UNIVERSITY OF ŽILINA
Faculty of Mechanical Engineering
Department of Materials Engineering

SEMDOK 2014

19th International seminar of Ph.D. students

under the auspices of
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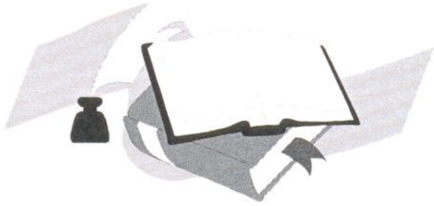
dean of the Faculty of Mechanical Engineering of the University of Žilina



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SELECTING THE OPTIMAL WELDING TECHNOLOGY OF HIGH STRENGTH STEEL OF THE S690QL CLASS

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Abstract

In this paper is presented the detailed procedure for selecting the optimal technology for welding of the responsible welded structures made of high strength steel S690QL. This steel belongs into category of steels that possess exquisite mechanical properties, especially what concerns the strength and impact toughness, both at room and elevated temperatures. On the other hand, this steel is prone to appearance of cold cracks, what makes its welding difficult. Selection of the optimal welding technology, which is the subject of this work, is aimed at preserving the favorable mechanical properties both in the welded metal and the melting zone, as well as in the heat affected zone as the most critical zone of the welded joint.

Key words: *High strength steel, S690QL, Mechanical properties, Weldability.*

1. Introduction

There are several factors that influence weldability of the high strength steel: chemical composition of the base metal (BM), type of the filler metal (FM) and welding procedure. The further influential factors are: the quantity of hydrogen diffused from the weld into the base metal, thickness, type and distribution of joints, kind of applied heat treatment, order of deposition of individual welds, etc. This is why the weldability should be estimated first. The next to be conducted are the mechanical investigations, both at room and elevated temperatures, for the purpose of establishing the mechanical properties of the welded joints. The model investigations are to be performed next; their output parameters include results of mechanical investigations, visual appearance of the weld, measured hardness and metallographic recordings of certain zones of the welded joint, as well as the impact toughness of the welded joint critical zones.

The S690QL class steel belongs into a group of special thermo-mechanical (TMO) low alloyed steels; the producer provides declaration of chemical composition on delivery [1-3]. The carbon content is limited to 0.20 %, so the steel should possess good weldability. Microalloying elements cause improvement of mechanical properties of those steels; especially effective are niobium and boron which are deoxidizing the steels and cause the fragmentation of metal grains. There are three different modifications of the S690 steels: S690Q, S690QL and S690L1, which only differ with regard to guaranteed impact toughness: S690Q – KV = 27 *J* at -20°C; S690QL – KV = 69 *J* at -40°C, S690QL1 – KV = 27 *J* at -60°C [2, 3]. Mass application of the high strength steel of this class occurred due to exceptional mechanical characteristics (tensile strength and yield stress) as well as favorable impact toughness. Basic data provided by the steel manufacturer can be found in corresponding references [1-3, 5].

It should be emphasized that application of these steels is limited for the working conditions when the temperature does not exceed 500 °C, since above this limit the mechanical properties worsen [2, 3].

2. Weldability of the base metal

Weldability of high strength steels can be determined by calculating according to the equivalent carbon (CE) and proneness of the steel towards the cold cracks. Depending on formula for calculating the CE and thickness of the welded parts, the limiting values of CE vary (Table 1).

Based on results from Table 1, steel manufacturers recommend the preheating temperature that enables hydrogen diffusion from the joint zone and extending of the HAZ cooling time, for the purpose of obtaining the softer structure [1, 2, 5]. Besides the chemically equivalent carbon, one can theoretically estimate risk of appearance of cold, hot, lamellar and annealing cracks [1, 5]. According to formulae of different authors, the considered steel is highly prone to appearance of cold cracks. Risk of hot cracks is not so prominent, but risk of lamellar and annealing cracks is [1, 2]. Thus, the manner and procedure of welding should be so chosen that the reliable welded joint can be realized, which during exploitation would not be prone to appearance of any cracks that can cause brittle fracture of the welded structure.

Table 1

Values of the chemically equivalent carbon [1, 4]

Mark	Thickness, *mm*	Chemically equivalent carbon, CE %	
		$CEV = C + \frac{Mn}{6} + \frac{Cr+Mo+V}{5} + \frac{Ni+Cu}{15}$ %	$CET = C + \frac{Mn+Mo}{10} + \frac{Cr+Cu}{20} + \frac{Ni}{40}$ %
S690QL	20	0.43 - 0.55	0.29 - 0.36
	30	0.46 - 0.55	0.31 - 0.36
	60	0.57 - 0.55	0.35 - 0.36

For the S690QL steel the preheating temperature is recommended to be within range 150 – 200 °C, and maximum interpass temperature should be $T_{interpass}$ = 250 °C in order to prevent porosity in the weld metal caused by air turbulence, and also not to cause worsening of the steel's mechanical properties realized by the thermo-mechanical treatment of steel.

3. Selection of the welding technology

Based on manufacturer's recommendation and experience of other users, it was decided, for responsible joints, to apply filler metals of austenitic structure of the smaller strength than the base metal for the root weld layers, while for the rest of the weld layers (filling and cover ones) to apply the filler metals of the strength similar to that of the BM.

Thus, the proposed welding technology assumes deposition of the root welds by the MMAW electrode E 18 8 Mn B 22 – diameter Ø 3.25 mm; deposition of the filling layers is done by the GMAW electrode wire Mn3Ni1CrMo – diameter Ø1.2 mm (Fig. 1). For deposition of the covering layers the GMAW procedure was selected due to better productivity with respect to the MMAW [1, 2]. The welded plate dimensions were 400×200×15 mm. After deposition of the root pass 1 it was subsequently partially grooved by the graphite electrode arc-air procedure and the new root pass was deposited in the complete argon protected atmosphere by the austenite electrode 8 (Fig. 1).

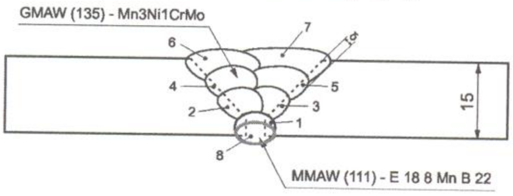


Fig. 1. Combined MMAW/ GMAW deposition of weld layers

Table 2

Chemical composition and mechanical properties of the filler metals [1, 2].

Electrode type	Chemical composition, %						Mechanical properties of the pure weld metal			
	C	Si	Mn	Cr	Ni	Mo	R_m, MPa	R_p, MPa	A_5, %	KV, J
E 18 8 Mn B 22	0.12	0.8	7	19	9	-	590 - 690	> 350	> 40	> 80 (+20°C)
Mn3Ni1CrMo	0.6	0.6	1.7	0.25	1.5	0.5	770 - 940	> 690	> 17	> 47 (-40°C)

Table 3

Welding parameters [1]

Parameters	I, A	U, V	v_z, cm/s	v_t, m/min	q_l, J/cm	δ, mm	Protective gas	Protective gas flow l/min
Root passes MMAW	120	24.5	0.2	-	12000	1.7	-	-
Filling welds GMAW	240	25	0.35	8	14885	2	Ar/18 % CO_2	14

4. Experimental investigation of the welded joints

Experimental tests of the S690QL steel specimen consisted of mechanical tensile test and impact toughness test. The tensile test was performed on prepared from the 15 *mm* thick plate; 4 specimens were prepared for the Base Metal (BM) tests and 4 specimens wee aimed for testing the welded joint material [5, 6]. Tests were performed according to standard SRPS EN 10002-1 [8].

Table 4

Experimental results of the tensile test [1-3, 5, 6].

Sample No.	L_0, *mm*	S_0, *mm*^{2}	$R_{p0.2}$, *MPa*	R_m, *MPa*	A_g, %	$A_{11.3}$, %
Base metal – S690QL						
1	89.28	50.27	781.94	797.81	1.73	14.19
2	89.28	50.27	809.40	839.92	5.79	11.30
3	88.42	50.01	800.41	835.52	4.86	9.98
4	88.29	50.27	811.95	842.45	5.48	10.92
Welded joint – Plate 1 (REL/MAG)						
1	89.28	50.27	809	840	11.30	50.27
2	89.42	50.27	764	831	9.77	50.27
3	88.96	49.39	760	812	5.49	49.39
4	88.96	49.39	740	804	5.38	49.39

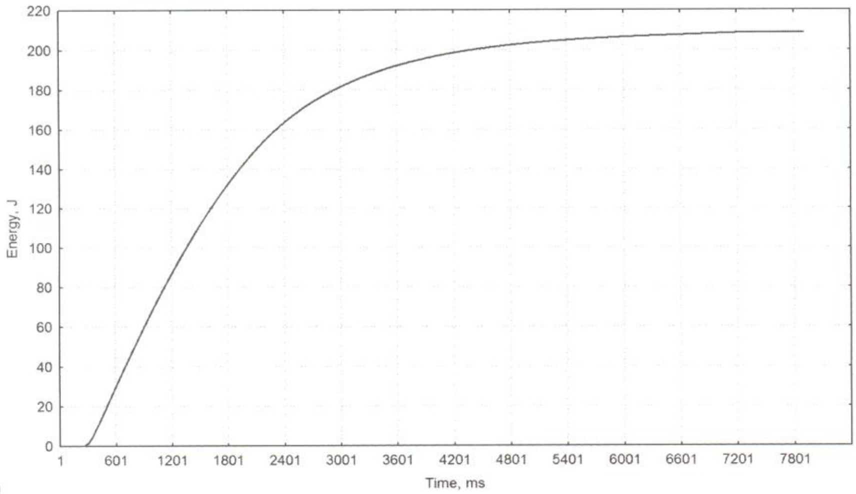
Specimens were prepared for the impact toughness tests, according to the similar procedure as for the tensile test specimens; six aimed for testing the BM and three for testing the impact toughness of the weld metal, root metal and HAZ. Tests were done on the Charpy pendulum, both at room and lower temperatures, according to standard EN 10045-1 [9]. Table 5 gives results of the impact tests; Figure 2 a shows the energy vs. time diagram and 5b shows appearance of the fracture surfaces of the representative sample.

Table 5

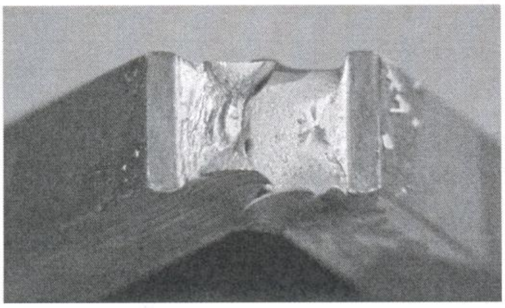
Impact energy absorbed at room and lower temperatures

Steel mark	Temperature, °C	Impact energy absorbed, J			
		Base metal	Weld metal	Weld root metal	HAZ
S690QL	+20	235.2; 222.4; 234.7	24.2; 45.5; 34.7	85.8; 89.5; 54.1	189.2; 172.8; 209.7
	-40	219.6; 19.8; 206.1	-	-	-

Besides the presented results, in favor of selected welding technology, were deciding also the plasticity properties of the executed welded joints, estimated according to the share of the plastic fracture in the total fracture surface (Fig. 2b), which was, in all the zones of the executed joint, within range 92.41 – 99.81 %, what represents exceptional results from the aspect of the welded joints plasticity.



a)



b)

Fig. 2. HAZ sample #3; a) impact energy vs. time diagram; b) fracture surfaces appearance

5. Conclusion

After the detailed analysis of the most important properties of the base metal; estimates of its weldability, selection of the optimal combination of the filler metals, procedure and technology of welding and voluminous model investigations, the optimal technology of welding was established, which was then applied on the real structure. That structure was then subjected to rigorous tests and it fulfilled all the requirements necessary for field work, where it turned as a very reliable one.

In establishing the optimal technology experimental results of the sample welds tensile and impact tests were used as indicators. During the tensile tests samples' fractures occurred outside the welded joint zone, what means that strength of the welded joint was higher than that of the base metal. Impact toughness was within limits required by the appropriate standards, especially in the HAZ as the most critical zone of the joint. The recorded metallographic structure revealed that appearance of the brittle martensitic structure of the welded metal was avoided.

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