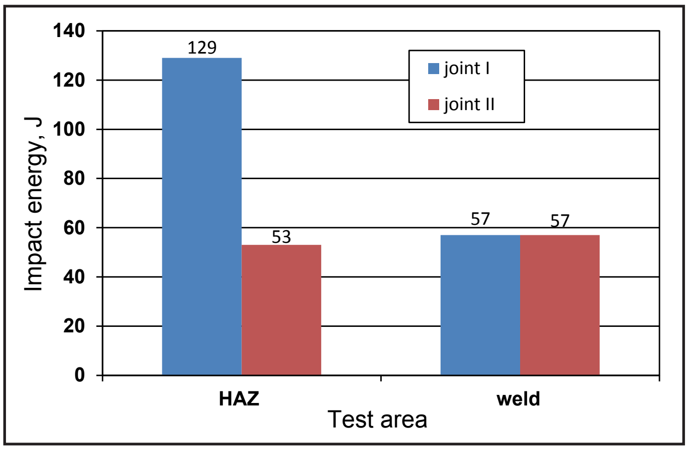

Fig. 3. Toughness of the HAZ and of the weld metal in joint I (welded once) and joint II (welded for the second time)

In cases of both welds, impact energy was restricted within the range of 42 to 60 J, where the mean value in relation to both cases amounted to 57 J. As can be seen, there was no significant difference as regards the impact energy of both welds. In turn, as regards the HAZ, impact energy significantly differed in relation to both cases. In terms of the joint welded once, impact energy was restricted within the range of 110 to 142 J, with the mean of five measurements amounting to 129 J. As regards the joint welded for the second time, impact energy was restricted within the range of 50 to 60 J, where the mean of five measurements was 57 J.

Macro and Microscopic Metallographic Tests

Macroscopic metallographic tests were performed using a stereoscopic microscope and a magnification of 25x, whereas microscopic metallographic tests were performed using a magnification of 200x and that of 500x. The microscopic metallographic tests were performed using an Eclipse MA200 light microscope (Nikon). The microstructural tests involved the HAZ at the half of the joint thickness. The tests were focused on the HAZ as this area was characterised by significantly differing mechanical properties (in terms of both joints). The macroscopic metallographic tests results are presented in Figure 4, whereas the microscopic metallographic test results are presented in Figure 5.

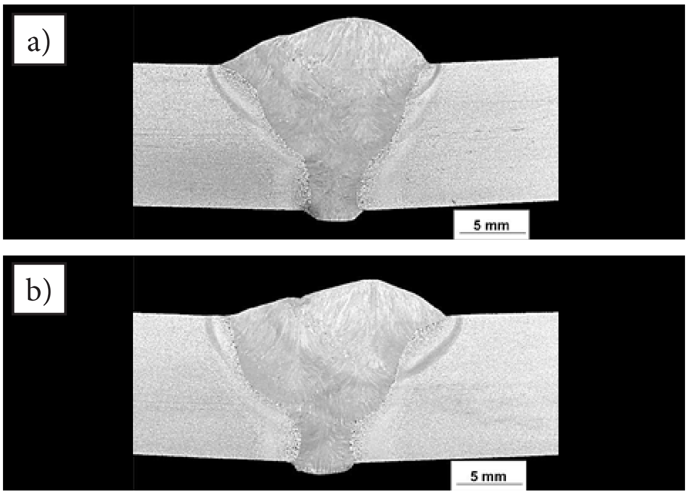

Fig. 4. Macrostructure of the joint welded once (a) and the joint welded for the second time (b)

Table 4. Impact energy test results in relation to joint I and joint II

Joint no.	Test area	Measurement no. 1	2	3	4	5	Mean, J
I	HAZ	134	122	110	138	142	129
	Weld	59	42	57	—	—	53
II	HAZ	50	60	52	54	54	57
	Weld	60	58	54	—	—	57

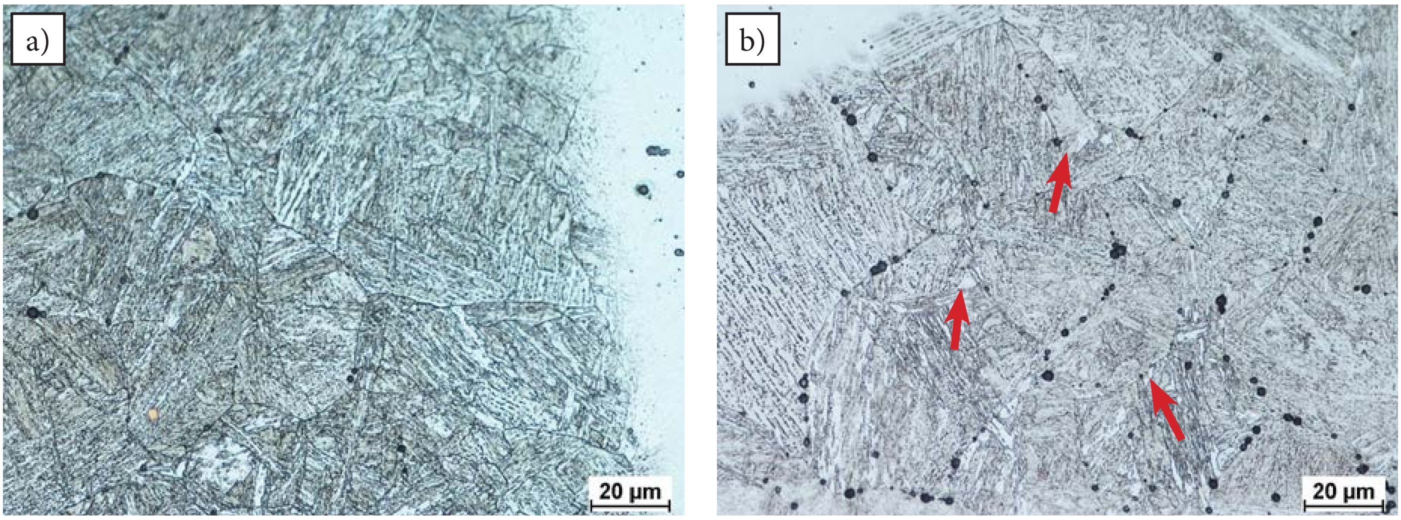

Fig. 5. Microstructure of the HAZ in terms of the joint welded once (a) and the joint welded for the second time with marked areas containing retained austenite (b)

The macrostructural tests did not reveal the presence of incomplete fusions (welding imperfections) in both joints. In addition, the shape of the fusion line was very similar in both cases, which confirmed that welding conditions (in both cases) were comparable.

The microscopic metallographic tests revealed that the HAZ structure in joint I was composed of martensite with few carbide precipitates located along grain boundaries (Fig. 4a). In turn, the HAZ structure in joint II was composed of martensite with retained austenite and numerous carbide precipitates located along grain boundaries (Fig.4b).

Hardness Measurements in Cross-Sections of Welded Joints

Cross-sectional hardness measurements involving the welded joints were performed using a KB50BVZ-FA machine (KB Prüftechnik) and an indenter load amounting to 98.1N (HV10). Measurements were performed from the weld axis in both directions, where the distance between successive measurement points amounted to 1 mm and the measurement line was located at the half of the weld thickness. The hardness test results are presented in Figure 6.

Analysis of Test Results

The visual and radiographic tests of the welded joints did not reveal the presence of any imperfections, the geometry of which could preclude the joints from being qualified as representing quality level B according to PN-EN ISO 5817:2014. Joint I contained few gas pores not exceeding 1 mm in diameter (Fig. 2).

Tensile tests involved three specimens representing each joint. In each case, the specimen ruptured in the HAZ of the base material. As regards joint I, the mean strength R_m (of three measurements) amounted to 849.7 MPa. In terms of joint II, the mean value amounted to 843.7 MPa, i.e. was lower by 6 MPa. Such a small difference between the strength values in relation to both joints justifies the conclusion that welding performed two times does not reduce tensile strength. The impact strength tests of the weld revealed that the impact energy in relation to the joint welded once and that concerning the joint made for the second time amounted to

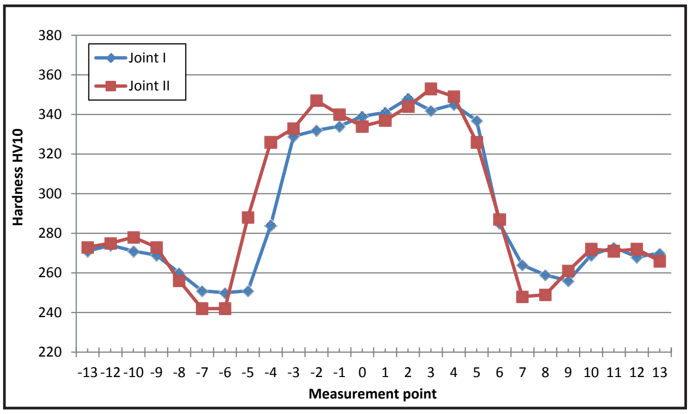

Fig. 6. Distribution of hardness in the cross-section of the joint welded once (Joint I) and the joint welded for the second time (Joint II)

53 and 57J respectively. In both cases, the weld deposit contained the molten filler metal with a slight amount of the molten base material of the fusion zone. In both cases the weld metal was subjected to the same number of welding thermal cycles. However, significant differences as regards impact energy were observed in relation to the HAZ. In terms of the joint welded once, the mean impact energy (of five tests) amounted to 129 J, whereas as regards the joint made for the second time, the value of impact energy was a mere 57 J. The aforesaid considerable impact energy-related differences in the HAZ of both joints were responsible for the fact that microscopic metallographic tests involving both joints were focused only on the HAZ area.

The microscopic metallographic tests revealed that as regards joint I, the HAZ structure was composed of tempered martensite with a slight amount of carbides precipitated along grain boundaries. In the aforesaid case, the slight amount of carbide precipitates could be ascribed to the multiple thermal cycle accompanying the making of successive weld runs (6 runs). In joint II (i.e. made for the second time), the HAZ microstructure contained significant amounts of carbides precipitated along grain boundaries and retained austenite in the martensitic matrix. The mechanism of retained austenite formation was probably connected with the fact that during the slow cooling of the HAZ area, through a long hold within the temperature range of 800 to 500°C, the austenite got gradually enriched in carbon. Each subsequent thermal cycle accompanying the making of subsequent weld runs was responsible for even greater enrichment of the austenite in carbon. After cooling to ambient temperature, some part of the austenite transformed into very hard and brittle martensite, whereas some other part of the austenite was so enriched in carbon that the temperature at the beginning of martensitic transformation *Ms* was lower than ambient temperature. The above-named austenite was stable thermally, yet not mechanically. Probably, during the fracture tests, after being exposed to stresses, the austenite transformed into martensite, facilitating crack initiation, and, at the same time, reducing the toughness of the HAZ. In addition, the presence of numerous carbides precipitated along grain boundaries also reduced the toughness of the HAZ. The above-presented mechanism leading to the reduction of the HAZ toughness could imply that the application of faster cooling after the making of each weld run combined with the adjustment of welding parameters reducing a heat input to the joint could have a favourable effect on the toughness of the welded joint. It could also be assumed that another removal of the weld followed by the making of a joint could reduce the HAZ toughness even further, thus resulting in the failure to satisfy the condition of the minimum normative impact energy in relation to steel S690QL, i.e. kV ≥ 30 J in relation to a standard specimen at a temperature of -40°C.

The hardness measurement performed in the cross-section of the welded joints revealed that the hardness HV10 of the base material amounted to 265÷275 units. In the weld and in the HAZ directly adjacent to the fusion line, the hardness value in both cases amounted to 320÷355 HV10. In the HAZ softening area, the hardness of the joint welded once was 250÷255 HV10, whereas that of the joint made for the second time amounted to 242÷249 HV10. As regards joint II, the HAZ softening was only slightly greater than that observed in terms of joint I.

Conclusions

1. The two-time thermal cycle accompanying the repair welding of the 12 mm thick sheets made in steel S690QL enabled the making of joints satisfying the requirements of standard PN-EN ISO 15614-1.

2. The two-time thermal cycle accompanying the welding of the 12 mm thick sheets made in steel S690QL (simulation of repair welding) triggered a negligibly small decrease in the

tensile strength of the HAZ, which as regards joint I amounted to 849.7 MPa, and in terms of joint II was 843.7 MPa.

3. The two-time thermal cycle accompanying the welding of the 12 mm thick sheets made in steel S690QL (simulation of repair welding) was responsible for a decrease in impact energy in the HAZ from 129 J do 57 J. The foregoing justifies the conclusion that repair welding performed three times could make it impossible to satisfy the condition of the minimum normative impact energy in relation to steel S690QL, i.e. amounting to 30 J at a temperature of -30°C.

4. The microscopic metallographic tests revealed that welding performed two times increased the precipitation of carbides along grain boundaries and the presence of retained austenite in the HAZ. Both structural constituents were probably responsible for the significant decrease in the toughness of the joint in the HAZ.

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