Key Engineering Materials
ISSN: 1662-9795, Vol. 755, pp 96-105
doi:10.4028/www.scientific.net/KEM.755.96

Submitted: 2017-04-25
Revised: 2017-05-21
Accepted: 2017-05-24
Online: 2017-09-14

Application of the High Strength Steel HARDOX 450 for Manufacturing of Assemblies in the Military Industry

Vukić LAZIĆ[1,a], Dušan ARSIĆ[2,b*], Ružica R. NIKOLIĆ[3,c], Dejan DJORDJEVIĆ[4,d], Radica PROKIĆ-CVETKOVIĆ[5,e] and Olivera POPOVIĆ[6,f]

[1,2]University of Kragujevac, Faculty of Engineering, Sestre Janjić 6, 34000 Kragujevac, Serbia

[3]University of Kragujevac, Faculty of Engineering, Sestre Janjić 6, 34000 Kragujevac, Serbia and University of Žilina, Research Center, Univerzitna 8215/1, 010 26 Žilina, Slovakia

[4]Milanović Engineering d.o.o., Sobovica, 34321 Kragujevac, Serbia

[5,6]University of Belgrade, Faculty of Mechanical Engineering, Kraljice Marije 16, 11000 Belgrade, Serbia

[a]vlazic@kg.ac.rs, [b]dusan.arsic@fink.rs, [c]ruzicarnikolic@yahoo.com, [d]cmz@fink.rs, [e]rprokic@mas.bg.ac.rs, [f]opopovic@mas.bg.ac.rs

Keywords: High strength steel, HARDOX 450, welding technology, hardness, microstructure

Abstract: The problems related to welding of the high strength steel, aimed for manufacturing of welded structures operating in the prominent wear conditions, is considered in this paper. The paper presents an analysis of possibilities and prescribing the technology for welding the high strength steel HARDOX 450. The methodology for estimate the weldability of this steel was established in the theoretical part of the paper, as well as calculations of the welding parameters, while the hardness was investigated in details and the macro and micro structures of the individual welded joint zones were estimated in the experimental part. Obtained experimental results could be usefully applied for selecting and establishing the optimal welding technology for structures made of this steel. The technology thus established and the GMAW welding regime can enable successful execution of the welded joints and reduce the possibility for appearance of flaws and cracks to a minimum.

Introduction

The high strength steels are relatively new materials that are increasingly used, in both civil and military engineering. They are intensively developing since the nineties of the last century. Today, through the adequate alloying processes and thermo-mechanical processing, they can reach strength of several thousands of MPa. Development of this type of steels is very intensive, since there is a trend in the modern industry towards reducing the mass and weight of structures what further influences the energy and fuel consumption, mobility of vehicles, welding processes, etc. Considering that this can be achieved by increase of the material's strength, development of these steels is oriented in that direction.

The Hardox 450 steel (commercial manufacturer's mark – SSAB, Sweden) has high strength, as well as hardness, due to special heat treatment processes (quenching and sequential tempering). It should not be preheated prior to welding to temperatures over 250ºC; the post-welding heat treatment is not recommended, as well. This steel is used for manufacturing the parts subjected to wear [1-4], especially for surfaces exposed to severe abrasion, like: trucks' load crates, high-pressure vessels, railway wagons, tanks for transporting gasses, housing parts of freight truck for trenches excavation, supports and legs for supporting the vehicle for the missiles launching, as a core design material for the production of ballistic barriers or traps at the shooting ranges for small arms, etc. However, this steel possesses satisfactory toughness and plasticity [5-6].

Quality of the welded joint depends on properties of the base metal (BM) and the filler metal (FM), geometry of the groove, skill of the welder and welding equipment condition. The biggest problem, which is related to weldability of this steel, especially for work pieces of large thickness, refers to possibility of cold cracks appearance. They appear as a consequence of the high content of hydrogen or presence of martensite in the structure [7-8]. Those problems mainly can be solved by proper selection of electrodes (austenite or electrodes whose flow stress does not exceed 500 MPa), controlled heat input and, only in special cases, by preheating or post-welding heat treatment. All these said, point to conclusion that if one needed to obtain good properties of the welded joint, it is necessary to follow the recommendations presented in the specialized literature and instructions [1-3, 9-10, 15].

The Base Metal and its Weldability

Chemical and mechanical properties. The steels of the Hardox class, delivered in the form of thin sheets or plates, are aimed for high wear loads, since they possess high hardness, strength and superior toughness. They are used for producing the mining equipment, which is exposed to different types of wear loadings, sliding and impact loading, frequently in combination with large deformations. Application of the Hardox steel plates, with hardness of 400 or 500 [HV], can guarantee endurance of the hardest wear conditions. The Hardox steel is five times more constant than the low carbon steels. Its strength is very high and so is its stability at different temperatures in the most extreme operating conditions. All these make the Hardox steel highly resistant to impact loads. The Oxelösund steel plant provides the data on the Hardox 450 steel chemical composition and mechanical properties given in Tables 1 and 2, respectively [2, 10].

Table 1. Prescribed chemical composition of the Hardox 450 steel (s = 6 [mm])

Mark	Required	Chemical elements content, [%]										
		C	Mn	Si	P	S	Cr	Mo	Ni	B	CEV	CET
Hardox 450	Prescribed max	0.21	160	0.70	0.025	0.010	050	0.25	0.25	0.004	0.41	0.32

Table 2. Mechanical properties of the Hardox 450 steel (s = 6 [mm])

Yield stress, $R_{p0.2}$ [MPa]	Tensile strength, R_m [MPa]	Elongation, A_5 [%]	Impact toughness KV [J]
1200	1400	10	40 (-40ºC)

All the known thermal cutting procedures can be used for cutting the Hardox plates. The steels of this class are very sensitive to heat input and this is why the special attention should be paid to influence of the applied cutting procedure and risk of appearance of hard and brittle phases in the structure.

Weldability of the Hardox 450 steel. The chemically equivalent carbon (CEV) for these steels is calculated according to expression:

$$CEV = C + \frac{Mn}{6} + \frac{Cr + Mo + V}{5} + \frac{Ni + Cu}{15}.$$

The usual values of the equivalent carbon for the Hardox 450 steel, for thicknesses of 4 to 80 [mm], are within range CE = 0.41 – 0.62.

The Hardox 450 steel can be welded by any arc welding by melting procedure. However, the general weldability of these steels is not guaranteed, due to what the corresponding precautionary measures are required, starting from selection of the welding procedure, filler metal, up to the welding regime and strictly controlled heat input, i.e. the linear welding energy. Thus, in manufacturing the responsible welded structures of the Hardox steel, it is necessary to preserve the primary steel properties, i.e. strength, hardness and toughness (especially in the heat affected zone) [1, 10].

Measures to reduce the risk of appearance of cold cracks. Appearance of hydrogen, creation of brittle structures and presence of tensile stresses in the welded joint, represent the main causes of initiation of cold cracks. Possibility for appearance of cold cracks can be reduced to the least extent if the required recommendations are followed [1, 10]:

- Apply preheating and maintain the interpass[1] temperature;
- Reduce the content of the diffused hydrogen (H < 5 [ml/100 g] of the weld metal);
- Use only dry and clean filler metals;
- Remove all the dirt (pollutants) from the welding zone (moisture, greases, oils or rust);
- Apply all the necessary measures to reduce the residual stresses in the welded joint;
- Apply the proper welding order;
- Adopt the correct distance in the groove's root, regardless of the joint type (max. 3 [mm]);
- After each layer (pass) deposition knock it off and clean the caterpillar from the slag.

The hydrogen brought into the welded joint can be removed by diffusion. The preheating and high heat input are reducing the cooling rate of the welded joint. The higher temperature accelerates the diffusion and reduces the quantity of hydrogen remained in the weld. Reducing the cooling rate decreases the HAZ hardness, as well as the level of the residual stresses, what contributes to lowering the risk of cold cracks. The preheating temperature depends on the quantity of the input heat, value of the chemically equivalent carbon and the heat removal over the base metal (thickness and directions of the heat conduction) [11]. The recommended preheating temperatures for the Hardox 450 steel are from 100 [ºC] for BM thickness up to 50 [mm], 125 [ºC] for thicknesses from 50 to 100 [mm] and within range 150 to 175 [ºC] for thicknesses above 50 [mm].

The preheating temperature should be maintained and controlled during the welding process. The limit thickness when the preheating must not be applied depends on the yield stress of the base metal. The special attention should be paid to preheating when the fixture welds and the root passes are executed. Additional heating of the welded joint immediately after the welding also enables easier removal of hydrogen from the weld. The temperature of the additional heating should be equal to the preheating temperature. The time of keeping the weld at that temperature should at least [5 min/mm] of the thin sheet thickness, but not less than one hour.

During the Hardox steel welding one should specially control the limited heat input, as the most important factor for the controlled cooling of the HAZ, for keeping the structure and properties obtained by the controlled rolling and cooling – the time $t_{8/5}$ concept [11]. In that sense, the recommendations were given for the quantity of the input heat (q_1, [kJ/mm]), depending on the type of material and total thickness, for achieving the satisfactory combination of hardness and toughness of the Hardox steel in the HAZ. The input heat should be within range 1 [kJ/mm] for thicknesses less than 20 mm, over 2 [kJ/mm] for thicknesses from 20 to 40 [mm] and 2 to 2.5 [kJ/mm] for thicknesses larger than 40 [mm] [1, 10]. To summarize, smaller or larger heat input influences the following properties of the welded joint: toughness of the HAZ, strength and deformations of the joint, residual stresses in the welded joint and width of the HAZ.

Welding of the thin sheet overpainted by the anticorrosive basic paint can lead to appearance of porosity. The porosity can be reduced to the least possible extent by adequate selection of the type and thickness of the basic coating of the paint and by application of the corresponding welding parameters. In such a case the welding is executed without limitations prescribed by relevant standard and without need for removal of the basic paint coating.

[1] *Interpass* is the transition temperature to which the single pass weld is cooled down and at which the next pass deposition starts.

Selection of the Filler Metal, Method and Technology of Welding

Selection of the filler metal. For welding of the Hardox class steels one should use the filler metals that possess increased toughness, i.e. the yield stress below 500 MPa (Table 3). If the weld is exposed to intensive wear, one should use electrodes for hard facing for welding of the final layers. The preheating can be avoided by application of the austenite stainless steel DM AWS 307 and AWS 309 [1-3, 11]. In table 3 are presented data on selected electrode wire for welding.

Table 3. Chemical composition of the electrode, type of gas and mechanical properties of the pure weld metal

Wire type	Chemical composition, [%]						Gas mixture Ar/CO_2, [%]	Mechanical properties of the pure weld metal			
SŽ Jesenice	C	Si	Mn	Cr	Ni	Mo		R_m, [MPa]	R_{eH}, [MPa]	A_5, [%]	KV, [J]
VAC 60	0.1	0.9	1.5	-	-	-	82/18	510 to 590	410 to 490	22 to 30	80 to 125

Selection of the welding method. Taking into account the thin sheet thickness, weldability of the base metal and energetic possibilities of the welding procedure, the semi-automatic welding procedure with melting electrode wire was selected in the protective gas atmosphere (MAG).

Selection of the protective gas. Selection of the protective gas or gas mixture plays an important role in the MAG/MIG welding. At present, mainly are used protective gas mixtures, due to numerous advantages that they possess with respect to pure gases during the welding procedure – easy transfer of the BM, easier establishing of the electric arc, reduced bursting of the BM. In all the protective gas welding procedures the gas flow depends on the work-piece thickness and type of joint.

Selection of the welding parameters. It is done according to expressions presented in [1] and [3]. In Table 4 are presented the calculated parameters of the MAG welding.

Table 4. The MAG welding parameters

Parameter	Notation	Unit	Sample 1		Sample 2	Sample 3	
			root	filling	filling	root	filling
Groove cross section area	A	[mm^2]	14.143		16.287	16.287	
Weld cross section area	A_z	[mm^2]	29.3	29.3	36	29.9	35.2
Mass of 1 [cm] long weld	M	[g]	2.3	2.3	2.826	2.347	2.763
Melted wire quantity	$m_{1.2}$	[g/s]	0.709	0.709	2.069	1.670	2.013
Current	I	[A]	207	207	207	315	315
Arc voltage	U	[V]	19.9	19.9	19.9	24	24
Welding rate	v_z	[cm/s]	0.709	0.709	0.732	0.711	0.729
Wire melting rate	v_t	[m/min]	5.9	5.9	5.9	11.285	13.6
Linear energy	q_l	[J/cm]	4938	4938	4783	9038	8815
Number of passes	n	-	1	1	1	1	1

Calculation of the preheating temperature. The calculation of the preheating temperature is generally done according to empirical expressions of different authors by which the affinity to creation of the cold cracks within the HAZ is being established [3]. In this paper the preheating temperature was adopted according to Table 5, recommended by the steel manufacturer [2, 10].

Estimate of the Hardox 450 Steel's Tendency to Creation of Cracks

Estimates of tendency towards creation of cold cracks. Calculation of the cooling rate at 300 [ºC] can be done according to Cottrell's expression (v_h, ºC) or according to expression obtained by solving the partial differential equations of heat flow (v_{300}, ºC) and according to Meiner (v_{cr}, ºC), Table 5 [3].

Table 5. Results of the cooling rate calculations at 300ºC [3]

v_h						
T_o, ºC	Plate notation		q_l, [J/cm]	s, [mm]	N	v_h, [ºCs^{-1}]
20	Plate 1		4931.56	6	1.890	7.371
20	Plate 2		4783.34	6	1.890	7.769
20	Plate 3 (root pass)		9038	6	1.890	2.492
20	Plate 3 (filling pass)		9916.7	6	1.890	2.10
v_{300} *						
T_p, ºC	Plate notation	N_2	N_3	P_x	T_K, [ºC]	v_{300}, [ºCs^{-1}]
151	Plate 1	0.75	0.75	0.0725	151	0.615
151	Plate 2	1.5	1.5	0.037	151	0.327
151	Plate 3 (root pass)	1.5	1.5	0.037	151	0.091
151	Plate 3 (filling pass)	1.5	1.5	0.037	151	0.076
v_{kr} *						
T_p, ºC	Plate notation	k	N_3	v_{kr}, [ºCs^{-1}]		Remark
151	Plate 1	3.0	0.75	6.674		Thin sheet
151	Plate 2	3.0	1.5	6.674		Thin sheet
151	Plate 3 (root pass)	3.0	1.5	6.674		Thin sheet
151	Plate 3 (filling pass)	3.0	1.5	6.674		Thin sheet

* with the following thermo-physical constants: $\lambda = 0.3[\mathrm{J \cdot cm^{-1} \cdot s^{-1} \cdot {}^{o}C^{-1}}]$, $\rho \cdot c = 5[\mathrm{J \cdot cm^{-3} \cdot {}^{o}C^{-1}}]$.

Calculated values of the welded joint's cooling rate enable estimates of the affinity towards appearance of the cold cracks according to different expressions (parameters) presented in Tables 6 to 8.

Table 6. Probability of appearance of cold cracks according to Ito and Bessyo formula [12]

Plate number	P_C, [%]	P_W, [%]	P_{CM}, [%]	H_2 ml/100[g]	Preheating temperature [ºC]	Affinity condition	Remark
Plate 1 Plate 2 Plate 3	0.336	0.327	0.276	3	151	$0.25 < P_C < 0.5$	Prone

Table 7. Probability of appearance of cold cracks according to Prochazka's formula [13]

Plate number	P_{hP}	P_{CM} [%]	H_2 [ml/100g]	Preheating temperature [ºC]	Affinity condition	Remark
Plate 1 Plate 2 Plate 3	0.287	0.276	3	151	$P_{hP} > 0.24$	Prone

Table 8. Probability of appearance of cold cracks according to parameter P_s [3]

Plate number	T_P [ºC]	v_{300} [ºC s^{-1}]	v_{kr} [ºC s^{-1}]	H_2 [ml/100g]	s [mm]	P_S	Affinity condition	Remark
Plate 1	20	0.615	6.674	3	6	-0.656		Not prone
Plate 2	20	0.327	6.674	3	6	-0.931	P_S < - 0.5	Not prone
Plate 3 (root)	20	0.091	6.674	3	6	-1.486		Not prone
Plate 3 (filling)	20	0.076	6.674	3	6	-1.564		Not prone

Estimates of tendency towards creation of hot cracks. Estimate of probability towards creation of hot cracks is established based on the CE_m and HCS parameters [3]. Results are given in Table 9.

Table 9. Probability of appearance of hot cracks [3]

Steel	Parameter	Value	Affinity condition	Remark
Hardox 450	CEm	0.243	> 0.45%	Not prone
	HCS	0.14	> 2	Not prone

Estimates of tendency towards creation of annealing cracks. Estimate of probability towards creation of is performed according to the parametric expressions for calculating of Δg and P_a [3]. Results are presented in Table 10.

Table 10. Probability of appearance of annealing cracks [3]

Steel	Parameter	Value	Affinity condition	Remark
Hardox 450	ΔG	0	ΔG ≥ 0	Not prone
	P_a	-1.811	$P_a > 0$	Not prone

Estimates of tendency towards creation of lamellar cracks. Steel is considered as resistant to lamellar cracks if the value of the parameter P_L is less than 0.40. Obtained result for the Hardox steel is 0.338 what means that it is not prone towards creation of lamellar cracks.

Experimental Investigations

Preparation for welding. This implies scheduled number of technological operations in order to prepare the plates for the welding procedure. The groove edges and immediate vicinity up to 10 mm away must be cleaned to metallic shine (Fig. 1). It is very important to obtain the uniform distance between the prepared plates. The preparation includes the following operations: cutting of plates, cleaning and fixture welds. The plates dimensions, as well as shapes and dimensions of grooves, with the order of welding passes execution for but welding for samples 1, 2 and 3 are shown in Fig. 3. Prior to execution of welding three fixture welds are done by the MAG procedure. For samples 1 and 2 three fixture welds were done, each approximately 10 mm long, Fig. 2. For the third sample five fixture welds were done approximately 15 [mm] long. During the fixture weldings the constant space between the plates was kept by distance sheets of 2 [mm] thickness.

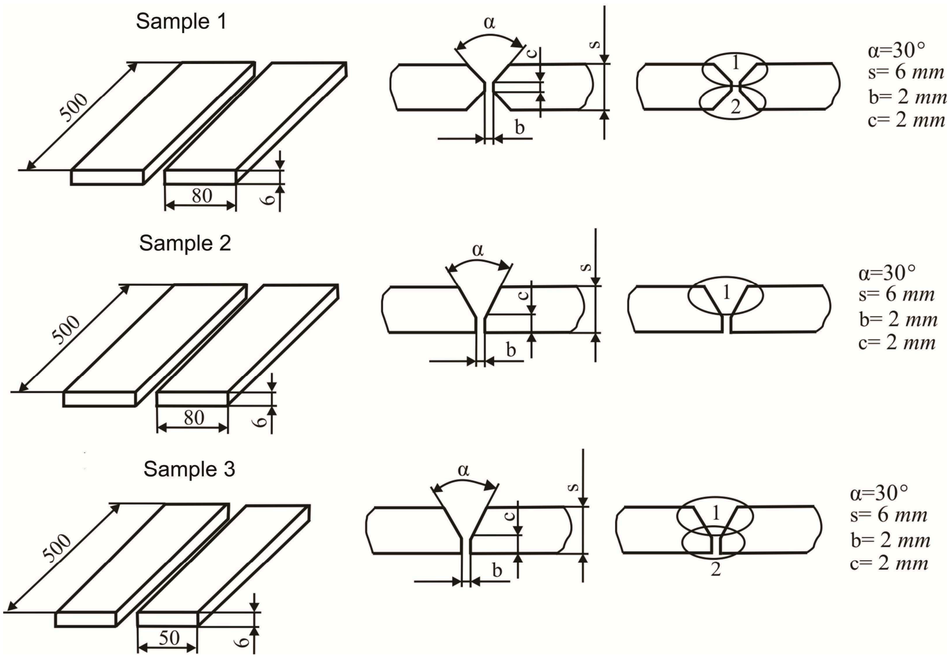


Fig. 1. Plates dimensions, shape and dimensions of grooves with order of passes execution

Fig. 2. Places of fixture welds for samples 1 and 2; 3 welds approximately 10 [mm] long.

Measurements of hardness. The metallographic slits, for measurements of hardness and reading-off the microstructure, were prepared from welds executed with two and single pass welding. Hardness was measured by the Vickers method (HV_5) according to Fig. 3.

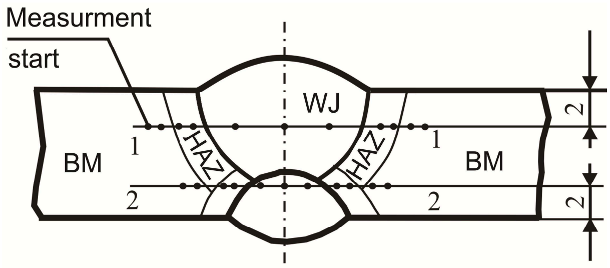


Fig. 3. Hardness measurements scheme

The hardness distribution diagrams, for samples 1 and 2 are shown in Fig. 4.

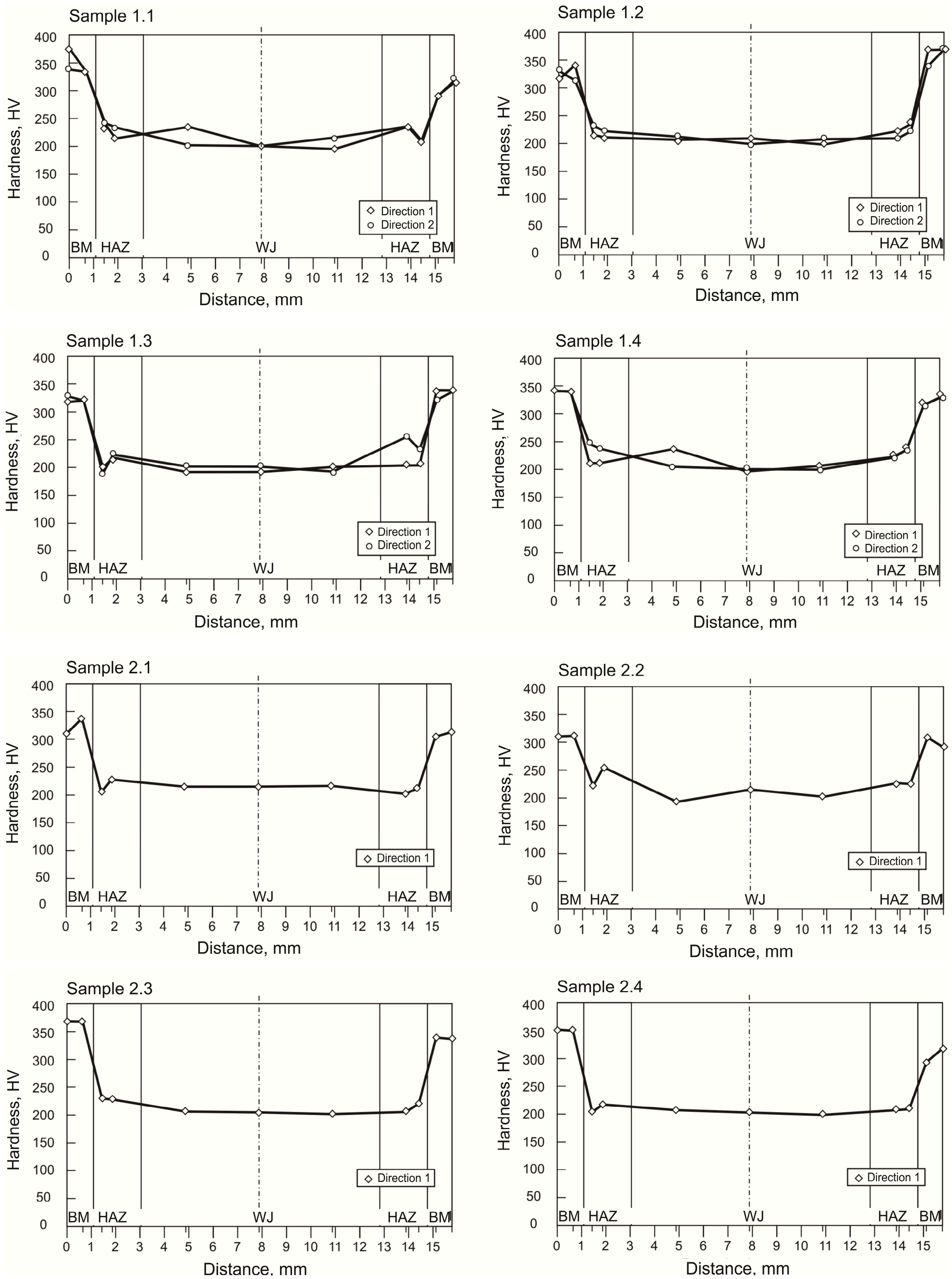
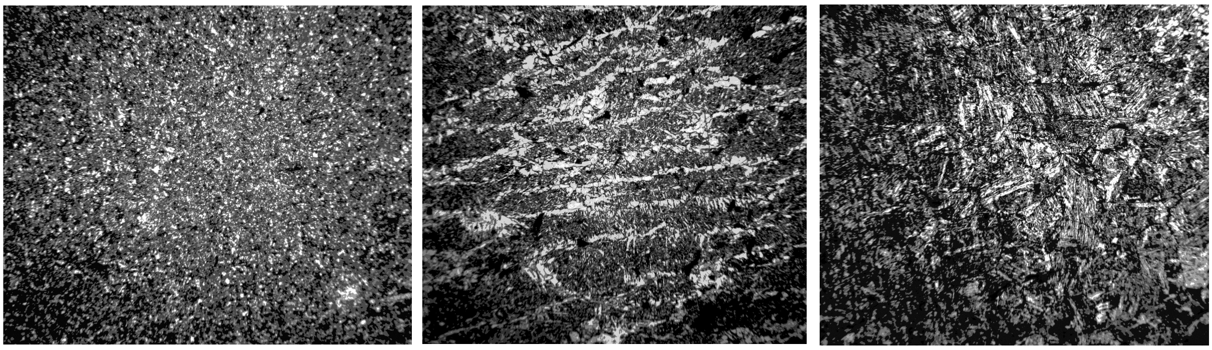


Fig. 4. Hardness distribution (HV) in welded joints of different metallographic slits [3]

Metallographic investigations. Macroscopic investigation consisted of visual inspection of samples with looking glass and low magnification (20 ×). Macrostructure was investigated directly on the samples' surfaces, which were prepared by degreasing, grinding and etching. The welded joint zones were clearly distinguished – the weld metal, the heat affected zone and the base metal.

The optical microscope REICHERT (magnification 50 to 1000 ×) was used for measuring and reading-off the microstructures of the welded joint characteristic zones (Fig. 6). The microstructures of the base metal (BM), weld metal (WM) and heat affected zone (HAZ) are shown in Figs 5 a), b) and c), respectively.



a) BM – Interphase tempering structure (200×)　b) WM – Ferrite and lamellar perlite (200×)　c) HAZ – Widmanstetten structure (200×)

Fig. 5. Microstructures of welded joint individual zones [3]

Discussion of Results

From the hardness distribution diagram (Fig. 5) one can notice that the maximum hardness values of the HAZ and the weld metal are significantly lower than the base metal hardness. These is a deviation from the usual requirement for the uniform hardness distribution as the welded joint property. However, since the maximum hardness values in the HAZ are lower than 350 HV one should not expect presence of the martensite microstructure in the welded joint and therefore there are no conditions for creation of cold cracks. On the other hand, despite the fact that the unfavorable martensite structure was not created in the welded joint, the undesired phenomena of hardness and strength decreases in the HAZ and WM occurred. The hardness and strength drop can be explained by uneven heating process and cooling of individual welded joint zones, what significantly deviates from the primary procedure of steel manufacturing. The unevenness of mechanical properties of the welded joint individual zones is a consequence of existence of non-uniform temperature field and unfavorable thermal cycle. Depending on the quantity of the input heat, the irreversible deterioration of thermo-mechanical processing occurs, as well as reducing of toughness and softening due to uneven temperature cycle. The area of the lower hardness in the HAZ can be critical with respect to possible fracture, what appeared especially dangerous for possible fatigue fracture due to stress concentration. This is why it is necessary, for welding of the Hardox 450 steel, to maintain narrow range of the input heat quantity, to maintain the interpass temperature, to select the optimal cooling time $t_{8/5}$ and follow restrictions related to additional heat treatment after the welding [1-3].

Conclusions

The microstructures shown in Fig. 5 were the interphase tempering structure of the base metal, the ferrite and lamellar perlite in the weld metal and the Widmanstetten structure in the heat affected zone. Appearance of the unfavorable Widmanstetten structure in the HAZ is undesirable since it causes reducing of the mechanical properties, primarily the toughness. This leads to conclusion that the adopted welding technology should be corrected.

Results of the conducted investigations point to complexity of the selection procedure of the optimal welding technology for the Hardox 450 steel. The special attention should be paid to the output properties of the HAZ as the most critical zone of the welded joint. From the presented results follow that the quantity of the input heat during the welding primarily depends on the plates thicknesses and number of passes, what should be kept in mind in the real practice welding of this steel.

It is also concluded that the multi-pass welding is optimal. The reason for such a conclusion lies in the fact that during the multi-pass welding a transformation of the unfavorable structures created after the first pass occurs due to heat input during the second pass what causes the tempering effect. In this way the more favorable mechanical properties of the welded joint individual zones are obtained.

Results of investigations presented in this paper can be useful for experts in engineering practice who are dealing with manufacturing the welded structures made of the Hardox 450 steel.

Acknowledgement

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, TR35024 and TR33015.

References

[1] M. Jovanović, V. Lazić, Instruction for welding the high strength steels, Hardox 500, Faculty of Mechanical Engineering, Kragujevac, 2008 (In Serbian)

[2] D. Djordjević, Estimates of technological-metallurgical weldability of high strength steels, The Specialist Engineer Thesis, Faculty of Mechanical Engineering, Kragujevac, 2010 (In Serbian)

[3] V. Lazić, M. Jovanović, D. Djordjević, S. Aleksandrović, P. Marinković, B. Krstić, R. Čukić, Estimates of weldability and selection of the optimal technology for welding of high strength steel Hardox 450, Proc. of "WELDING and NDT 2012", Divčibare, Serbia, (2012) 29-30.

[4] D. Forsström, P. Jonsén, Calibration and validation of a large scale abrasive wear model by coupling DEM-FEM Local failure prediction from abrasive wear of tipper bodies during unloading of granular material, Eng. Failure Analysis 66 (2016) 274-283.

[5] A. Neimitz, Ductile fracture mechanisms in the high-strength steel Hardox-400. Microscopic observations and numerical stress-strain analysis, Procedia Materials Science 3 (2014) 270-275.

[6] M. Mazur, K. Mikova, Impact resistance of high strength steels, Materials Today: Proceedings 3 (2016) 1060-1063.

[7] S. Frydman, L. Konat, G. Pkalski, Structure and hardness changes in welded joints of Hardox steels, Archives of Civil and Mechanical Engineering 8(4) (2008) 15-27.

[8] R. Ulewicz, M. Mazur, O. Bokůvka, Structure and mechanical properties of fine-grained steels, Periodica Polytechnica Transportation Engineering 41(2) (2013) 111-115.

[9] T.B. Larsson, T. Berglund, Handbook on WELDING of Oxelösund steels, Oxelösund, 1992.

[10] http://www.ssabox.com (accessed February 2017).

[11] V. Lazić, A. Sedmak, M. Živković, S. Aleksandrović, R. Čukić, R. Jovičić, I. Ivanović, Theoretical-experimental determining of cooling time (t8/5) in hard facing of steels for forging dies, Thermal science, 14(1) (2010) 235-246.

[12] Y. Ito, K. Bessyo: J. Iron and Steel Institute (13) (1972), 916-930.

[13] J. Prochazka et al.: Technologie slevani tvareni a svarovani – Edični stredisko ČVUT, Praha, 1985.

[14] E. Doncheva, B. Medjo, A. Sedmak, Finite element analysis of fracture resistance parameters for stationary semi-elliptical surface cracks in high strength steel, Structural Integrity and Life 15 (3) (2015) 131-134.

[15] D. Arsić, M. Djordjević, J. Zivković, A. Sedmak, S. Aleksandrović, V. Lazić, D. Rakić, Experimental-Numerical Study of Tensile Strength of the High-Strength Steel S690QL at Elevated Temperatures, Strength of Materials, 48 (5) (2016) 687-695.