



# OPTIMAL WELDING TECHNOLOGY OF HIGH STRENGTH STEEL S690QL

Dušan Arsić<sup>1,\*</sup>, Vukić Lazić<sup>1</sup>, Ružica Radoslava Nikolić<sup>1,2</sup>,  
Srbislav Aleksandrović<sup>1</sup>, Branislav Hadzima<sup>2,3</sup>, Milan Djordjević<sup>1</sup>

<sup>1</sup> Faculty of Engineering, University of Kragujevac, Sestre Janjić 6, 34000 Kragujevac, Serbia

<sup>2</sup> Research Centre, University of Žilina, Univerzitná 8215/1, 010 26 Žilina, Slovak Republic

<sup>3</sup> Faculty of Mechanical Engineering, University of Žilina, Univerzitná 8215/1, 010 26 Žilina, Slovak Republic

\*corresponding author: tel.: +421948610-520, e-mail: ruzicarnikolic@yahoo.com

## Resume

In this paper, the detailed procedure for defining the optimal technology for welding the structures made of the high strength steel S690QL is presented. That steel belongs into a group of steels with exceptional mechanical properties. The most prominent properties are the high tensile strength and impact toughness, at room and at elevated temperatures, as well. However, this steel has a negative characteristic - proneness to appearance of cold cracks. That impedes welding and makes as an imperative to study different aspects of this steel's properties as well as those of eventual filler metal. Selection and defining of the optimal welding technology of this high strength steel is done for the purpose of preserving the favorable mechanical properties once the welded joint is realized; properties of the welded metal and the melting zone, as well as in the heat affected zone, which is the most critical zone of the welded joint.

## Article info

### Article history:

Received 28 October 2014

Accepted 19 January 2015

Online 17 February 2015

### Keywords:

High strength steel  
S690QL;  
Mechanical properties;  
Weldability;  
Impact toughness;  
Hardness.

Available online: <http://fstroj.uniza.sk/journal-mi/PDF/2015/05-2015.pdf>

ISSN 1335-0803 (print version)

ISSN 1338-6174 (online version)

## 1. Introduction

In order to establish the optimal welding technology of any steel one first has to estimate its weldability. That property is being influenced by many different factors, out of which the most important ones are the chemical composition of the base metal (BM), the type of the filler metal (FM) and the welding procedure. The other factors affecting the weldability are the quantity of hydrogen diffused from the weld into the base metal, thickness of the part to be welded, type and distribution of joints, heat input, type of the applied heat treatment and order of deposition of individual welds – layers and so on. The chemical composition data are usually obtained from the manufacturer of particular steel; however, it is always useful to verify them by additional tests in accredited laboratory. Then, one has to perform tensile test

and the impact test of the base metal, to verify its mechanical properties. The establishing of steel's weldability is also done by calculating the chemically equivalent carbon. Finally, one has to perform the test weldings on models – samples from the base metal with application of various filler metals, varying the heat input, welding procedure and eventual additional heat treatment. Performing a sort of sensitivity theory, by keeping all but one parameter constant, and repeating the procedure for all the parameters, one comes up with their optimal combination, in this case the result is the optimal welding technology for the high strength steel S690QL.

## 2. Weldability of the base metal

The S690QL class steel is a special thermo-mechanically obtained (TMO) low-alloyed steel which, according to ISO 15608

standard classification belongs to 3.1 group – thermo-mechanically treated fine grain steels and cast steels, with  $R_{p0.2} > 360$  MPa (N/mm<sup>2</sup>). The chemical composition is prescribed by the steel producer, Table 1 [1 - 3, 6]. The carbon content is limited to 0.20 %, what improves the weldability. Addition of small amounts of alloying elements also improves mechanical properties of steel. Here should be emphasized the effect of niobium and boron, which are deoxidizing the steel causing significant fragmentation of metal grains.

Main reasons for massive application of this steel are its high tensile strength and yield stress and favorable impact toughness what enables application of small thicknesses and consequently lowering the construction's mass. The basic data on mechanical properties, provided by the manufacturer are presented in Table 2 [1 - 6].

It should be emphasized that, due to special procedure of thermo-mechanical manufacturing of this class of steels, their application is limited to operating temperatures that do not exceed 580 °C, since if that

happened the mechanical properties of steels are significantly worsened. Weldability can be determined by calculations according to the chemically equivalent carbon and proneness of particular steel towards formation of cold cracks. Values of those equivalents vary depending on the applied calculation method and thickness of the welded parts, Table 3.

Based on results from Table 3, steel manufacturer recommended that the welding preheating temperature should be within the interval 150 to 200 °C. The temperature thus adopted should enable removing of hydrogen from the joint zone and extend the heat-affected zone (HAZ) cooling time, for the purpose of obtaining the favorable structure of the welded metal [1, 2, 5].

Besides the chemically equivalent carbon, the danger of appearance of the cold cracks, lamellar and annealing cracks, was estimated, as well [1, 5]. According to various authors' formulae, the considered steel is extremely prone to forming of cold cracks. The proneness towards formation of hot cracks is not prominent, but danger of formation of lamellar and annealing cracks exists [1, 2].

Table 1

*Prescribed chemical composition, %.*

C	Mn	Si	P	S	Cr	Mo	Ni	V	Al	B	Cu	Ti	N	Nb
0.2	1.5	0.6	0.02	0.01	0.7	0.7	2.0	0.09	0.015	0.005	0.30	0.040	0.01	0.04

Table 2

*Prescribed mechanical properties [1 - 6].*

Steel mark	Thickness (mm)	R <sub>m</sub> (MPa)	R <sub>p</sub> (MPa)	Impact energy (J)	A <sub>5</sub> (%)	Microstructure
S690QL	4.0-53.0	780-930	700	69 J at -40°C	14	Interphase Q+T structure
	53.1-100		650			
	100.1-130		630			

Table 3

*Values of the total chemically equivalent carbon [1 - 4].*

Thickness (mm)	5	5-10	10-20	20-40	40-80	80-100	100-160
$CET = C + \frac{Mn + Mo}{10} + \frac{Cr + Cu}{20} + \frac{Ni}{40}$	0.34	0.31	0.31	0.36	0.39	0.39	0.41
$CEV = C + \frac{Mn}{6} + \frac{Cr + Mo + V}{5} + \frac{Ni + Cu}{15}$	0.48	0.48	0.48	0.52	0.58	0.58	0.67



This is why the welding parameters have to be such to ensure the reliable welded joint, which would not be the point of the potential fracture during exploitation.

### 3. Proposed welding technology

Prior to presenting the proposed welding technology, some of the most important recommendations regarding the welding process are enumerated [1 - 5]:

1. Reduce the hydrogen content in the welded joint ( $H < 5$  ml/100 g of the weld metal);
2. Select the adequate preheating and interpass temperatures;
3. Apply combination of the low-hydrogen austenitic and ferritic filler metals (electrodes/wires) with mandatory storage and drying according to manufacturer's prescriptions;
4. Remove all the impurities from the melting zone and perform welding at the low air humidity;
5. By proper selection of the joint type and clearance within the joint (maximum 3 mm) ensure measures necessary for reducing the residual stresses in the welded joint;
6. Select the optimal welding order, which would reduce the residual stresses and strains;
7. Adopted recommended values of the preheating and interpass temperatures are valid only in the case that the heat input is about 170 kJ/mm or higher (welding with relatively low speed);
8. If the environmental humidity is increased, or the temperature is below 5 °C, the lowest preheating temperature must be increased for 25 °C. This contributes to strength of the auxiliary stapling pre-joints that are executed with the heat input of about 100 kJ/mm;
9. The heating-through time should be 2 – 5 min/mm of joint thickness, with slow heating and cooling;
10. The auxiliary pre-joining should be done with the same procedure and filler metal as the root pass, of 40 – 50 mm length.

Then the model – test weldings were done with the technology that included selecting of the preheating temperature, filler metals, welding procedures, order of deposition and type of the interpass and cover layers. Two welding technologies were applied.

For the S690QL steel, the recommended preheating temperature should be 150 – 200 °C; while the maximum interpass temperature should be  $T_{\text{interpass}} = 250$  °C in order to prevent porosity in the weld metal, which is caused by air turbulence, but one must be careful not to worsen the mechanical properties of steel realized by primary treatment.

After studying the manufacturer's recommendations and experience of other authors, it was decided that welding of responsible joints should be done in the following way: the root weld layers to be deposited by the filler metals of austenitic structure of the smaller strength than the base metal, while the filling and cover layers to be deposited by the filler metals of the strength similar to that of the BM. In that way, by applying the austenitic highly plastic filler metal, the root portion of the joint obtains necessary plasticity properties, while the filling and the cover layers provide for the necessary strength of the joint [2].

Thus, the first proposed welding technology assumes:

- deposition of the root weld layer by the MMAW (111) procedure with electrode E 18 8 Mn B 22 (Commercial mark: INOX B 18/8/6-Interpass electrode for root welds for reducing the residual stresses, increasing plasticity and toughness of the welded joint. Especially recommended for very rigid structures.) – of diameter 3.25 mm;

- deposition of the filler weld layers (passes) by the GMAW procedure with the electrode wire Mn3Ni1CrMo (Commercial mark: MIG 75-for welding of the fine-grained high strength steels with yield stress up to

690 MPa.) – of diameter 1.2 mm (Fig. 1);

- deposition of the cover layer by the GMAW due to its higher productivity with respect to MMAW [1 - 3].

The sample weldings were done on plates of dimensions 400×200×15 mm. After deposition of the root layer 1, it was subsequently partially grooved by the graphite electrode by the arc-air procedure and then the new root layer was deposited in the complete argon protective atmosphere and austenitic electrode 6 (Fig. 1).

Test welding according to the second technology assumed the following:

- deposition of the root weld layer by the GMAW procedure with the electrode wire of austenitic type of lesser hardness and strength than the base metal;

- deposition of the cover weld layers by the GMAW procedure with the electrode wire of strength similar to the BM;

The second plate was deposited by this procedure and the two technologies were compared.

The first welding technology parameters are presented in Tables 4 and 5, while the second technology parameters are presented in Tables 6 and 7.

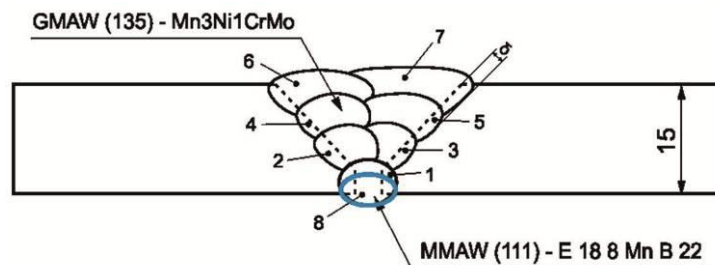


Fig. 1. Deposition of layers MMAW/GMAW.

Table 4

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

Electrode type	Chemical composition (%)						Mechanical properties			
	C	Si	Mn	Cr	Ni	Mo	R <sub>m</sub> (MPa)	R <sub>p</sub> (MPa)	A <sub>5</sub> (%)	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 5

Welding parameters [1, 2].

Parameters	I (A)	U (V)	V <sub>w</sub> (mm/s)	V <sub>m</sub> (m/min)	q <sub>i</sub> (J/mm)	δ (mm)	Protective gas	Protective gas flux (l/min)
Root welds (MMAW)	120	24.5	2.0	-	1200	1.7	-	-
Cover welds (GMAW)	240	25	35.	8	1488.5	2	Ar + 18% CO <sub>2</sub>	14

I – welding current; U – welding voltage; V<sub>w</sub> – welding speed; V<sub>m</sub> – melting speed; q<sub>i</sub> – driving energy (heat input); δ – penetration depth

Table 6

Chemical composition and mechanical properties of electrode wires [1 - 4, 13].

Wire type	Chemical composition (%)						Mechanical properties			
	C	Si	Mn	Cr	Ni	Mo	R <sub>m</sub> (MPa)	R <sub>p</sub> (MPa)	A <sub>5</sub> (%)	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 (+20°C)
Mn3Ni1CrMo (EN 12534)	0.6	0.6	1.7	0.25	1.5	0.5	770 - 940	> 690	> 17	> 47 (-40°C)

Table 7

Welding parameters [1, 2].								
Parameters	I (A)	U (V)	$V_w$ (mm/s)	$V_m$ (m/min)	$q_l$ (J/mm)	$\delta$ (mm)	Protective gas	Protective gas flux (l/min)
Root welds (GMAW)	190	22	3.0	8	1120	1.7	Ar + 18% CO <sub>2</sub>	14
Cover welds (GMAW)	240	25	3.5	8	1488.5	2	Ar + 18% CO <sub>2</sub>	14

*I* – welding current; *U* – welding voltage; *V<sub>w</sub>* – welding speed; *V<sub>m</sub>* – melting speed; *q<sub>l</sub>* – driving energy (heat input); *δ* – penetration depth

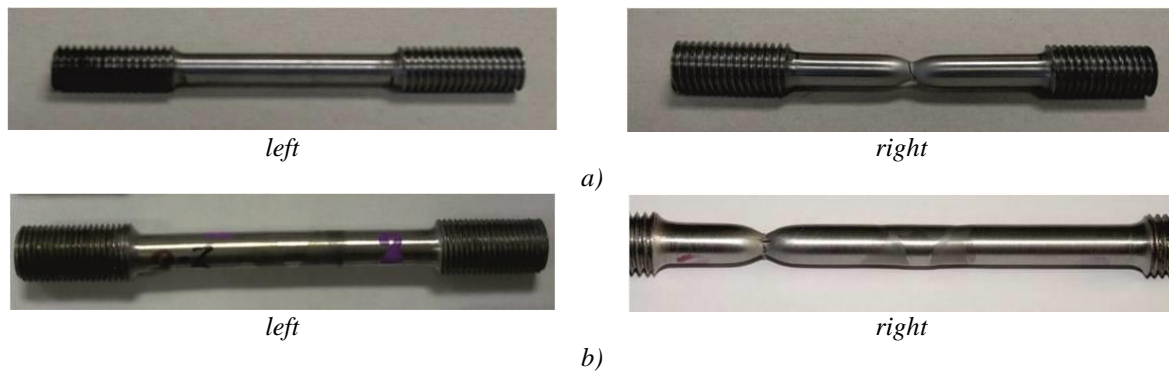


Fig. 2. Tensile test samples: Appearance before the tests (left) and after the tests (right); a) Base metal; b) Welded joint. (full colour version available online)

#### 4. Experimental investigation of the base metal and executed test welded joints

Experimental investigation of the base metal – steel S690QL and the executed welded joints included tensile tests, impact toughness tests, hardness measurements and investigations of microstructure.

##### 4.1. Tensile test

From the 15 mm thick plate four samples were prepared for testing the base metal and four samples for testing the properties of the welded joint, executed according to both technologies. Samples were taken transverse to welded joint, in such a manner that the welded joint is in the middle, so the sample contains both weld metal, the Heat Affected Zone and the base metal. None of samples has fractured in either HAZ or weld metal, as the most critical zones of the welded joint.

In Fig. 2 are presented appearances of the tensile test samples of both types, prior

to and after the tensile tests. Tests were done according to standard ISO 4136:2012 [8]. Obtained results are presented in Table 8.

##### 4.2. Impact toughness test

According to the procedure similar to one for the tensile tests, samples were prepared for the impact toughness test: six samples for the base metal, and three samples for each of the weld metal, joint's root and heat-affected zone. Tests were done on the Charpy pendulum in the accredited laboratory. Results of tests performed at the room and elevated temperatures are presented in Table 9. Tests were executed in accordance with standard ISO 148-1 [9]. Actual appearance of samples and schematic drawing are presented in [4].

Test results are presented in Fig. 3 to 7. They include values of the impact energy and impact toughness of the base metal, weld's face, weld's root and the melting zone, respectively, for both plates, i.e., two different welding technologies.

Table 8

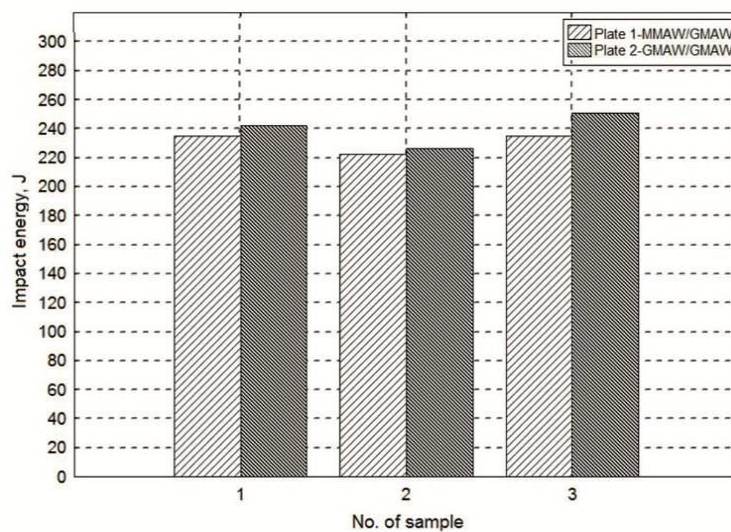
Experimental results of tensile testing [1- 4, 14].

Specimen No.	L <sub>0</sub> (mm)	S <sub>0</sub> (mm <sup>2</sup> )	R <sub>p0.2</sub> (MPa)	R <sub>m</sub> (MPa)	A <sub>11.3</sub> (%)
Base metal – S690QL					
1	89.28	50.27	781.94	797.81	14.19
2	89.28	50.27	809.40	839.92	11.30
3	88.42	50.01	800.41	835.52	9.98
4	88.29	50.27	811.95	842.45	10.92
<b>Welded joint (GMAW/MMAW) – Technology # 1</b>					
1	89.28	50.27	809	840	11.30
2	88.42	50.27	764	831	9.77
3	86.96	49.39	760	812	5.49
4	86.96	49.39	740	804	5.38
<b>Welded joint (MMAW/MMAW) – Technology # 2</b>					
1	87.63	50.39	794	834	11.59
3	89.49	50.39	784	834	9.12
4	90.92	49.89	782	833	10.92
5	88.75	50.27	779	837	11.48

Table 9

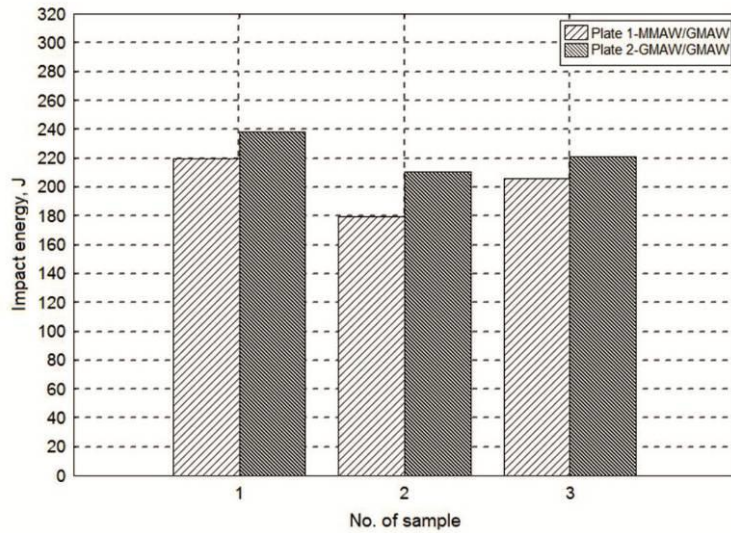
Impact energy values at room and elevated temperatures

Steel mark	Temperature, °C	Base metal		Weld metal	Root weld	HAZ	Sample #
		Sample #	Impact energy, J	Impact energy, J	Impact energy, J	Impact energy, J	
S690QL	+20	1	235.2	24.2	85.8	189.2	1
		2	222.4	45.5	89.5	172.8	2
		3	234.7	34.7	54.1	209.7	3
	-40	4	219.6	-	-	-	-
		5	179.8	-	-	-	-
		6	206.1	-	-	-	-



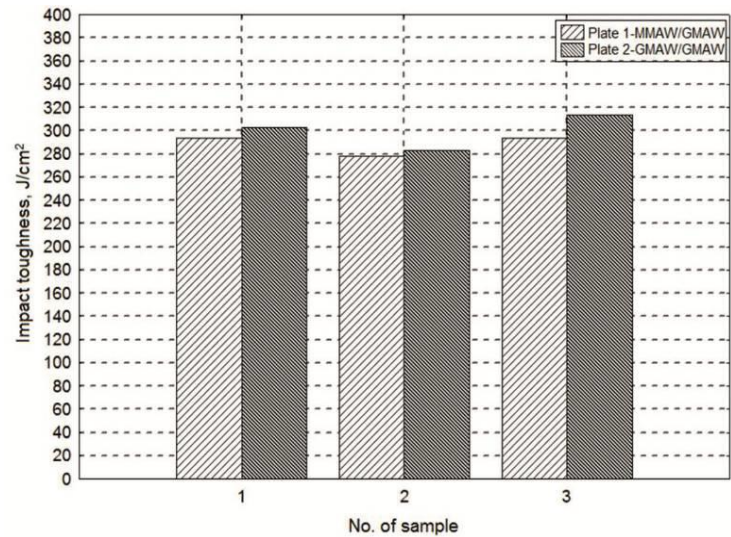
a)  $T = 20\text{ }^{\circ}\text{C}$ ;

Fig. 3. Comparative presentation of impact energy values for the two plates – BM.

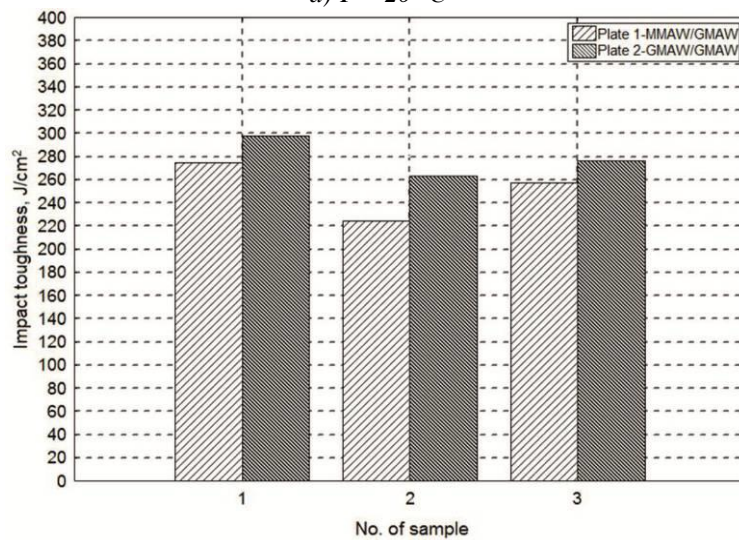


b)  $T = -40\text{ }^{\circ}\text{C}$

Continuing of Fig. 3. Comparative presentation of impact energy values for the two plates – BM.

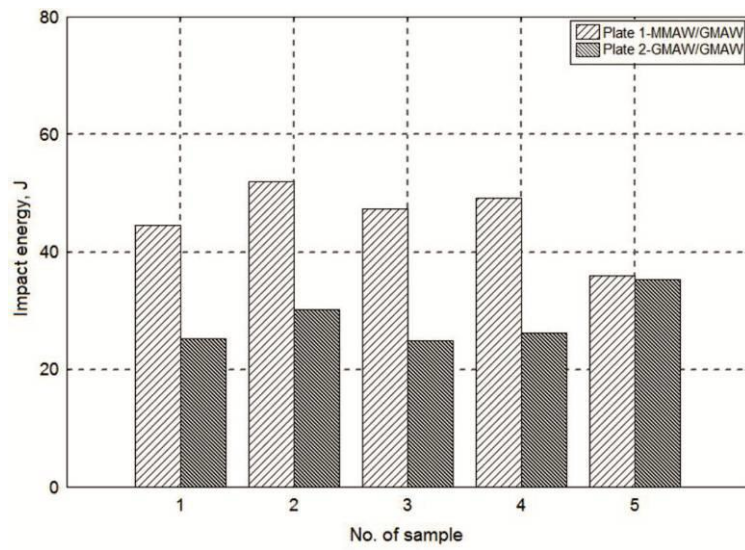


a)  $T = 20\text{ }^{\circ}\text{C}$

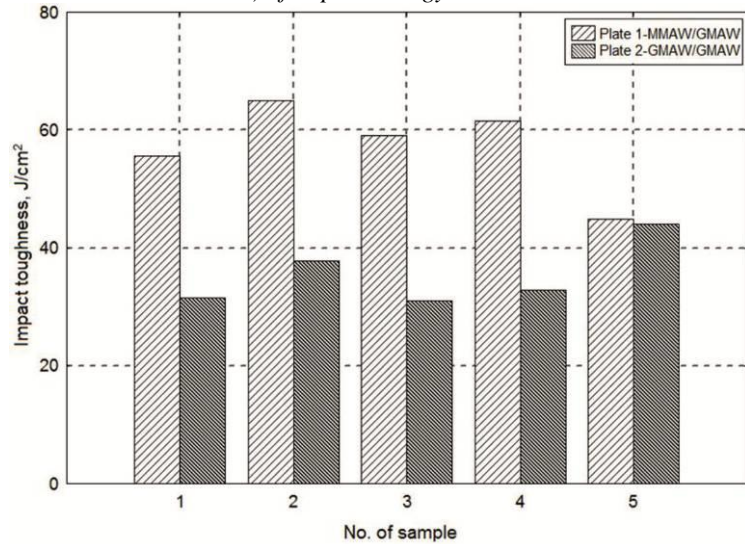


b)  $T = -40\text{ }^{\circ}\text{C}$

Fig. 4. Comparative presentation of impact toughness values for the two plates – BM.

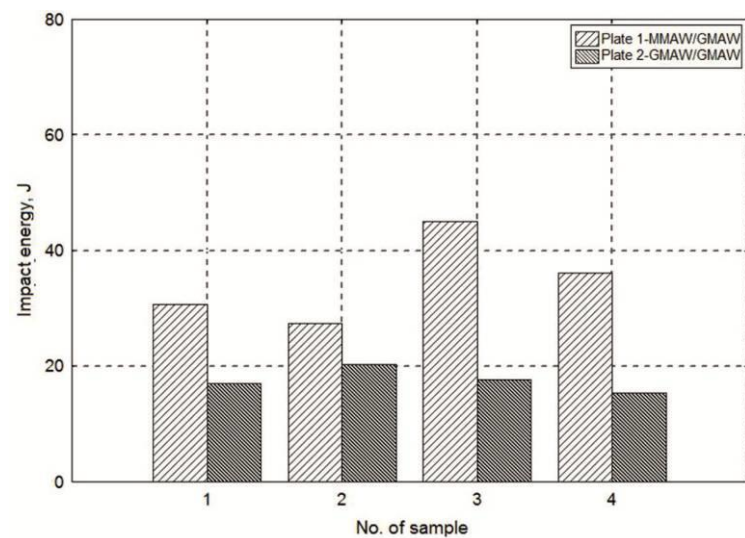


a) of impact energy values



b) of impact toughness values at  $T = 20\text{ }^{\circ}\text{C}$

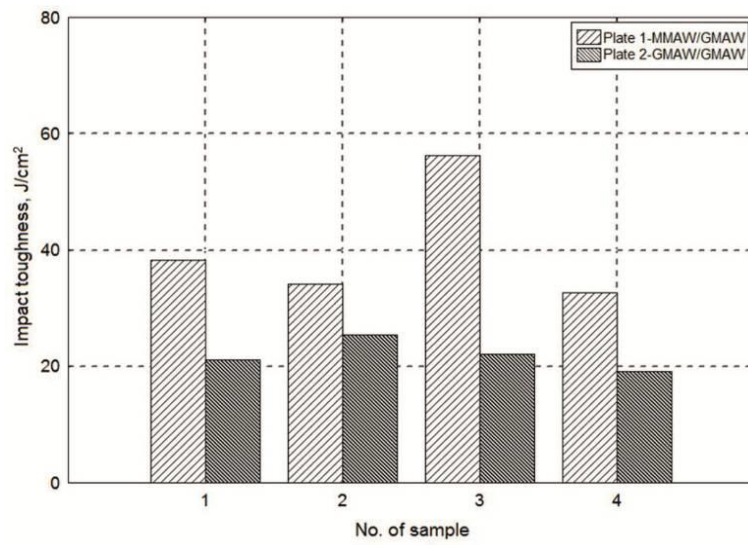
Fig. 5. Comparative presentation for the two plates – weld face.



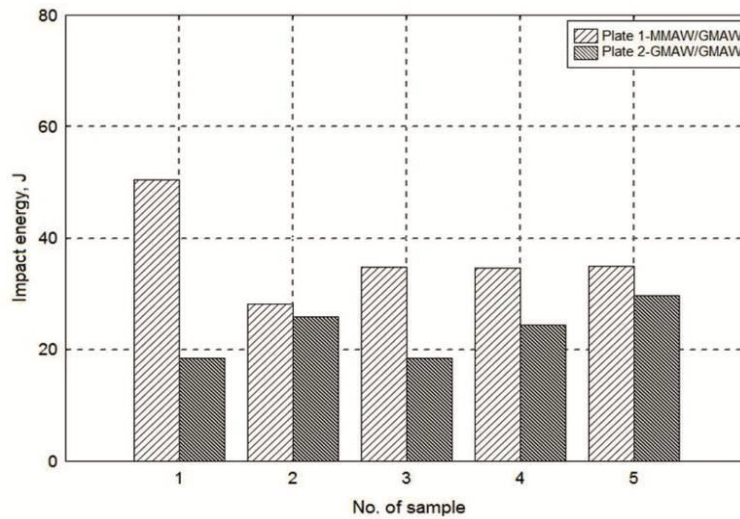
a) of impact energy values

Fig. 6. Comparative presentation for the two plates – weld root.

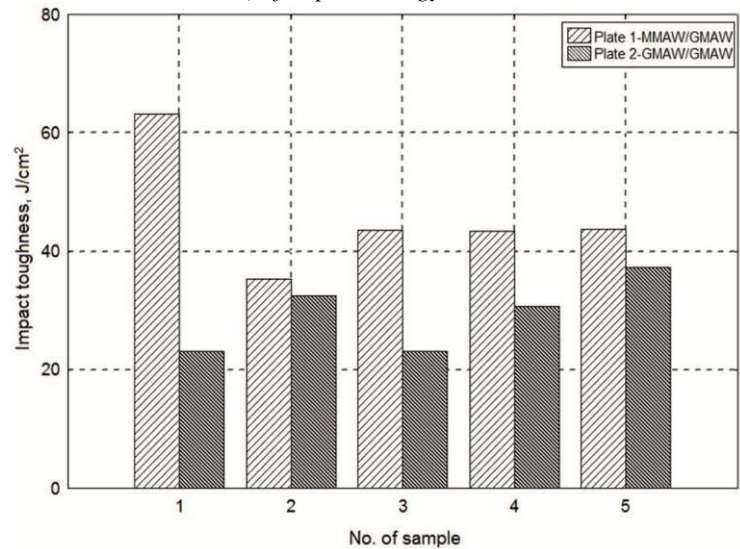




b) of impact toughness values at  $T = 20^{\circ}\text{C}$   
Continuing of Fig. 6. Comparative presentation for the two plates – weld root.



a) of impact energy values



b) of impact toughness values at  $T = 20^{\circ}\text{C}$ .  
Fig. 7. Comparative presentation for the two plates – weld root – melting zone.

Testing of the welded joint at  $-40\text{ }^{\circ}\text{C}$  was not performed since the analyzed/welded structure is predicted to operate at room temperature conditions (up to  $40\text{ }^{\circ}\text{C}$  at the most). Thus, it was not necessary to test the impact toughness at lower temperatures.

#### 4.3. Hardness measurements and investigation of microstructure

Hardness was measured of the base metal (BM), in the HAZ and weld metal (WM) along the straight lines perpendicular to the welded joint, Fig. 8. Hardness was measured at three points at least, along a single line for each of the characteristic zones, WM, HAZ (both sides) and BM (both sides). The first indent in HAZ ought to be as close as possible to the melting zone (border WM – HAZ). That also applies for the root. Obtained results show slight deviations of values for the homogeneous zones (BM, WM), but those deviations are somewhat larger for the HAZ, as well as for the melting zone borders.

Measured values of the base metal hardness were within range  $274 - 281\text{ HV}_{10}$  (according to standard ISO 6507-1:2005) [10]. Hardness of the heat-affected zone (HAZ is the most critical region of the welded joint) did not exceed the permissible limits and it was within range  $350 - 380\text{ HV}_{10}$ . The investigation of microstructure was primarily related to

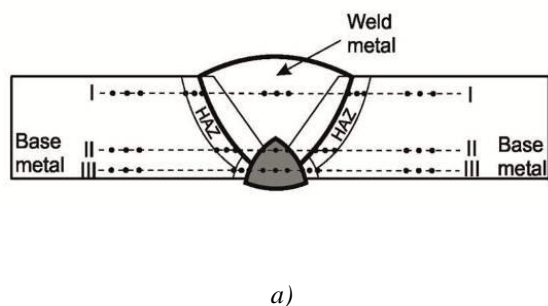
establishing the size and distribution of grains. The structure of the considered steel was estimated as interphase – tempered, Fig. 9 [2].

Hardness within the HAZ is increasing due to the heat input, i.e., within this zone a self-hardening occurred (martensite and low bainite appeared) what has caused a slight increase of hardness. Self-hardening was caused by relatively fast cooling after the welding. This is why, instead of expected hardness drop, as a consequence of the heat input during tempering, hardness increases in this type of steels, since they are extremely prone to self-hardening, Fig. 9. Hardness drop in the weld metal was expected due to austenitic filler metal.

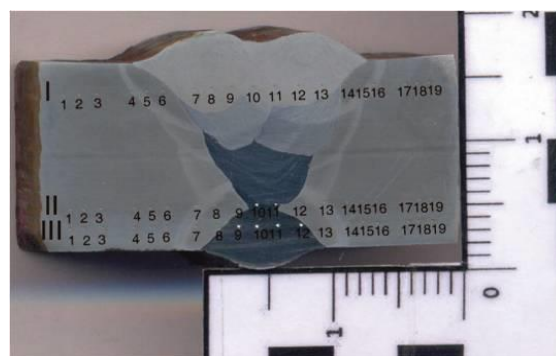
In addition, the steel manufacturer forbids heating of these steels to temperatures above  $200\text{ }^{\circ}\text{C}$ , exactly for this reason, i.e., due to increase of hardness and brittleness, but due to welding, temperature increase is unavoidable. Note: For these steels, hardness increase is allowed up to values  $370 - 380\text{ HV}$ .

#### 4.4. Optimal welding technology application on a real structure

Prescribed welding technology obtained on models – test welds, was then "transferred" to the real structure. The welded part was tested in rigorous conditions, since it is subjected to high dynamic and impact loads during exploitation, Fig. 10.

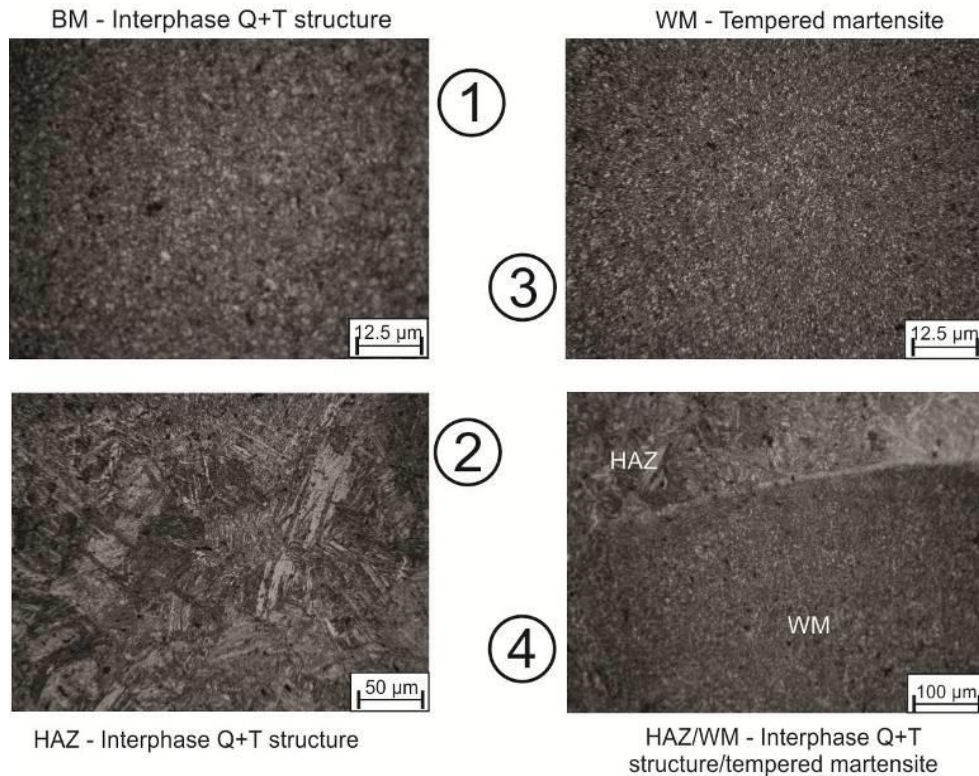
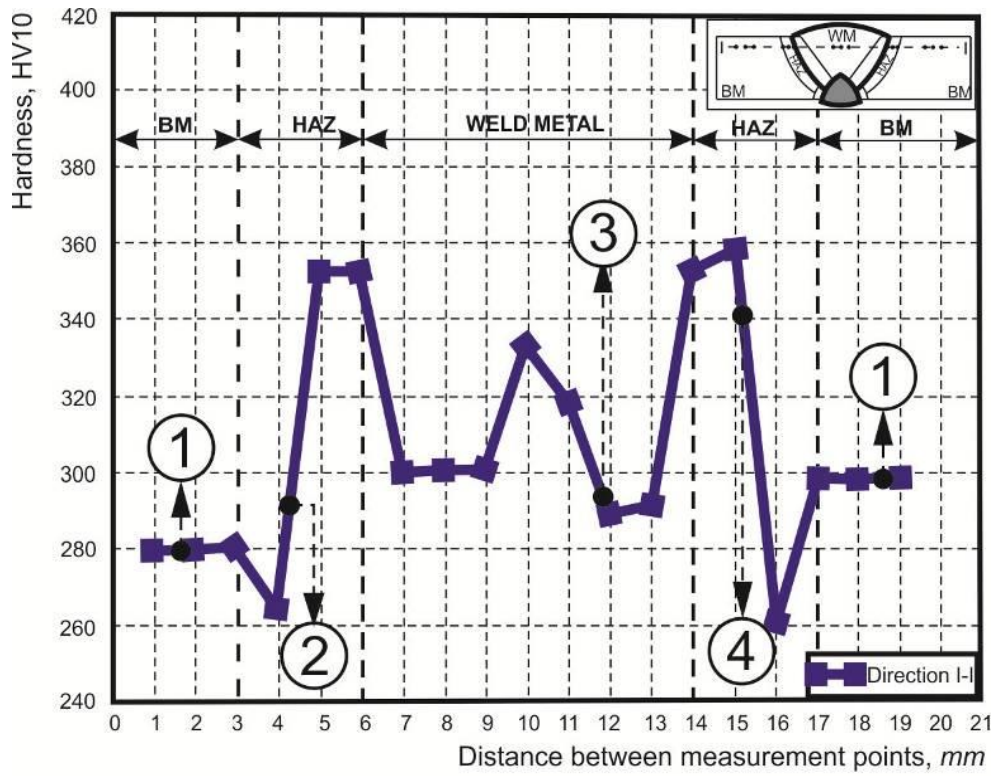


a)



b)

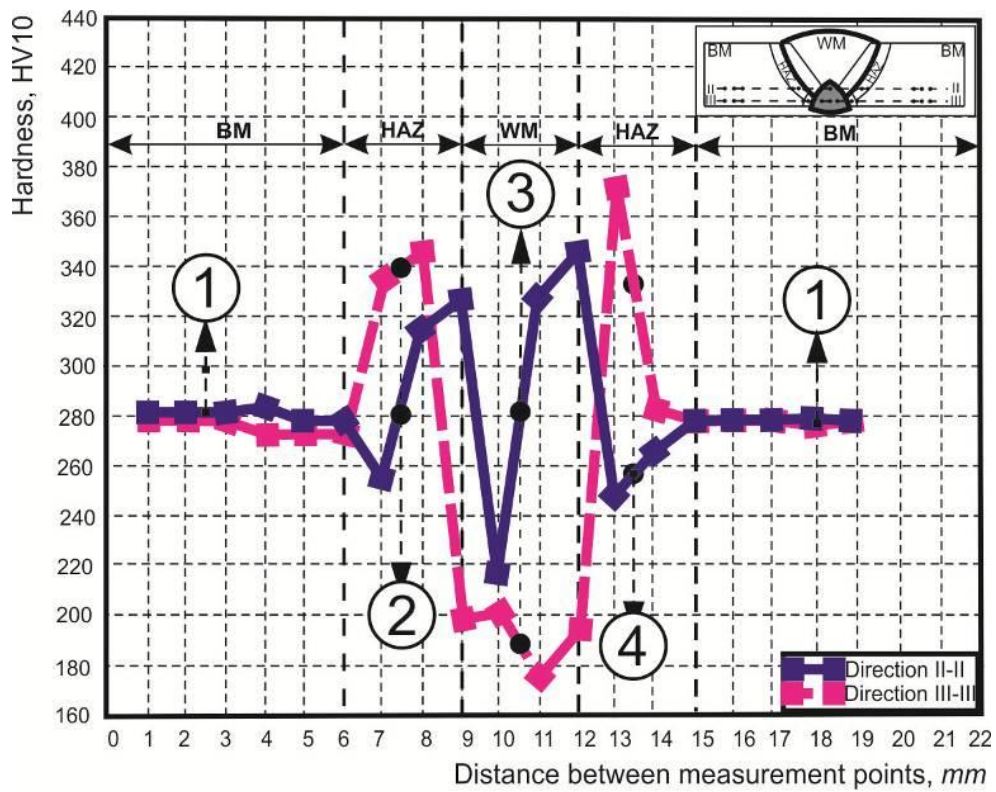
Fig. 8. Hardness measurement: a) schematics of measurements directions; b) appearance of a metallographic sample for hardness measurement and microstructure estimates.  
(full colour version available online)



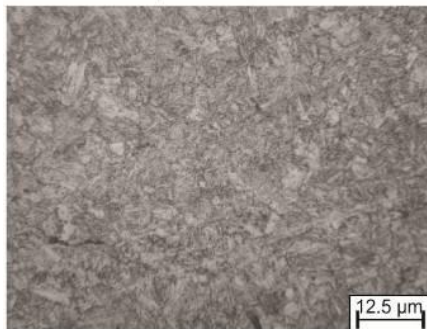
a) direction I – I

Fig. 9. Hardness distribution and microstructure of characteristic zones of the welded joint – sample 1.

(full colour version available online)

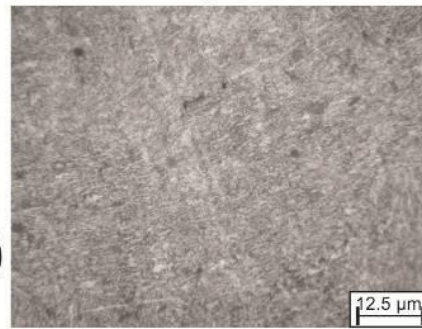


BM - Interphase Q+T structure

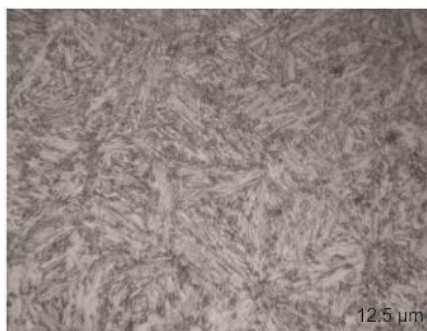


①

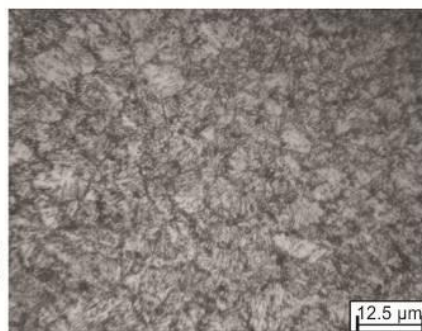
WM - Tempered martensite



③



②



④

HAZ - Interphase Q+T structure

HAZ - Interphase Q+T structure

b) directions II - II and III - III

Continuing of Fig. 9. Hardness distribution and microstructure of characteristic zones of the welded joint – sample 1.

(full colour version available online)



Fig. 10. Portion of an assembly welded by the prescribed technology: a) welded joint; b) penetrant liquid control of the weld.

(full colour version available online)

## 5. Discussion of results

Experimentally obtained results of mechanical properties confirmed the fact that the S690QL class steel has exceptional properties, even superior to values prescribed by standard (EN 10025:2004). That enables and justifies their application for manufacturing the very responsible structures (even with reduced total mass/weight).

Average values of results of the hardness measurements results show that the base metal for the plate welded by the second technology (GMAW/ GMAW) produced the welded joint of higher strength and toughness. However, the analysis of impact energy and impact toughness of the welded joints showed that the first technology (MMAW/ GMAW) gave results that were more favorable (Figures 5 - 7).

The impact toughness was used as the main parameter for selecting the optimal welding technology, since the construction requirement was to obtain the welded joint of adequate strength with simultaneous good ductility properties in the HAZ and the weld's root. The reason was that the obtained technology was planned to be applied to a joint, which would be subjected to dynamic loads in exploitation [12]. Toughness was additionally improved due to root welding by highly plastic austenitic electrode. Based on those results, it was concluded that the first proposed

technology was the optimal one, i.e., more favorable of the two, since the values of impact toughness obtained on samples were greater for about 55 %.

Another parameter that was decisive in analysis which of the two technologies was better, were the results of plasticity of executed test welded joints. The share of plastic fracture on the fractured surfaces of specimens, taken from all the zones of the welded joints, was within range 92.41 – 99.81 %, what represents the exceptional results from the aspect of plasticity of the welded joints [2 - 3, 11].

## 6. Conclusions

Application of S690QL steel is primarily related to very responsible structures that are assembled by welding. In regards to that, it should be emphasized that when selecting the welding technology one must keep in focus all the influential factors. Selecting the adequate and optimal welding technology is imperative since the uncontrollable heat input could lead to worsening of the exceptional steel properties obtained by complex heat and mechanical treatments.

After the detailed analysis of the most important mechanical characteristics of the base metal – steel S690QL – estimates of its weldability, selecting of the optimal combination of the filler metals, welding

procedures and technology, the optimal welding technology was established, which was then applied to the real structure. Thus assembled structure was subjected to rigorous tests; it fulfilled all the prescribed requirements in operation in the field, and it was proven as very reliable.

Experimental results of the tensile and impact tests, as well as those of metallographic investigations, were used as indicators of the properly selected technology:

1. During the tensile test the sample fracture occurred outside of the welded zone, what shows that the welded joint had higher strength than the base metal;

2. Impact test provided good results concerning the welded joint toughness especially in the heat-affected zone and in the weld's root, as the most critical zones of the welded joint.

Results for the first plate (the MMAW/GMAW technology) produced for about 55 % higher values of the impact toughness than for the second plate (the GMAW/GMAW technology)!

3. Hardness measurements and estimate of microstructure of all the zones of the welded joint, conducted at the end of tests, have shown that by proper selection of the welding procedure and parameters, one can avoid creation of the brittle martensitic structure; consequently, hardness of the welded samples was within permissible limits.

The tendency is ever-present for increasing the productivity in manufacturing, i.e. increasing the welding speed at the expense of quality of the executed welded joints. However, when welding of the responsible structures is concerned, as structures made of the S690QL steel are, safety of structures must not be compromised.

Due to all the aforementioned, in order to obtain adequate properties of the welded joint, it is mandatory to follow all the recommendations of the steel's

manufacturer, as well as of the other researchers that have investigated this topic.

### **Acknowledgment**

*This research was partially financially supported by European regional development fund and Slovak state budget by the project "Research Centre of the University of Žilina" - ITMS 26220220183 and by the Ministry of Education, Science and Technological Development of Republic of Serbia through grants: ON174004, TR32036, TR35024 and TR33015.*

### **Note**

The shorter version of this work was presented at "SEMDOK 2014" Conference in Terchova, Slovakia, 29-31 January 2014 – reference [3].

### **References**

- [1] M. Jovanović, V. Lazić: Instructions for welding of high strength steel WELDOX 700, Faculty of Mechanical Engineering in Kragujevac, Belgrade/Kragujevac, 2008. (in Serbian).
- [2] D. Arsić: Estimates of weldability and selection of optimal welding technology for welding high strength steel class S690QL, MSc Thesis, Faculty of Engineering in Kragujevac, Kragujevac, 2013. (in Serbian).
- [3] D. Arsić, M. Djordjević, V. Lazić, S. Aleksandrović, R. Nikolić: In Proc. of 19th International PhD. students' seminar SEMDOK 2014, Ed: P. Palcek, EDIS Zilina 2014, pp. 5-9
- [4] D. Arsić, V. Lazić, R. R. Nikolić, S. Aleksandrović, P. Marinković, M. Djordjević, R. Čukić: Mater. Eng. – Mater. Inz. 2013 20(4) (2013) 174-183.
- [5] V. Lazić, S. Aleksandrović, R. Nikolić, R. Prokić-Cvetković, O. Popović, D. Milosavljević, R. Čukić: Procedia Eng. 40 (2012) 310-315.
- [6] www.ssab.com/weldox-700-UK-data (accessed in October 2014).
- [7] T. B. Larsson, T. Berglund: Handbook on WELDING of Oxelösund steels, Steel plant SSAB Oxelösund, Sweden, 1992.
- [8] ISO 4136:2012 Destructive tests on welds



- in metallic materials -- Transverse tensile test. International Organization for Standardization.
- [9] ISO 148-1:2009 - Metallic materials — Charpy pendulum impact test — Part 1: Test method. International Organization for Standardization.
- [10] ISO 6507-1:2005 - Metallic materials -- Vickers hardness test -- Part 1: Test method. International Organization for Standardization.
- [11] G. Jung: Plasticity-based distortion analysis for fillet welded thin plate T-joints, Ph.D. Dissertation, The Ohio State University 2003.
- [12] H. K. D. H. Bhadeshia, D. J. C. MacKay, L.-E. Svensson: J.I Mater. Sci. Technol. 11(10) (1995) 1046-1051.
- [13] N. Gubeljak: Int. J. Fract. 100 (1999) 155–167.