AFFECT OF TEMPERING TEMPERATURES ON MECHANICAL PROPERTIES OF WELD JOINTS IN LOW-ALLOY CREEP-RESISTANT STEELS

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VLIV TEPLOTY POPOUŠTĚNÍ NA MECHANICKÉ VLASTNOSTI SVAROVÝCH SPOJŮ NÍZKOLEGOVANÝCH ŽÁROPEVNÝCH OCELÍ

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Abstrakt

Článek se zabývá vytvrzováním svarových spojů oceli 15 128, T23, T24 a T25 během dlouhodobé expozice při zvýšených provozních teplotách. Pozorované vytvrzování souvisí s dodatečnou precipitací disperzních částic. U oceli 15 128 byly pomocí elektronové mikroskopie identifikovány vytvrzující částice MX. Byl prokázán vliv teploty popouštění na mechanické a především plastické vlastnosti svarových spojů. V případě ocelí T23 a T24, které by se měly využívat pro výrobu tzv. membránových stěn, je snahou výrobců zcela vynechat popouštění po svařování. Dosažené výsledky však dokazují, že velikost sekundárního vytvrzení jednoznačně závisí na aplikaci popouštění po svařování. U nepopuštěných svarových spojů došlo k nepřípustnému zvýšení tvrdosti v průběhu expozice při provozní teplotě. Výsledky tohoto výzkumu mohou být využity pro zvýšení provozní spolehlivosti energetických zařízení vyrobených z ocelí 15 128, T23 nebo T24, případně T25.

Abstract

This article presents hardening of weld joints in 15 128, T23, T24 and T25 grade steels during extensive exposure at elevated operating temperatures. The monitored hardening relates to the supplementary precipitation of dispersed particles. Electron microscopy identified hardening particles MX in 15 128 grade steel. The affect of tempering temperature on mechanical and, in particular, plastic properties of weld joints was demonstrated. In the case of T23 and T24 grade steels, which should be used for manufacture of so-called membrane walls, manufacturers are making efforts to completely leave out tempering after welding. However, achieved results show that the extent of secondary hardening is clearly dependent on application of tempering after welding. Non-tempered weld joints are subject to unacceptable increase of hardness during exposure to operating temperatures. The results of this research can be applied to increase the operating reliability of power engineering equipment manufactured from 15 128, T23, T24, or T25 grade steels.

Key words: Low-alloy steel, creep resistant steel, PWHT, secondary hardening, MX particles, T23, T23, T25, 15 128

1. Introduction

From the end of the 1980´s there is an intensive global effort in development aimed at increasing the efficiency of thermal power stations. The main method of increasing thermal efficiency is to increase the parameters of steam to the so-called above-critical or super-critical level. Pressure exceeding 260 bars and temperature around 600 °C are regarded as super-critical steam parameters; pressure over 300 bars and temperature over 600 °C are called ultra-super-critical parameters [4].

The development of thermal power stations must coincide with the development of creep-resistant steels. The primary requirements are a raised creep strength, excellent resistance to oxidization and, last but not least, resistance to corrosion at elevated temperatures. In the low-alloy steels sector the most widely used steel is 2,25%Cr-1%Mo (10CrMo9-10), also known as T22, or 13CrMo4-4 steel. These steels do not have a sufficient creep strength if they were to be used to manufacture boiler membrane walls operated at super-critical parameters. In the 1990´s this feature led to the development of new perspective steels for membrane wall manufacture, called T23 (HCM2S) and T24 (7CrMoVTiB7-7). The philosophy behind the development of T23 and T24 grade steels, is based on two primary directions. First, it means a raising of the creep resistance in comparison to the conventional T22 grade steel (2,25%Cr1%Mo), by means of suitable supplementary alloying with carbide- and nitride-forming elements. The same is achieved using vanadium, tungsten and niobium in T23 grade steel, and vanadium, molybdenum and titanium in T24 grade steel. The second goal is an improvement in the weldability of these steels by reducing the carbon content to under 0,10%.

However, we must not forget that in the former Czechoslovakia, in the second half of the 20th century, engineers developed and introduced for practical use a 0,5%Cr-0,5%Mo-0,3%V type steel alloyed with vanadium and called 15 128, which achieved significantly higher creep strength values than 10CrMo9-10 grade steel. The disadvantage of 15 128 steel is a high sensitivity of its mechanical properties to the welding process and parameters of heat treatment, including tempering. These technological obstacles were most likely the main reason why 15 128 steel, even through its excellent creep-resistant properties, never became globally widespread.

Also, theoretical observations explain the need for tempering of weld joints of steels alloyed with vanadium, eventually titanium and niobium. The essence of the high creep resistance of these steels is dispersion of fine particles MX, which have a high dimensional stability during extensive thermal exposure. On the other hand, the presence of dispersed particles MX significantly affects the steel's plastic properties. So-called secondary hardening occurs during operation. A completely balanced condition is not achieved in the structure of these steels after the usual heat treatment, which comprises normalization and subsequent tempering at temperatures up to 760 °C. During subsequent extensive exposure at operating temperatures additional precipitation of MX particles occurs due to oversaturation of the solid solution. This process is most marked in weld joints, where the welding process causes various levels of dissolution of dispersed particles. If weld joints are not subsequently tempered or tempering is performed incorrectly, the structure is not homogenous and later thermal exposure causes secondary hardening due to supplementary precipitation of dispersed particles.

2. Weld Joints of 15 128 Grade Steel

During the experimental programme test weld joints were prepared on tubes made from 15 128.5 grade steel using welding process 111 and electrode EB 321. Three tempering temperatures were tested - 650, 680 and 715 °C. These samples were then subject to simulated operating conditions at a temperature of 450 °C. The affect of the tempering temperature on weld metal hardness is illustrated in Fig. 1. Material tempered at 650°C shows, during exposure, a hardness 60 to 70 HV10 higher than weld metal tempered at 715°C, which means an increase in hardness by 25% average. After reducing the tempering temperature from 715°C to 680°C, weld metal hardness increased by an average 15% during subsequent thermal exposure. Significant differences in weld metal hardness of weld joints subject to various tempering can be seen in the initial condition, i.e. prior to extensive thermal exposure [1]. Very similar curve profiles were recorded for the overheated and normalization zones of the Heat Affected Zone (HAZ), all results are published in paper [2].

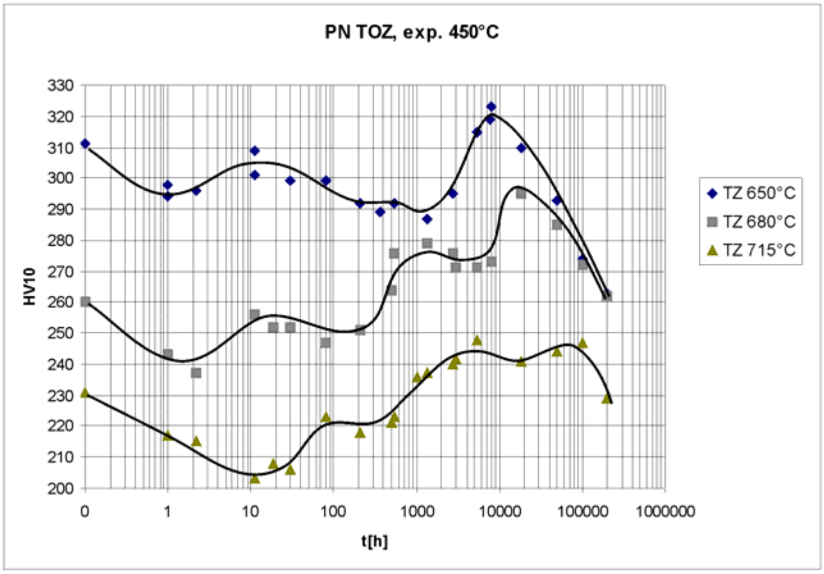

Fig.1 Comparison of hardness profiles in the normalization zone of HAZ for 15 128 steel in dependence on weld joint tempering temperature, operating temperature 450°C

KCV notch toughness values were determined for selected samples. A curve made from these values has its minimum in the maximum hardness area and in the area of hardness decrease it has an increasing trend.

Experimental results show that the notch toughness of weld joints is significantly dependent on the tempering temperature. The greatest difference was seen when the tempering temperature was dropped from 715°C to 680°C. In the initial condition the notch toughness of weld metal tempered at 715°C is 40% higher during sub-creep exposure and this difference increases locally to as much as 100%, see Fig. 2 [2].

Measurements of hardness and notch toughness show the presence of secondary hardening in weld joints of 15 128 steel operated at higher temperatures. These results were backed by a microstructral analysis of dispersed particles using an electron microscope. Image analysis was used to determine parameters of the dispersion phase of MX particles in investigated samples. Three samples, marked 1.0, 1.1 and 1.20, were selected. Sample 1.0 represents the initial condition, sample 1.1 represents maximum hardening after exposure for 50 hrs at 550°C, and sample 1.20 represents a decrease in hardness – 547 hrs at 550 °C. Calculation results for the equivalent particle diameter d_{ekv}, number of particles per unit area n_s, number of particles per unit volume n_v, and mean inter-particle spacing λ are presented in Table 1.

The mean inter-particle spacing was calculated according to Ashby [6]:

$$\lambda = 0{,}69 \cdot \left(n_v \cdot d_{ekv}\right)^{-\frac{1}{2}} - \sqrt{\frac{2}{3}} \cdot d_{ekv} \qquad (1)$$

where:

d_{ekv}…………………. equivalent particle diameter [nm]

λ ……………………. mean inter-particle spacing [nm]

n_v ………………….. number of particles per unit volume

Table 1 Calculation results for dekv ns, nv a λ

Sample No.	**A_X [nm^2]**	**d_{ekv} [nm]**	**n_s [m^{-2}]**	**n_v [m^{-3}]**	**λ [nm] (Ashby)**
1.0.	168,24 ±10,59	13,65 ±0,33	$2{,}13037.10^{14}$	$1{,}79595.10^{22}$	32,92
1.1.	124,01 ±3,24	12,10 ±0,15	$7{,}96117.10^{14}$	$7{,}08676.10^{22}$	13,68
1.20.	246,10 ±8,04	16,91 ±0,29	$2{,}81644.10^{14}$	$1{,}82597.10^{22}$	25,46

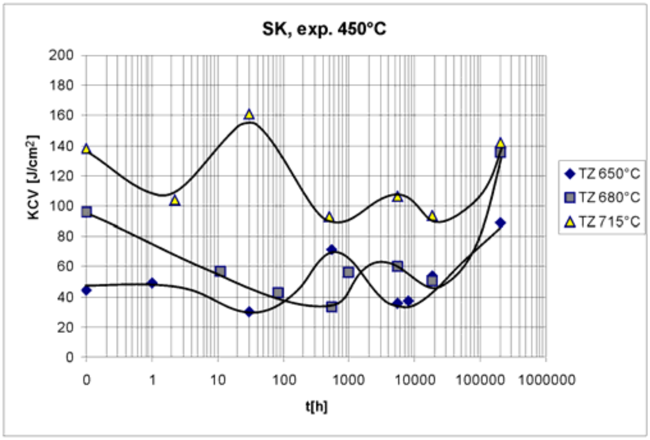

Fig.2 Comparison of weld metal (EB 321) notch toughness profiles in dependence on weld joint tempering temperature, operating temperature 450°C, parent material: 15128 steel

Electron microstructural analysis together with image analysis confirmed that during extensive thermal exposure in the sub-creep zone, changes in dispersion phase of the welds of 15128 grade steel occur. To be specific, this is a process of supplementary precipitation and process of MX particles growth. The maximum hardness during thermal exposure corresponds to the area of supplementary precipitation of MX particles (sample 1.1). This is indicated by the highest count of particles per unit volume, smallest particle size and smallest mean inter-particle spacing. On the other side, hardening curves with a steep drop in hardness indicate an area of growth of secondary phase particles (sample 1.20). Proof of this is the largest mean particle area, marked drop in number of particles per unit volume and almost a double increase in the mean inter-particle spacing with respect to the supplementary precipitation area. The significant influence of the dispersion phase on mechanical properties of 15 128 grade steel is confirmed by the fact that dislocation density was practically constant during extensive thermal exposure [2].

3. Weld Joints of T23, T24 and T25 Grade Steels

As a result of the proposed alloying with carbide-forming elements and a reduced carbon content, T23 and T24 grade steels have excellent mechanical properties at elevated temperatures and are distinguished also by improved weldability. The essence of their high creep resistance is, just as for 15 128 steel, very stable dispersed particles MX. (In the case of low-alloy steels these are vanadium, titanium or niobium carbides or carbo-nitrides.) For T23 and T24 grade steels we can expect similar secondary hardening of weld joints during tempering or extensive thermal exposure as for 15 128 steel. T25 grade steel is currently in an experimental stage an its chemical composition is derived from T24 and 15 128 steels. Compared to T23 and T24 steels this steel has a decreased molybdenum content to approx. 0,5%. Reduction of the molybdenum content is based on thermo-dynamic calculations which are described in [5]. Orientation chemical composition of T23, T24, T25 and 15 128 grade steels is presented in Table 2.

Table 2 Orientation chemical composition of 15128, T23, T24 and T25 grade steels

Steel	C	Mn	Si	Cr	Mo	V	W	Nb	Ti	N	B
15 128	0,13	0,6	0,3	0,5	0,5	0,3	-	-	-	-	-
T23	0,08	0,4	Max. 0,50	2,25	0,15	0,25	1,6	0,05	-	Max. 0,03	Max. 0,0060
T24	0,09	0,5	0,3	2,5	1,0	0,25	-	-	0,05 0,10	Max. 0,012	Max. 0,0070
T25	0,08	0,45	0,3	2,2	0,3	0,3	-	0,04	-	Max. 0,03	Max. 0,0050

The experimental programme included fabrication of test weld joints on plates from T23, T24 and T25 grade steels using welding process 111, electrode Thyssen Cr2VW, or Thyssen Chromo3V. A selection of the weld joints were tempered at 760, and 750°C respectively, and the remainder was left non-tempered (i.e. “as welded” condition). Samples were subject to simulated operation at 500°C and subsequently hardness was measured in individual zones of the weld joint. Fig.3 shows hardness curves for the overheating zone of HAZ for T23 steel during simulated operation at 500°C. Fig.4 shows the same for T24 steel, and Fig.5 for T25 steel.

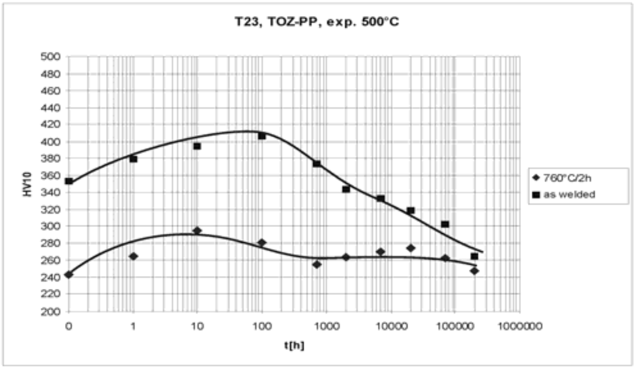

Fig.3 Hardness profiles in the overheated zone of HAZ for T23 grade steel, operating temperature 500°C

In the next stage selected samples were subject to measurement of KCV notch toughness. The notch toughness profile has its minimum in the maximum hardness area and a rising trend in the area of decreasing hardness, just as in the case of 15 128 grade steel. The affect of tempering after welding on notch toughness of the HAZ in T24 grade steel is depicted in Fig. 6. Similar notch toughness profiles were found for T23 and T25 grade steels. Measured values clearly show that non-tempered weld joints suffer a significant loss of plastic properties. The achieved results are in line with results measured in weld joints of 15 128 grade steel [2].

Hardness profile curves show that welds not subjected to tempering undergo marked hardening in a relatively short time of 100, 2000 hrs respectively. Over longer times (over 14000 hrs) hardness decreases. Maximum hardness values are 410 and 430 HV10 units, which are unacceptable with respect to standard EN 288-3 [3]. Measured values show a presence of secondary hardening of weld joints of T23, T24 and T25 grade steels. The hardening mechanism is, as in the case of 15 128 grade steel, given by supplementary precipitation of dispersed particles MX.

Fig.6 shows a marked difference between the notch toughness of tempered and non-tempered weld joints. While the notch toughness of the overheated zone of HAZ in a tempered joint is about 180 J/cm^2 under high-temperature exposure (testing temperature of 20°C), in non-tempered condition KCV values are very low at around 20 J/cm^2.

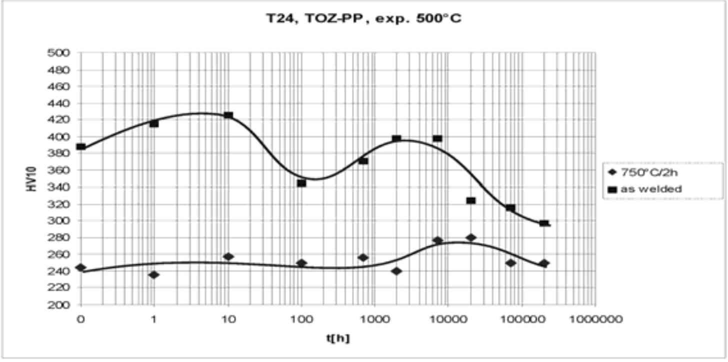

Fig.4 Hardness profiles in the overheated zone of HAZ for T24 grade steel, operating temperature 500°C

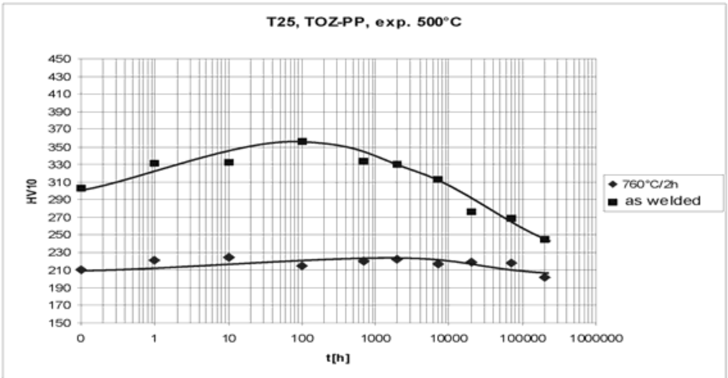

Fig.5 Hardness profiles in the overheated zone of HAZ for T25 grade steel, operating temperature 500°C

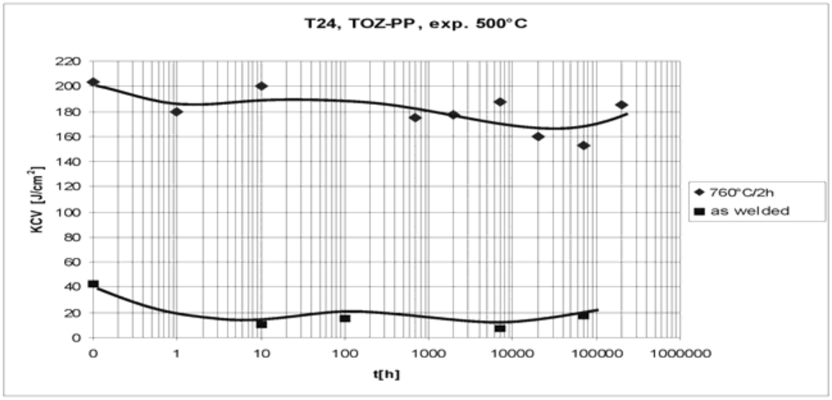

Fig.6 Notch toughness profiles in the overheated zone of HAZ for T24 grade steel, operating temperature 500°C

4. Conclusion

Results presented in this article demonstrate that weld joints of low-alloy creep-resistant steels hardened by dispersed MX nano-particles are subject to a process of secondary hardening during extensive thermal exposure at elevated temperatures. The extent of this hardening depends on the temperature and duration of tempering after welding. Weld joint brittleness also depends on the operating temperature of the welded unit. In 15 128 grade steel brittleness is seen at temperatures under 500°C, for T23 and T24 grade steels we can expect brittleness at even lower temperatures.

From the achieved results we can conclude that tempering of weld joints from 15 128, T23, T24 and T25 grade steels is highly significant especially in terms of obtaining sufficient plastic properties. Omission of tempering after welding of T23 and T24 grade steels is highly problematic. For welds in 15 128 grade steel the optimal tempering temperature is 715 to 730°C. While for T23, T24 and T25 grade steels can be recommended tempering temperatures in the range of 750 to 760°C in order to achieve permissible hardness and sufficient durability of weld joints.

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