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ABSTRAKT / ABSTRACT

Zhodnotenie zvariteľnosti vybratých vysokopevných ocelí

Weldability estimates of some high strenght steels

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Abstrakt:

Vysoko pevná oceľ bola vyrobená špeciálnymi postupmi legovania, ohrevu a mechanického opracovania. Vysokopevné ocele skupinu ocelí s vynikajúcimi mechanickými vlastnosťami. Priaznivé mechanické vlastnosti, primárne pevnosť, húževnatosť a tvrdosť umožnili ich intenzívnu aplikáciu vo výrobe zváraných konštrukcií. V tomto príspevku sú prezentované štyri charakteristické a bežne aplikované Švédske ocele WELDOX 700 (S690QL), HARDOX 500, ARMOX 500 a DOMEX 700. Nakoľko sa používajú hlavne na zvárané konštrukcie, v príspevku sú, okrem podrobných údajov o ich chemickom zložení a mechanických vlastnostiach, prezentované aj údaje o ich schopnosti spájania zváraním, ako aj problémy objavujúce sa počas ich zvárania. V závere je stručne uvedený spôsob výberu optimálnej technológie zvárania pre oceľ WELDOX 700.

Abstract:

High strength steels are manufactured by special procedures of alloying and heat and mechanical treatment. They represent a group of steels with exquisite mechanical properties. Favorable mechanical properties, primarily tensile strength, impact toughness and hardness, enabled their intensive application for manufacturing of responsible welded structures. In this review paper are presented four characteristic and widely applied Swedish steels: WELDOX 700 (S690QL), HARDOX 500, ARMOX 500 and DOMEX 700. Since they are mainly used for welded structures, in the paper are, besides the detailed data on their chemical composition and mechanical properties, also presented data on their weldability and problems that appear during their welding. At the end is briefly presented a way of selecting the optimal welding technology for the WELDOX 700 steel.

High strength steels (HSS) belong into a group of high quality steels, with exceptional mechanical properties, especially in regards with tensile strength (R_{eH} > 360 MPa). However, their deficiency - the limited and difficult weldability must not be ignored. In other words, some of them have good weldability but some of those steels are weldable only with application of special measures related to controlled heat input, which is the only way that their favorable mechanical properties could be kept within the heat-affected zone (HAZ) of the welded joint. That condition could be met only if the optimal welding technology (OWT) is applied.

Existing, scarce and often unclear and insufficient, recommendations for selection of the optimal welding technology are one of the causes of large number of flaws in welded joints. Mentioned problems, as well as others, can be successfully solved by proper selection of the welding procedure, the adequate filler metal and technology of welding. All those should be verified by experiments conducted in laboratory or in real operating conditions, certainly not in arbitrary conditions and in some "ad-hoc" used workshop.

When complex welded constructions are made, especially the ones made of steels with 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 values of those temperatures could be found, depending on the thickness of the welded plates, i.e., their thickness equivalents. However, this influence has not been analysed particularly for the welded joints of high strength steels, which are very sensitive not only to local heat input during the welding process, but also to elevated working temperatures.

Technologists dealing with welding must be provided with the possibility to predict in advance, in a very short time period, both mechanical and metallurgical properties of joints of high strength steels, without conducting large number of practical tests or relying on personal experience of a designer.

The objective of this work was to present at one place a brief review of some of the most applied typical representatives of high strength steels, which are mainly aimed for manufacturing the responsible steel structures for various applications. Besides the chemical composition we present the most important mechanical properties of those steels, while for the steel of class Weldox 700 is also provided somewhat more detailed procedure od selecting the optimal welding technology.

2. The most important representatives of certain groups of high strength steels

Here are presented four high strength steels, which are the typical representatives of four different groups: construction steel – Weldox 700E (S690QL), steel resistant to wear – Hardox 500, the armor (bulletproof) steel Armox 500T and general construction carbon-manganese steel Domex 700 MC D.

2.1 Weldox 700 (S690QL)

The HSS Weldox 700E (this steel according to standard EN 10025–6:2004 + A1:2009 has mark S690QL) is produced according to strictly controlled chemical composition, with exceptional mechanical properties, within the very narrow tollerance limits. The structure is ferrite-pearlite, so it belongs into the group of well weldable steels, but only for plates of very small thickness. This steel is obtained by the thermal-mechanical treatment of steel's semifabricated pieces at high temperatures. Chemical composition and mechanical properties of this steel are presented in Tables 1 and 2, respectively, [1-7].

Tab. 1 *Prescribed chemical composition of Weldox 700E (S690QL) steel (prescribed maximum amounts)*

Chemical elements content, %														
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

Tab. 2 *Weldox 700E mechanical properties and microstructure*

Thickness, *mm*	R_m, *MPa*	$R_{p0.2}$, *MPa*	A_5, %	Impact energy, *J*	Microstructure
4 - 53	780 – 930	700	14	69 J at -40ºC	Interphase tempering structure
53.1 - 100	780 - 930	650			
100.1 - 130	710 - 900	630			

Weldability of this type of steels is conditional. Despite the fact that the carbon content is limited to 0.20%, steel is prone to appearance of cold cracks. Weldability can be calculated via the chemically equivalent carbon (CE), and obtained results are presented in Table 3, for two different formulae [1-5, 7]. The CEV formula is given by the International Institute for Welding (IIW), while the CET formula is given by the steel manufacturers.
For values CEV or CET less than 0.45 the weldability is conditional, i.e., preheating and additional measures must be applied.

Tab. 3 *Values of total CE Carbon of Weldox 700E in %*

Thickness, *mm*	5	5-10	10-0	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

Problem that relates to weldability of this steel, especially when the parts of greater thickness should be welded, concerns possibility of appearance of cold cracks. This problem can mainly be solved by the controlled heat input and in some special cases with preheating and additional heat treatment post welding. There one assumes that the filler metals applied must be with low hydrogen content.

Considering that this steel is conditionally weldable, the preheating temperature must first be determined. Authors of this paper have, in some previous works [1-5, 7], already given some recommendations that should be obeyed for successful welding of this steel as well as the detailed procedure of the welding procedure itself.

2.2 Hardox 500

Steels of the Hardox class are produced according to the strictly prescribed chemical composition and in precisely defined manufacturing phases. That enabled realization of exceptional mechanical properties within the very narrow tolerance limits. This steel has exceptionally high strength and hardness, thanks to special het treatment procedures (quenching and sequential tempering). It is not recommended for preheating at temperatures higher than 250ºC and it should be subjected to additional heat treatment only exceptionally. It is aimed for manufacturing parts that are exposed to intensive wear and especially for the working surfaces subjected to abrasion. In Tables 4 and 5 are given the chemical composition of this steel and its mechanical properties, respectively, [8-9].

Tab. 4 *Prescribed chemical composition of Hardox 500 steel (prescribed max)*

Chemical composition, %								
C	Mn	Si	P	S	Cr	Mo	Ni	B
0.3	1.6	0.7	0.02	0.01	1.5	0.6	1.5	0.005

Tab. 5 *Hardox 500 mechanical properties and microstructure*

Thickness, *mm*	R_m, *MPa*	$R_{p0.2}$, *MPa*	A_5, %	Impact energy, *J*	Hardness, *HBW*	Microstructure
4 - 32	≈ 1400	≈ 1250	10	27 J at 0ºC	500	Interphase tempering structure
32 - 80						

The biggest problem that relates to weldability of this class of steels, especially for welding of parts of the bigger thickness, concerns appearance of the cold (hydrogen) cracks. That problem could be solved by adequate selection of the filler metals (austenitic electrodes or electrodes whose yield stress does not exceed 500 MPa), by controlled heat input and only is special cases by preheating or additional heat treatment. Here also one assumes that the filler metals must have low hydrogen content. Due to all the aforementioned, to achieve favorable properties of the welded joints of this steel, one first has to estimate the weldability of this steel, by the chemically equivalent carbon, Table 6. However, it is also necessary to respect recommendations from authors who were dealing with this problem earlier, [9].

Tab. 6 *Values of total CE Carbon of Hardox 500*

Thickness, *mm*	5	5-10	10-20	20-40	40-80
$CET = C + \frac{Mn+Mo}{10} + \frac{Cr+Cu}{20} + \frac{Ni}{40}$	0.34	0.36	0.43	0.45	0.47
$CEV = C + \frac{Mn}{6} + \frac{Cr+Mo+V}{5} + \frac{Ni+Cu}{15}$	0.49	0.52	0.64	0.66	0.75

For values of weldability less than 0.45 (obtained by the CET formula), for thicknesses up to 20 mm one does not need to apply preheating, while for bigger thicknesses preheating is necessary.

2.3 Armox 500

Steel Armox 500 belongs into a group of armor (bullet-proof) high strength steels, which are obtained by special procedures of thermo-mechanical treatment (Q+T – quenching plus tempering) and it represents one of the optimal armor steels, with respect to hardness, toughness and ballistic properties. It is used for production of the protective plates on vehicles and static structures. It is easily machined and has favorable ratio of hardness and impact toughness, for providing the maximum anti projectiles protection. It is delivered with thickness in range of 3 to 80 *mm*. In Tables 7 and 8 are given the chemical composition and mechanical properties of the Armox 500T steel, respectively. According to manufacturer's recommendations this steel should not be heated above 200ºC since that causes significant drop of mechanical properties [10].

Tab. 7 *Prescribed chemical composition of Armox 500T steel (prescribed max) [10]*

Chemical elements content, %								
C	Mn	Si	P	S	Cr*	Mo	Ni*	B
0.32	1.2	0.4	0.015	0.010	1.0	0.7	1.8	0.005

* For plate thickness greater than 70 mm: Cr ≤ 1.5% and Ni ≤ 3.5%.

Tab. 8 *ARMOX 500T mechanical properties and microstructure [10]*

Thickness, *mm*	R_m, *MPa*	$R_{p0.2}$, *MPa*	A_5, %	Impact energy, *J*	Hardness, *HBW*
3 - 80	1450 - 1750	≈ 1250	8	25 J at -40ºC	480 - 540

Weldability of steels of the Armox class is conditional, but the great strength and increased content of carbon of this steel can lead to the most dangerous flaws – cold cracks. This is why it is recommended to weld this steel with electrodes that have low hydrogen content. The Armox steels can be welded by the MAG procedure or by procedure in the gas protective atmosphere. The Armox plates are manufactured in such a way that they possess precisely controlled carbon content, to preserve favorable weldability properties with simultaneous achieving favorable hardness, strength and ballistic properties of the welded structures. The characteristic values of chemically equivalent carbon through which one estimates weldability are given in Table 9 [11]. It is also recommended that the Armox steels should be welded by austenitic electrodes or ferritic filler metals with mandatory preheating at temperatures 75 to 200ºC and one should also respect recommendations by authors who were dealing with problematics earlier, [10-11].

Tab. 9 *Values of total CE Carbon of ARMOX 500T*

Thickness, *mm*	3 - 150
$CEV = C + \frac{Mn}{6} + \frac{Cr+Mo+V}{5} + \frac{Ni+Cu}{15}$ *	0.67 – 0.75

* Carbon equivalent (CEV) in accordance with IIW.

The weldability of this steel is conditional and the preheating is necessary for all thicknesses of the base metal.

2.4 Domex 700

Steels of the Domex class are manufactured according to the special procedure of thermo-mechanical treatment and micro alloying. They possess low carbon content, but increased content of manganese, what classifies them into the group of the C-Mn steels. Besides C and Mn, small contents of elements, like Nb and Ti, that assist grain size reduction, are added, what enables obtaining of favorable mechanical properties and microstructure of those steels. In comparison to some similar steels, from other groups, one can say that the Domex steels possess somewhat higher content of Nb, Ti and V. Besides the micro alloying elements, the very important role play the thermo-mechanical treatment, which consists of heating to austenization temperature, followed by intensive rolling at that temperature, finally followed by gradual cooling. In that way, one achieves the optimal combination of high strength, good metal forming ability, welding and toughness [12].

Domex 700 MC D steels are applied form producing of very responsible welded structures like chassis of heavy vehicles, cranes and vehicles of heavy mechanization. The good mechanical properties of those steels enable application of materials of lesser thickness what leads to mass reduction of structures. The Domex 700 MC D steel is delivered in form of plates of different sizes and thicknesses from 2 to 10 *mm* [12].

Chemical composition and mechanical properties of the Domex 700 MC D steel are given in Tables 10 and 11, respectively [12].

Tab. 10 *Prescribed chemical composition of DOMEX 700 MC steel (prescribed max.)*

Chemical elements content, %								
C	Mn	Si	P	S	Al	Nb	V	Ti
0.12	2.1	0.1	0.025	0.010	0.015	0.09	0.2	0.15

* Can contain Mo ≤ 0.5% and B ≤ 0.005%.

Tab. 11 *DOMEX 700 MC D mechanical properties and microstructure*

Steel mark	R_m, *MPa*	$R_{p0.2}$, *MPa*	A_5, %	Impact energy, *J*
DOMEX 700 MC D	750 - 950	700	12	40 J at -20ºC

Weldability of the Domex 700 MC D steel is very good due to low content of carbon and impurities P and S. Welding can be performed without preheating [12-13] and this steel is not prone to appearance of cracks. Mechanical properties of the welded joint usually do not differ than those of the base metal characteristics. In the case when load acts directly to the welded joint, it is recommended to conduct welding with filler metals of somewhat smaller strength than that of the base metal. Welding in the gas protective atmosphere is recommended [12].

3. Selection of optimal welding technology of the Weldox 700 steel

The optimal welding technology of the WELDOX 700 (S690QL) steel was prescribed based on weldability estimate (via CE), recommendations by the steel manufacturers and by other authors form this field, as well as on numerous model investigations, performed by authors of this paper. Weldability was estimated according to formulae from Table 3. Obtained results show that it is necessary to apply preheating to temperatures within range 150 to 200ºC. The prescribed welding technology assumes application of filler metals (FM) of different characteristics for different layers: for the root pass one should apply an austenitic FM with strength smaller than that of the base metal (BM) – procedure known as *undermatching*, while for the cover passes (layers) one should use the FM with properties similar to those of the BM.

3.1 Proposed welding technology

The proposed welding technology assumes deposition of the root welds by the MMAW electrode E 18 8 Mn B 22 – diameter Ø 3.25 *mm*; deposition of the filling layers is done by the MAG electrode wire Mn3Ni1CrMo – diameter Ø 1.2 *mm* (Figure 1). For deposition of the covering layers the MAG procedure was selected due to better productivity with respect to the MMAW [1-2]. The welded plate dimensions were 400×200×15 mm. After deposition of the root pass # 1 it was subsequently partially grooved by the graphite electrode arc-air procedure and the new root pass was deposited in the complete argon protected atmosphere by the austenite electrode 8. In Table 12 are shown the chemical composition and mechanical properties of the filler metals and in Table 13 are given the proposed welding parameters [1-2, 4].

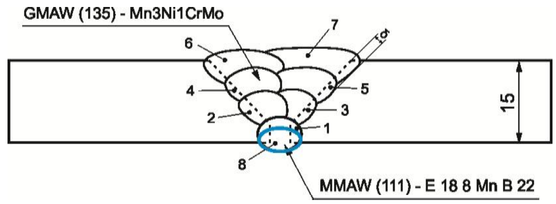


***Fig. 1** Combined MMAW/MAG deposition of weld layers*

***Tab. 12** Chemical composition and mechanical properties of the filler metals*

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

***Tab. 13** Welding parameters*

Parameters*	I, *A*	U, *V*	V_w, *mm/s*	V_m, *m/min*	q_l, *J/mm*	δ, *mm*	Shielding gas	The shielding gas flux, *l/min*
Root weld	120	24.5	2.0	-	1200	1.7	-	-
Filler welds	240	25	3.5	8	1488.5	2	Ar/18% CO_2	14

* I – welding current; U – welding voltage, v_w – welding speed., v_m – melting speed, q_l – driving energy (heat input), δ – penetration depth.

3.2 Experimental investigation of the welded joints

3.2.1 Tensile testing

Experimental tests of the S690QL steel specimens consisted of mechanical tensile test, impact toughness test and hardness measurements. The tensile test was performed on specimens prepared from the 15 *mm* thick plate; 4 specimens were prepared for the base metal (BM) tests and 4 specimens were aimed for testing the welded joint material (Figures 2 and 3) [1-2, 4]. Tests were performed according to appropriate standard [14]. The obtained results are shown in table 14.

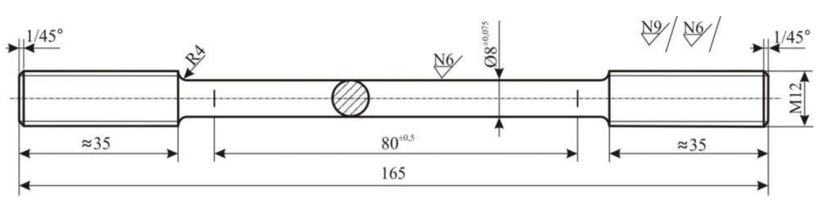


***Fig. 2** Specimen for tensile testing*

Specimen before testing - BM

Specimen after testing - BM

Specimen before testing - WJ

Specimen after testing - WJ

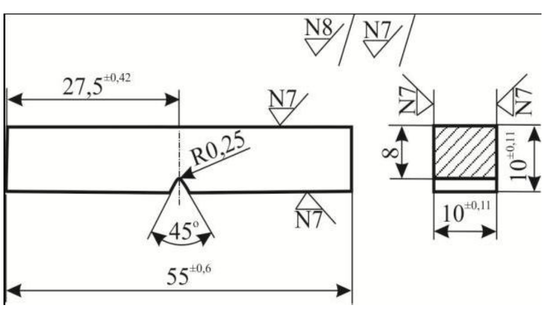
Fig. 3 *Specimens appearance before and after testing*

Tab. 14 *Experimental results of the tensile test* [1-5]

Sample No.	L_0, *mm*	S_0, *mm*^{2}	$R_{p0.2}$, *MPa*	R_m, *MPa*	$A_{11.3}$, %
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
Welded joint (MMAW/MAG)					
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

3.2.2 Impact toughness testing

Specimens were prepared for the impact toughness tests (Figure 4), according to the similar procedure as for the tensile test specimens; six aimed for testing the BM and three for testing the impact toughness of the weld metal, root metal and HAZ. Tests were done on the Charpy pendulum, both at room and lower temperatures, according to standard EN 10045-1 [15]. Table 15 presents results of the impact tests.



a)

b)

Fig. 4 *Appearance of specimen for impact toughness testing: a) drawing; b) fracture surfaces appearance*

Tab. 15 *Impact energy absorbed at room and lower temperatures* [1-2]

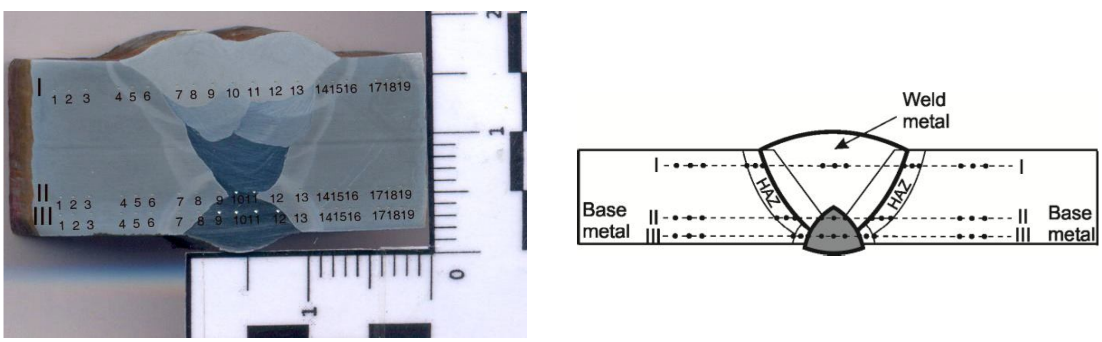
Temperature, ºC	Impact energy, *J*			
	Base metal	Weld metal	Root weld metal	HAZ
+ 20	235.2; 222.4; 234.7	24.2; 45.5; 34.7	85.8; 89.5; 54.1	189.2; 172.8; 209.7
- 40	219.6; 179.8; 206.1	-	-	-

Besides the presented results, the plastic properties of the executed welded joints, were deciding in favor of selected welding technology, as well. They were estimated according to the share of the plastic fracture in the total fracture surface (Figure 4b), which was within range 92.41 – 99.81%, in all of the executed joints' zones [2, 4]. That represents exceptional results, from the aspect of the welded joints plasticity.

3.2.3 Hardness measurement

For hardness measurements of individual welded joints' zones, two special metallographic samples were prepared (Figure 5). The microstructure of the characteristic zones was red-off from them, as well. Hardness was measured by the Vickers method, indentation force was 100 *N*, according to standard SRPS EN ISO 9015-1:2013 [16].

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. 5b). Along a single line hardness was to be measured at least at three points 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). This also applied 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.



a) b)

Fig. 5 *a) Metallographic sample for hardness measurement and microstructure estimate b) hardness measurement directions.*

Hardness of the BM was about 280 HV, while in all the other zones it did not exceed 350 HV, what is considered as the acceptability limit. In paper [1] is presented more detailed analysis of the hardness distribution and estimate of the microstructure.

4. Conclusion

Taking into account that the high strengths steel application is intensively expanding, authors considered that a brief review of a few prominent representatives' mechanical properties would be useful. Data are also provided on four selected steels' chemical compositions, as well as discussion of their weldability properties and measures for their improvement. Besides providing those data for WELDOX 700, HARDOX 500, ARMOX 500 and DOMEX 700, the procedure of prescribing the optimal welding technology for one steel from the WELDOX 700 group is also presented. The experimental procedure for testing the obtained properties of the welded joint of this steel was given, as well.

After the detail analysis of the most important properties of the base metal and estimation of its weldability, choosing of the optimal combination of filler materials, welding method and technology, and extensive model investigation, the optimal welding technology was established, which has been applied on real construction. That welded construction was subjected to rigorous tests and it fulfilled all the requirements necessary for fieldwork, where it turned as a very reliable one.

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

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