IOP Conference Series: Materials Science and Engineering

PAPER • OPEN ACCESS

Qualification of the welding technology of the structural steel S355J2G3

To cite this article: V Lazić *et al* 2018 *IOP Conf. Ser.: Mater. Sci. Eng.* **419** 012019

IOP Conf. Series: Materials Science and Engineering **419** (2018) 012019 doi:10.1088/1757-899X/419/1/012019

Qualification of the welding technology of the structural steel S355J2G3

V Lazić[1], D Arsić[1], I Ilić[2], S Aleksandrović[1], R Nikolić[3], M Djordjević[4] and B Hadzima[3]

[1]Faculty of Engineering, University of Kragujevac, Sestre Janjić 6, 34000 Kragujevac, Serbia
[2]Wacker Neuson Kragujevac Ltd, Milice Miljojković 13, 340000 Kragujevac, Serbia
[3]Research Center, University of Žilina, Univerzitna 8215/1, Žilina, Slovakia
[4]Faculty of Technical Sciences, University of Priština, Knjaza Miloša 7, 38220 Kosovska Mitrovica, Serbia

E-mail: dusan.arsic@fink.rs

Abstract. The selection procedure and qualification of the optimal welding technology for the structural steel S355J2G3 are presented in this paper. The considered steel is widely applied for manufacturing the supporting structures in various areas, especially in civil and mechanical engineering. It is delivered mainly in form of plates of various thicknesses and solid profiles of various diameters. Considering that welding is mostly used in manufacturing of structures, it is very important to be aware of possibilities for this steel welding, as well as of problems that may arise during that process. Here are presented: a calculation procedure of the base metal's weldability, selection of the filler metal and the welding technology, with results of experimental testing of the base metal and welded samples. The following experimental investigations were performed: tensile, bending and impact toughness test, metallographic investigations and hardness measurement. All the samples were cut out from the welded plates. Obtained results have shown that the structural steel S355J2G3 is suitable for welding, since there is no danger of appearance of cracks or other defects. With adequate choice of the welding technology the mechanical properties of the welded joint can be comparable to those of the base metal.

1. Introduction

This paper deals with investigation of weldability of the structural steel S355J2G3 and possibilities for its application for building the welded structures. The S355J2G3 steel belongs into a group of unalloyed (carbon) structural steels with the yield stress of 355 MPa and it is aimed for manufacturing the responsible support structures in various industries like bridge building, ship building, manufacturing of industrial equipment, metal working industry, machine building industry, etc. The steel is delivered in form of bars of various diameters and in form of plates of various thicknesses. The latter form of steel is the most frequently aimed for welding, thus its possibility for being welded must be known.

Here is presented an analysis of the base material and the welded samples by the destructive tests, which included the following: tensile tests, bending tests, metallography and hardness measurements. Besides that, the prescribed welding technology is presented, as well. The presented analysis can be considered as a kind of qualification of the welding technology of the S355J2G3 steel. Authors of this paper were already dealing with similar analyses of the welding technologies of other types of steel, like the high-strength steels S690QL [1-2] and HARDOX [3], tool steels for hot working [4-5], high-speed cutting steels and carbon steels [6-7], etc.

2. The base metal

As stated earlier, the paper presents analysis of the base metal and the welded joint of the S355J2G3 whose chemical composition, application and mechanical properties are given in Tables 1 and 2 [8].

Table 1. Chemical composition of the S355J2G3 steel.

Chemical composition, %													
C	Mn	Si	P	S	Al	Cu	Cr	Ni	Mo	Ti	V	Nb	N
0.16	1.36	0.021	0.013	0.005	0.04	0.02	0.02	0.01	0.004	0.01	0.005	0.028	0.007

Table 2. Different notations and mechanical properties of the S355J2G3 steel (EN 10025) [8].

Standard			Mechanical properties					
EN 10027-1	EN 10027-2	DIN 17100	R_m, MPa	R_{eH}, MPa				
			Thickness 3-100 mm	<16	16-40	40-63	63-80	80-100
S355J2G3	1.057	St 52-3N	490-630	355	345	335	315 325	305 315

The steel hardness in the annealed condition is about 230 HBS, while in the drawn condition it is about 260 HBS. The elongation of the steel is higher than 20 % for the plates of thickness up to 100 mm, while for the thicker plates the guaranteed elongation is 18 %. The similar is valid for the impact toughness. Though the minimal toughness, prescribed by the standard, is 27 J at – 20 °C, what can be also seen from the steel's notation, for plates of thickness < 100 mm that value is higher than 35 J.

The S355 steels are being delivered in qualities JR, J0, J2 (J2G3, J2G4), K2 (K2G3, K2G4). The difference in quality is related to weldability and guaranteed impact toughness at lower temperatures. Letter J denotes guaranteed impact toughness of 27 J, letter K of 40 J and letter L of 60 J at lower temperature, which is denoted by a number behind one of those letters. Thus, steel S355J2G3 has the guaranteed toughness of 27 J at – 20 °C. G3 denotes supply condition - normalized or normalized rolled plate. Authors of [9] have shown that (even highly alloyed) steel's toughness can be positively influenced by adding some micro-alloying elements.

Besides the earlier mentioned areas of application of this steel, it is also used for manufacturing the cold-rolled thin sheets and pipes. It is frequently used for manufacturing the shafts, axles, gears, spring carriers, screws, covers, casings, etc. Considering the mechanical properties, the structural steels must possess high yield stress, sufficient plasticity, high creep strength and strength at elevated temperatures, satisfactory toughness and dynamic strength. Besides those, the structural steels have to be resistant to wear and corrosion, machinable by particles detachment (cutting), weldable, convenient for cold forming (bending, punching, deep drawing), etc. Generally, the structural steels are divided into:

- Carbon steels for supporting (carrying) structures and
- Steels for machine building.

Taking into account that the chemical composition is not guaranteed for this group of steels, due to the higher presence of impurities with respect to other steels, the generic structural steels are not predicted for the heat treatment. Steels for the supporting structures are mainly grouped according to the value of the yield stress and impact toughness. Marking of the structural steels is done according to the

EN 10027-1 standard. They possess the yield stress within range 190 - 370 MPa, with elongation of 10 - 28 %. The yield stress is higher with the increased carbon content and share of pearlite in the microstructure. These steels are mainly used within the temperature range – 40 - +50 °C.

3. The welding technology

Prior to prescribing the welding technology, the calculation of the base metal weldability was done, according to standard formulas for the carbon equivalent for the low-alloyed steels [3]:

$$CE = C + \frac{Mn}{6} + \frac{Cr + Mo + V}{5} + \frac{Ni + Cu}{15}, \ \% \tag{1}$$

$$CE = C + \frac{Mn}{6} + \frac{Si}{24} + \frac{Ni}{40} + \frac{Cr}{5} + \frac{Mo}{4} + \frac{V}{14}, \ \% \tag{2}$$

$$CE = C + \frac{Mn}{20} + \frac{Ni}{15} + \frac{Cr + Mo + V}{10}, \ \% \tag{3}$$

The steels that have *CE* less than 0.45 % are considered as well weldable. The steels with the higher values of the carbon equivalent are considered as the conditionally weldable, since they must be subjected to special regimes: preheating, additional heating and/or post-welding heat treatment. Results obtained are as follows: according to formula (1) *CE* = 0.395 %; according to formula (2) *CE* = 0.393 % and according to formula (3) *CE* = 0.235 %. It can easily be concluded that the S355J2G3 steel belongs into a group of well weldable steels and that the preheating prior to welding is not necessary.

Taking that into account, the solid electrode wire G3Si1 (according to standard ISO 14341-A) of diameter Ø1 mm was selected as the filler metal, while the GMAW (135) procedure in the protected gas mixture Ar + 18 % CO_2 was selected for executing the welding. The welding parameters were I = 140 A, U = 23 V with welding speed of 300 mm/min. Welding was executed in the horizontal position. Between the two welds the break of 3 to 5 min was prescribed to avoid the plates' deformations.

Within the samples preparation, welding of plates of two thicknesses of 8 and 30 mm was performed. The 8 mm thick plates were welded in the V groove and 30 mm thick plates were welded by the "double V" or the X groove. Samples for bending and hardness measurements were prepared from the thinner welded plates (8 mm), while samples for tensile test and impact toughness test were prepared from the thicker welded plates (30 mm).

4. Experimental procedure and discussion of results

4.1. The tensile test

This experiment was done at the room temperature in the static loading conditions until the tearing, in series of 3 samples. The shape, dimensions and actual appearance of a sample are presented in Figure 1. Samples were made of the considered carbon steel S355J2G3, cut out from the welded plate in such a way that they contained the welded joint, while there were also samples prepared without the welded joint portion, i.e. of the base metal only.

Tensile tests were conducted in the specialized laboratory on the testing machine with the loading range 1 to 100 kN. The deformation rate was 10 mm/min. Obtained results are presented in tables 3 and 4, while the summary diagrams for the tensile test of the base metal and the welded joint are shown in Figures 2 and 3, respectively.

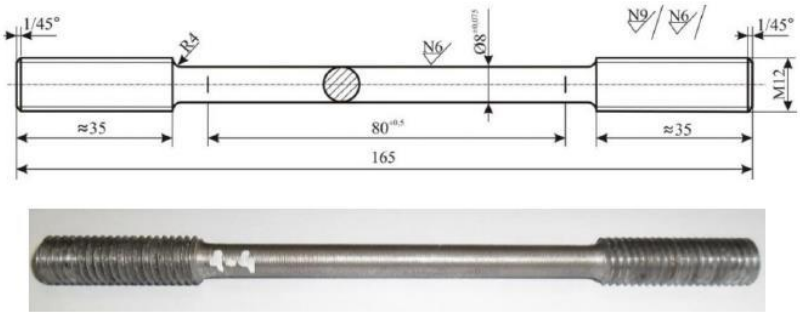


Figure 1. Drawing and actual appearance of the tensile test samples.

Table 3. Experimental results of the S355J2G3 steel tensile test – base metal.

Sample number	S_0 , mm^2	L_0, mm	$R_{p0.2}$, MPa	R_m, MPa	A, %
1	49.02	140	522.70	633.11	5.37
2	49.02	140	537.86	638.21	4.82
3	49.02	140	538.54	643.78	4.93

Table 4. Experimental results of the S355J2G3 steel tensile test – welded joint.

Sample number	S_0 , mm^2	L_0, mm	$R_{p0.2}$, MPa	R_m, MPa	A, %
1	49.02	140	522.70	633.11	5.37
2	49.02	140	537.86	638.21	4.82
3	49.02	140	538.54	643.78	4.93
4	44.18	90.00	411.15	535.97	14.24
5	44.18	90.00	420.26	546.79	16.79
6	44.18	90.00	405.96	526.92	13.98
7	44.18	90.00	405.77	530.69	16.60
8	44.18	90.00	399.93	532.80	18.46
9	45.36	90.00	393.49	524.93	13.44
10	45.36	90.00	406.62	535.46	18.16
11	44.18	90.00	414.84	531.80	13.41

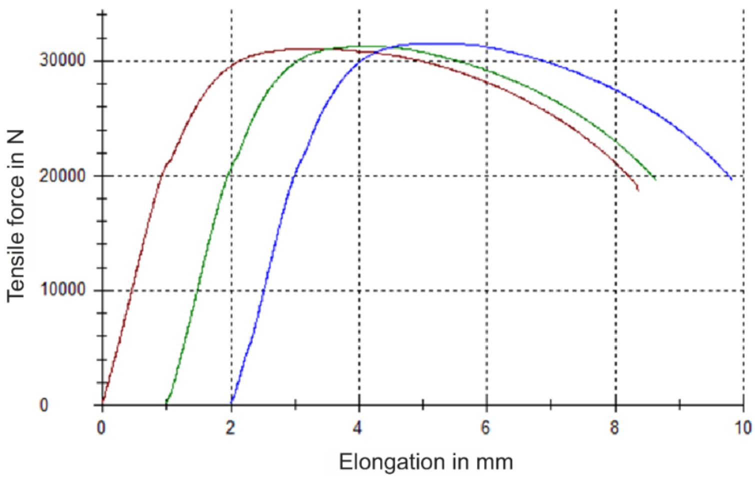


Figure 2. Summary diagram of the base metal tensile test.
(Curves in order from left to right correspond to samples 1 to 3 in Table 3).

The tearing point in all the tested samples was outside the welded joint zones, i.e. in the base metal, what is a good indicator that the applied welding method and welding technology parameters and conditions were properly selected and applied.

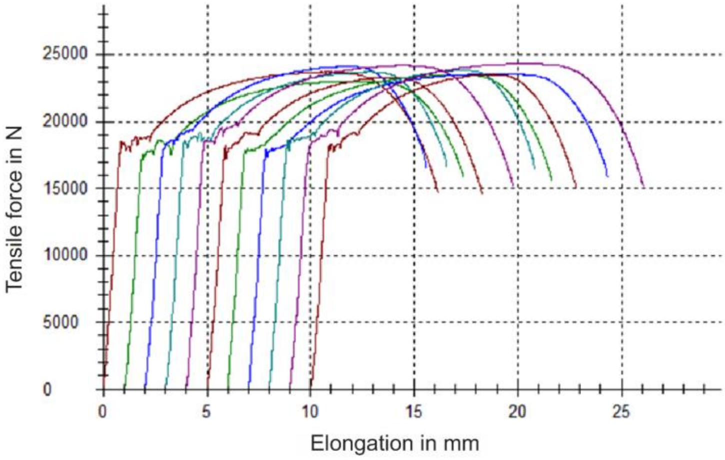


Figure 3. Summary diagram of the welded joint tensile test.
(Curves in order from left to right correspond to samples 1 to 11 in Table 4).

4.2. The bending test

The bending test is often used in practice. Samples for the bending test are usually of the circular or rectangular cross-section; in this particular case the cross-section was rectangular. The welded samples were, after the adequate preparation, subjected to the bending force, Figure 4. If during the bending test, the sample has reached the required value of the bending angle without appearance of cracks, the test result is considered as positive. The results of the bending test serve for determination of the welded joint plasticity. If the small cracks are noticed during the test, the result is negative, under the condition that the bending angle is smaller than the required one.

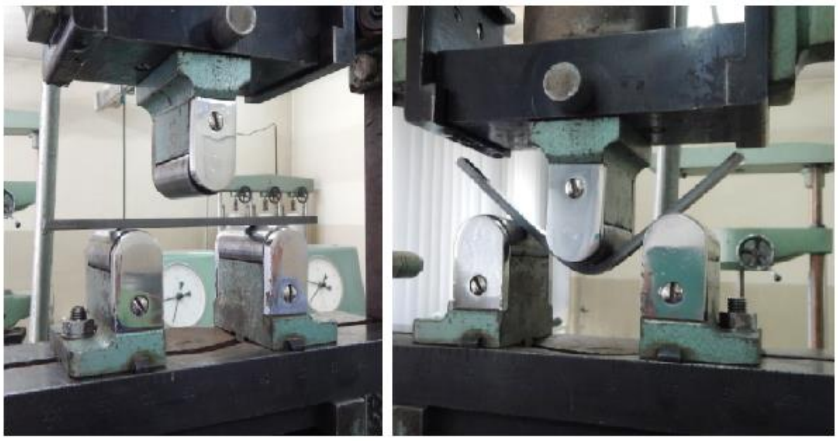


Figure 4. The bending test

The objective of the bending test was determination of the deformation capability of the welded joint and the heat affected zone of the weld. The test was performed in the standardized conditions, by continuous bending with the loading rate of 10 mm/min. The plasticity measure is the bending angle. Results of the bending test are shown in Tables 5 to 7.

Table 5. Experimental results of the bending test of the base metal – BM.

Sample number	Temperature °C	Maximum force range F_{max}, daN	v_{def}, mm/min	F_{max}, daN	Bending angle α, °
1				165	80
2	20	10000	10	165	89.5
3				160	89

Table 6. Experimental results of the bending test of the weld's face – WF.

Sample number	Temperature °C	Maximum force range F_{max}, daN	v_{def}, mm/min	F_{max}, daN	Bending angle α, °
1				167	90.5
2	20	10000	10	165	88
3				129	92,5

Table 7. Experimental results of the bending test of the weld's root – WR.

Sample number	Temperature °C	Maximum force range F_{max}, daN	v_{def}, mm/min	F_{max}, daN	Bending angle α, °
1	20	10000	10	155	89

4.3. The impact toughness test

This test was conducted on samples made from the base metal, as well as those with the welded joint, executed by the MAG procedure. The samples were tested on the Charpy pendulum in the accredited laboratory according to the ISO TC/164/SC 4 standard, on samples with dimensions 55×10×10 mm. The notch – groove for testing the impact toughness was first cut along the axis of the welded joint, then in the melting zone and, finally, in the heat affected zone, both at the weld's face and the weld's root sides. The welded joint characteristic zones were chemically etched by the 4 % solution of the nitric acid, what made them visible for precise notching the groove for the impact test in the desired zones.

The technical drawing of the sample for the impact toughness tests, as well as appearance of the actual samples, are presented in Figure 5. Results of the impact toughness tests of the base metal (BM), weld metal (WM), melting zone (MZ), HAZ and at the weld's root (WM-R) and the face (WM-F) side are presented in Tables 8 to 13, respectively, and in Figure 7, while the appearance of the sample from the weld metal, before and after the test, is shown in Figure 6.

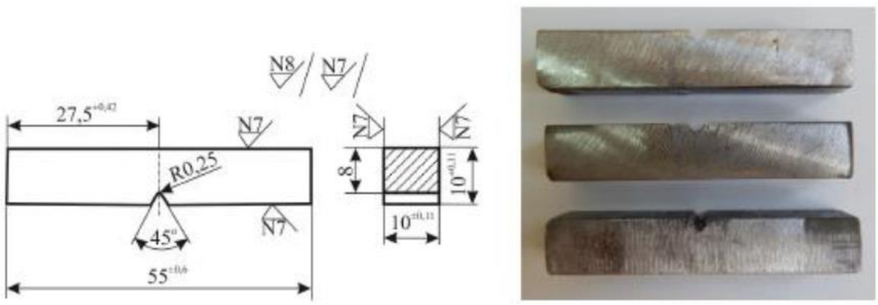


Figure 5. Technical drawing and actual appearance of samples for the impact toughness tests.

Table 8. Experimental results of the impact toughness test – BM.

Sample number	Temperature, °C	Absorbed energy A_0, J	Average value, J
1	20	180	179
2		178	
3		179	
4		182	
5		178	
6		178	

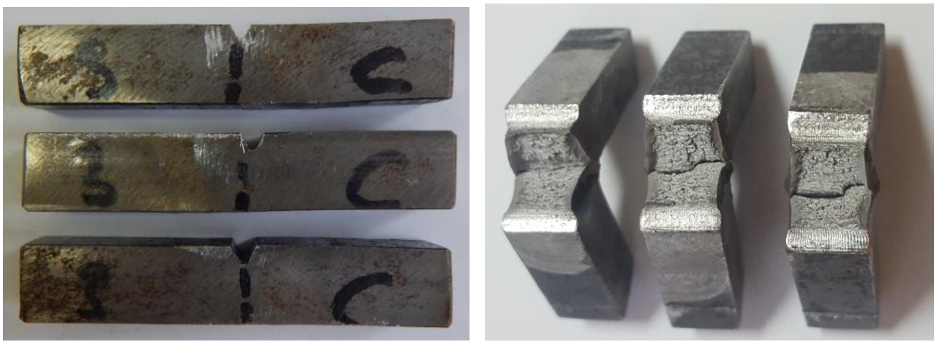


Figure 6. Appearance of the weld metal samples before and after the impact toughness tests.

Table 9. Experimental results of the impact toughness test – WM.

Sample number	Temperature, °C	Absorbed energy A_0, J	Average value, J
1	20	146	151.3
2		158	
3		150	

Table 10. Experimental results of the impact toughness test – MZ.

Sample number	Temperature, °C	Absorbed energy A_0, J	Average value, J
1	20	168	167.3
2		184	
3		150	

Table 11. Experimental results of the impact toughness test – HAZ.

Sample number	Temperature, °C	Absorbed energy A_0, J	Average value, J
1	20	152	152

Table 12. Experimental results of the impact toughness test – WM-Root.

Sample number	Temperature, °C	Absorbed energy A_0, J	Average value, J
1	20	120	110
2		90	
3		120	

Table 13. Experimental results of the impact toughness test – WM-Face.

Sample number	Temperature, °C	Absorbed energy A_0, J	Average value, J
1		164	
2	20	140	148
3		140	

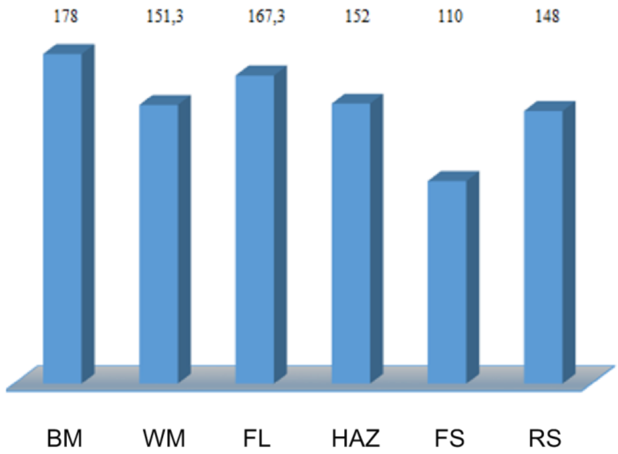


Figure 7. Histogram presentation of the absorbed fracture energy for various positions of the notch; BM, WM, FL (fusion line), HAZ, FS (face side), RS (root side)

Experimentally determined values of the fracture energy exhibit very small deviations; the force vs. time dependencies exhibit the similar character. Thus, the obtained results can be considered as relevant for the further analysis.

Based on the fracture energy, obtained for the various positions of the notch at the welded joint's face, one can conclude that the highest values of the fracture energy are obtained for the samples made of the base metal, somewhat smaller values were for the samples with the notch in the melting zone, HAZ and the weld metal. The smallest values were obtained for the samples with the notch in the weld's root.

Obtained results indicate the drop of the toughness of the welded joint zone with respect to the base metal. Such a case is unfavorable from the homogeneity aspect, as well as the safety of the welded joint, since appearance of the zones of the lower impact toughness may be the places where the stress concentration may arise, causing micro cracks that could lead to fracture of the welded structure. The very significant indicator of the material's toughness is also the share of the brittle and ductile fracture. The larger the share of the brittle fracture the higher is the possibility for appearance of the brittle fracture, and vice versa. What concerns the base metal, its characteristics related to toughness are exceptionally favorable at the room temperature.

4.4. Hardness measurements and metallographic investigations

This part of investigation assumed measuring of the micro-hardness in three different, mutually parallel directions, on the sample with the welded joint, executed by the MAG procedure.

For the 8 mm thick plate the measurement direction I-I includes the base metal, the heat affected zone and the weld metal, while the direction II-II is placed along the root pass in the weld metal zone. Measurement was executed according to the SRPS EN ISO 9015-1:2013 standard. Appearance of the sample and the measurement directions are shown in Figure 8, while the results of the hardness measurement are given in Table 14.

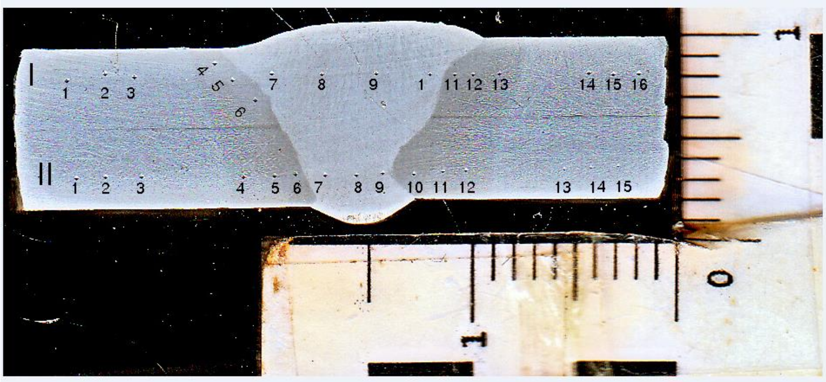


Figure 8. Micro-hardness mesurements points on the metallographic sample - 8 mm thick plate

Table 14. Micro-hardness mesurements results for the sample made from the 8 mm thick plate [HB].

	Mesurement points														
Measurement direction	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
I	170	176	176	183	192	192	189	185	189	199	199	189	170	170	170
II	170	176	176	177	177	189	185	185	191	192	192	185	170	176	176

For the 30 mm thick plate the measurement direction I-I includes the base metal, the heat affected zone and the weld metal. The II-II direction is selected along the middle of the joint in the zone where the mixing of the root pass and the cover filler metal occurred. The III-III direction was placed on the root pass side in the welded joint zone where the dominant influence is exhibited by the way of the weld execution, parameters and the filler metal of the root pass. The micro-hardness measurement points on the sample, as well as the sample appearance after the executed micro-hardness measurements are presented in Figure 9, while the obtained results are given in Table 15.

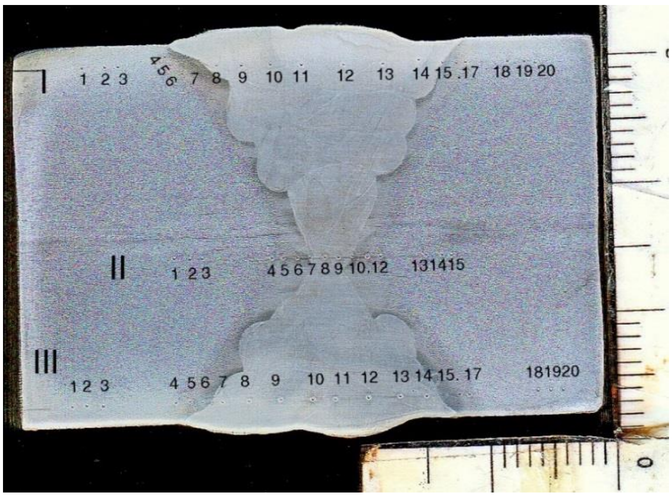
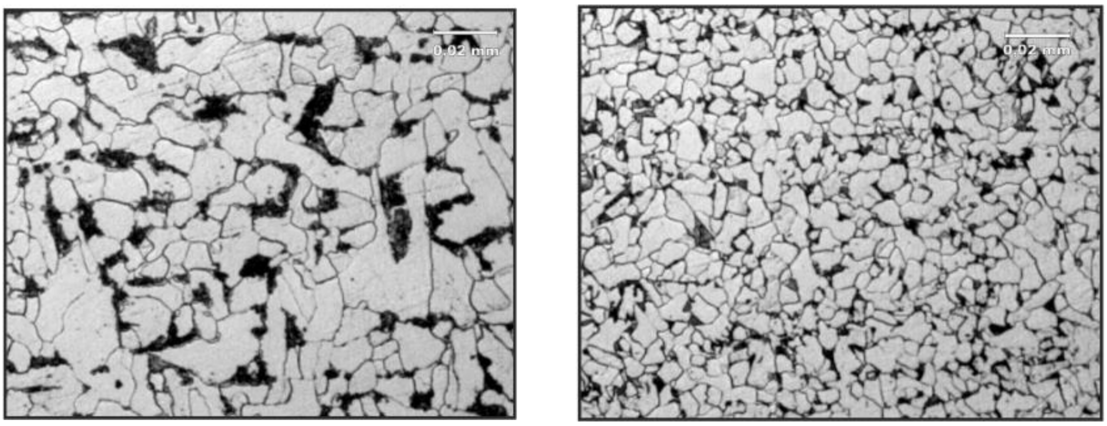


Figure 9. Micro-hardness mesurements points on the metallographic sample - 30 mm thick plate

Table 15. Micro-hardness mesurements results for the sample made from the 30 mm thick plate [HB].

	Mesurement points														
Measurement direction	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
I	156	206	199	213	322	206	206	193	199	206	193	236	245	193	156
II	165	185	199	228	213	206	206	221	199	187	170	165	165	165	-
III	160	199	245	297	206	206	206	193	199	199	193	185	254	254	213

Results of the metallographic analysis are shown in Figure 10. They pointed to conclusion that the structure was homogeneous, pearlite-ferrite, without appearance of the brittle zones that should be pointed at, which could lead to catastrophic damages [10-11]. The reason for that is the very good weldability of the base metal, as well as the adequately selected welding parameters and the filler metal. In addition, no geometric defects, like scratches, dimples, dross inclusions etc., which could influence the quality of the welded joint, were noticed on any of the samples. Besides that, the filling of the groove was homogeneous and sufficient, since in the case of the too high overfill of the weld, the dynamic strength of the welded joint would be compromised [12].



(a) (b)

Figure 10. Microstructure: (a) the base metal – pearlite-ferrite structure
(b) the heat affected zone – the normalization zone with ferrite-pearlite structure.

The objective of the whole technology qualification, which is proven by all the tests performed on the welded joints, as well as on the base metal, is thus fulfilled. This particular steel can be used as a part of the bridge constructions and can be welded by the proposed technology. Furthermore, the verified technology can be applied for welding of other types of steels, as well, with necessary adjustments regarding the different material's mechanical properties, weldability and hardness. In any case, additional tests would have a good guidance with the procedure here presented.

5. Conclusions

Based on the conducted experiments and certificate by the adequate accreditation body, the so-called qualification and verification of the selected welding technology was performed.
Based on the experimental investigations, the following conclusions were reached:

- The tensile tests have shown that the most important properties of the welded joint (strength and deformation) are approximately the same or even higher than those of the base metal;
- The impact toughness tests of the welded joint individual zones led to establishing the fact that there were no large deviations with respect to impact toughness of the base metal and that no brittle fracture was registered;

- The conducted bending tests have shown the exceptionally high plasticity of the base metal and the welded joint (at the sides of the weld's face and root) and that there are no major differences in obtained results;
- The macro-graphic tests have shown that the multi-pass weld was homogeneous, of the regular shape and without noticed defects;
- The hardness measurements in the individual welded joint's zones (in the three selected directions) have shown that there were no significant deviations in the measured values, namely that there are no present brittle zones, since all the measured values were lower than the critical one (350 HB).

Based on all the above one can conclude that the selected welding technology was qualified and verified (certified by the authorized accreditation body) and that it can be successfully applied in manufacturing the real structures made of the S355J2G3 steel.

The technology thus qualified is ready for welding of any structural part of the bridge constructions and can be, with necessary adjustments be applied for other types of steels welding.

Acknowledgements
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" and by the Ministry of Education, Science and Technological Development of Republic of Serbia through grant TR35024.

References

[1] Arsić D, Lazić V, Nikolić R, Aleksandrović S, Hadzima B and Djordjević M 2015 The optimal welding technology of high strength steel S690QL *Materials Engineering - Materiálové inžinierstvo* **22** (1) 33-47
[2] Lazić V, Aleksandrović S, Arsić D, Sedmak A, Ilić A, Djordjević M and Ivanović L 2016 The influence of temperature on mechanical properties of the base material and welded joint made of steel S690QL *Metalurgija - Metallurgy* **55** (2) 213-216
[3] Lazić V, Arsić D, Nikolić R, Djordjević D, Prokić-Cvetković R and Popović O 2017 Application of the high strength steel HARDOX 450 for manufacturing of assemblies in the military industry *Key Engineering Materials* **755** 96-105
[4] Arsić D, Lazić V, Samardžić I, Nikolić R, Aleksandrović S, Djordjević M and Hadzima B 2015 Impact of the hard facing technology and the filler metal on tribological characteristics of the hard faced forging dies *Tehnički Vjesnik – Technical Gazette* **22** (5) 1353-1358
[5] Arsić D, Lazić V, Sedmak A, Nikolić R, Aleksandrović S, Djordjević M, Bakić R 2016 Selection of the optimal hard facing (HF) technology of damaged forging dies based on cooling time t8/5 *Metalurgija - Metallurgy* **55** (1) 103-106
[6] Ratković N, Arsić D, Lazić V, Nikolić R, Hadzima B, Palček P and Sedmak A 2017 Influence of friction welding parameters on properties of the Al-Cu joint *FME Transactions* **45** (1) 165-171
[7] Ratković N, Lazić V, Arsić D, Nikolić R, Meško J and Nigrovič R 2016 Influence of the friction time on the shape and microstructure of the mixing zone of the friction welded joint *Manufacturing Technology* **16** (6) 1355-1359
[8] European Committee for Standardization (CEN) 2011 Hot rolled products of structural steels: Technical delivery conditions for non-alloy structural steels *Eurocode 3, Part 2 (EN10025-1:2011)*
[9] Todić A, Čikara D, Todić T, Pejović B, Čamagić I and Vukojević V 2017 The Influence of the Vanadium Content on the Toughness and Hardness of Wear resistant High-alloyed Cr-Mo Steel *FME Transactions* **45** (1) 130-134
[10] Nourya P and Eriksson K 2017 Failure analysis of martensitic stainless steel bridge roller bearings *Engineering Failure Analysis* **79** 1017-1030

[11] Bošnjak S, Arsić M, Savićević S, Milojević G and Arsić D 2016 Fracture analysis of the pulley of a bucket wheel boom hoist system *Eksploatacja i Niezawodnosc – Maintenance and Reliability* **18** (2) 155-163
[12] Djoković J, Nikolić R, Bujnak J and Sedmak A 2016 Influence of welding geometry on cylindrical welded joint life *Structural Integrity and Life* **16** (1) 35-38