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Effect of a One-Time Repair of a Welded Joint Made in Steel S960QL on the Properties of the HAZ

Abstract: The fabrication of steel structures is often accompanied by the necessity of removing defects and welding imperfections formed during welding. An additional thermal cycle accompanying the making of a new weld has an undoubtedly detrimental effect on the mechanical properties of the heat affected zone (HAZ). The article discusses results of technological tests concerning the effect of MAG repair welding on the properties of the HAZ butt joints made of steel S960QL.

Keywords: repair welding, properties of the HAZ, steel S960QL,

DOI: 10.17729/ebis.2019.1/2

Introduction

Recent years have seen an increase in the use of high-strength (both toughened and TMCP) steels in various sectors of industry, including the shipbuilding industry, civil engineering, water-power engineering, nuclear power engineering, off-shore structures (e.g. oil rigs), construction of pipelines and in the production of construction equipment. The use of high-strength steels enables the making of significantly lighter structures having smaller dimensions, yet without compromising appropriate mechanical properties. The above-named reduction of weight and dimensions translated into lower transport costs and cheaper welding resulting from the reduced consumption of welding consumables and significantly shorter welding processes [1-3].

Many sectors of the heavy industry (pipeline construction, production of construction machinery etc.) are characterised by the continuous pursuit of higher productivity and lower production costs (higher competitiveness), also in terms of structures made of high-strength steels [4-8]. The foregoing necessitates the search for solutions enabling the faster performance of welding operations, e.g. by increasing a welding rate or the thickness of layers (particularly a root run).

An unavoidable aspect accompanying the making of (in particular manually) welded joints is the formation of various welding imperfections. Usually, welding imperfections formed when welding high yield point steels include transverse cracks, localised porosity, uniformly arranged gas pores, lacks of sidewall fusions and lacks of penetration. The aforesaid imperfections are usually removed through grinding or using thermal processes. Afterwards, new welds are made in areas of

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previously removed welding imperfections. The article presents the effect of repair welding on the mechanical properties and the HAZ microstructure of MAG welded joints made of 12 mm thick steel S960QL.

Base material and filler metal

The base material used in the tests was a plate made of steel S960QL (according to PN-EN 10025-6:2009) having dimensions of 350 mm × 200 mm × 12 mm. The minimum normative mechanical properties of the steel included $R_m \geq 980$ MPa; $R_e \geq 960$MPa; $A_5 \geq 10\%$ as well as the minimum impact energy at a temperature of -40°C ≥30 J (at a temperature of -20°C ≥40 J). The chemical analysis of the steel was verified using spark source optical emission spectrometry and a Q4 TASMAN spectrometer (Bruker). The test results are presented in Table 1.

The filler metal used in the tests was a STEIN-MEGAFIL 1100 electrode wire having a diameter of 1.2 mm (classification: PN-EN ISO 18276-A T 89 4Mn2Ni1CrMo M M 1 H5). The mechanical properties of the weld deposit according to the manufacturer were the following: $R_e > 960$ MPa; $R_m > 980$ MPa; $A_5 > 14\%$, impact energy > 55 J at a temperature of -20°C (>47 J at the temperature used during the tests, i.e. -40°C). The shielding gas used in the test was mixture PN-EN ISO 14175-M21-ArC-18.

Tests and results

The tests involved the making of two test joints 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-bevelled (through machining) in order to reach a depth enabling the removal of the weld without damaging the HAZ. The plates prepared in the above-presented manner were subjected to another welding process and to mechanical tests. The edges of the base material were prepared by subjecting them to mechanical bevelling (Fig. 1).

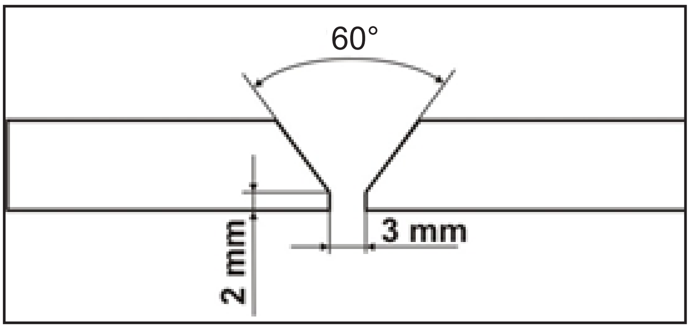

Fig. 1. Pre-weld joint preparation

Before tacking, the edges of the base material were degreased using acetone. Afterwards, the edges were tacked using three 5 mm long welds. The tacked steel plates were fixed on a welding table using cam-lever grips. Preparations also involved the use of a ceramic strip forming the root of the weld as well as a run-on and a run-off plate used to stabilise welding parameters at the beginning of the welding process and to terminate electric arc outside the joint. The test joints were made using a MultiSurfacer D2 Weld automated welding station (Welding Alloys) provided with a microprocessor-based control system enabling the adjustment of a specified welding rate and the repeatable positioning of the welding torch mounted in the set of supports of the welding station. The preheating temperature amounted to 100°C, whereas the interpass temperature was maintained below 230°C. Temperature was measured using a contact thermometer. Both joints were made in the flat positon (PA) using parameters presented in Table 2. The welded joins were designated using Roman numerals, i.e. I – in relation to the joint welded once and II – in relation to the joint made two times.

Table 1. Results of the analysis of the chemical composition of steel S960QL

Contents of chemical elements, % by weight													
C	Si	Mn	P	S	Cr	Mo	Ni	Cu	Al	Ti	V	B	Fe
0.16	0.38	1.43	0.01	0.002	0.56	0.44	0.03	0.03	0.03	0.005	0.034	>0.001	rest

Table 2. Parameters used in the MAG welding of plates made of steel S960QL

Bean no.	Welding current, A	Arc voltage, V	Filler metal wire feeding rate, m/min	Welding rate, cm/min	Heat input*, kJ/mm
1	153	15,5	3,5	8	1,43
2÷9	235	26,0	6,0	40	0,73

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

Visual and radiographic tests

The test joints were subjected to visual tests in accordance with the PN-EN ISO 17637:2017-02 standard *Non-destructive testing of welds – Visual testing of fusion-welded joints*. The tests aimed to identify a quality level according to PN-EN ISO 5817:2014. In both cases, the test joints were free from any welding imperfections. The tests revealed that the joints represented quality level B. The face and the root of the welds are presented in Figure 2.

Afterwards, the joints were subjected to radiographic tests aimed to check the joints for the presence of welding imperfections in the form of incomplete fusion and porosity. The tests, performed in accordance with the PN-EN ISO 17636-1:2013 standard revealed that the joints represented quality level B. Joint-related radiograms are presented in Figure 3.

Tensile strength tests

Tensile strength tests were performed in accordance with the PN-EN ISO 4136:2013 standard, using an Instron 4210 testing machine. Each joint was sampled for three specimens. In each case, the rupture took place in the weld metal. The results of the tensile strength tests are presented in Table 3.

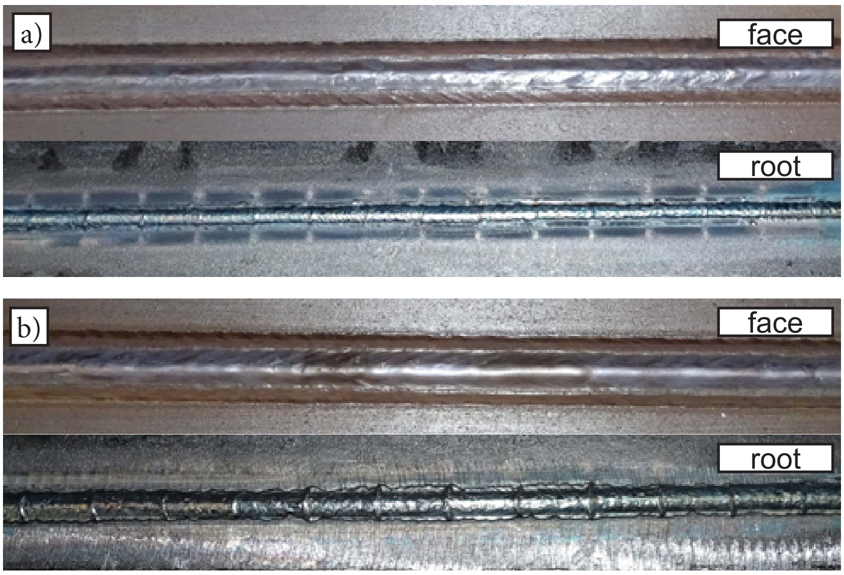

Fig. 2. Face and root of the weld in the welded joint made of steel S960QL once (a) and two times (b)

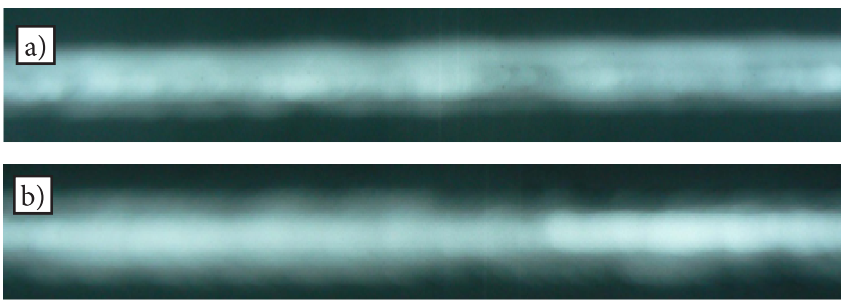

Fig. 3. Radiogram of the joint welded once (a) and two times (b)

Table 3. Results of the tensile tests of the joints made of steel S690QL

Joint designation	Test results, MPa			Average value MPa
	1	2	3	
I	948	952	938	946
II	934	924	925	928

The tensile strength of the test joints amounted to 924÷952 MPa. The average value (out of three tests) related to the joint made once amounted to 946 MPa, whereas that related to the joint made two times amounted to 928 MPa. In both cases, the tensile strength did not exceed the normative tensile strength for steel S960QL, amounting to 980 MPa (according to PN-EN 10025-6:2009). In each case, the obtained strength was lower than the minimum strength of the weld deposit amounting to 980 MPa in accordance with the PN-EN ISO 18276 standard. Therefore, the tested strength was the tensile strength of the weld metal and not of the HAZ. The difference in the tensile strength of the weld made once and that made two times was relatively small and amounted to 18 MPa. Assuming that, in each case, the weld metal was made using the same filler metal, the above-named difference could not be recognised as demonstrating the negative effect of the two-time welding thermal cycle on the tensile strength of the weld metal.

Impact strength test

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

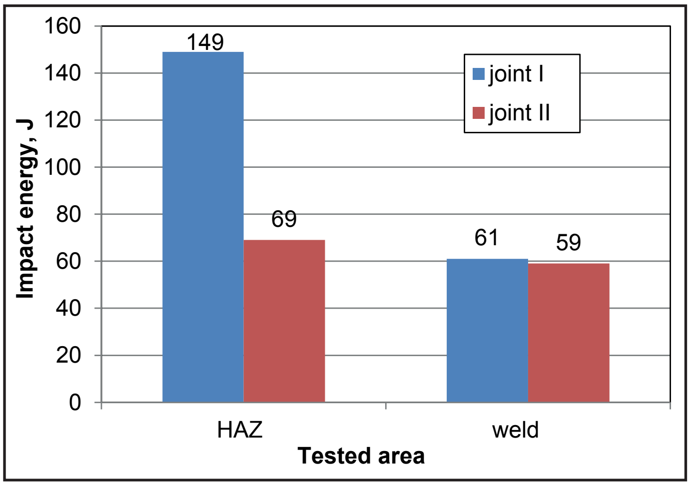

Fig. 4. Toughness of the HAZ and of the weld metal in the joint welded once (I) and in the joint welded two times (II)

In terms of both welds, the impact energy was restricted within the range of 58 J to 64 J. The average impact energy amounted to 61 J and 59 J in relation to the joint made once and that made two times respectively. As can be seen, the difference in impact energy in relation to both welds was negligibly small. However, in terms of the HAZ, the impact energy was significantly different. As regards the joint made once, the impact energy was restricted within the range of 82 J to 178 J, with the average value (out of five tests) amounting to 149 J. As regards the joint made two times, the impact energy was restricted within the range of 52 J to 98 J, with the average value (out of five tests) amounting to 69 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 500x. The microscopic metallographic tests were performed using an Eclipse MA200 light microscope (Nikon). The microstructural tests concerned the HAZ at the half of the joint thickness. During the tests, particular attention was paid to the HAZ as the area characterised by significantly varying mechanical properties (in both joints). The results of the macroscopic metallographic tests are presented in Figure 5, whereas the results of the microscopic metallographic tests are presented in Figure 6.

Table 4. Results of the impact energy tests in relation to the joint made once and the joint made two times

Joint designation	Tested area	Impact energy, J					
		Measurement 1	Measurement 2	Measurement 3	Measurement 4	Measurement 5	Average
I	HAZ	178	82	144	176	164	149
	Weld	64	58	62	—	—	61
II	HAZ	52	72	72	98	53	69
	Weld	58	62	58	—	—	59

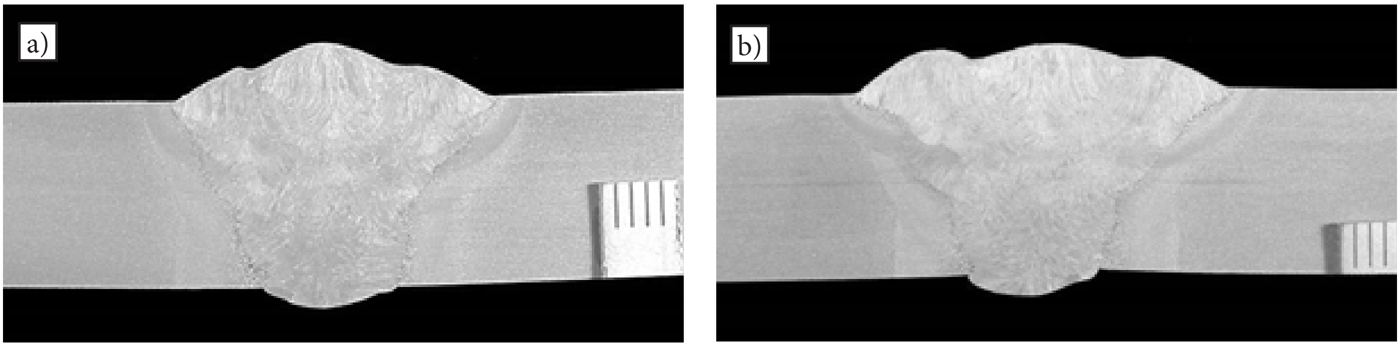

Fig. 5. Macrostructure of the joint made once (a) and the joint made two times (b)

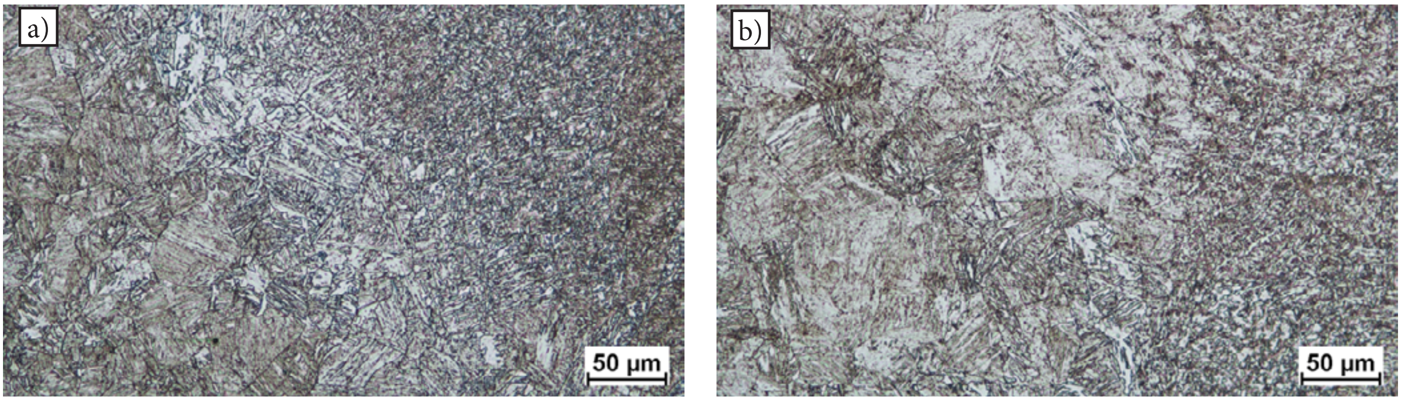

Fig. 6. Microstructure in the HAZ of the joint subjected to one-time (a) and two-time (b) welding

The macrostructural metallographic tests revealed that neither joint contained welding imperfections in the form of incomplete fusion. The fact that the shape of the fusion line was very similar in both cases demonstrated that the welding conditions accompanying the making of the joints were comparable. The microscopic metallographic tests revealed that the structure of the HAZ of the joint made once was composed of martensite (Fig. 6a). In turn, the HAZ of the joint made two times was composed of martensite and a slight amount of (probably) retained austenite. In addition, the tests revealed the significant grain growth in the joint subjected to two-time welding (Fig. 6b).

Cross-sectional hardness measurements of the welded joints

Cross-sectional hardness tests of the welded joints were performed using a KB50BVZ-FA hardness tester (KB Prüftechnik) and an indenter load of 98.1N (HV10). The measurements were performed in both directions from the weld axis. The distance between successive measurement points amounted to 1 mm. The measurement line was located at the half of the weld thickness. The results of the hardness tests are presented in Figure 7.

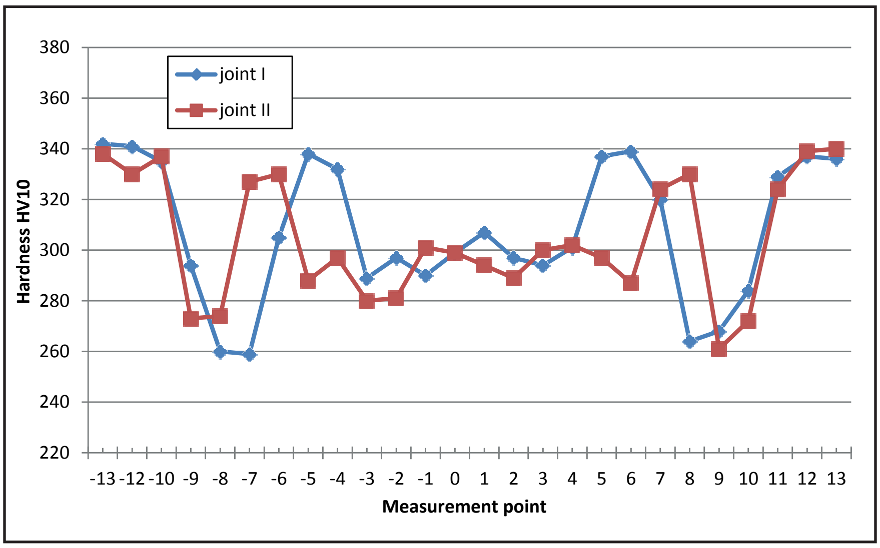

Fig. 7. Hardness distribution in the cross-section of the joint welded once (I) and the joint welded two times (II)

Analysis of test results

The visual and radiographic tests of the joints did not reveal the presence of any unacceptable imperfections. The joints represented quality level B in accordance with the PN-EN ISO 5817:2014 standard.

Tensile strength tests involved three specimens sampled from each joint. Because of the fact that in each case the specimen ruptured in the weld, only the strength of the weld metal was subjected to tests. As regards joint I, the average (out of three measurements) tensile strength R_m amounted to 946 MPa. In turn, in terms of joint II, the average strength amounted to 928 MPa (was lower by 18 MPa). Such a small difference in the strength of both welds and the fact that the weld metal was the mixture of the molten filler metal with a slight amount of partly melted base material could justify a conclusion that the two-time welding did not reduce tensile strength. The impact strength tests of the weld revealed that the impact energy in relation to the joint made once and that made two times amounted to 61 J and 59 J respectively. As mentioned before, in both cases the weld deposit was composed of the molten filler metal with a slight amount of the molten base material from the fusion zone. This means that, regardless of the number of repairs, the weld metal was always subjected to the same number of welding thermal cycles. Therefore, it can be expected that both the toughness and the other mechanical properties of the weld metal should remain unchanged regardless of the number of repairs. However, significant differences in impact energy were observed in relation to the HAZ of both joints. In the joint made once, the average (out of five tests) impact energy amounted to 149 J, whereas in terms of the joint made two times, the impact energy amounted to a mere 69 J. The result satisfied the condition of the minimum normative impact energy in relation to steel S960QL, i.e. 30J at a temperature of -40°C. However, it can be assumed that another thermal cycle will reduce the HAZ toughness further, precluding the satisfaction of the above-presented condition. To determine possible reasons for such a significant difference in impact energy in relation to the HAZ of both joints, it was necessary to perform microscopic metallographic tests. The results of the microscopic metallographic tests revealed that the HAZ structure of joint I was composed of tempered martensite. The microstructure of the HAZ of the joint made two times (joint II) contained (probably) retained austenite. In addition, the HAZ of the joint made once was characterised by significantly greater grain growth, which undoubtedly led to the reduction of the toughness of this area. The above-presented mechanism of the HAZ toughness reduction could imply that the accelerated cooling used after the making of each bead of the weld and the application of welding parameters reducing a heat input to the joint would favourably affect the toughness of the welded joint. It can also be assumed that the removal of the weld again followed by the making of another joint (three-time welding) might decrease the toughness of the HAZ even further so that the condition of the minimum normative impact energy for steel S960QL, i.e. 30 J in relation to a standard specimen, at a temperature of -40°C could not be satisfied.

The cross-sectional hardness measurement of the joints revealed that the hardness of the base material amounted to 330÷342 HV10. The test concerning the HAZ of the welded joints revealed the presence of two areas of clearly varying hardness. In the area of the HAZ adjacent to the base material, the hardness was lower than that of the base material and amounted to 259÷261 HV10 in the joint welded once and 261÷274 HV10 in the joint welded two times. In the second area of the HAZ, adjacent to the fusion line, hardness increased significantly in the direction of the weld and amounted to 332÷339 HV10 as regards the joint made once and 324÷330 HV10 in terms of the joint made two times. The weld hardness amounted to 280÷307 HV10. In the softened area of the HAZ, the hardness of the joint made once amounted to 250÷255 HV10, whereas that of the joint made two times amounted to 242÷249 HV10. The softening in the HAZ on the base material side was slightly reduced, yet an increase in hardness near the fusion line was also slightly lower in this joint in comparison with the joint made two times. In addition, the width of changes in hardness from the weld axis was slightly greater in the joint welded two times, which could be ascribed to the fact that the joint was subjected to two thermal cycles.

Conclusions

1. The two-time thermal cycle accompanying the repair welding of 12 mm thick plates made in steel S960QL enables the making of joints satisfying the requirements of the PN-EN ISO 15614-1 standard.

2. The reduced tensile strength of the weld metal in relation to that of the HAZ precluded the investigation concerning the effect of repair welding on changes in the mechanical properties of the HAZ.

3. The two-time thermal cycle accompanying the repair welding of 12 mm thick plates made in steel S960QL (repair welding simulation) reduces the impact energy in the HAZ from 149 J to 69 J, which justifies a conclusion that the three-time repair welding will preclude the satisfaction of the requirement concerning the minimum normative impact energy which, in relation to steel S960QL, amounts to 30J at a temperature of -40°C.

4. The microscopic metallographic tests revealed that the two-time welding was responsible for significant grain growth of the HAZ metal and the presence of, probably, residual austenite. Both phenomena were probably responsible for the significant reduction of the joint toughness in the HAZ.

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