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Dependence of Mechanical Properties of the Base Metal and Welded Joint of the High Strength Steel S690QL on Elevated Temperatures

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In this paper is analysed behaviour of mechanical properties of the welded joint and base material of high strength steel S690QL at elevated temperatures. The exposure to elevated temperatures could lead to deterioration of mechanical properties of steel as well as to decreasing of load bearing capacity. Since this steels belongs to a group of steels with exquisite mechanical properties, the aim of this work is to show which is the critical temperature when its mechanical properties are going to worsen. For that purpose, an experimental investigation has been carried out. The specimens were taken both from the welded plate and the base material. The welding was performed with GMAW procedure using two types of filler metals with different mechanical properties for root layer and cover ones. The experiment was performed within the temperature range 20°C to 550°C. The obtained results show the difference with respect to several references, including the European standards, steel producers recommendations and some other researches results. Therefore, studying of mechanical properties of this steel at elevated temperatures is of the utmost importance.

Keywords: High strength steel, S690QL, Welded joint, High temperature, Mechanical properties.

1. INTRODUCTION

With constant advancements in the field of welding technology, there is a growing need for high strength construction steels such as the steel grade S690QL which is analysed in this paper. In order to maintain good weldability, the carbon content in high strength steels has to be as low as possible (max 0.22%) and the steel should have good mechanical properties which would make the welded construction reliable and light. When complex welded constructions are made, especially the ones made of steels of wide cross-sections, the steel is often heated (preheated, additionally heated and tempered), and the process engineers and designers often find themselves in a dilemma concerning the maximum temperatures allowed for this process. In the literature, wide ranges of these temperatures can be found, depending on the thickness of the welded plates i.e., their thickness equivalents. The aim of this experimental paper is to determine the maximum working temperatures at which both base metal (BM) and weld metal (WM) keep thier high strength values.

Dependance of mechanical properties of the base material and welded joints on the temperature has been subject of numerous investigations [1-6]. Due to that, we want do give our contribution to understanding of influence of high temperatures on mechanical properties.

The results shown in the papers [1-4, 6-8] represent a good starting point to understanding the influence of temperature on the base material mechanical properties. However, this influence has not been analysed particularly for the welded joints of high strength steels, which are very sensitive not only to local input of heat that ocurrs during the welding process but also to elevated working temperatures. Due to these reasons we have chosen to perform complex experimental investigations both of the base material and the welded joints. Some of our published papers [9, 10, 11] studied the high steel grade S690QL and certain zones of welded joints from the aspect of mechanic and metallurgical properties. In these papers different welding methods and different filler materials were used in order to find the most suitable welding technology. In the present paper we have chosen the MAG welding method and two different filler materials. The root passage was done using austenitic filler material, and the passes were filled with the filler material of the strength similar to the base material strength. Thus, good ductility of the joint and the minimum stress concentration are achieved, while residual stresses in the welded joints are significantly decreased.

2. SELECTION OF THE MOST SUITABLE WELDING TECHNOLOGY

1.1. Base metal

Since behaviour of the steel S690QL is studied at elevated temperatures, the welded joints have to be welded using the most suitable welding technology. The steel S690QL is produced under special conditions by heating up to the austenite region, rolling and finally by controlled cooling. The steel produced in such a thermo-mechanical treatment process (Quenching + Tempering – Q + T steel) is highly resistant and has good toughness which is maintained even at low temperatures [12]. There are three modifications of this steel that differ only in the guaranteed impact toughness. In fact, all the modifications have the same guaranteed impact toughness of 27 J but different transient temperatures. For the steel grade S690QL it is 47 J at -40°C. The chemical composition and the most important mechanical properties of the steel S690QL are given in Tables 1 and 2 [9, 10, 11, 16].

1.2. Selection of the welding technology

The MAG/MAG method was proposed For welding of the steel grade S690QL the proposed method is MAG/MAG (GMAW/GMAW), and two different filler materials [11, 12] for the root pass and the cover welds were chosen (Tab. 3).

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Table 1. Chemical composition of the steel S690QL

Steel mark	Require-ment	Chemical composition, %														
		C	Mn	Si	P	S	Cr	Mo	Ni	V	Al	B	Cu	Ti	N	Nb
S690QL	Specified max	0.20	1.50	0.60	0.020	0.010	0.70	0.70	2.0	0.09	0.015	0.005	0.30	0.040	0.010	0.040

Table 2. Mechanical properties of the base metal and the microstructures

Steel mark	Thickness, mm	R_m, MPa	$R_{p0.2}$, MPa	A_5, %	Microstructure
S690QL	4.0 - 53.0	780 – 930	700	14	Interphase tempered structure

Table 3. Chemical composition and mechanical properties of electrode wires [9, 10, 13]

Filler material	Chemical composition, %						Mechanical properties of the pure weld metal			
	C	Si	Mn	Cr	Ni	Mo	R_m, MPa	$R_{p0.2}$, MPa	A_5,%	KV,J
T 18 8 Mn R M 3 (EN ISO 17633-A)*	0.1	0.8	6.8	19	9	-	600 - 630	> 400	> 35	> 60 (+20ºC)
Mn3Ni1CrMo ** (EN 12534)	0.6	0.6	1.7	0.25	1.5	0.5	770 - 940	> 690	> 17	> 47 (-40ºC)
* T 18 8 Mn R M 3	Rutile, highly productive, filled electrode wire for applying root welds in order to increase ductility of the welded joint.									
** Mn3Ni1CrMo	For welding of small grain high strength steels of yield strength up to 690 MPa.									

The MAG/MAG method involves applying the root weld bead in Ar+18% CO_2 shielding gas, using plastic rutile filled electrode wire T 18 8 Mn R M 3 (EN ISO 17633-A) of significantly lower yield stress compared to the base material and applying other weld beads in Ar+18% CO_2 shielding gas with the filler material Mn3Ni1CrMo (EN 12534) of the strength similar to the strength of the base material. The chemical composition and mechanical properties of the filler materials are given in Table 3. The thickness of the welded plates was 15 mm. The applied root pass (1) was partially grooved using a graphite electrode by the arc-air method and a new root weld pass was applied (8) using austenite electrode (Fig. 1). This procedure is carried out in order to correct the mistakes that might have occurred if there was no proper protection from the damaging effect of the air gases.

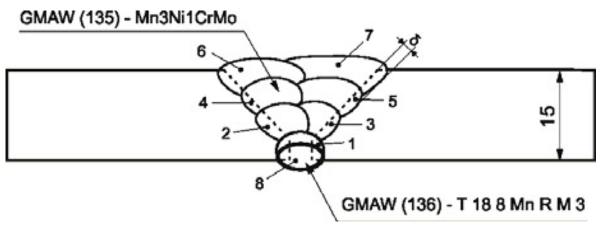


Figure 1. Applying a weld bead using the MAG/MAG method

3. EXPERIMENTAL INVESTIGATION OF THE WELDED JOINTS

The purpose of choosing the most suitable welding technology is to get welded joints whose mechanical and structural properties will resemble the base material properties. The first in order of investigations was tensile testing. Specimens for the tensile testing (Fig. 2), hardness measurement and microstructure testing were prepared according to appropriate standards [14, 15] and used in this paper. Test specimens for the tensile testing were prepared from the base material and from the welded plates. Figure 2 shows the drawing of the test specimens for the tensile testing, and Figures 3 and 4 shows the test specimens before and after the tensile testing [14].

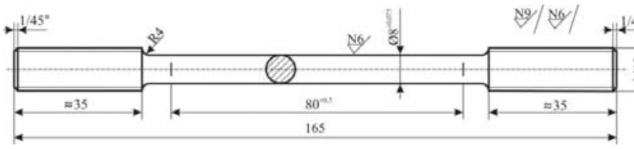


Figure 2. Test specimens for the tensile testing

BM tensile testing specimen

BM test specimen after the testing

Figure 3. Tensile testing specimens made of the base material before and after the testing

WJ tensile testing specimen

WJ test specimen after the testing

Figure 4. Tensile testing specimens made of the base material and welded joints before and after the testing

A homogenous temperature field was formed within the chamber using the controller. Three thermocouples were used to maintain the temperature and a homogenous temperature field. The testing machine with heating chamber on it is shown in figure 5.

Mechanical properties were determined according to the standard that propose all of testing conditions (EN ISO 6892-2) [14].

Figure 5. Zwick Roell Z100 testing machine with a chamber for testing at elevated temperatures

For each testing temperature, two test specimens were prepared, one of the base material and the other of the welded joints. The tests were initially conducted at 20°C, 250°C, 350°C, 450°C (two specimens at every temperature), and then three specimens were tested at 500°C at three more at 550°C. The obtained results are shown in Table 4.

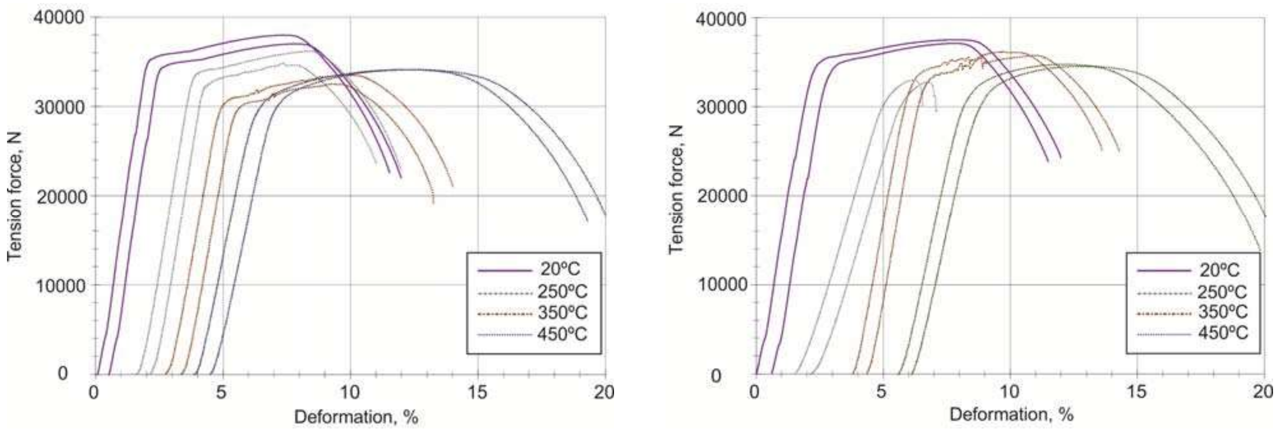
Table 4. Experimental results obtained by tensile testing performed on the specimens made of the base material and the welded joints

Testing temperature, °C	Specimens			
	Base material		Welded joint	
	$R_{p0.2}$	R_m	$R_{p0.2}$	R_m
20	736.6/736.7	793.1/794.3	769.8/779.6	835.5/850.5
250	691.2/702.2	742.8/754.7	715.1/718.9	725.1/785.7
350	665.3/678.9	727.4/748.4	727.9/728.3	804.1/806.3
450	634.2/650.2	718.9/749.4	655.9/671.2	754.5/756.4
500	612.4/617.1/650.2	658.4/662.5/749.4	-	-
550	532.9/547.7/577.3	560.1/583/611.5	-	-

The graphic representations of obtained results are given in form of diagrams (Fig. 6 and 7). The diagrams show two curves for each temperature (for two specimens). The second curve represents the repeated test and it is shifted from the coordinate beginning in order to give a clearer picture.

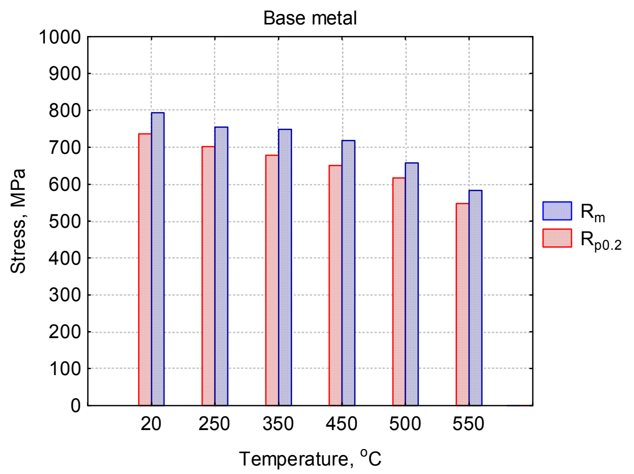
Testing of the base material has shown that a significant decrease in mechanical properties occurs at the temperatures higher than 450°C (Fig. 6a). With further increase in temperatures this decrease is more and more evident (Table 4 – shaded cells). As for the joints welded using the proposed technology, the decrease in mechanical properties occurs at temperatures higher than 450°C (Fig. 6b). Though an unexpected decrease in mechanical properties and significantly less ductility of the welded joint were registered at the temperature of 250°C, they were attributed to the noticed non-metal inserts in the cross-sections of the broken specimens.

Figure 7 shows histograms of mechanical properties (tensile strength - R_m and yield stress – $R_{p0.2}$) obtained by experimental tensile testing at room and elevated temperatures.



a) b)

Figure 6. Diagrams of tensile testing for: a) base material and b) welded joints



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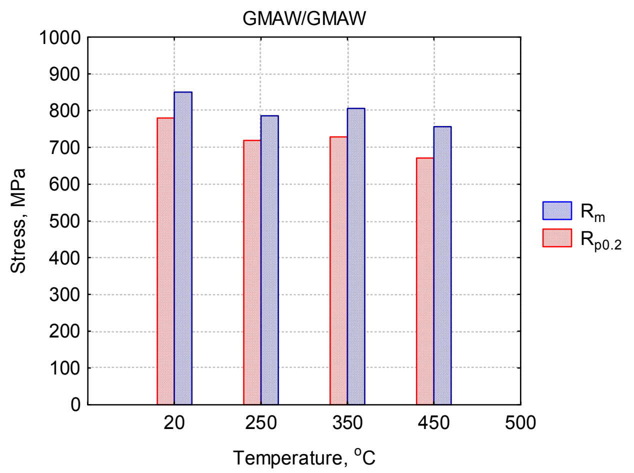

b)

Figure 3. Histograms of the obtained values ($R_{p0.2}$ and R_m) at elevated temperatures for: a) base metal and b) welded joints

After tensile testing investigation of the hardness distribution and the microstructure was performed. The diagram of hardness and microstructure for the characteristic zones of the welded joints obtained using the MAG/MAG welding method is shown an figure 4.

The decrease of hardness in weld metal zone is expected because the selected filler material for applying root welds has austenitic structure and low hardness in order to decrease stress level in the joint and to increase the welded joint plasticity.

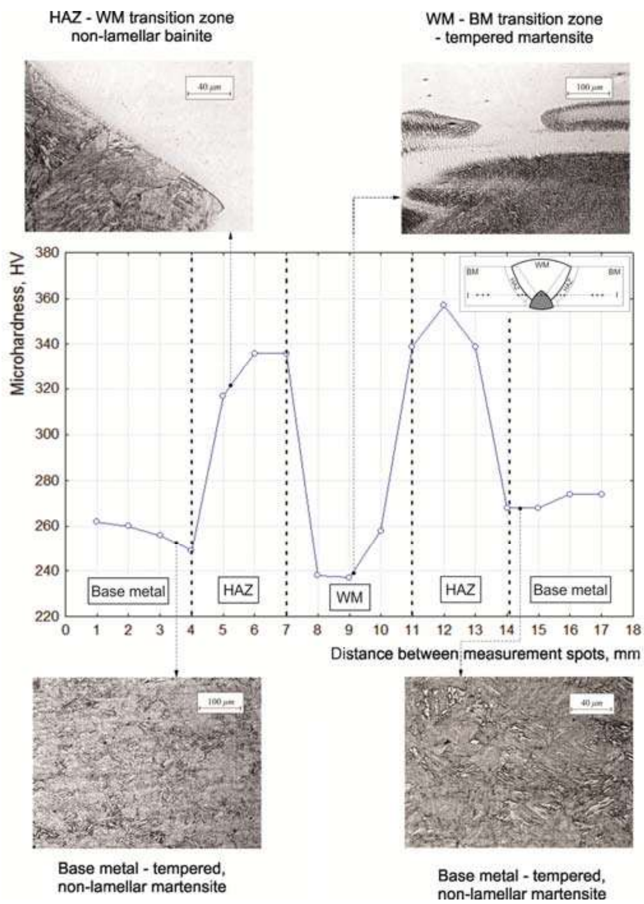

Figure 4. Microhardness distribution and the microstructure for the joint obtained using the MAG/MAG method

4. CONCLUSIONS

The results obtained in this paper show the influence of elevated temperatures on mechanical properties of the steel S690QL. Both the base material and the welded joints obtained using the MAG/MAG method were studied. The base material was tested for the temperature range from 20 to 550°C, while the welded joints were tested for the temperatures in the range from 20 to 450°C.

The obtained experimental results have shown a significant decrease in the yield stress and tensile strength of the base material at temperatures higher than 450°C. The studied welded specimens exhibited a decrease in their mechanical properties at temperatures higher than 450°C. So, the conclusion is that the constructions made of this steel should not be used at temperatures higher than 450°C.

Since the obtained results for the base material and the welded joints have similar results, it can be concluded that the choice of welding technology was right. It also should be emphasized that the choice of welding technology was not a random; a large number of tests was carried out on specimens/models using different welding methods (REL/MAG, MIG/MAG, MAG/MAG), and different filler materials, energy welding parameters as well as other relevant parameters.

In our opinion one should be very careful to choose the right temperature (for preheating, additional heating and tempering) in building welded constructions exposed to dynamic loading. We hope that the results obtained in this paper will be prove useful to process engineers in building welded constructions made of the steel S690QL and in working with them.

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