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Estimates of weldability and selection of the optimal procedure and technology for welding of high strength steels

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Abstract

High strength steels belong into a group of high quality steels, with exceptional mechanical properties, especially in regards to tensile strength. At the same time, as their deficiency is emphasized the limited and difficult weldability. In other words, some of those steels are weldable only with application of special measures related to controlled heat input. In that way, the favorable mechanical properties can be kept within the heat affected zone, with condition that the optimal welding technology is selected. Existing, very scarce and often unclear and insufficient recommendations for selection of the optimal welding technology are one of the causes of large number of flaws in welded joints. Mentioned problems, as well as others, can be successfully solved by proper selection of the procedure, filler metal and technology of welding, verified by experiments conducted in laboratory or in real operating conditions. Those experiments can not be performed in arbitrary conditions. Thus, partially due to results reported in this paper, technologists will obtain the possibility to predict in advance, in a very short time period, the mechanical and metallurgical properties of joints of this class of high strength steels. This will be possible without conducting the large number of practical tests or relying on personal experience of a designer.

Keywords: High strength steel S690QL; weldability; welding technology; microstructure; toughness;

1. Introduction

In this paper are considered problems of high strength steels welding, with special attention being devoted to special low-alloyed steels of the S690QL class (EN 10025-6). Their microstructure is interphase tempered

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structure. Thus they belong into the group of well weldable steels, but only for the plates of relatively low thickness. They are obtained from the steels semi-products, by the combined process of the heat treatment and mechanical processing, at high temperatures, with controlled cooling. Those steels are used for manufacturing of the highly responsible welded structures [1-5].

The quality of the welded joint depends on properties of the base metal and the filler material, the selected method of welding, the groove geometry, welding parameters, the welder's skills, as well as on the conditions of the welding equipment. The biggest problem though, which is related to weldability of those steels, especially for welding of the thicker parts, is the possibility of appearance of the cold cracks and residual stresses [1-2, 5-8]. Those problems can mainly be solved by application of the interlayer-rutile soft austenite electrodes, by controlled introducing of heat and, in special cases, by application of the heat treatment [1-2, 5, 9-12].

2. Base metal and its weldability

In this paper is analyzed weldability of the S690QL steel (Weldox 700 – SSAB commercial mark). Chemical composition, the most important mechanical properties and impact toughness values are available in corresponding references [1-2, 10]. Weldability is being assessed computationally according to total equivalent Carbon and tendency to appearance of cold cracks. Taking into account that we consider welded joints of 3–50 mm thickness, it is necessary to apply the preheating [1-2, 10].

2.1. Guidelines for preventing the cold cracks

As it was already mentioned, the steels in question are prone to forming of cold cracks. Here we are drawing attention to some recommendations from literature [1-5, 7-10, 13], which should be respected in welding of this class of steels. They are mainly related to the following: lowering the content of Hydrogen in the weld, proper selection of the temperature regime for the heat treatment as well as the inter-layer temperature, application of the adequate filler material, proper preparation of the groove and its vicinity prior to welding, retaining the recommended heat inflow within the strict narrow limits, proper realization of the pre-connecting joints, etc.

The recommended preheating temperatures, for the normal stiffness conditions, are especially important for the pre-connecting joints and rutile pass. The highest preheating temperatures are being applied for the strict stiffness conditions, which are being determined by the combined thickness of plates. For the S690QL steel, the recommended preheating temperature is 150–200°C, and the maximum interpass temperature is $T_{\text{interpass}} = 250°C$. The recommended working temperatures should prevent the appearance of cold cracks, which can appear on the melting surface of the base metal, as well as inside the weld metal, especially if the filler material is of high strength. However, due to difficult working conditions, the preheating is often avoided. Namely, during laying down the filling interpasses, the spontaneous stress relaxation occurs due to action of the brought-in heat with the additional layers. The preheating can be avoided also if the additional heating of the welded joint is applied, as well as by the increase inflow of heat and application of the austenite filler materials.

3. Selection of the filler material, procedure and welding technology

3.1. Filler material

For welding of the S690QL steel by manual arc welding, one should use the covered basic redry electrode, or generally speaking, the welding methods that would guarantee low content of Hydrogen in the weld metal

(≤ 5 ml/100 g) [1-2, 7, 10]. By application of filler materials with the lower strength than the base metal's, one can achieve the higher toughness of the welded joint, the higher resistance to cold cracks and lower residual stresses in the welded joint, especially in the heat affected zone (HAZ). The pre-connecting joints and the first pass are being done with the filler material of the lower strength, while the remain passes are then done with filler materials of the higher strength. This technique is being applied when approximately same resistance properties in all the parts of the welded joint are being required by technical conditions [1-2, 10-12].

In this paper is analyzed the following combination of the filler materials: for the rutile welds–electrode INOX B 18/8/6 (MMA) and for the filling welds–electrode wire MIG 75 (GMAW in the gas mixture Ar+18 % CO_2). In Table 1 are presented the most important properties of the considered filler materials.

Table 1. Chemical composition, mechanical properties and application of the used filler materials [14 – Fiprom Jesenice]

FM mark	Chemical composition, %						Mechanical properties of the pure weld metal			
	C	Si	Mn	Cr	Ni	Mo	f_u, Pa	f_y, MPa	ε, %	KV, J
INOX B 18/8/6*	0.12	0.80	7.00	19.0	9.0	-	590-690	> 350	> 40	> 80 (+20ºC)
MIG 75**	0.60	0.60	1.70	0.25	1.5	0.50	770-940	> 690	> 17	> 47 (-40ºC)
INOX B 18/8/6	Applied as interpass electrode for deposition of the rutile layer in order to reduce the level of residual stresses, increase plasticity and toughness of the welded joint									
MIG 75	For welding of the small grain steels of higher strength with the yield stress of 690 MPa.									

*) INOX B 18/8/6 = E 18 8 Mn B 22 (EN 1600); **) MIG 75 (SŽ Fiprom Jesenice, Slovenia) = Mn3Ni1CrMo (EN 12534)

3.2. *Selection of the procedure and parameters of welding*

The test weldings were done with varying the energetic parameters within the recommended limits. Besides the visual control of the test joints, additional investigations were done by destruction of those realized welds. In that way we came up with the optimal welding regime. The geometry of welds was evaluated on performed test joints, because it is, besides the welding depth, hardness and microstructure of the welds individual zones, the basic criterion for the process control to grant approval to this manufacturing operation.

In Table 2 are given the basic welding parameters, driving energy and expected welding depth. The adopted welding parameters enable obtaining of the necessary welding depths, the required joint geometry and favorable microstructure and hardness of the HAZ.

Table 2. Basic welding parameters for corner multipass welds

Weld type	Basic welding parameters					q_l	δ
	I, A	U, V	v_z, cm/s	v_t, m/min	Q, l/min	J/cm	mm
Rutile welds (MMA)	120	24.5	0.20	-	-	12000	1.8
Filling welds (GMAW)	220-250	24-25	0.35-0.40	6-8	15-20	12822-13281	1.8-1.86

4. Metallographic investigations of the welded joints

Several tents of test weldings were performed with the selected combination of the filler materials and adopted welding parameters, both on characteristic corner and butt joints [1, 10]. The macrographic and micrographic investigations were then performed on those samples, and, indirectly, qualifications of the welders were checked, too. As the first, measurements of the most important geometric characteristics of welds was done, and then was also measured hardness of individual zones of welds and the microstructure was established of those zones. The samples were selected, prior to welding, based on the geometric similarity to the real joints within the structure.

In Figure 1 is presented the macrographic appearance of one of many samples selected for metallographic investigations, as well as some of the characteristic microstructures of individual zones of the but weld.

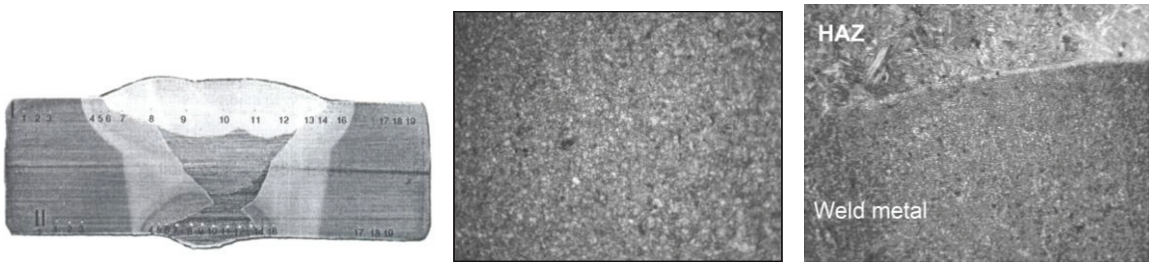

Fig. 1. Left: Macrostructure of the but joint and points were hardness was measured; Microstructures of individual zones of the welded joint (200 ×) [1, 10]. Middle: BM – interphase tempering structure; Right: HAZ – interphase tempering structure + tempered martensite.

Through analysis of large number of metallographic samples, realized by the previously described combination of the filler materials and welding regime, it was established that they all have almost the same type of microstructure and approximately the same values of hardness were measured in individual joint zones. Thus, one can say that values of hardness and red-off microstructures of individual weld zones mainly satisfy requirements of standard and corresponding internal technical recommendations [2, 7-9].

5. Mechanical investigations of welded joints

5.1. Tensile tests

The base metal and the weld samples were subjected to tensile test on the ZWICK/ROEL Z 100 testing machine with the force range 0–100 kN. The strain rate was 10 mm/min. Tests were conducted at Faculty of Engineering in Kragujevac and in the accredited laboratory in Zastava – Automobiles. The samples appearance prior to and after the tests is shown in Figure 2, while the characteristic tension diagram is presented in Figure 3, with some of the processed summary results given in Table 3.

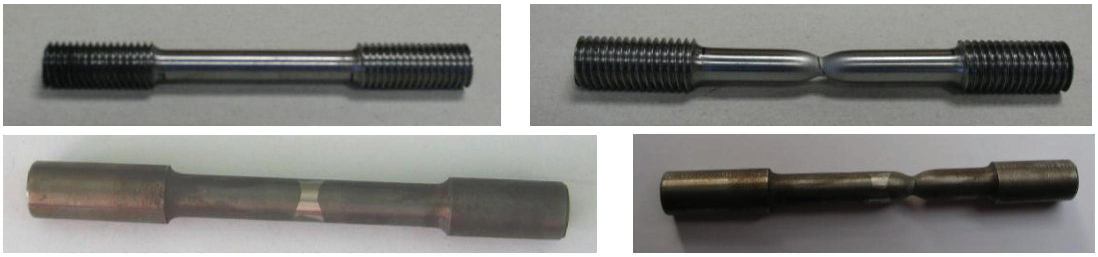

Fig. 2. Test samples appearance: upper figures BM sample before (left) and after (right) the test; lower figures: weld metal sample before (left) and after (right) the test.

In similar manner were tested the weld metal samples. Obtained values were within the following limits: f_u = 910-913 MPa, f_y = 870-878 MPa and ε = 8.75-10.2%, what is within prescribed resistance limits, but with somewhat worse plasticity properties than characteristic ones for this class of steels.

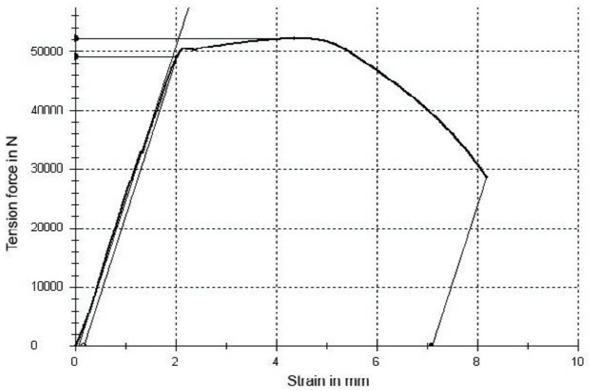

Fig. 3. Tension diagram of the BM sample # 1.

Table 3. Summary results of the base metal S690QL tension test

Sample #	L_0	S_0	$f_{y\,0,2}$	f_u	ε
1	mm	mm^2	MPa	MPa	%
2	48.00	50.52	972	1032	14.65
3	48.00	50.52	977	1037	14.78
4	48.00	50.39	996	1033	14.92

5.2. Impact tests

For the impact testing samples were also prepared both from the base metal and the welded joint material; they were tested at the Sharpy pendulum in two accredited laboratories (Zastava automobiles in Kragujevac and The "Goša" Institute in Smederevska Palanka). Results of the toughness tests of the base metal and the weld, at the room and the lower temperatures are resented in Table 4 [1, 10].

Table 4. Fracture energy absorbed by samples at impact test of the base metal and welded joint

Material	Temperature, °C	Fracture energy, KV, J
Base metal S690QL	+ 20	172; 166; 171; 158 (10 × 10);
	0	157; 201 (10.1 × 8.1) and 184; (10 × 8)
	- 20	177; (10 × 8.1); and 191 (9.9 × 8) and 186 (10.1 × 8.1)
	- 40	157; 167; 155 (10 × 10)
Welded joint S690QL	0	43.2; 40.2; 44.2; 29.4; 31.4 (10 × 8.1) and 29.4 (9.9 × 8)
	- 20	33.4; 33.4;16.7; (10 × 8.1) and 30.4 (10.1 × 8) and 34.3; 19.6 (10 × 8)

In testing of the absorbed fracture energy, obtained values were significantly lower than for the base metal but only in two cases they were slightly lower than the prescribed values.

6. Conclusion

After the detailed analysis of the most important properties of the base metal and estimates of its weldability, selection of the optimal combination of the filler materials, methods and technologies of welding, as well as conducted voluminous model and other standard tests, we established the optimal technology of welding, which was then applied at very responsible welded structure. This structure was realized with the proposed technology and when subjected to rigorous tests it proved itself as very reliable.

Due to all that was said, we must emphasize that, in order to achieve adequate properties of the welded joints, close to properties of the base metal, one must obey recommendations prescribed by the steel manufacturers, as well as knowledge reported by other researchers in the field. Since the literature in this area does not contain an abundance of papers, we consider that our work is an attempt to establish the necessary procedure for welding of the very responsible structures. For the more complete estimate of the welded joints' reliability, additional investigations need to be conducted, especially from the aspect of the welded structures integrity, based on methods and criteria of fracture mechanics.

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References

[1] Jovanović, M., Lazić, V.: Instructions for welding of the high strength steel WELDOX 700, Faculty of Mechanical Engineering, Belgrade/Kragujevac, 2008.

[2] Larsson, T. B., Berglund, T.: Handbook on WELDING of Oxelösund steels, Sweden, 1992.

[3] Müsgen, B. und Hoffmann K.: Improvement of the fatique strength of welded high strength steels, *Thyssen Technishe Berichte,* Heft 1, 1978, pp. 67-79.

[4] Müsgen, B.: High strength quenched and tempered steels-production, properties and applications. *Metal Construction,* 1985, pp. 495-500.

[5] Hajro, I., Pašić, O., Burzić, Z.: Characterization of welded joints on highstrength structural steel S690QL, *Welding and welded structures*, 55, 4, 2010, pp. 123-129.

[6] Clarin, M.: High Strength Steel -Local Buckling and Residual Stresses, Luleå University of Technology, Luleå, 2004.

[7] Determination of suitable minimum preheating temperature for the cold-crack-free welding of steels. IIW-Doc. IX-1631-91.

[8] Determination of the effect of welding on the maximum hardness in the heat-affected zone of welded joints. IIW-Doc. IX-1342-84.

[9] Determination of the effect of welding on the toughnees in the heat-affected zone of welded joints. IIW-Doc. IX-1340-84.

[10] Jovanović, M., Lazić, V., Marinković, P., Nedeljković, B., Aleksandrović, S., Milosavljević, S.: Estimates of weldability and selection of the optimal procedure and technology of welding of high strength steel WELDOX 700, 26th Meeting "Welding 2010", Tara, Serbia, p. 82. (CD)

[11] Jovanović, M., Lazić, V., Josifović, D., Adamović, D.: Surwey of structural steels and estimates of their weldability, Faculty of Mechanical Engineering, Kragujevac, 1995, pp 125-132.

[12] Lazić, V., Adamović, D., Josifović, D., Jovanović, M.: Contribution to defining the limiting parameters of the structural high strength steels welding, Faculty of Mechanical Engineering, Kragujevac, 1995, pp 133-140.

[13] Lazić, V., Sedmak, A., Živković, M., Aleksandrović, S., Čukić, R., Jovičić, R., Ivanović, I.: Theoretical-experimental determining of cooling time ($t_{8/5}$) in hard facing of steels for forging dies, *Thermal science*, 14, 1, 2010, pp. 235-246.

[14] Filler materials manufacturers catalogues: SŽ Fiprom Jesenice Slovenija, Bohler-Kapfenberg, Messer Griesheim-Frakfurt am Main, Esab- Goteborg, Lincoln Electric-SAD etc.