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MECHANICAL PROPERTIES OF P92 WELDED JOINT AFTER 3000 HOURS OF ANNEALING AT 600 AND 650°C

P92 steel is a modern martensitic heat-resistant steel currently used for seamless products for pressure equipment operating in supercritical operating parameters. The paper presents the results of a study on the strength properties and structure of a P92 steel welded joint used for pressure components of power units. The paper presents an assessment of the suitability for further operation of both the parent material and a circumferential similar welded joint of finished products in the form of P92 steel pipes after annealing for 3000 hours at 600 and 650°C. Annealing at 650°C results in faster increase in the size of the precipitates and their coagulation along grain boundaries of former austenite and martensite laths. The changes in mechanical properties were compared in relation to the state of the structure of the parent material and the material of the welded joint. Quantitative analysis of $M_{23}C_6$ precipitates was also carried out.

Keywords: P92 steel; similar welded joint; microstructure; mechanical properties testing; annealing

1. Introduction

The construction of boilers for supercritical steam parameters in Poland requires the launch of tests and analyses to determine the strength of individual pressure components of the units in question. To the greatest extent, this applies to pressure components with the highest operating parameters, which are undoubtedly pipelines and steam collectors [1-4]. For materials of pipelines and collector pipes, the dominant factor causing material degradation is the phenomenon of creep [1]. A number of microstructural properties and mechanical tests should be compared to see how the material degrades as a function of time [5-7].

Therefore, the investments related to the construction of boilers with supercritical parameters implemented in Poland in recent years have led to the launch of extensive research on materials intended for operation at elevated and high temperatures, carried out jointly by boiler manufacturers and research and scientific units, allowing for gaining experience and know-how. The effect of the cooperation in the field of research preceding the application of the new generation of creep-resistant steels is the verification of the required level of strength and technological properties [8-12].

In assessing the reliability and safe operation of pressure equipment, an important criterion is the knowledge of their material condition in terms of long-term operation. This is related to the concept of service life, which is defined as a property that characterises the ability to maintain the required performance properties (mainly creep resistance) until reaching the agreed limit state, in which further operation is not recommended [1,13-17].

P92 steel is a martensitic creep-resistant steel from the group of steels with 9% chromium content, used for seamless pipes according to EN 10216-2 or according to ASTM A213 and A335, intended for pressure equipment. The steel was developed in the 1990s. Compared to the standard X20CrMoV11-1 steel, the chemical composition was modified by introducing 1.8% of tungsten and micro-additives of niobium, boron and nitrogen, and by reducing the molybdenum content to 0.5%. It is characterised by good strength properties, appropriately high corrosion resistance, good weldability and heat resistance at elevated temperatures [18-21].

According to the literature data, the identification of the precipitates using selective electron diffraction with TEM showed the presence of MX and $M_{23}C_6$ precipitates in P92 steel in the delivery condition. MX precipitates were observed inside

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martensite laths, on dislocations and on subgrain boundaries. In turn, $M_{23}C_6$ carbides were observed mainly along grain boundaries of former austenite and martensite lath boundaries. In the initial state, dislocation density was 2.69 ±2.11*1014 disl/m^2 in P92 steel. The average diameter of the precipitates and MX and $M_{23}C_6$ particles in P92 steel in the delivery condition was 29.2±7 nm and 110.1±46 nm, respectively [22-24].

The aim of the study is to the compare microstructure and strength properties of the welded joint in the initial state and after simulation in conditions corresponding to the operating conditions of the pipeline. Currently, there is still a lack of detailed results of research on the microstructure and mechanical properties of the welded joint of P92 steel, which are important from the scientific and practical point of view.

2. Specimens

For the tests, T/P92 steel tubular welded joints were made, simulating the joints of key pressure components of modern boilers for supercritical parameters. The subject of the study were Ø76.1×20.0 P92 thick-walled welded joints similar to those made for the construction project of a 900 MW power unit. The root layer of the welded joint was obtained using the TIG method using argon as a forming gas (welding with Böhler welding wire), and the filling and face layer – using the MMA method (manual metal arc welding). The detailed parameters of welding and the PWHT chart are shown in Fig. 1. TABLE 1 summarises the chemical composition of the original material and consumables used for welding the examined sections in relation to the requirements of the standard (EN 10216-2 – pipe material, ISO 3580 – coated electrodes and EN ISO 21952-A – welding wire).

3. Testing methodology

The welded joints were cut longitudinally, and they were used to prepare samples for strength tests in the delivery condition, samples for annealing for 3000 hours at 600°C and samples for annealing for 3000 hours at 650°C. The samples were annealed in air atmosphere in furnaces produced by Łukasiewicz Research Network – Institute for Ferrous Metallurgy in Gliwice.

The observation of the microstructure of the joint material made of P92 steel was carried out on metallographic microsections showing the joint zones (Fig. 2). The microsections on the

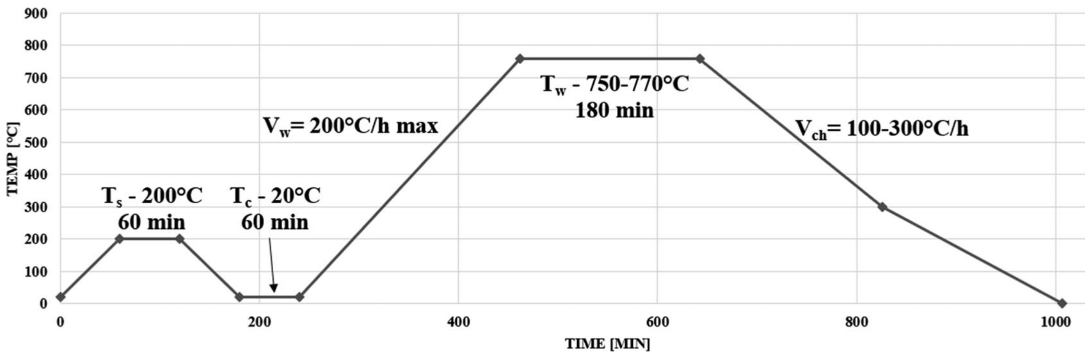

Fig. 1. Welding parameters of the tested joint and post-welding heat treatment (T_s – welding temp., T_c – cooling temp., V_w – heating rate to OC, T_w – holding temp., V_{ch} – cooling rate)

TABLE 1

Chemical composition of materials used for obtaining the joint (acc.to PN-EN10216-2, PN-EN ISO 3580, PN-EN ISO 21952)

<table>
<tr><th>Material norm</th><th colspan="2"></th><th>C</th><th>Si</th><th>Mn</th><th>P max</th><th>S max</th><th>Nb</th><th>Ti</th><th>V</th><th>Zr</th></tr>
<tr><td rowspan="4">PN-EN 10216-2:
Seamless steel tubes for pressure purposes</td><td colspan="2" rowspan="4">X10CrWMoVNb9-2
1.4901</td><td>0.07
to 0.13</td><td>≤0.50</td><td>0.30
to 0.60</td><td>0.02</td><td>0.01</td><td>0.04
to 0.09</td><td>0.01
max</td><td>0.15
to 0.25</td><td>0.01
max</td></tr>
<tr><td>Cr</td><td>Mo</td><td>Ni</td><td>N</td><td>B</td><td>Al tot</td><td>Cu</td><td colspan="2">W</td></tr>
<tr><td>8.5
to 9.5</td><td>0.30
to 0.60</td><td>≤0.40</td><td>0.030
to 0.070</td><td>0.001
to 0.006</td><td>≤0.02</td><td>—</td><td colspan="2">1.50 to 2.00</td></tr>
<tr></tr>
<tr><td>Material norm</td><td></td><td>C</td><td>Si</td><td>Mn</td><td>Cr</td><td>Ni</td><td>Mo</td><td>V</td><td>Nb</td><td>W</td><td>N</td></tr>
<tr><td>PN-EN ISO 3580: Welding consumables – coated electrodes for creep resistant steels</td><td>X10CrWMoVNb9-2
1.4901</td><td>0.10</td><td>0.30</td><td>0.50</td><td>8.60</td><td>0.50</td><td>0.40</td><td>0.20</td><td>0.05</td><td>1.50</td><td>0.05</td></tr>
<tr><td>Material norm</td><td></td><td>C</td><td>Si</td><td>Mn</td><td>Cr</td><td>Mo</td><td>Ni</td><td>W</td><td>V</td><td>N</td><td>Nb</td></tr>
<tr><td>PN-EN ISO 21952: Welding consumables – wires, rods and binders for creep resistant steels</td><td>X10CrWMoVNb9-2
1.4901</td><td>0.10</td><td>0.30</td><td>0.70</td><td>8.60</td><td>0.55</td><td>0.70</td><td>1.60</td><td>0.20</td><td>0.04</td><td>0.04</td></tr>
</table>

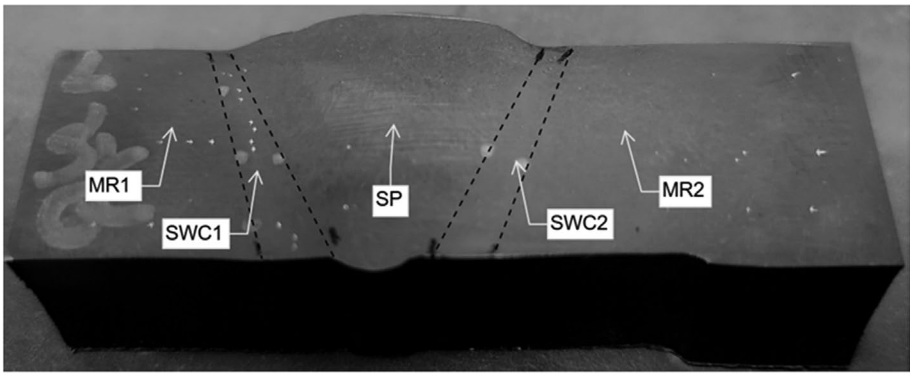

Fig. 2. Observation diagram for joint microstructure

cross-section of the joint sections were obtained by grinding and machine polishing as well as etching. The examination of the microstructure of the material in the delivery condition and after annealing for 3000 h at 600°C and after 3000 h at 650°C were carried out using an Inspect F scanning electron microscope with magnification up to 5000×.

The quantitative analysis of the precipitates was carried out using the image analysis system. The image analysis system was calibrated using the scale marker placed in structure images. The calibration coefficient was: 1 pixel = 0.040 μm. A measuring frame of 1020 × 940 pixels was applied to every analysed image.

The mechanical properties of the welded joint were tested using a Zwick Z250 universal testing machine with a maximum load of 250 kN. The samples were tested in accordance with the PN-EN ISO 6892-1:2016-09 standard. The tests of mechanical properties were performed both for samples of the welded joint in the delivery condition and for samples after annealing for 3000 h at 600°C and for samples after annealing for 3000 h at 650°C. The mechanical tests were carried out at room temperature (T = 25°C) and at elevated temperature (T = 550°C).

4. Study results

The observation of the original material in the delivery condition for both sides of the joint revealed the structure of tempered lath martensite with very fine precipitates of the $M_{23}C_6$ type along the boundaries of former austenite grains and martensite laths, which is correct for the initial state of the tested steel [22]. In this article, the description of microstructural changes was limited to the parent material zone. A detailed atlas of structural changes with the division into zones of the welded joint was discussed in [24].

The examination of the microstructure of the similar welded joint after annealing at 600°C showed that the microstructure of the tested steel is slightly different from the one observed for the initial state, i.e. the microstructure of tempered lath martensite with a noticeable, but only slight increase in the amount and size of precipitates of the $M_{23}C_6$ type (Fig. 3-5), mainly along the boundaries of former austenite grains. The precipitation growth process is faster at 650°C. The examination of the microstructure of the parent material of the similar welded joint after annealing at 650°C showed a slightly higher dynamics of the precipitation process than at 600°C. The structure of tempered lath martensite was observed with a noticeable, slight increase in the size of numerous precipitates and their coagulation, mainly along former austenite grain boundaries with numerous precipitates along former austenite grain boundaries and martensite laths.

The measured average diameter of $M_{23}C_6$ precipitates along former austenite grain boundaries and martensite laths was 165 nm, 208 nm and 224 nm, respectively for the delivery condition and the ageing temperature of 600 and 650°C, which, according to the diagram for assessing the degree of degradation of P92 steel due to prolonged exposure to elevated temperature,

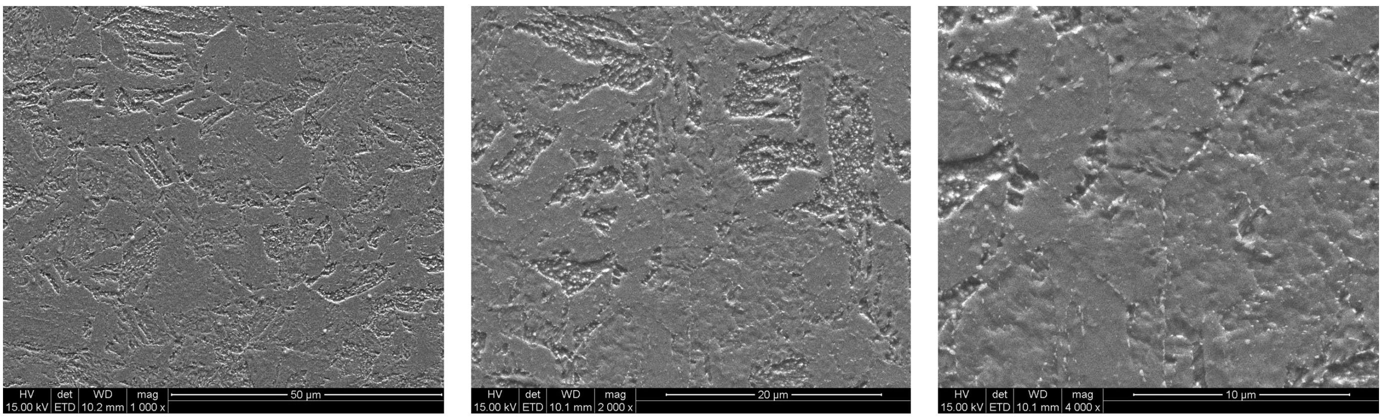

Fig. 3. Microstructure of material of the tested joint in the delivery condition

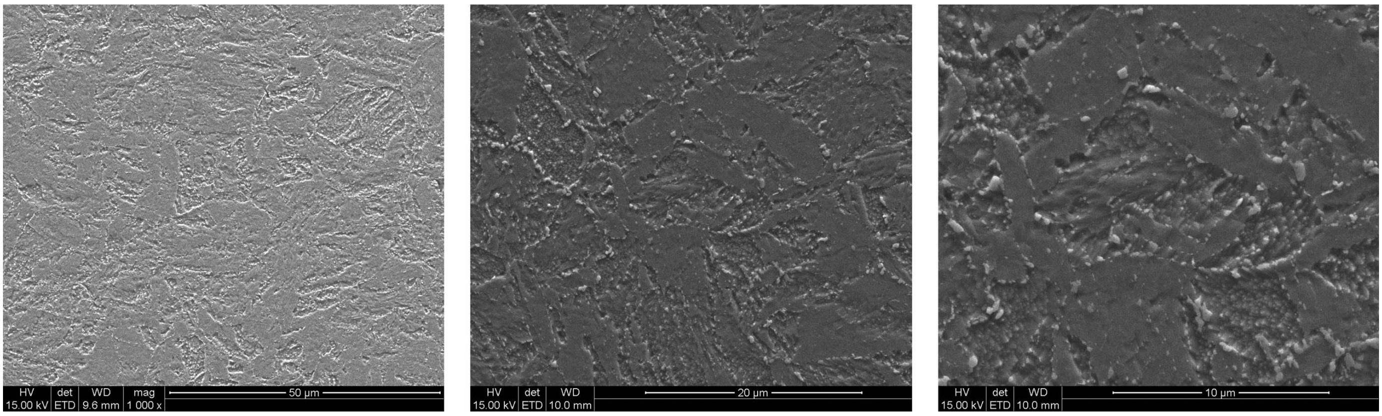

Fig. 4. Microstructure of the tested joint after annealing for 3000 h at 600ºC

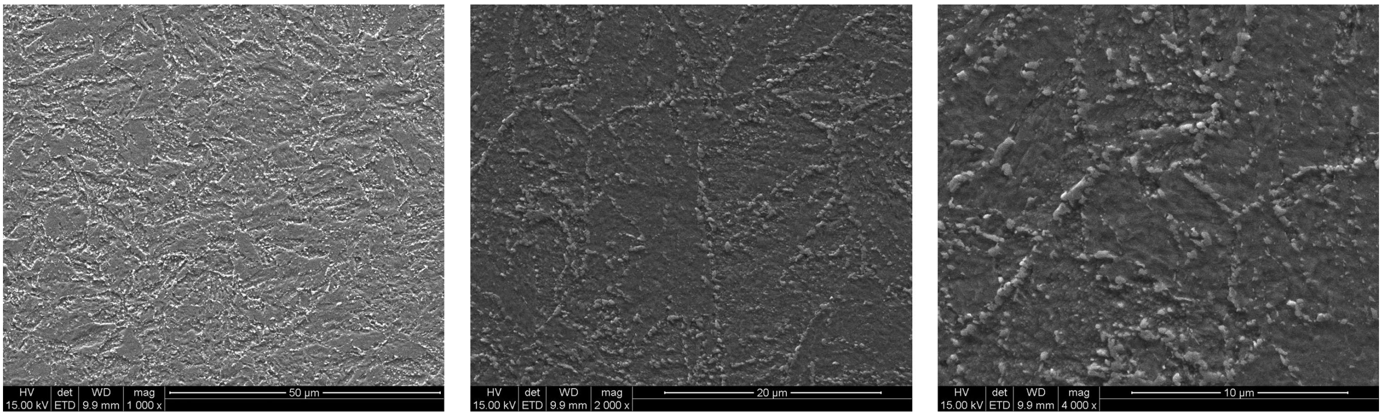

Fig. 5. Microstructure of the tested joint after annealing for 3000 h at 650°C

indicates the estimated degree of exhaustion of up to 0.2 [25]. Measuring the average diameter of secondary secretions is important in assessing the degree of depletion. It allows not only the estimation of exhaustion based on model images of the structure presented in the atlases of the structures of the tested steel but also on forecasting the increase of precipitates based on the data published in [25]. Quantitative analysis of selected microstructure images allowed to development of a database of measured diameters of precipitates at several temperature values. Similar test results were presented in [26].

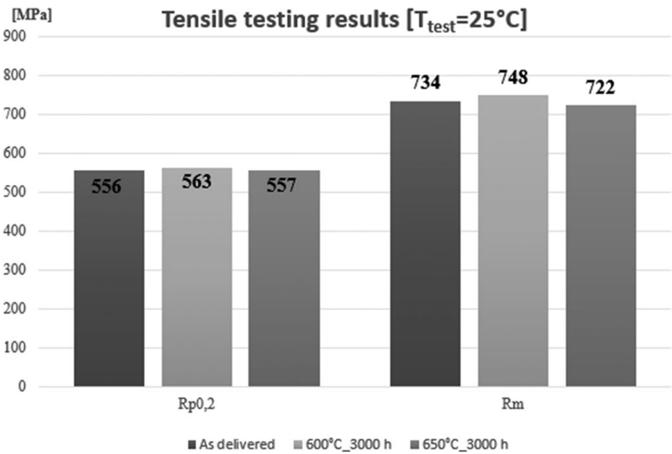

Fig. 6. Tensile test results for P92 welded joint samples

Fig. 6 summarises the test results obtained in the static tensile test for samples in the delivery condition and after annealing in a furnace with the application of the described parameters, while TABLE 2 shows comparatively the minimum values that the pipe material should have according to EN10216-2.

TABLE 2

Minimum values of tensile properties for P92 steel pipes per EN10216-2

	Rp0,2 [MPa]	**RM [MPa]**	**El. [%]**
T = 25°C	440	620-850	19
T = 550°C	300	—	—

The results of tests of mechanical properties at T = 25°C of P92 steel after annealing at 600°C, compared to the material in the delivery condition, show a slight increase in the value of yield strength (Rp0,2) and tensile strength (RM). The sample after annealing at 650°C shows a slight decrease in the value of yield strength and a slight increase in tensile strength. The nature of changes in mechanical properties of P92 steel with a similar course was also presented in [22].

Comparing the results of mechanical tests at T = 550°C of samples after annealing at 600°C and 650°C with the results presented in the tables in the EN10216-2 standard for pipes, it can be concluded that both samples showed higher values of yield strength than the minimum assumptions of the EN10216-2 standard (TABLE 2). The values of tensile strength at elevated temperature and elongation values are not standardised values in EN10216-2.

5. Conclusions

- The examination of the microstructure of the original material of the welded joint in its initial state and after annealing did not reveal the presence of defects in the form of microcracks or discontinuities, which proves that the welding process was correctly performed.
- Annealing for 3000 hours at 600°C of the welded joint made of P92 steel showed that only slight changes in the form of precipitation processes were observed in the microstructure, mainly along former austenite grain boundaries and martensite laths.
- Annealing for 3000 hours at 650°C of the welded joint made of P92 steel confirmed the literature data that the material degradation dynamics in the microstructure was higher than at 600°C. A faster increase in the size of the precipitates and their coagulation along grain boundaries of former austenite and martensite laths was observed.
- The performed quantitative analysis of $M_{23}C_6$ precipitates after annealing, related to the diagram of changes in the classification of the P92 steel structure.
- The results of testing the mechanical properties of samples of welded joints, both at room and at elevated temperature, meet the requirements for the parent material – i.e. pipes made in accordance with EN10216-2.

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