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- **MCAW(138) electrodes with reduced emission of welding fume**
  Dr. Eng. Krzysztof SADURSKI – Lincoln Electric International

- **Problematika použitia zámkových spojov v tlakových nádob z Cr-Ni austenitických ocelí a ich opráv**
  Doc. Ing. Milan ČOMAJ, PhD. – TAYLOR-WHARTON SLOVAKIA s.r.o., Košice

- **Experimentálne výskumy zváraných vzoriek z vysokopevnej ocele**
  Experimental investigations of the high-strength steel welded samples
  Prof. Vukić LAZIĆ, PhD.[1], Res. Ass. Dušan ARSIĆ, MS.[1], Prof. Srbislav ALEKSANDROVIĆ, PhD.[1], Prof. Ružica R. NIKOLIĆ, PhD.[2], Res. Ass. Milan DJODJEVIĆ, MS.[1], Prof. Branislav HADZIMA, PhD.[2]
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- **Chyby vysokofrekvenčných zvarov tenkostenných rúrok**
  Defects in high – frequency welds of thin-walled tubes.
  doc. Ing. Peter BERNASOVSKÝ, PhD.
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Experimentálne overovanie zvarových spojov z vysokopevnej ocele

Experimental investigations of the high-strength steel welded samples

Experimentelle untersuchungen der hochfesten stahl schweissproben

Prof. Vukić LAZIĆ, PhD.[1), Res. Ass. Dušan ARSIĆ, MS.[1), Prof. Srbislav ALEKSANDROVIĆ, PhD.[1), Prof. Ružica R. NIKOLIĆ, PhD.[2), Res. Ass. Milan DJODJEVIĆ, MS.[1), Prof. Branislav HADZIMA, PhD.[2)

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Abstrakt:

Zameranie výskumu a výsledkov prezentovaných v tomto príspevku bolo v experimentálnom hodnotení zváraných vzoriek z vysokopevnej ocele S690 QL. S cieľom stanovenie optimálneho postupu zvárania boli verifikované rôzne parametre zvolenej technológie, čo zahŕňalo overenie chemického zloženia dodaného materiálu, stanovenie jeho zvárateľnosti, určenie typu prípadného spracovania (resp. tepelných spracovaní) a overenie, či pripravené zvarence spĺňajú požadované mechanické a metalurgické vlastnosti. V príspevku sú uvedené výsledky len časti realizovaných testov – skúšky ťahom pre stanovenie mechanických vlastností, Charpyho skúšky pre stanovenie húževnatosti vzoriek a overenie zvárateľnosti prostredníctvom TTT diagramov vzoriek zváraných dvoma rôznymi technológiami zvárania.

Abstract:

The subject of the research, results of which are presented in this paper, was experimental investigation of welded samples of the high strength steel S690 QL. In order to establish the optimal welding procedure, one has to check and/or verify different parameters of the chosen technology. That includes verifying the chemical composition of the delivered base metal, determining its weldability, deciding on the type of eventual heat treatment(s) and then checking that the executed welded joints possess the required mechanical and metallurgical properties. This paper reports results from only a part of the performed tests – the tensile test for establishing the mechanical properties, the Charpy impact toughness test and the weldability verification by the TTT diagrams of samples welded by the two different welding technologies.

Keywords:

High-strength steel S690 QL, mechanical properties, Charpy toughness test, weldability, TTT diagrams

1. Introduction

Structures made of the high-strength steels are generally very responsible and important, thus they have to be manufactured without any defects or flaws. Since the majority of joining of the structural parts is done by welding, it is natural that, to achieve safe and reliable structure, the welding procedure itself, as well as the whole technology of joints execution, must be as close to perfect as possible. This is why the optimal welding technology must be defined what includes several major points: verifying the base metals' and selected filler metals' composition and mechanical properties, checking the base metals' weldability, selecting the adequate welding procedure, determining which, if necessary, heat treatments would be applied, and finally, checking that the executed joints really possess the required properties, both mechanical and metallurgical.

Defining the optimal technology of high-strength steels was subject of research of numerous authors, including the authors of this paper. In previous manuscripts of this group of authors [1-5] the detailed instructions were given related to defining the optimal welding technology of different high-strength steels, including S690 QL, with respecting the recommendations by the steel supplier [6]. In papers [7-13] were also considered different problems related to welding of high-strength steels, like: tendency to formation of cold cracks during the welding with proposition of measures to avoid that phenomenon, replacing the expensive austenite electrodes by the low-hydrogen ferrite filler metals, behavior of the HSS at medium and elevated temperatures, selection of the welding technology based on microstructure and required output properties of the welded joints, etc.

2. The base metal

The S690 QL steel is produced under special conditions, by the thermo-mechanical processing (TMP) **–** heating up to austenite region, multi-phase rolling and then controlled cooling. This is why this steel has the high resistance properties (yield stress and tensile strength) and favorable toughness stable at low temperatures, as well. It is produced in three modifications that differ from each other by guaranteed impact toughness; guaranteed impact toughness is at least 27 *J* but at different ductile-to-brittle-fracture transition temperatures. Thus, steel S690 QL possesses the impact toughness of 47 *J* at – 40 °C. Chemical composition and the most important mechanical properties are presented in Tables 1 and 2.

Tab. 1. Prescribed chemical composition of S690 QL steel

Element	**C**	**Mn**	**Si**	**P**	**S**	**Cr**	**Mo**	**Ni**	**V**	**Al**	**B**
Prescribed maximum %	0.20	1.50	0.06	0.02	0.01	0.7	0.7	2.0	0.09	0.015	0.005

Tab. 2. Mechanical properties and microstructure of S690 QL steel

Thickness *mm*	**R_m** *MPa*	**$R_{p0.2}$** *MPa*	**A_5** *%*	**Microstructure**
4.0 - 53.0	780 – 930	700	14	Interphase tempering structure
53.1 – 100.0	780 – 930	650	14	
100.1 – 130.0	710 – 900	630	14	

Weldability of the steel can be determined by calculations, according to chemically equivalent carbon (CE) and tendency towards cold cracks appearance.

Depending on applied formula for calculating the CEC and thickness of the welded parts, one can obtain different values of the total CE carbon.

Based on results from calculations and steel manufacturers recommendations the preheating temperature was selected to be within 150 to 200 °C [6]. That leads to extended time for hydrogen diffusion from the joint zone and to obtaining the more favorable structure of the heat affected zone (HAZ) [1, 5]. The maximal interpass temperature should be $T_{interpass}$ = 250 °C. This ensures that porosity of the weld metal, which appears due to air turbulence, would not be present and that mechanical properties of the steel would be maintained. During the welding the biggest problem are cold cracks, caused by hydrogen diffusion and residual hydrogen, which can appear in the heat affected zone (HAZ) or in the weld metal, especially when one applies the filler metals that have the yield stress of about 600 *MPa*.

3. The welding technologies

Two welding technologies were tested. Due to the required output properties of the welded joint, there was a dilemma how to deposit the root passes, manually with electric arc (MMAW) or by welding in the protective atmosphere (GMAW). For the filling passes and cover welds it was definitely decided to apply the GMAW method due to the higher productivity and welding velocity, with respect to the MMAW. So, two technologies MMAW/GMAW and GMAW/GMAW were applied and compared, Figures 1 and 2, with corresponding welding parameters and properties of the filler metals, given in Tables 3 and 4, [5-6].

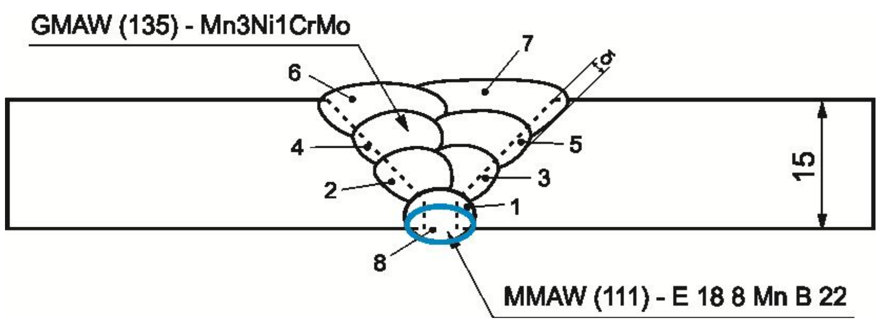

Fig. 1. Deposition of the weld layers by the MMAW/GMAW technology

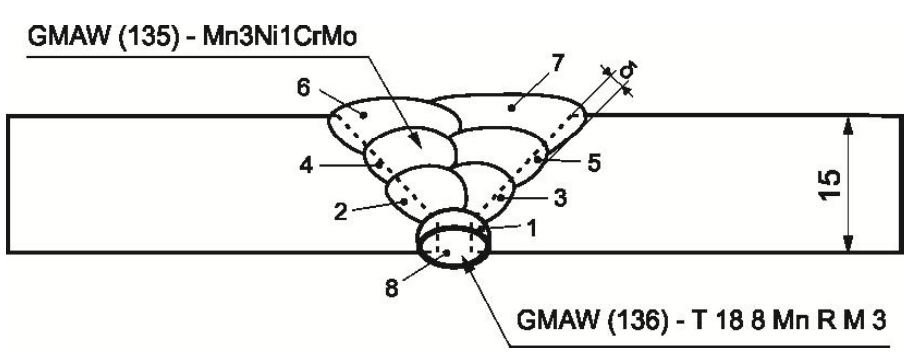

Fig. 2. Deposition of the weld layers by the GMAW/GMAW technology

Tab. 3. Chemical composition and mechanical properties of the filler metals for the MMAW/GMAW technology [1-5, 14]

Electrode type	Chemical composition, %						Mechanical properties of the pure metal			
	C	Si	Mn	Cr	Ni	Mo	R_m, *MPa*	R_p, *MPa*	A_5, %	KV, *J*
E 18 8 Mn B 22 (EN 1600)	0.12	0.8	7.0	19.0	9.0	-	590 - 690	350	40	80 +20ºC
Mn3Ni1CrMo (EN 12534)	0.6	0.6	1.7	0.25	1.5	0.5	770 - 940	690	17	47 -40ºC

Tab. 4. Chemical composition and mechanical properties of the filler metals for the GMAW/GMAW technology [1-4, 14]

Wire type	Chemical composition %						Mechanical properties of the pure metal			
	C	Si	Mn	Cr	Ni	Mo	R_m, *MPa*	R_p, *MPa*	A_5, %	KV, *J*
T 18 8 Mn R M 3 (EN ISO 17633-A)	0.1	0.8	6.8	19.0	9.0	-	600 - 630	400	35	60 +20ºC

4. Experimental investigations of the welded joints – results and discussion

The objective of this paper was to test the welded joints to verify if they possess the required mechanical and structural properties in all the weld's characteristic zones. Several tests were performed with the selected combination of the filler metals, welding procedures and welding parameters, on samples prepared by cutting from the two welded plates. The samples for tensile tests were prepared first [15]; then samples for the impact toughness tests [16] and finally for hardness measurements and microstructure analyses [17].

4.1. Tensile tests at room temperatures

Samples for tensile tests were prepared from the BM and from the two welded plates: plate 1 (MMAW/GMAW) and plate 2 (GMAW/GMAW) – 4 samples for each material according to standard SRPS EN 1002-1.

Obtained results are presented in tables 5 to 7 and corresponding diagrams are shown in Figures 3 to 5, respectively. Numbers of curves on diagrams refer to samples' numbers in corresponding tables. It should be emphasized that fracture of samples occurred mainly outside of the welded joints zones.

Tab. 5. Experimental results of the tensile tests – BM (S690 QL) [2-4]

Sample #	Measurement length l_0, *mm*	Reduction area S_0, *mm^2*	Yield stress $R_{p0.2}$, *MPa*	Tensile strength R_m, *MPa*	Elongation $A_{11.3}$, %
1	89.28	50.27	782	798	14.19
2	89.28	50.27	809	840	11.30
3	88.42	50.01	800	836	9.98
4	88.29	50.27	812	842	10.92

Tab. 6. Experimental results of the tensile tests – WJ (S690 QL) – plate 1 (MMAW/GMAW) [2-4]

Sample #	Measurement length l_0, *mm*	Reduction area S_0, *mm^2*	Yield stress $R_{p0.2}$, *MPa*	Tensile strength R_m, *MPa*	Elongation $A_{11.3}$, %
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

Tab. 7. Experimental results of the tensile tests – WJ (S690QL) – plate 2 (GMAW/GMAW) [2-4]

Sample #	Measurement length l_0, *mm*	Reduction area S_0, *mm^2*	Yield stress $R_{p0.2}$, *MPa*	Tensile strength R_m, *MPa*	Elongation $A_{11.3}$, %
1	87.63	50.39	794	834	11.59
2	89.49	50.39	784	834	9.12
3	90.92	49.89	782	833	10.92
4	88.75	50.27	779	837	11.48

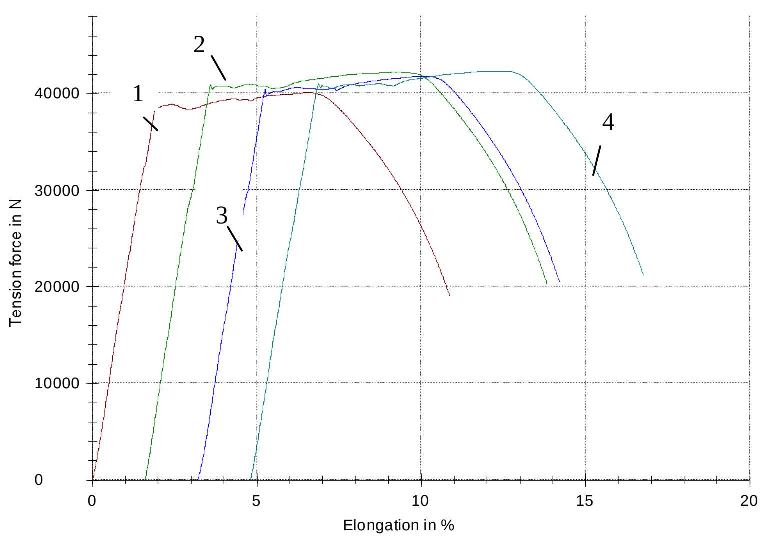

Fig. 3. Summary diagram of the tensile curves for the base metal

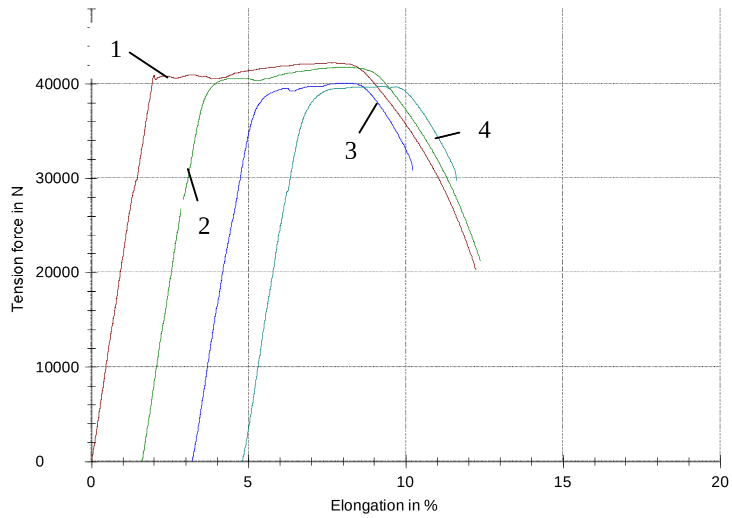

Fig. 4. Summary diagram of the tensile curves for the welded plate 1 (MMAW/GMAW)

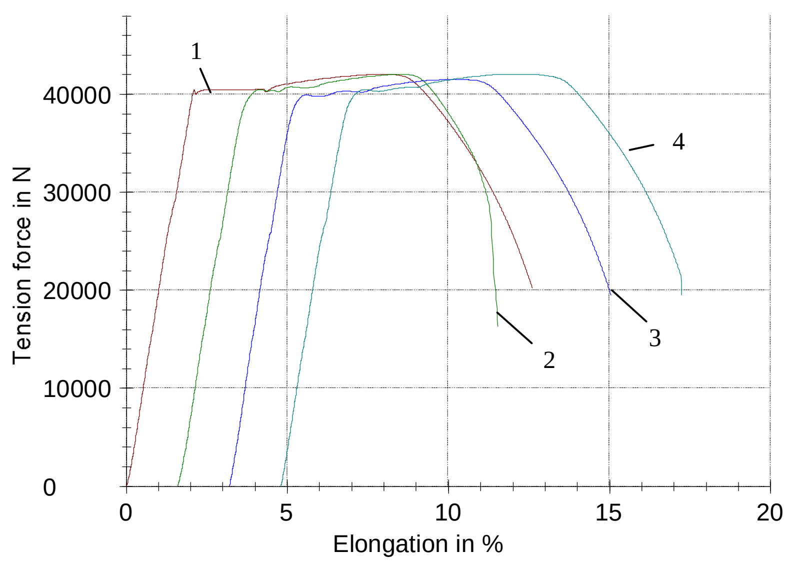

Fig. 5. Summary diagram of the tensile curves for the welded plate 2 (GMAW/GMAW)

4.2. Charpy impact toughness test

Samples were cut from the welded plates for testing of the base metal (BM) and individual zones of the welded joint: weld's face, weld's root and the melting zone. Tests were done on the Charpy pendulum in accredited laboratory according to standard SRPS C.A4.025. Figure 6 shows a drawing of a sample prepared for impact testing of the weld's face characteristic zones, while Figure 7 presents a drawing of a sample for impact toughness testing of the weld's root characteristic zones. The sample has V-notches located in the weld metal face, melting zone and heat affected zone. Three samples were prepared for each of the mentioned zones. All the samples were prepared according to standard EN 10045-1 (55×10×10 *mm*) [15]. Results of toughness tests for the base metal, weld face and weld root are presented in tables 8, 9 and 10, respectively.

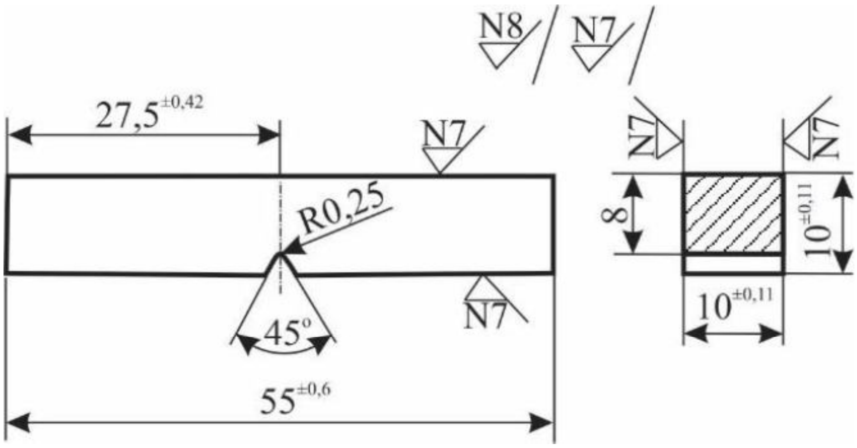

Fig. 6. Drawing of a sample for impact testing of the weld face's characteristic zones

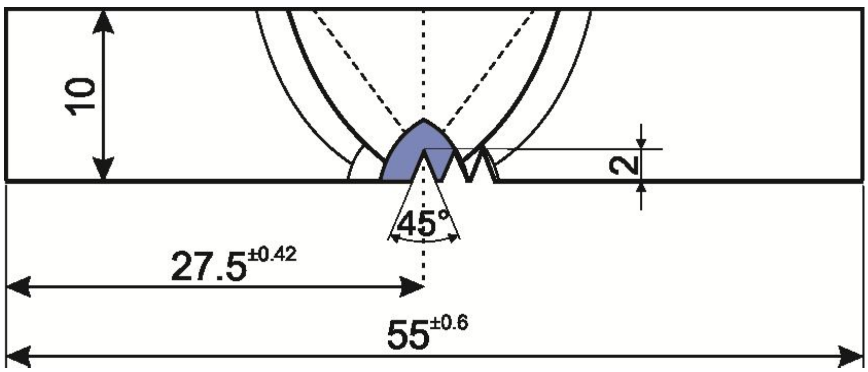

Fig. 7. Drawing of a sample for impact testing of the weld root's characteristic zones

Tab. 8. Consumed fracture energy values and impact toughness for BM at 20 °C and – 40 °C [2-4]

Temperature °C	Sample #	**Fracture energy *J***		**Impact toughness ×10^{-2} *J/mm^2***	
		Plate 1 MMAW/GMAW	Plate 2 GMAW/GMAW	Plate 1 MMAW/GMAW	Plate 2 GMAW/GMAW
+ 20	1	235.17	242.02***	293.96	302.52
	2	222.44	226.19**	278.05	282.74
	3	234.68	250.89*	293.34	313.61
- 40	4	219.59	238.10	274.49	297.62
	5	179.78	238.10	224.73	263.55
	6	206.08	221.39	257.60	276.74

* Representative sample shown in figures 8-9.
** Representative sample shown in figure 10.
*** Representative sample shown in figure 11.

Tab. 9. Consumed fracture energy and impact toughness for the weld face's characteristic zones at 20°C.

Temperature °C	V-notch position	Sample #	**Fracture energy *J*** Plate 1 MMAW/GMAW	Plate 2 GMAW/GMAW	**Impact toughness ×10^{-2} *J/mm²*** Plate 1 MMAW/GMAW	Plate 2 GMAW/GMAW
+20	Weld face	1	24.17	35.49	30.21	44.36
		2	45.53	35.86	56.91	44.82
		3	34.66	41.15	43.32	51.43
	Face melting zone	1	143.25	223.18	179.06	278.97
		2	143.00	251.68	178.86	314.61
		3	159.72	251.33	199.65	314.17
	HAZ	1	189.19	238.20	236.48	297.74
		2	172.75	225.67	215.94	282.09
		3	209.74	235.86	262.17	294.82

Besides results presented in table 8 and appearance of the sample's fracture surface (Figure 10b), diagrams were obtained showing variation of the force and energy with time. Based on that, it was possible to estimate the character of the samples' fracture. In Figures 8 and 9 are shown diagrams of force and fracture energy variation with time in the base metal for a representative sample (sample 3 – plate 2) tested at room temperature, while in Figure 10 is shown variation of the facture energy with time in the melting zone of the sample #2 made of the plate 2, as well as appearance of its fracture surface. In Figure 11 is given the variation of the fracture energy withy time in the HAZ of sample #1 made of plate 2, as well as appearance of the fracture surface.

When analyzing results obtained from table 10, one can notice a prominent drop of toughness in the weld's root, while results for the melting and HAZ zones are above expected, even comparable to values of impact toughness of the base metal. This fact could be confirmed by yet another indicator of the welded joint's plasticity – the area percentage share of the ductile fracture with respect to the whole fracture surface area.

Tab. 10. Consumed fracture energy and impact toughness for the weld root's characteristic zones at 20°C.

Temperature °C	V-notch position	Sample #	**Fracture energy *J*** Plate 1 MMAW/GMAW	Plate 2 GMAW/GMAW	**Impact toughness ×10^{-2} *J/mm²*** Plate 1 MMAW/GMAW	Plate 2 GMAW/GMAW
+20	Weld root	1	85.76	52.67	107.20	65.83
		2	89.45	51.24	111.82	64.05
		3	82.09	54.10	102.62	67.63
	Root melting zone	1	192.67	182.39	240.84	227.98
		2	182.27	178.72	182.27	223.39
		3	183.33	187.09	229.16	233.86
	HAZ	1	236.35	292.42	295.43	365.52
		2	251.16	209.96	313.95	262.45
		3	242.11	195.78	302.64	244.72

The share of the ductile fracture for samples with the V-notch located in the melting zone, was within range 95.43 – 99.41 % for the weld's face and 92.42 – 99.45

% for the weld's root. For samples for investigating the HAZ, those values were 93.00 – 99.81 % for the weld's face and 97.27 – 99.58 % for the weld's root.

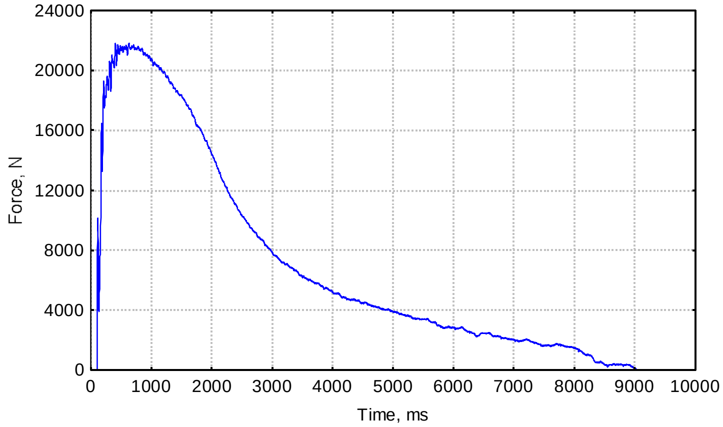

Fig. 8. Variation of force with time – BM (sample 3 – plate 2)

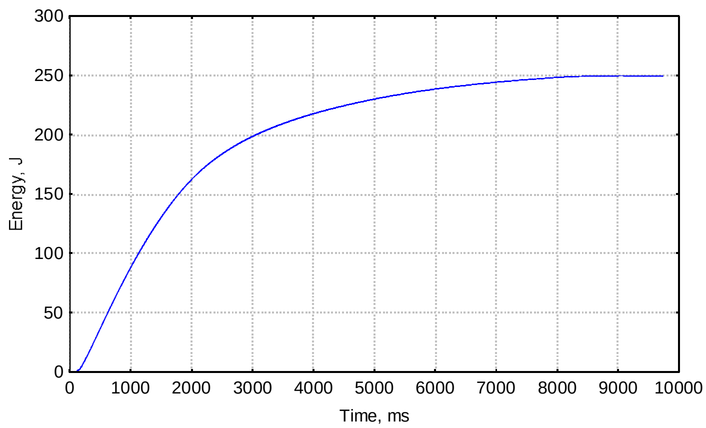

Fig. 9. Variation of fracture energy with time – BM (sample 3 – plate 2)

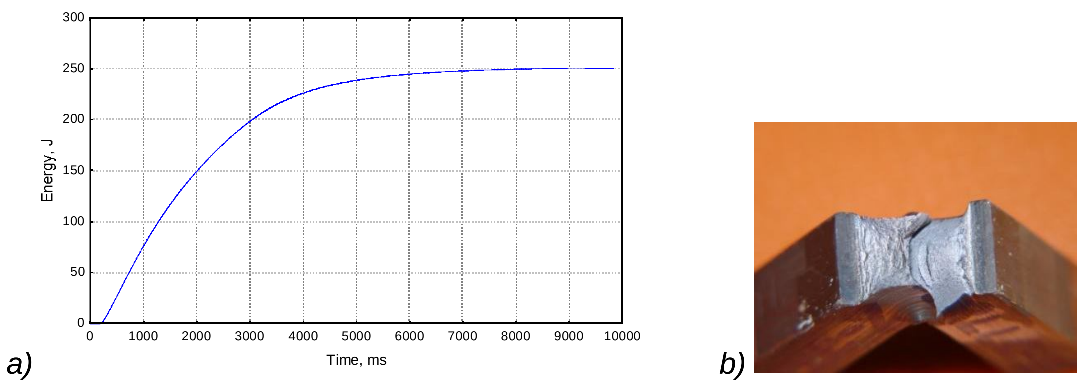

Fig. 10. Fracture energy variation with time:
a) melting zone (sample 2 – plate 2); b) appearance of the sample's fracture

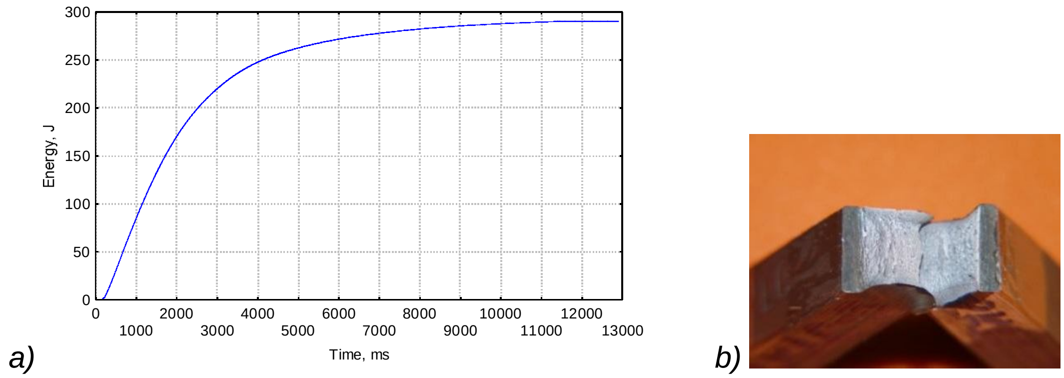

Fig. 11. Fracture energy variation with time:
a) heat affected zone (sample 1 – plate 2); b) appearance of the sample's fracture

Through detailed analyzing of the ductile fracture share in the complete fracture surface area one can state that slightly more favorable results were offered by plate welded by the GMAW/GMAW procedure, though results show that plates welded by both procedures are highly resistant to brittle fracture. When the speaking matter is the base metal, percentage share of ductile fracture in the total area was between 91 and 96 % at the room temperature and between 78.5 and 95 % at – 40 °C, what represents very high values and points to the favorable plasticity properties of the considered high-strength steel.

4.3. Weldabilty of the BM estimate by the TTT diagrams

Tentative evaluation of weldability and estimate of hardness and microstructure of HAZ can also be done based on the TTT diagrams for the considered steel, Figure 12 [18]. Namely, the cooling time in the most critical temperature zone between 800 °C and 500 °C (called $t_{8/5}$) can be calculated the most accurately according to expression (1) [17-18] and it is entered into the TTT diagram which then gives information about hardness and microstructure of the HAZ. If one obtains a good agreement of values red-off from the TTT diagram and actually obtained microstructure and measured hardness from experimental results, one can simplify the procedure of selecting the optimal technology of this steel welding by avoiding the expensive and complicated experiments.
Formula for calculating the cooling time $t_{8/5}$ reads [4]:

$$t_{8/5} = \frac{k \cdot q_l^n}{\beta \cdot (T_{av} - T_0)^2 \cdot \left[1 + \frac{2}{\pi} \cdot arctg\left(\frac{s - s_0}{\alpha}\right)\right]}, \quad s \tag{1}$$

where:

q_1 – welding driving energy [10^{-1}J/mm]
T_0 – preheating temperature of the welded parts [°C] (T_p = 150 °C)
T_{av} –
s – thickness of the welded plates [mm]
s_0 – reference thickness [mm];
k, n, α, β – coefficients depending on the type of welding

Data necessary for calculation of the cooling time $t_{8/5}$ are being adopted from the corresponding references [19-20] or being selected from Table 11. Results of the cooling time $t_{8/5}$ calculations are given in Table 12.

Tab. 11. Parameters needed for calculation of the cooling time $t_{8/5}$ [17, 18]

Welding procedure	k	n	s_0	α	T_{av}	β	
	-	-	mm	-	°C	But joint	Angle joint
MMAW	1.35	1.5	14.6	6	600	1	2.0
GMAW	0.345	1.7	13	3.5	600	1	1.7

Tab. 12. Cooling time $t_{8/5}$ calculation for root layers

Welding procedure	T_p °C	q_1 J/mm	$t_{8/5}$ s	HAZ hardness HV10	Structure
MMAW	150	1200	8.41	390	M + B
GMAW	150	1120	9.80	380	M + B

If the $t_{8/5}$ calculated times from Table 12 are entered into the TTT diagram of S690 QL steel, one obtains the cooling curves which show the expected hardness for the corresponding times $t_{8/5}$ (Figure 19). According to this time, one can read-off from the diagram the corresponding HAZ microstructure, as well. The cooling curves of both welding procedures of the root layers MMAW and GMAW are entered into the TTT diagram. In both cases, results obtained from diagrams are in high correlation with experimentally obtained results of hardness measurements and recorded microstructures. Speaking of the $t_{8/5}$ cooling time, one should know that steel S690 QL manufacturers' recommendations [19] are that the cooling time should be within interval 5 – 25 s, so that the output structure should not be purely martensitic.

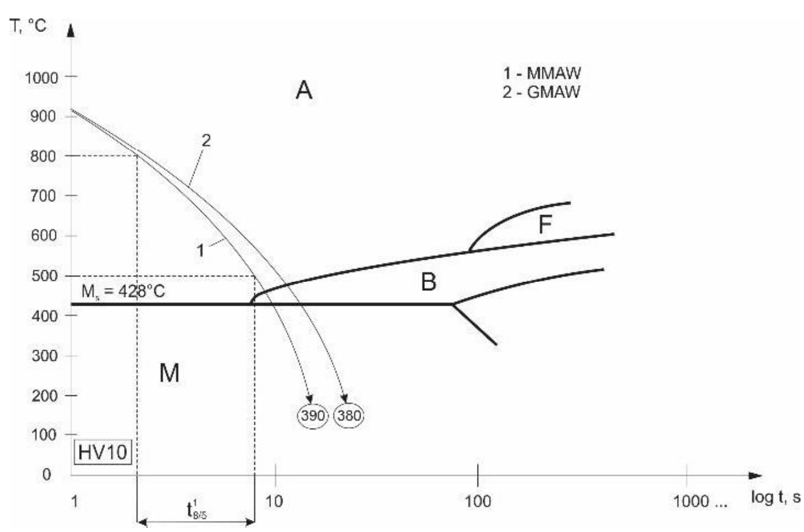

Fig. 12. The TTT diagram for S690 QL steel [22] with results for the two technologies entered

Results obtained in this paper show that with achieved cool speeds one gets the mixed martensitic-bainite structure and that hardness does not exceed 370 HV. The cooling time $t_{8/5}$ can be extended by bigger heat input (q_1) or by increasing the preheating temperature (T_0). Manufacturers' recommendations that the heat input should not exceed 17 kJ/cm and that T_0 < 200 °C, were respected within the proposed technology. Moreover, there is a reserve so both q_1 and T_1 could be extended and the given limits for the given steel would still be obeyed.

5. Conclusions

The detailed analysis of results obtained in this research (verification of the BM mechanical properties, tensile test and impact toughness test of the executed samples), as well as results reported earlier [4-5], the conclusion was that the technology, which included the MMAW/GMAW combination of the welding procedures, has advantage over the technology utilizing the GMAW procedure for both root and filling passes. Of all the tested parameters, the decisive role was played by the impact toughness test results. All the other parameters did not offer decisive advantage of either technology.

Thus adopted technology was applied to a real structure and results obtained from the tests in the real exploitation conditions justified this conclusion, [5].

The requirement for increased productivity of the welding technologies is constantly present in engineering practice, which, by no means should imply that it would be at the expense of reliability of the welded joints, i.e. the request that they possess necessary mechanical properties, primarily strength, plasticity and toughness, must come first.

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