Welding of the tube girder cover made of the C-Mn high strength steel

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The welding procedure and technology for welding the cover of the tube girder is presented in this paper. The tube cover is made of the C-Mn high-strength steel. The welding has to be performed over the whole perimeter in the V groove. Since the structure in question is a very responsible one (a part of the assembly of the large hadron collider – LHC), the check of the base metal chemical composition and the mechanical properties had to be conducted before actual prescribing of the welding process type and the complete welding technology. Then the weldability of the base metal was estimated, which showed that this particular steel was conditionally weldable with application of preheating. The welding technology was prescribed, based on the previously determined parameters including the welding procedure and the filler metals selection. The prescribed technology was afterwards executed on the selected experimental samples. To verify that the selected technology was adequate, the hardness and the microstructure of all the zones of the welded joints were determined. Analysis of executed experimental welds on chosen samples has confirmed that the welding technology was appropriate and that it could be applied to the real part – the LHC assembly.

Key words: tube girder, C-Mn steel, estimation of weldability, welding technology, filler metal, hardness, microstructure.

1. Introduction

The objective of the research, reported in this paper, was to determine which technology should be used for welding the cover onto the tube made of the C-Mn high strength steel. The welded tube girder is a part of the assembly of the large hadron collider (LHC) of the largest accelerator made under the auspices of CERN. According to Fig. 1 the tube and the cover should be welded over the whole perimeter (Fig. 1a) with previously prepared groove (detail "A" in Fig. 1b).

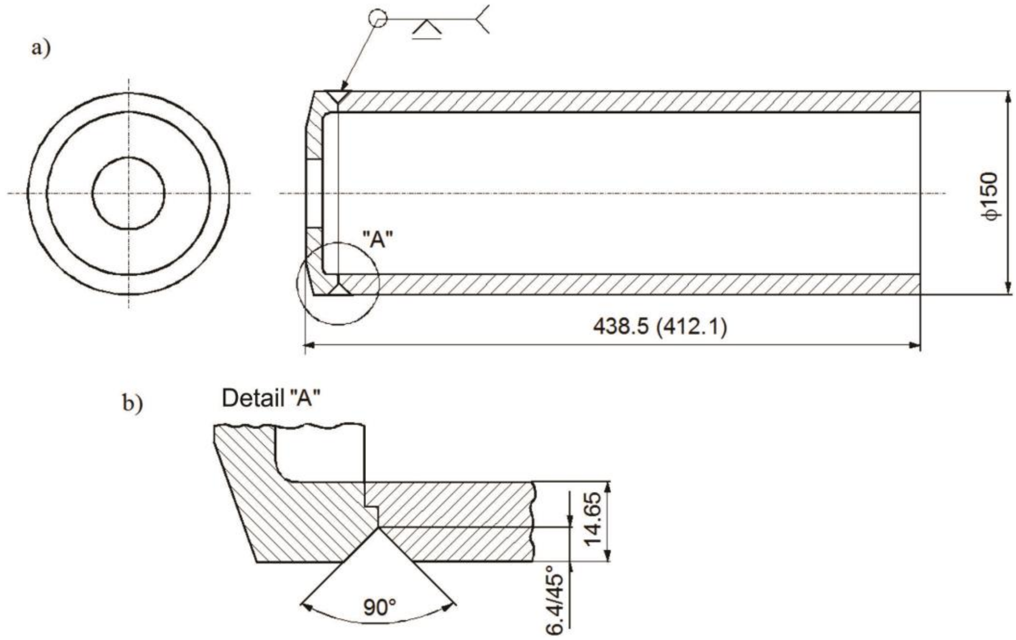


Fig. 1. *Welding of the tube and its cover (a) and appearance of the groove (b)*

Since this is an extremely responsible structure, the selection of the welding procedure must be preceded by verifying the base metal's chemical composition and mechanical properties, despite the declaration provided by the steel's manufacturer. This should be done before the welding of any responsible part since the possibility always exists that the data provided do not correspond to actual properties or composition of the delivered steel, what could cause problems in the part's exploitation, or even the catastrophic fracture [1].

2. Estimates of the base metal's weldability

The chemical composition and the mechanical properties of steel L355 (EN) i.e. St 52.0 (DIN), certified by the manufacturer and obtained by the chemical analysis, are presented in Table 1 [2, 3].

Table 1. *Chemical composition and mechanical properties of HSS L355 (St 52.0)*

Chemical composition, %									
	C	Si	Mn	P	S	Cr	Ni	Cu	Al
Catalogue	0.14-0.20	0.4-0.55	1.2-1.5	≤0.040	≤0.04	≤0.30	≤030	≤0.03	-
Analyzed	**0.17**	**0.45**	**1.33**	**0.008**	**0.009**	**-**	**-**	**-**	**0.028**

Mechanical properties			
	Yield stress R_{eH}, *MPa*	Tensile strength R_m, *MPa*	Elongation A_5, %
Catalogue	min 355	500-650	min 21
Analyzed	**377**	**577**	**30.8**

Based on the chemical analysis of the welded steel and microscopic examination it was established that this is the fine-grained C-Mn high strength steel of the ferrite-pearlite structure.

Prior to selecting the welding process, technology and eventual heat treatment (before or after the welding), it is necessary to estimate the weldability of this base metal [4-6].

2.1 Chemically equivalent carbon

The chemically equivalent carbon (*CE*) for this type of steels is calculated according to the following expression [7]:

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

Steels with value of *CE* > 0.45 % are considered as conditionally weldable (the application of the prior and post welding heat treatments is necessary – preheating and tempering), while the steels with value of *CE* ≤ 0.45% are considered as well weldable.

After substituting the corresponding values for all the chemical elements in expression (1) the obtained value of chemically equivalent carbon was *CE* = 0.392 %, what is obviously less than 0.45 %. Thus, this steel can be considered as well weldable.

However, after the weldability estimate, based on the equivalent carbon, due to extreme responsibility of this welded assembly and the whole structure, the checking of this steel's tendency towards creation of the hot and cold cracks during the welding was performed.

2.2 Parametric equations for evaluation of the steels tendency towards creation of cracks

2.2.1 Parametric equations for evaluation of tendency towards creation of cold cracks

For estimates of the C-Mn steel's tendency towards creation of cold cracks (when the yield strength is between 272 and 870 MPa), one applies equations that take into account the following parameters: *chemical composition* of the base metal and the *content of the diffused hydrogen*, as well as the *stiffness* and the *thickness* of the welded joint.

According to the Prochazka et al. [8], the following equations should be applied:

$$P_{hp} = P_{CM} + \frac{K}{40000} + 0.015 \cdot \log\frac{H}{2.77},\ for\ \mathrm{K} \le 1300, \tag{2}$$

$$P_{hp} = P_{CM} + \frac{K}{40000} + 0.075 \cdot \log\frac{H}{2.77},\ for\ \mathrm{K} > 1300, \tag{3}$$

$$P_{CM} = C + \frac{Si}{30} + \frac{Mn + Cu + Cr}{5} + \frac{Ni}{60} + \frac{Mo + V}{15} + 5 \cdot B, \tag{4}$$

where: $K = 70 \cdot s$ – is the stiffness factor of the but joints, *s*, *mm*, is the welded material thickness and *H*, $cm^3/100\ g$, is the content of the diffused hydrogen in the weld metal.
The welded joint, for which the obtained value of P_{hp} is ≤ 0.24 is considered as resistant to cold cracks, while for the values of $P_{hp} > 0.24$ the preheating is necessary to temperature of:

$$T_p = 1600 \cdot P_{hp} - 308,\ {}^{o}\mathrm{C}. \tag{5}$$

Under the assumption that the welding would be done in the protective gas atmosphere (80% Ar + 20% CO_2), with the dry and clean wire, value $H = 3$ *ml/100 g* was adopted. The maximum thickness of the welded part is $s = 14.65$ *mm*. According to those assumptions, the following values were obtained:

$K = 1025.25 < 1300$, $P_{CM} = 0.2515$, $P_{hp} = 0.278$, namely $\boldsymbol{T_p} = \mathbf{136\ {}^{o}C}$.

Analogously to formula for the chemically equivalent carbon, the indicator of tendency of the low alloyed steels towards creation of cold cracks during the welding could be calculated as [7]:

$$P_C = P_{CM} + \frac{s}{600} + \frac{H}{60}, \tag{6}$$

where:

$$P_{CM} = C + \frac{V}{10} + \frac{Mo}{15} + \frac{Mn + Cu + Cr}{20} + \frac{Ni}{60} + 5 \cdot B. \tag{7}$$

If the value of P_C is obtained to be within range $0.25 < P_C < 0.40$, at the medium driving energy, then the preheating is necessary, at temperature:

$$T_p = 1440 \cdot P_C - 392,\ {}^{o}\mathrm{C}. \tag{8}$$

With the same input parameters as for the previous estimate (expressions (2) to (5)), the following values were obtained:

P_{CM} = 0.2365, P_C = 0.3109, namely $\boldsymbol{T_p}$ **= 56ºC**.

The preheating temperature, for the conditionally weldable steels, could be also calculated according to expression, proposed by Seferian [9]:

$$T_p = 350 \cdot \sqrt{[C] - 0.25}\,, \text{ºC} \tag{9}$$

$$[C] = [C]_h + [C]_s = [C]_h (1 + 0.005 \cdot s) \tag{10}$$

$$[C]_h = C + \frac{Mn + Cr}{9} + \frac{Ni}{18} + \frac{7 \cdot Mo}{90}\,. \tag{11}$$

With the same input data as before the following values were obtained:

$[C]_h$ = 0.317, $[C]$ = 0.34, namely $\boldsymbol{T_p}$ **= 105 ºC**.

However, taking into account that the first (root) pass is the most important for obtaining the optimum structure of all the zones of the welded joint, somewhat higher preheating temperature, $\boldsymbol{T_{pmax}}$ **= 150 ºC**, was adopted for the test welding.
So the conclusion is that this steel is *resistant to cold cracks*, with application of preheating.

2.2.2 Parametric equations for evaluation of tendency towards creation of hot cracks

According to [7], tendency towards creation of hot cracks can be estimated according to the modified equivalent carbon:

$$CE_m = C + 2 \cdot S + \frac{Si - 0.4}{10} + \frac{Mn - 0.8}{12} + \frac{Ni}{12} + \frac{Cu}{15} + \frac{Cr - 0.8}{15}\,, \%\,. \tag{12}$$

Steels that have the value $CE_m > 0.45\%$ are prone to creating the hot cracks and vice versa.
Ito and Bessyo [10] have derived the following expression for estimates of tendency for creating the hot cracks, the so-called Hot Cracks Sensitivity factor – *HCS*:

$$HCS = \frac{C \cdot (S + P + \frac{Si}{25} + \frac{Ni}{100}) \cdot 10^3}{3 \cdot Mn + Cr + Mo + V}\,. \tag{13}$$

The permissible value of the *HCS* depends on the type of steel. Thus, for the carbon steels that are prone to creating the hot cracks the value should be $HCS > 4$, while for the high strength steels it amounts to $HCS > 2$ for thin sheets and $HCS > 1.6$ for thick sheets.
According to expressions (12) and (13), with the same input data as for previous calculations, the following values were obtained

$\boldsymbol{CE_m}$ **= 0.237 < 0.45** and ***HCS*** **= 1.49 < 1.6**,

which implies that the base metal St 52.0 is *resistant to hot cracks*.

3. Selection of the procedure and the technology of welding

The welding procedure selection for this type of steels should include all the factors that would eventually lead to desired properties of the welded joint, primarily its strength and favorable microstructure. Based on previous research by this group of authors [11-13] and material properties defined in the previous sections, as well as on the mentioned requirements for the welded joint properties, the selected procedure was welding in the protective gas atmosphere (gas mixture 80% Ar + 20 % CO_2), on the semi-automatic programmed machine for the circular welding.

Since this welding had to be executed with maximal precision, to avoid the influence of the radial deformations of the cover and the tube during the welding, their proper positions had to be secured. Thus, the two parts were fixed in the adequate mutual position with the three fixing welds, at 120° distances, Fig. 2. The fixing welding was done in the CO_2 protective atmosphere (CO_2 - GMAW), with the wire of diameter 1.2 *mm* and current $I \approx 200\ A$), while the length of welds was 20 *mm*. After the cooling to the room temperature, the beginnings and the ends of all the three welds were ground.

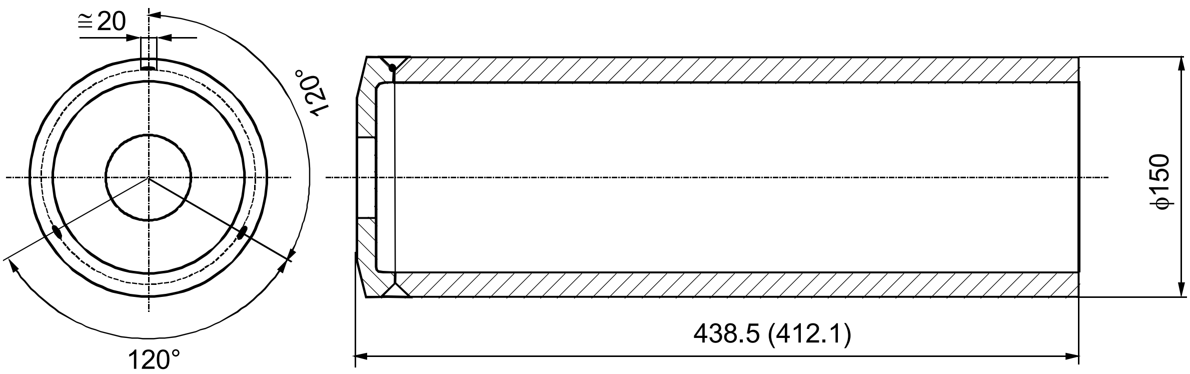


Fig. 2. *Schematic presentation of the cover to tube fixing-welding*

3.1 The technological welding parameters

The following technological parameters of welding in the protective gas atmosphere were applied:

- Grove area $A_z = 2 \cdot P_\Delta = 2 \cdot \frac{6.4 \cdot 6.4}{2} = 40.96\ \mathrm{mm}^2$
- Weld area $A_w \approx 1.2 \cdot A_z = 1.3 \cdot 40.96 = 53.248\ mm^2$
- Area of a single weld $A_{sw} \approx 25\ mm^2$
- Weld's mass per unit length $M = \rho \cdot A_z \cdot L = 7.85 \frac{g}{cm^3} \cdot 0.25 cm^2 \cdot 1 cm = 1.9625 g$
- Deposited material mass per time unit $m_{1.6} = 0.64 + 0.55 \cdot M - 0.055 \cdot M^2 \approx 1.51 g/s$
- Welding speed $v_w = \frac{m \cdot 6000}{A_z \cdot \rho} = \frac{1.51 \cdot 6000}{25 \cdot 7.85} = 46\ cm/min = 0.768\ cm/min$
- Wire melting rate $v_m = \frac{0.012732 \cdot A_z \cdot v_z}{d^2} = \frac{0.012732 \cdot 25 \cdot 46}{1.6^2} = 5.7\ m/min$
- Welding current intensity $I_{1.6} = 378 \cdot \log v_t + 26 = 378 \cdot \log 5.7 + 26 \approx 312\ A$
- Welding current polarity DC (E+)
- Working voltage $U = 14 + 0.05 \cdot I = 14 + 0.05 \cdot 312 \approx 30\ V$

– Welding input heat $q_l = \frac{U \cdot I}{v_z} \cdot \eta = \frac{30 \cdot 312}{0.768} \cdot 0.85 = 10359\, J / cm$
– Welding depth $\delta = 0.3 \cdot r = 0.3 \cdot 0.00537 \cdot \sqrt{q_l} = 0.3 \cdot 0.00537 \cdot \sqrt{10539} = 1.64\, mm$
– Protective gas type mixture (80% Ar + 20% CO_2)
– Protective gas flow rate $q \approx 18\, l/min$

Besides those technological parameters, one should also consider the following: the length of the drawn wire, the position of the electrode with respect to the joining plane, the distance of the gas nozzle from the working piece surface, polarity of the wire electrode, welding position, variable inductance, etc.
The calculated welding parameters serve as the initial ones in selecting the welding regime in protective gas atmosphere. They are being compared to parameters proposed from experience so that the eventual correction could be done before the actual welding is executed. After investigating the test welds, one should adopt the welding parameters that produce the best results.

3.2 The filler metal selection

Based on the authors' previous experience and recommendations from the electrodes' manufacturers, the steel (copper plated) wire VAC 60, Ø = 1.6 *mm* (SRPS C.H3 Č3203; DIN 8559/94 SG-2-CY 4233; AWS A5.-18-79 ER 70S-6) was used as the filler metal [14]. It is aimed for welding in the protective gas atmosphere. According to the manufacturer's recommendation this wire is adequate for welding of the non-alloyed and low-alloyed structural steels with strength up to R_m = 590 *MPa*, boiler thin sheets, ship thin sheets etc.
Mechanical properties of the pure weld metal and the chemical composition of the wire are given in Tables 2 and 3, respectively.

Table 2. *Mechanical properties of the pure weld*

Yield stress $R_{p0.2}$, *MPa*	Tensile strength R_m, *MPa*	Elongation A_5, %	Toughness (- 40 ºC) ISO-V, *J*
410-490	510-590	22-30	> 47

Table 3. *Chemical composition of the wire*

C	Si	Mn	P	S
0.08	0.90	1.50	<0.025	<0.025

3.3 Preparation and control of samples for test welding

As already emphasized, due to necessary precise executing of the welds, both on the test samples and on the real assembly, the circular radial deviation of each working piece was controlled (Fig. 3a). This deviation was within the range 0.1 to 0.2 *mm*, what was considered as acceptable. In addition, before the welding the fixed pieces were degreased by washing with an appropriate detergent and then dried.
To be sure that the adopted welding technology was the optimal one, numerous test welds were executed with the calculated welding parameters, in conditions with preheating (T_p = 150 ºC) and without the preheating, with three (Fig. 3b) and two passes (Fig. 3c).
From the tested welded pieces, the metallographic samples were then prepared by grinding. They served for measuring the micro hardness (HV1) and for checking the micro structure of all the zones of the welded joint.

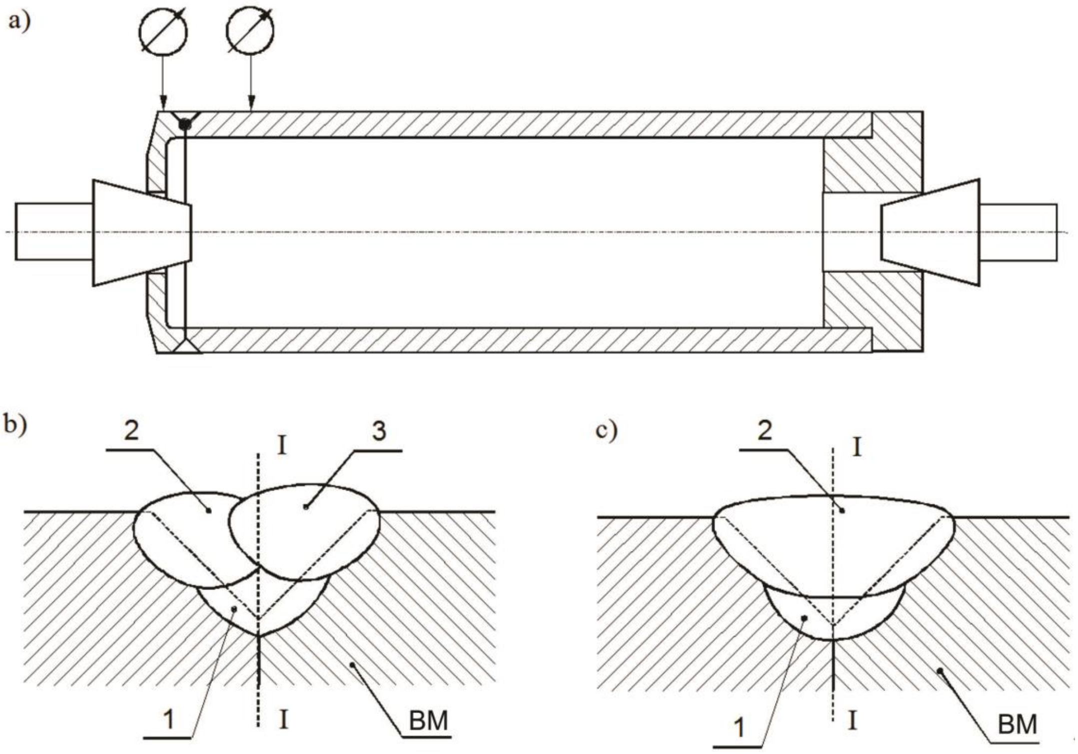


__Fig. 3.__ Schematic presentation of the circular deviation control (a); of the three-pass welding (b) and the two-layer welding (c).

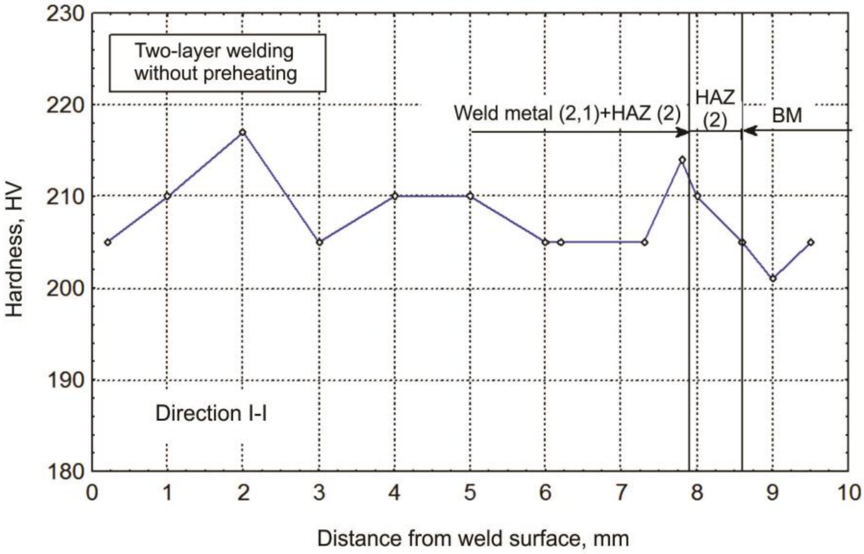
4. Results and discussion

Results of the hardness measurements in the individual zones of the welded joint and the obtained corresponding micro structures are shown in Table 4.

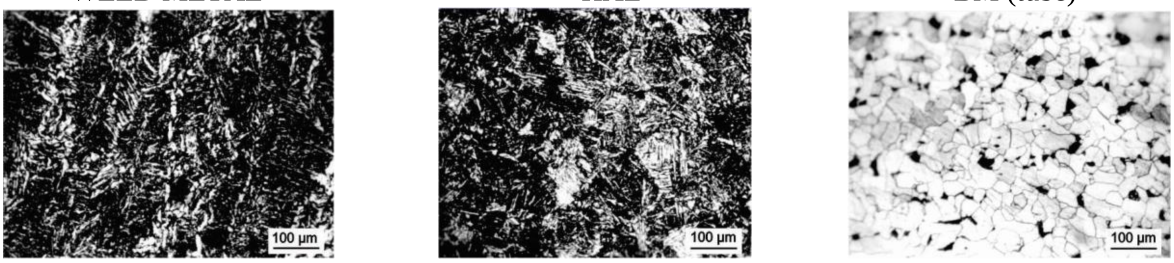
__Table 4.__ Measured hardness and microstructures of the welded joint individual zones

Number of layers/passes	Preheating temperature, °C	Maximal and minimal hardness (HV1) and Determined microstructure		
		Weld metal	$HAZ_{3,2,1}$ and $HAZ_{2,1}$	BM
3 passes	$T_p \approx 150$ °C	221-251 HV1 Fine grained Widmannstetten	210-227 HV1 Interphase + tempered martensite	201-210 HV1 Lamellar pearlite-ferrite
2 layers	$T_p \approx 20$ °C	205-217 HV1 Fine grained Widmannstetten	205-214 HV1 Interphase + tempered martensite	201-210 HV1 Lamellar pearlite-ferrite
3 passes	$T_p \approx 20$ °C	201-234 HV1 Fine grained Widmannstetten	219-229 HV1 Interphase + tempered martensite	201-210 HV1 Lamellar pearlite-ferrite

Hardness distribution and appearance of micro structures for the two-layer and three-pass welding are presented in Figs. 4 and 5, respectively (hardness measurement direction is the I-I direction shown in Figs. 3b and 3c).



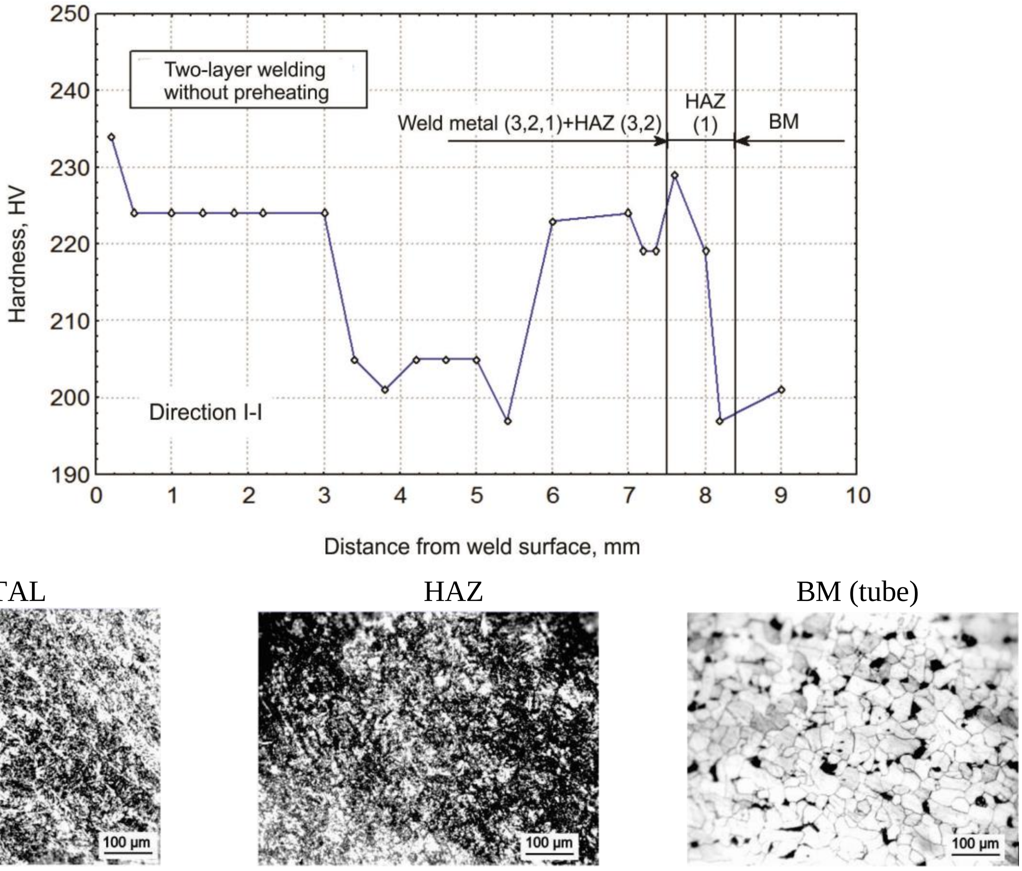
WELD METAL HAZ BM (tube)



Fine grained Widmannstetten Interphase + tempered martensite Lamellar pearlite-ferrite

Fig. 4. *Hardness distribution and appearance of micro structures in the two-layer welding*

Analysis of obtained results led to conclusion that no major differences were spotted either in values of measured hardness or in the microstructures in individual zones of the welded joint for the cases of welding with and without the preheating, both for the two or three layer welding. Welding of the cover to the tube with three passes (with or without preheating) was done primarily because of the large angle of the groove opening and necessary post treatment of the weld's face. The passes were executed immediately one after the other (Fig. 3b). The cover pass 2 tempers the root cover 1 and the cover pass 3 tempers the root pass 1 and partially the pass 2, as well. That produces significantly more favorable microstructure, avoids creation of the possible brittle phases and reduces the level of residual stresses, as well. With this type of welding the necessary overfill of the welded joint was created, which was later removed by machining for the final ultrasonic control.
During the welding the parameters, related to the driving energy of welding (power I, voltage U and the welding velocity v_w), were constantly monitored. The energy was within limits q_l = 9500-10500 *J/cm*. It provided the necessary welding penetration, favorable hardness and micro structure, as well as the adequate output mechanical properties of the welded joint.
Experimental investigations have confirmed that the base metal was the well weldable steel, thus either the previous or the additional heat treatment were not necessary. The preheating was applied as a precautionary measure to prevent formation of cracks and to lower the level of residual stresses in the HAZ.



Fine grained Widmannstetten | Interphase + tempered martensite | Lamellar pearlite-ferrite

Fig. 5. *Hardness distribution and appearance of micro structures in the three-pass welding*

Apart from the visual control and conducted metallographic tests, each welded joint on real parts was controlled by the ultrasonic defectoscopy in the laboratory, which was accredited for the non-destructive testing. In all the performed investigations, no flaws, external or internal, were noticed in the welded joints.

Besides the described experimental investigation, an additional checking if the adopted procedure and the welding parameters were adequate to ensure the favorable structure and mechanical properties of the welded joint (optimal toughness, adequate hardness, etc.), could be done by analyzing the continuous cooling diagram (CCT) of the steel, in the welding conditions. The characteristic cooling time between 800 ºC and 500 ºC ($t_{8/5}$), calculated according to empirical formula of Ito and Bessyo [10], would be entered into the CCT diagram. That would enable estimating of the microstructure, as well as reading-off the hardness and toughness of the HAZ, [11-13].

This analysis was not performed within this research since all the other parameters were showing that the selected welding procedure and technology were adequate.

5. Conclusions

Based on the conducted theoretical and experimental analysis, related to weldability of the base metal, adopted procedure, chosen filler metal, applied technology and control of the welded joints, the following conclusions were drawn:

- The base metal is from the class of the high strength steels and it belongs to a group of the well weldable steels (with application of preheating if necessary);
- This steel is not prone to creation of either cold or hot cracks during the welding;

- This steel is not prone to creation of brittle phases during the welding;
- Welding can be successfully executed in the protective gas atmosphere (mixture 80 % Ar + 20 % CO_2) with the proposed procedure and technological parameters;
- The three-pass welding is necessary due to structurally required type of the groove (too large groove opening);
- Neither unfavorable structures nor the zones of increased hardness were noticed during the experimental investigations;
- All the welded joints on the real parts were controlled by the ultrasonic defectoscopy and no flaws, external or internal, were registered.

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Note: The shorter version of this research was presented at the 44th International Conference "ZVARANIE 2016", reference [15].

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