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MICROSTRUCTURAL INVESTIGATION OF THE HEAT-AFFECTED ZONE OF SIMULATED WELDED JOINT OF P91 STEEL

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In the process of testing real components exposed to elevated temperature, it is not possible to neglect cracks. The most significant cracks can be induced by welding, which is applied for joining of structural components. Pressure equipment in service is also exposed to high pressure and high stresses. Materials for their manufacturing are designed to resist high stress at elevated temperature, and to meet requirements regarding creep resistance. The objective of this study is to investigate microstructure of different regions of the heat affected zone in T/P91 steels by using thermal simulation instead of welding.

Key words: welded, microstructures, P91 steel, heat affected zone, heat treatment

INTRODUCTION

Many power stations components are joined by welding. Welds can pose a particular problem because their regions might be of different microstructure and there could be presence of residual stresses. The parent material (PM), heat-affected zone (HAZ) and weld metal (WM) have different microstructural and mechanical properties, which characteristics are necessary to be determined. The T/P91 steel is used in normalized and tempered conditions. Normalizing is performed in temperature range from 1 040 °C to 1 080 °C. For wall thickness up to 80 mm, air cooling after normalization is enough to achieve a fully martensitic structure. For higher wall thickness, accelerated cooling is required in order to avoid ferrite fractions. After normalization, the tempering at 750 °C to 780 °C is required to reduce high martensite hardness of even 480 HV10. During tempering, chromium carbides of type $M_{23}C_6$, as well as fine V/Nb carbonitrides are precipitated, which stabilize the martensitic structure. That has positive effects on the long-term strength. Further hardening effect is obtained by fine distribution of V/N carbonitrides [1, 2].

The T/P91 steel is suitable for cold- and hot-operating conditions (600 °C), and can be welded by all current processes. As a result of temperature cycle during welding, the increase of local hardness occurs in WM and in nearby HAZ. This increased hardness must be reduced by post weld heat treatment (PWHT), which has to be performed within the tempering temperature range. In order to achieve the most favorable martensitic structure, the first step is full martensitic transformation of the weld, which can be obtained by cooling the weld down to less than the martensite finish temperature Mf, but always prior to PWHT. Optimized material properties are reached in the tempering temperature range from 750 °C to 765 °C. This paper presents microstructure, hardness and impact energy of four characteristic HAZ regions obtained by single-pass welding simulation. Test results of simulated specimens before and after PWHT are given.

EXPERIMENTAL PROCEDURE

Material characterization

The investigation was conducted on P91 steel, taken from a tube segment of outside diameter 540 mm, with wall thickness of 22 mm. Chemical composition of material is presented in the Table 1. Mechanical properties of PM are presented in the Table 2.

Table 1. **Chemical composition of the investigated material / % wt**

C	Si	Mn	P	S	Cr
0,10	0,44	0,46	0,02	0,01	8,81
Ni	Al	Nb/Cb	V	N	
0,40	0,04	0,08	0,23	0,05	

Table 2. **Mechanical properties of the investigated material**

Yield stress $R_{p0,2}$ / MPa	Ultimate tensile stress R_m / MPa	Elongation A_5 / %	Impact energy A / J at 20 °C
450	620	19	190

In the as-received condition, measured value of PM micro hardness is found to be 211 *HV1*. After annealing, new measured value of PM micro hardness was 207 *HV1*.

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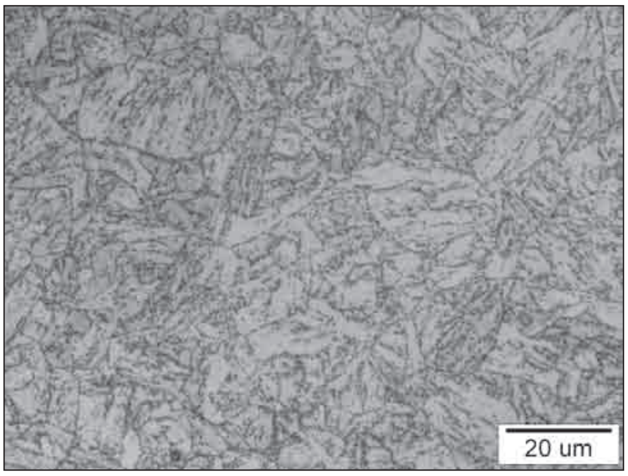


Figure 1 Microstructure of parent metal

The microstructure of PM was of tempered lath martensitic structure, with expressed grain boundaries (Figure 1). Carbides of $M_{23}C_6$ type, where the metal element was mostly chromium (Cr), were dispersed on prior austenite grain boundaries. Average grain size was 20 µm.

Simulation of HAZ

Simulation of HAZ generated in single-pass welding procedure of P91 steel was performed by the SMITWELD 1405 thermal simulator. Various welding cycles were investigated by using the 10 × 10 × 55 mm square specimens. Temperatures of characteristic material transformations occurring during the welding cycle were determined from a dilatometric curve, Figure 2, were characteristic transformation temperatures were A_{c1} = 857 °C and A_{c3} = 914 °C. The material was heated at a rate of 150 °C/s. During the cooling, formation of martensite started at a temperature of 403 °C, and was completed at 317 °C. *Different regions of HAZ* were produced by s*imulating single-pass welding at fourteen different temperatures, ranging from* 1300 °C to 600 °C. Some of those results are presented in this paper. The preheat temperature was 200 °C, heating rate was 150 °C/s and the cooling time $t_{8/5}$ was 20 s. Afterwards, all samples were subjected to two-hour PWHT at 760 °C.

Fine grain heat-affected zone (FGHAZ), represented the region in HAZ where peak temperatures of around 1 100 °C, just above A_{C3} transformation temperature, enabled the formation of small austenite grains [3]. Peak temperature was insufficiently high for fully dissolution of precipitates, in this way limiting the grain growth by fixing austenite grain boundaries. Martensite microstructure appeared during cooling after welding. FG region of the HAZ was the weakest region in ferritic steels welded joints during creep loading. So called *Type IV cracks* may occur in FGHAZ at longer operating time with lower stress levels [3,4].

While heating during welding, peak temperatures between A_{c1} and A_{c3} resulted in partial transformation of ferrite into austenite. Partial dissolution of precipitates, as well as coarsening of undissolved precipitates may occur in this region of HAZ, especially during subsequent PWHT. Microstructure consisting of newly formed virgin martensite and the tempered original microstructure appeared after cooling. The intercritical heat-affected zone (ICHAZ) was characterized by a small grain size and, generally, exhibited the lowest hardness values [2]. This sub-zone of the HAZ showed susceptibility to Type IV cracking similar to the FGHAZ region, Figure 3 (c).

Metallographic analysis

Microstructure of tempered martensite of the sample simulated at 1 300 °C was coarser and non-uniform, Figure 3 (a). The average grain size was found to be 36 µm. As it can be seen in Figure 3 (b), the fine grained heat affected zone (FGHAZ) was not clearly apparent; the microstructure consisted of martensite tempered during the PWHT. The measured average grain size was 15 µm. Partial transformation of initial tempered mar-

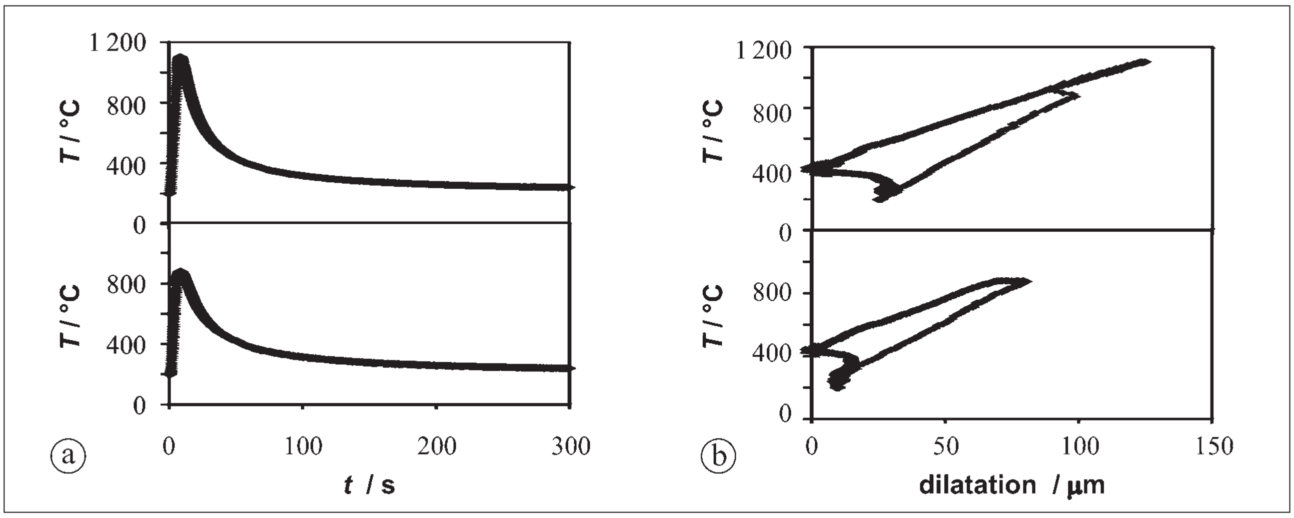
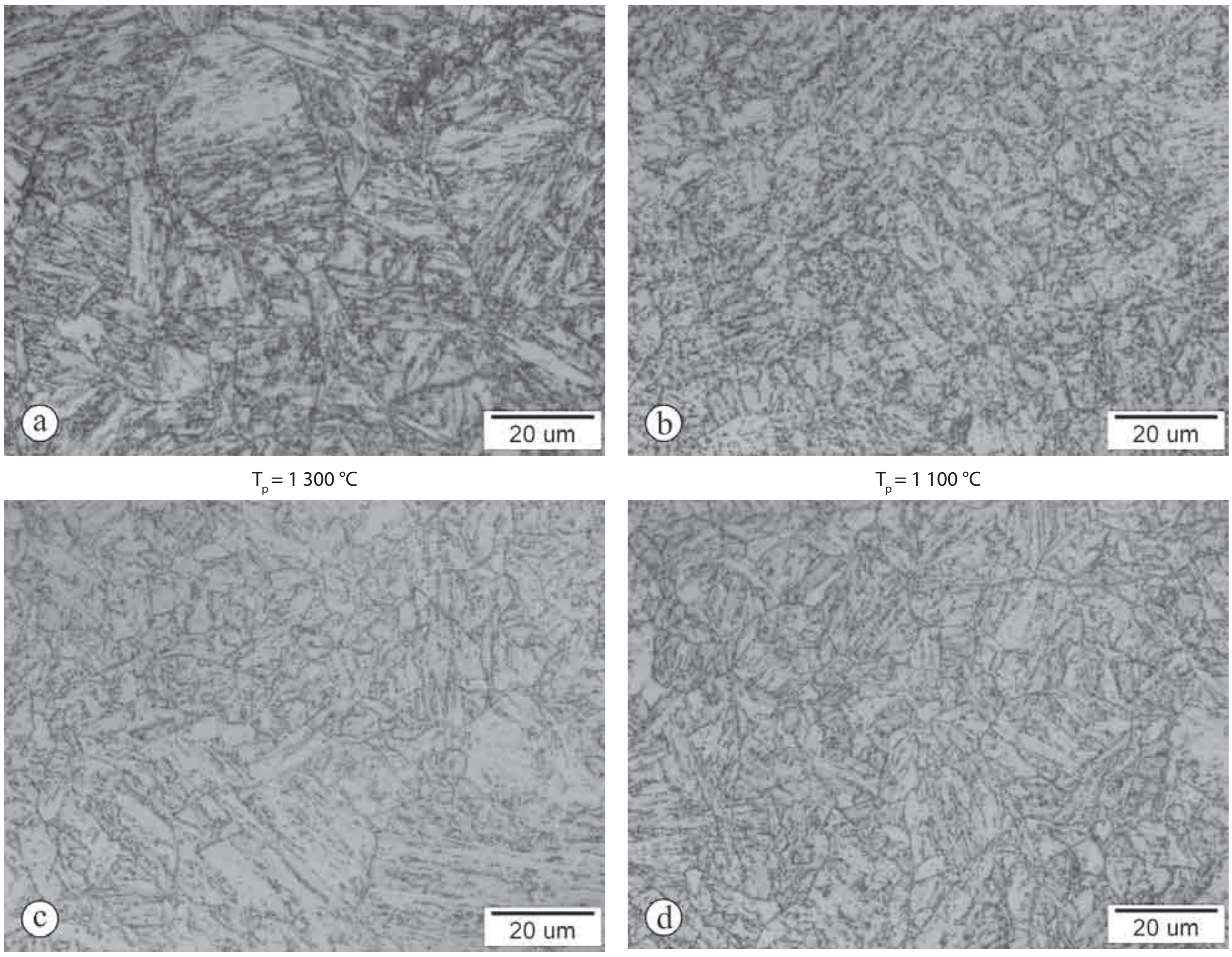


Figure 2 Welding thermal cycle (a) and dilatometric curves (b) for P91 steel obtained at simulation temperature of 1 100 °C and 875 °C



T_p = 1 300 °C

T_p = 1 100 °C

T_p = 875 °C

T_p = 700 °C

Figure 3 Microstructure of simulated specimens (with indicated applied simulating temperature) after performed PWHT

tensite to austenite was observed at simulation temperatures in the range of 825 ºC to 875 ºC. Figure 3 (c) shows the partial transformation of initial tempered martensite to austenite. Peak temperature was between A_{c3} and A_{c1} transformation temperatures for P91 steel. The martensite was later tempered during the PWHT. Finally, the microstructure shown in Figure 3 (d) was uniform, consisting of tempered lath martensite, and was close to the microstructure of unchanged parent material in which no visible changes in constituents' morphology occurred.

RESULTS AND DISCUSSION

The microhardness measured values of PM, FGHAZ and ICHAZ before and after subsequent PWHT are shown in the Figure 4.

PWHT had no significant influence on PM hardness, but subsequent PWHT significantly affected HAZ constituent hardness because of newly formed quenched (non-tempered) martensite, which appeared in matrix just after welding/simulation. In FGHAZ region, microhardness measured before PWHT was around two times higher than after performed PWHT, which indicated the necessity of preheating before welding in order to avoid cold cracks. The preheating temperature has to be between 200 °C and 300 °C. The microhardness of IC-HAZ region measured after welding - simulation was around 380 HV1, which is a standard value for this type of alloy-250 HV1. After PWHT, which directly affected tempering of martensite formed during cooling after welding, hardness of ICHAZ region was lower than of

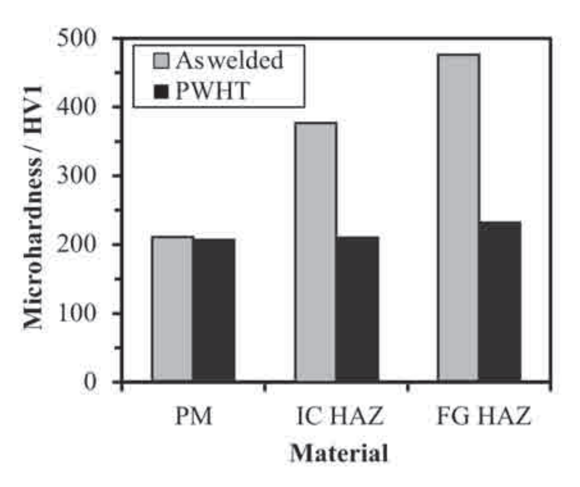


Figure 4 Hardness of PM and simulated specimens with/without PWHT

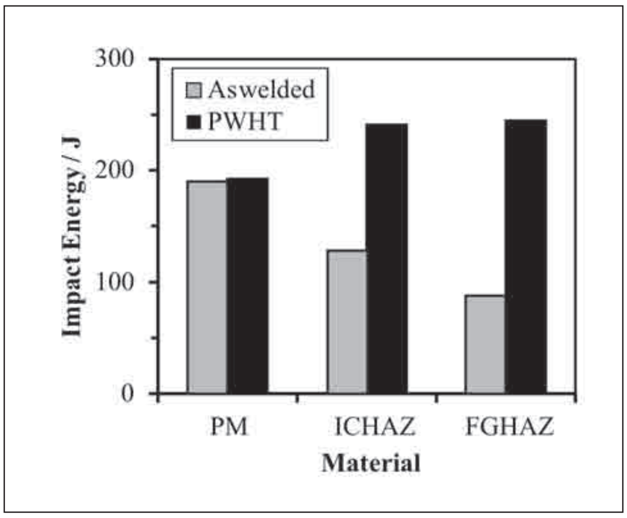


Figure 5 Impact energy of the PM and simulated specimens with/ without PWHT

recommended value. Figure 5 shows impact energy values of PM, FGHAZ and ICHAZ measured before and after PWHT.

Steels for elevated temperature application have to exhibit good ductility, both at operating and at room temperatures (start-up and shut-down situations), [3]. Good ductility of WM can be achieved by multipass welding technique with lower heat input during welding. HAZ microstructure after welding is fully martensite. As martensite in microstructure of material increases hardness and decreases ductility, [5-7], it is crucially to perform PWHT after welding, which, according to recommendations, has to be between 740 °C and 760 °C, and has to last from 2 to 8 hours, depending on material thickness and geometry of welded joint. The PWHT temperature higher than 760 °C has to be avoided so that A_{c1} temperature is not exceeded.

CONCLUSIONS

Welding thermal cycle has negative influence on HAZ mechanical properties. In order to avoid cold cracking in HAZ, it is important to perform preheating before starting the welding operation. It is important that the quantity of unintentionally introduced hydrogen during welding is minimized. During cooling after welding/simulation, quenched (non-tempered) martensite is formed in the structure of HAZ, whereas FGHAZ and ICHAZ hardness increases. This quenched (non-tempered) martensite has also negative impact on impact energy, which is almost two and half times lower than the PM impact energy. PWHT at temperature of 760°C during 2 hours has good influence on mechanical properties because the hardness decreases, while ductility increases in FGHAZ and ICHAZ regions. PWHT has also crucial impact on creep strength properties of mentioned steels [3].

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