MICROSTRUCTURAL PARAMETERS AND MECHANICAL PROPERTIES OF THE THERMALLY SIMULATED HAZ SAMPLES OF T24 STEEL

SZTEFEK Radek[1], VODÁREK Vlastimil[2], SCHWARZ Drahomír[2], JAROLÍMOVÁ Mária[2]

[1] *Vítkovice Heavy Machinery a.s., Ostrava, Czech Republic, EU, radek.sztefek@vitkovice.cz*

[2] *VŠB – Technical University of Ostrava, Ostrava, Czech Republic, EU, vlastimil.vodarek@vsb.cz*

Abstract

The paper is dealing with microstructural characterisation and mechanical properties of thermally simulated parts of the heat affected zone in homogeneous weldments of T24 steel. The study has been targeted on the blunt peripheral weld joints of T24 steel between two tubes, which are an integral part of the production of membrane walls. Investigations on thermally simulated HAZ samples were performed in two states: after simulation (as-welded) and after PWHT 740 °C / 1 h. Thermal cycles for simulation of basic parts of HAZ in homogeneous welds of T24 steel were obtained by real measurements with subsequent corrections based on numerical simulations of welding using the Sysweld software. Thermal simulations were carried out on samples of Vallourec & Mannesmann tubes using a simulator TCS 1405. On the thermally simulated samples hardness and impact energy were evaluated. Microstructural characterisation was carried out using both light microscopy and transmission electron microscopy. Extraction replicas were used for identification of minor phases. Results of thermal simulations were validated on a real weldment. Results on simulated samples reasonably complied with results obtained on the real homogeneous weldment of T24 steel.

Keywords: weld joint, T24 steel, HAZ, thermal cycle, thermal simulation, precipitation.

1. INTRODUCTION

The main effort of T/P24 (7CrMoVTiB10-10) steel development was to get the steel grade with higher creep characteristics than is the creep resistance of low-alloy steels of Cr-Mo type (T/P22) [1-3]. Furthermore, the aim was to get the steel grade that could be welded without preheating and additional heat treatment after welding (PWHT) [1]. In modern boilers T24 steel has been designed for the construction of membrane walls, which constitute the walls of evaporators. Due to many defects during manufacture, transport and shortly after commissioning of these membrane walls, a lot of attention has been paid to problems of weldability of T/P24 steel [3]. This is also closely related to the Czech Republic where T24 steel was applied in the construction of a new boiler unit in the Ledvice power plant.

This paper is dealing with microstructure and mechanical properties of the thermally simulated parts of heat affected zone (HAZ) in homogeneous weldments of T24 steel. The evolution of microstructure, hardness and impact energy was studied in basic parts of HAZ in the simulated state (as-welded) and after PWHT.

2. EXPERIMENTAL

A blunt peripheral weld joint between two T24 tubes of Ø 42.8 x 7.1 mm was made using the welding method 141 with preheating to ca 150 °C. Thermocouples were used for the evaluation of thermal cycles during welding. Chemical composition of welded tubes A, manufactured by V&M tubes, is shown in **tab. 1**. Union I P24 (W ZCrMo2VTi/Nb - EN 12070) wires with a diameter of 2.4 mm were applied as filler material. The measurement of thermal cycles during welding was done in order to get time-temperature information for each zone of HAZ. The measured parameters were validated using numerical simulations of welding by the Sysweld software and were compared with published data (mainly $\Delta t8/5$) [2, 3]. The following parts of HAZ were simulated: overheated (CG – coarse grained) zone, normalized (FG – fine grained) zone and intercritical (IC) zone. Parameters of the thermal cycles for individual parts of HAZ are shown in **tab. 2**.

Table 1 Chemical composition of T24 steel (wt. %)

Material	C	Si	Mn	P	S	Al	Cr	Mo	V	Ti	N	B
A	0.084	0.271	0.54	0.010	0.0028	0.014	2.463	0.962	0.228	0.064	0.0095	0.0048
B	0.078	0.29	0.55	0.017	0.0025	0.012	2.522	0.975	0.224	0.084	0.0098	0.0022
Ref. [4]	0.05 - 0.10	0.15 - 0.45	0.30 - 0.70	max. 0.020	max. 0.010	max. 0.020	2.20 - 2.60	0.90 - 1.10	0.20 - 0.30	0.05 - 0.10	max. 0.010	0.0015- 0.0070

The thermal simulations of basic parts of HAZ were carried out on bars with dimensions of 10.2 x 10.2 x 70 mm. These bars were cut from tubes B (V&M tubes) having chemical composition shown in **tab. 1**. Quality heat treatment of tubes consisted of normalization at 1000 °C followed by tempering at 750 °C for 30 minutes. The thermal simulation of individual parts of HAZ was carried out using a unit TCS 1405 (THERMAL CYCLES SIMULATOR) at the Research and Testing Institute in Pilsen.

Table 2 Parameters of thermal cycles for studied parts of HAZ

Parameter	Overheated zone	Normalized zone	Intercritical zone
Initial temperature (preheat)	150 °C for 30 s		
Heating rate	60 °C / s		
Max. temperature of thermal cycle- T_{max}	1350 °C	1000 °C	860 °C
Holding time at T_{max}	1 s		
Cooling rate between T_{max} and 800 °C	24 °C / s	20 °C / s	10 °C / s
Parameter $\Delta t8/5$	36.5 s	39 s	43 s
Cooling below 500 °C	air		

Characterisation of microstructure and mechanical properties was carried out in both as-welded state (after simulation) and after PWHT (740 °C / 1 hour). Microstructure and hardness were evaluated on cross sections cut in the half length of samples. Microstructure of the thermally simulated parts of HAZ was studied by light microscopy. Microstructure was revealed by etching in a Nital solution. Precipitation processes were investigated using TEM. Minor phases on carbon extraction replicas were identified by a combination of EDX and electron diffraction techniques. Hardness evaluation of the thermally simulated samples was carried out according to ČSN EN ISO 9015-1 and ČSN EN ISO 6507-1 standards. The average hardness HV 10 was determined as the arithmetic mean of 10 measurements and standard deviations were calculated. Furthermore, the notch energy was evaluated at ambient temperature on three bars for each simulated part of HAZ. The impact energy test was carried out according to EN ISO 148-1.

3. EVALUATION OF MECHANICAL PROPERTIES

Results of hardness measurements on both as-welded (after simulation) and tempered (after PWHT) samples are plotted in **Fig. 1**. In the simulated overheated zone of HAZ the hardness level exceeded the critical value of 350 HV. Nevertheless, after PWHT hardness in this zone of HAZ decreased to an acceptable value. Hardness of the as-welded normalized zone of HAZ was only slightly below the maximum allowed hardness. It is worth noting that after PWHT hardness of the intercritical part of HAZ was lower than hardness of the T24 steel in the as-received condition.

The average value of impact energy in overheated zone of HAZ in the as-welded state dropped below 40 J, which was the minimum required value for tubes of T24 steel according to ČSN EN 10216-2+A2. PWHT resulted in an increase of impact energy above this limit. Impact energy in the as–welded state of thermally simulated FG and IC zones of HAZ was lower than that of T24 steel in the initial state (after quality heat treatment). However, after PWHT impact energy in simulated FG and IC zones of HAZ significantly increased, **Fig. 2**.

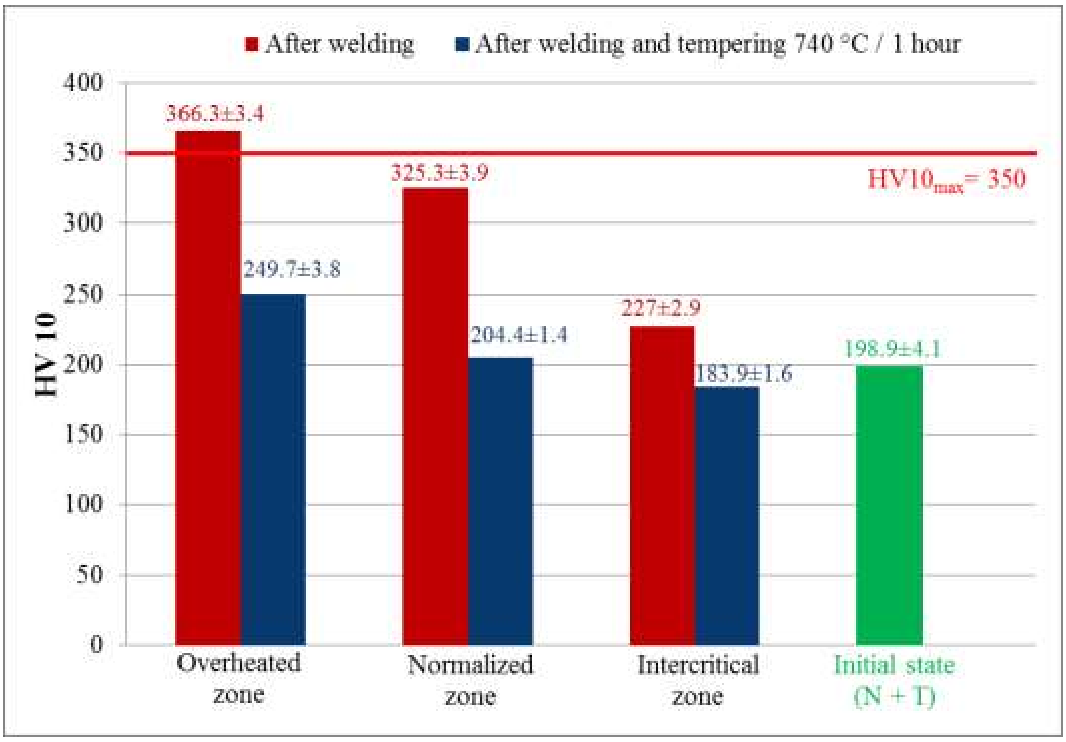


Fig. 1 Hardness HV 10 of thermally simulated parts of HAZ and of T24 tubes after quality heat treatment

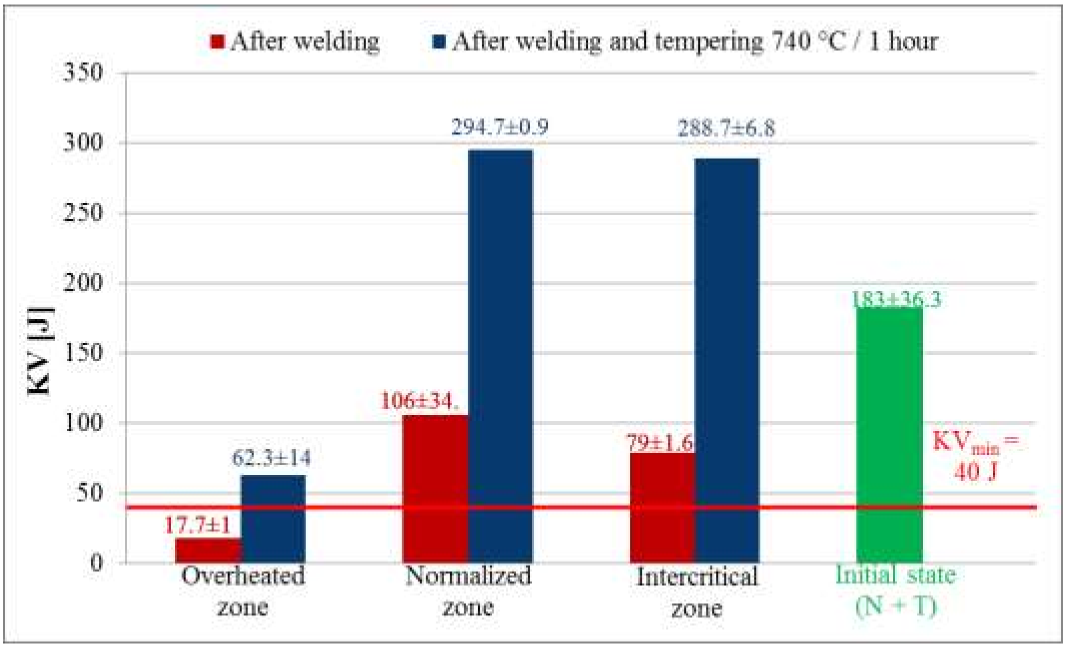
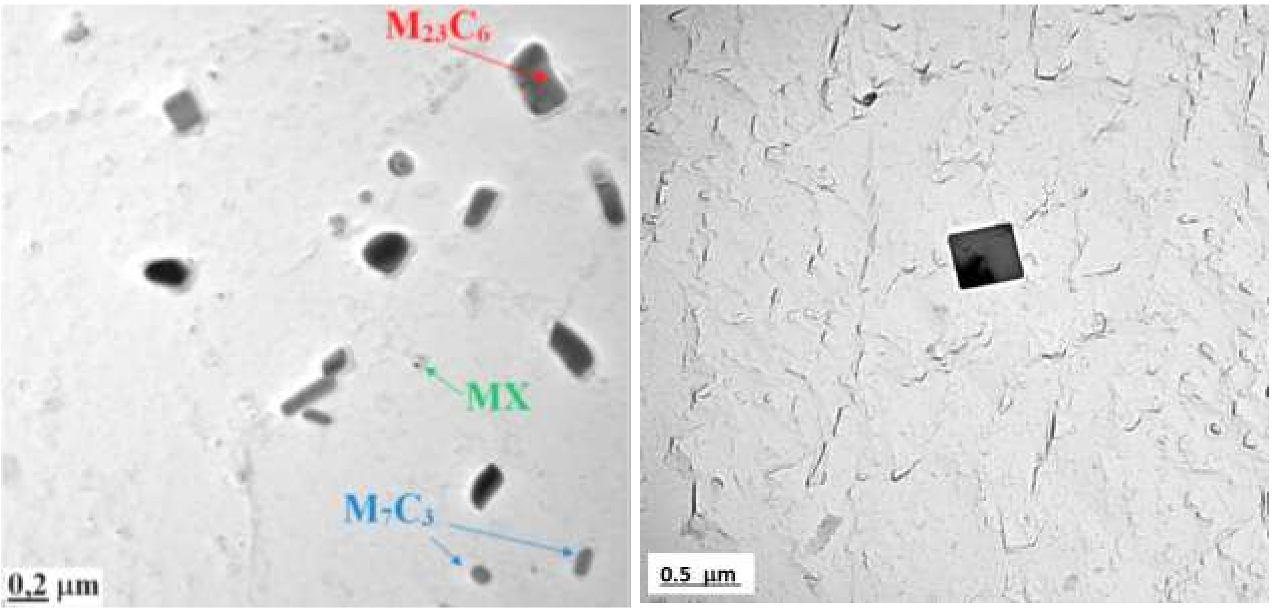


Fig. 2 Impact energy of thermally simulated parts of HAZ and of T24 tubes after quality heat treatment

4. MICROSTRUCTURE CHARACTERISATION

Microstructure of T24 tubes in the as – received state consisted of tempered bainite. Rectangular particles in the matrix were identified as nitrides or carbonitrides of titanium (TiX). These particles can form in the melt or during solidification of steel [5]. The size of these primary TiX particles reached up to several micrometers. Heterogeneous nucleation of TiX particles on alumina particles was frequently observed. Tempering at 750 °C resulted in an intensive precipitation of minor phases, **Fig. 3a**. Prior austenite grain boundaries were decorated by a discontinuous network of $M_{23}C_6$ particles, middle size particles were identified as M_7C_3 carbides and fine particles were formed by MX phase. They were rich in vanadium and titanium. Furthermore, a high amount of molybdenum (up to 50 wt.%) was dissolved in these fine particles [6].

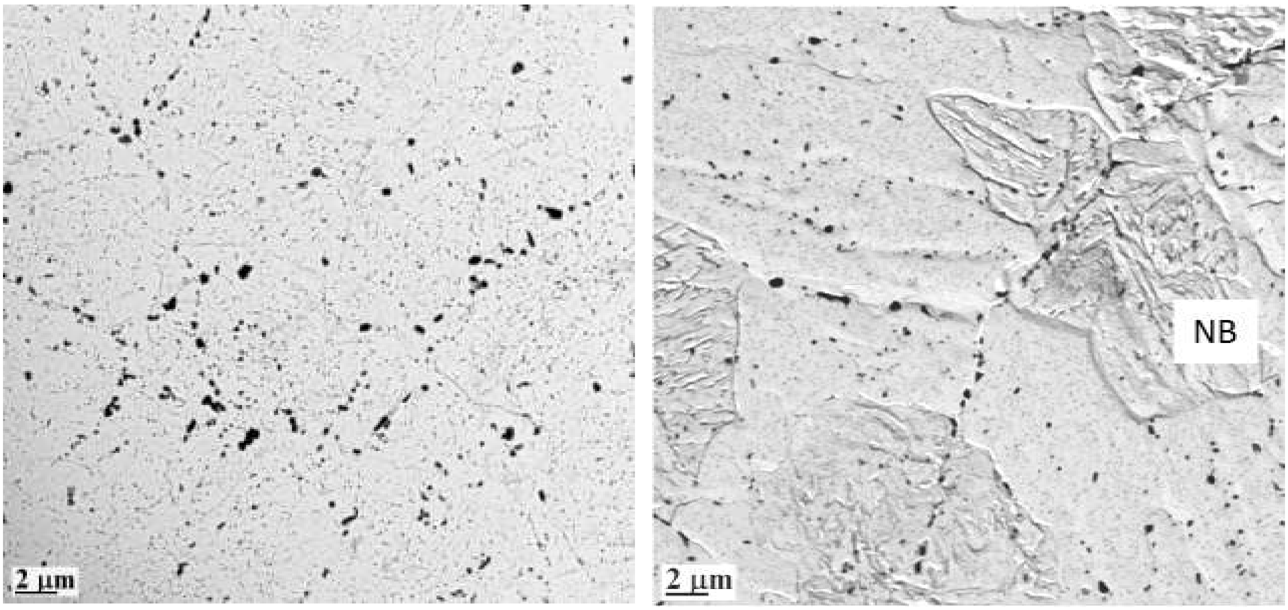


a) b)

Fig. 3 a) Precipitation of $M_{23}C_6$, M_7C_3 and MX particles in T24 tubes after quality heat treatment, b) undissolved particle of TiX in the overheated zone of HAZ

4.1 Microstructure of the thermally simulated samples

The thermal cycle corresponding to the overheated zone of HAZ resulted in a significant coarsening of the prior austenite grain size. During the thermal cycle intensive dissolution of precipitates occurred. All phases, except for primary TiX particles, dissolved. **Fig. 3b** shows an undissolved particle of TiX. Fine intragranular particles were identified as cementite which formed during bainitic transformation of austenite. **Fig. 4a** shows precipitation in the sample after the thermal cycle at 1000 °C (FG zone). During the cycle the microstructure was fully re-austenitized but dissolution of precipitates was only partial. All minor phases formed during quality heat treatment were identified: $M_{23}C_6$, M_7C_3 and MX. Furthermore, fine particles of cementite, which formed during bainitic decomposition of austenite, were present. As evident re-austenitization resulted in a significant reduction of austenite grain size. Discontinuous networks of coarse particles in **Fig. 4a** mark the original positions of prior austenite grain boundaries. Most precipitates were inherited from the as-received state. The thermal cycle at 860 °C (IC zone) resulted in partial austenitization of the matrix. Dissolution of precipitates during the thermal cycle was only partial. All minor phases formed during quality heat treatment were identified: $M_{23}C_6$, M_7C_3 and MX. Discontinuous networks of particles in **Fig. 4b** mark the original positions of austenitic grain boundaries. NB areas in **Fig. 4b** correspond to new bainite which formed during decomposition of austenitic islands. Precipitation of fine particles of cementite in NB islands was revealed. However, most precipitates in **Fig. 4b** were inherited from the as-received state.

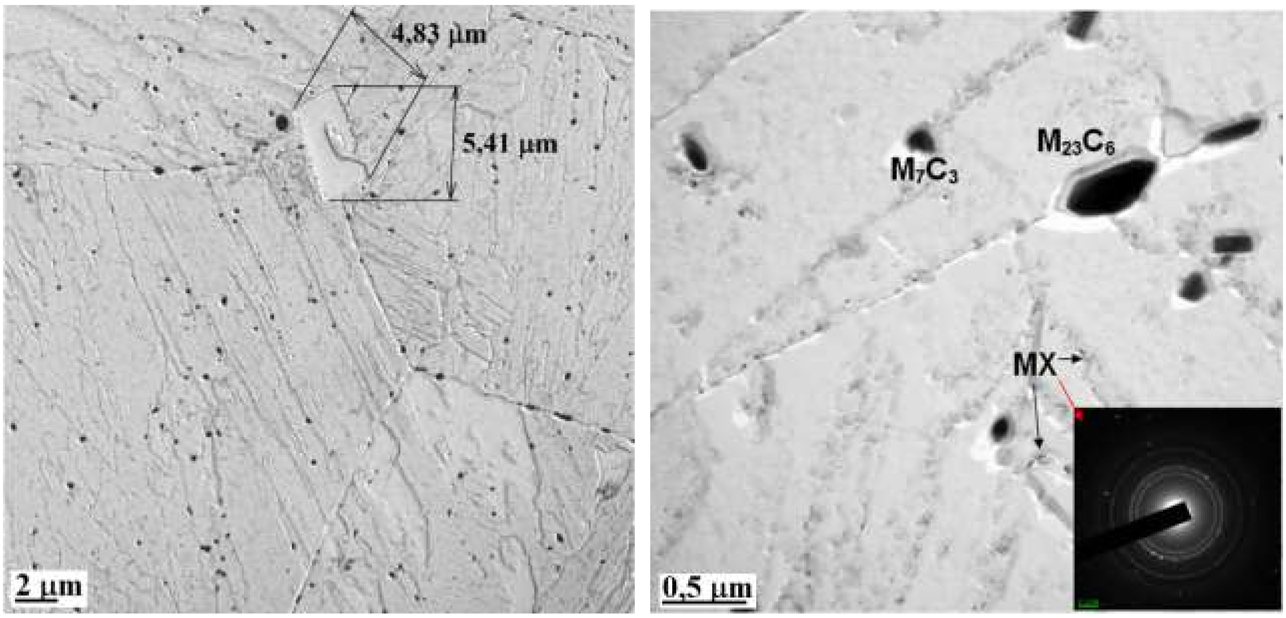


a) b)

Fig. 4 Precipitation in the thermally simulated samples, a) precipitation in the normalized (FG) zone, b) precipitation in the intercritical (IC) zone

4.2 Microstructure of the thermally simulated samples after PWHT

Total dissolution of minor phases during the thermal cycle at 1350 °C resulted in an intensive re-precipitation during PWHT [6]. **Fig. 5a** shows precipitates in the overheated zone of HAZ after tempering. The following minor phases were present in the tempered bainite: $M_{23}C_6$, M_7C_3 and MX. Minor phases are marked in **Fig. 5b.** Fine particles of MX were rich in titanium, vanadium and molybdenum (up to 50 wt.%).



a) b)

Fig. 5 a) Precipitation in the overheated zone of HAZ after PWHT, b) $M_{23}C_6$, M_7C_3 and MX particles, insert: SAEDP of MX phase

An imprint of a coarse particle (ca 5 μm) in **Fig. 5a** corresponds to primary TiX. Such coarse particles could have a negative effect on toughness. An insert in **Fig. 5b** proves that fine particles are MX phase and not M_2X phase. PWHT of samples after the thermal cycles at 1000 °C and 860 °C was accompanied by less pronounced re-precipitation of minor phases. PWHT resulted in dissolution of cementite particles which formed during bainitic decomposition of austenite.

CONCLUSION

- The thermal cycle at 1350 °C resulted in total dissolution of all minor phases formed during quality heat treatment. Coarsening of prior austenite grains occurred. Hardness of bainite exceeded 350 HV which is usually regarded as the maximum acceptable value. At the same time the impact energy did not reach the required level. PWHT at 740 °C was accompanied by an intensive re-precipitation of minor phases and recovery of the matrix. After PWHT both hardness and impact energy met the requirements.
- Mechanical properties of the thermally simulated normalized and intercritical parts of HAZ complied with the requirements. Only partial dissolution of precipitates occurred during these thermal cycles. PWHT was accompanied by a reduction of hardness and by a significant increase in impact energy in both samples. Re-precipitation processes during PWHT were less intensive than those in the overheated part of HAZ.
- Results of thermal simulations were validated on the real homogeneous weldment of T24 tubes [6]. Furthermore, it was demonstrated that exposition of as-welded T24 weldments to the working temperature (575 °C) was accompanied by secondary hardening in the overheated part of HAZ. This resulted in a further increase in hardness and a reduction of impact energy [6].
- The results of investigations prove that in order to prevent unacceptable hardening of the overheated part of HAZ in homogeneous T24 weldments the application of PWHT is needed.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the financial support from the projects No. LE13011 “Creation of a PROGRES 3 Consortium Office to Support Cross-Border Co-operation”, the project No. LO1203 "Regional Materials Science and Technology Centre - Feasibility Program" funded by Ministry of Education, Youth and Sports of the Czech Republic and the project No. SP2014/193.

REFERENCES

[1] HUSEMANN R. U., BENDICK W., HAARMANN K. The new 7CrMoVTiB10-10 (T24) Material for Boiler water-walls. ASME PWR- Vol. 34, 2005, pp. 663-640.

[2] XAVIER C. R., DELGADO H. G., CASTRO J. A. Numerical evaluation of the weldability of the low alloy ferritic steels T/P23 and T/P24. In Materials Research. February 2011, pp. 73-90.

[3] METZER K., HELMICH A., KOPP A., MAILE K., BÖSE J., A. Klenk, Materials Science Based Investigations on T24 Weldments, in: 38th MPA Seminar, Stuttgart, 2012, pp. 438 – 453.

[4] ČSN EN 10216-2+A2. Bezešvé ocelové trubky pro tlakové nádoby a zařízení - Technické dodací podmínky - Část 2: Trubky z nelegovaných a legovaných ocelí se zaručenými vlastnostmi při zvýšených teplotách. 2008, s. 48.

[5] GLADMAN T. The physical metallurgy of micro-alloyed steel. 1st Edition. The Institute of Materials, London. 1997, 374 p, ISBN: 978-1-902653-81-5.

[6] SZTEFEK R. Svařitelnost a vlastnosti svarových spojů oceli T24 (7CrMoVTiB10-10, 1.7378). PhD Thesis, VŠB – TU Ostrava, Ostrava 2014, pp. 119.