

K. SÓWKA¹, M. SROKA^{2*}**PROPERTIES OF PIPE WELDS AFTER LONG-TERM THERMAL EXPOSURE AT 650°C**

This study examines the strength characteristics and microstructural evolution of welded joints in X10CrWMoVNb9-2 (P92) steel piping used for pressure-critical components in power generation systems. The research evaluates the effects of prolonged thermal exposure through 3,000 and 10,000 h annealing cycles at 650°C. Microstructural analyses were conducted using scanning electron microscopy (SEM), while mechanical performance was assessed via tensile testing.

The investigation identified a direct correlation between microstructural degradation and diminished mechanical performance, a critical factor for high-temperature applications. Strength reductions were attributed to progressive coagulation of $M_{23}C_6$ carbides and Laves phase precipitation. The comparative analysis quantified property changes between the as-received parent material and weld metal, establishing baseline-to-aged condition performance metrics. These findings underscore the importance of microstructural stability in maintaining the operational integrity of P92 steel components under prolonged thermal stress, particularly in ultra-supercritical power plant environments.

Keywords: P92 martensitic steel; annealing; SEM analysis; tensile properties; microstructural degradation

1. Introduction

Ferritic steels, particularly high-chromium ferritic grades, constitute a critical material group in modern power engineering, enabling efficiency improvements in steam boilers through operational steam temperatures of 560-630°C. P92 steel, a low-carbon alloy containing 8.5-9.5% chromium with supplementary alloying and microalloying additions, is classified as a difficult-to-weld material [1-5].

The pursuit of enhanced power plant efficiency through elevated steam parameters has driven increased demand for research on pressure vessel materials and their welded joints capable of withstanding extreme operating conditions. Investigations into the properties of welded joints following prolonged high-temperature exposure are critical for ensuring the safety and operational reliability of energy infrastructure. Systematic analysis of microstructural transformations, mechanical performance, and service-related changes in welded connections enables deeper understanding of material degradation mechanisms [6-9].

Furthermore, long-term annealing studies provide essential data for modelling joint behaviour under operational conditions and predicting service life. The development of advanced assessment methods for evaluating the technical state of joints

after extended high-temperature service is pivotal for effective lifecycle management of power plant components. A holistic approach integrating microstructure analysis, mechanical property evaluation, and creep resistance assessment offers comprehensive insights into welded joint performance under near-actual service conditions [2,3,10,11].

P92 steel, classified as a ferritic alloy steel, represents an enhanced variant of P91 steel through tungsten addition (1.5-2.0%) and reduced molybdenum content (0.35-0.55%), while maintaining chromium levels at 8.5-9.5% alongside other alloying and microalloying elements [12]. Its key advantage lies in 30% superior creep strength compared to P91 in the 590-650°C range, achieving 131 MPa at 600°C for 100,000 h service life. Primary applications focus on power generation, particularly in ultra-supercritical units for main steam lines, reheat systems, and steam headers operating at pressures up to 30 MPa and temperatures reaching 610°C. Welding of P92 steel necessitates strict control of thermal cycles, limitation of linear heat input, and mandatory post-weld heat treatment (PWHT) to mitigate residual stresses [2,3,10,13,14].

The objective of this research is to examine and contrast the microstructural characteristics and mechanical properties of the welded joint, both in its initial condition and after thermal

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exposure simulating the pipeline's operational environment. There remains a significant gap in comprehensive data regarding the microstructure and mechanical attributes of P92 steel welded joints, which is crucial from both scientific and practical perspectives.

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 was $\varnothing 88,9 \times 17,5$ P92 thick-walled welded joints like those made for the construction project of a 900 MW power unit. The joint penetration, i.e. the root layer of the joint, was made using the 141 method – GTAW, welding with a non-consumable tungsten electrode with an additional material in the form of solid wire and in a 100% argon gas shield of the root. The filling layers and the face of the weld were made using the 111 method – SMAW, i.e. welding with a covered electrodes. This combination of welding methods ensures high quality of the welded joint, it is a typical solution used for responsible components of the power industry, which undoubtedly are high-pressure pipelines. The welding of the joint was performed while maintaining parameters such as: interpass temperature between 200 and 300°C, heating rate to annealing temperature, annealing time of 180 minutes at a temperature between 750 and 770°C, and finally, an appropriate cooling rate after annealing range from 200 to 300°C/h. These parameters ensure the best possible technological properties of the joint in its initial state. The chemical composition of the original material and consumables used for welding the examined sections in relation to the requirements of the standard (PN-EN 10216-2 – pipe material, ISO 3580 – coated electrodes and PN-EN ISO 21952-A – welding wire).

3. Testing methodology

The welded joints were cut longitudinally, and used to prepare samples for strength tests in the delivery condition, samples for annealing for 3,000 h at 650°C and samples for annealing for 10,000 h at 650°C. The samples were annealed in air atmosphere without stress applied to the sample in furnaces produced by Łukasiewicz Research Network – Upper Silesian University of Technology in Gliwice. Annealing at 650°C was chosen to accelerate microstructural degradation and changes in mechanical properties without altering the nature of the ongoing processes. This temperature was selected because it is higher than the typical operating temperature of P92 steel (610–620°C), which allows for confirmation of the steel's application range by demonstrating a significant acceleration of degradation processes specifically at 650°C. The annealing time was selected to ensure that the research could be completed within the timeframe of the scientific project. The minimum exposure time was 3000 hours, after which noticeable changes were already observed, while the

maximum duration was 10,000 hours, allowing the study to fit within the planned research schedule.

The observation of the microstructure of the joint material made of P92 steel was carried out on metallographic microsections showing all the joint zones (Fig. 1). The microsections on the 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 3,000 h and 10,000 h at 650°C were carried out using a JEOL JSM-7200F high-resolution scanning electron microscope with magnification up to 40,000 $\times$.

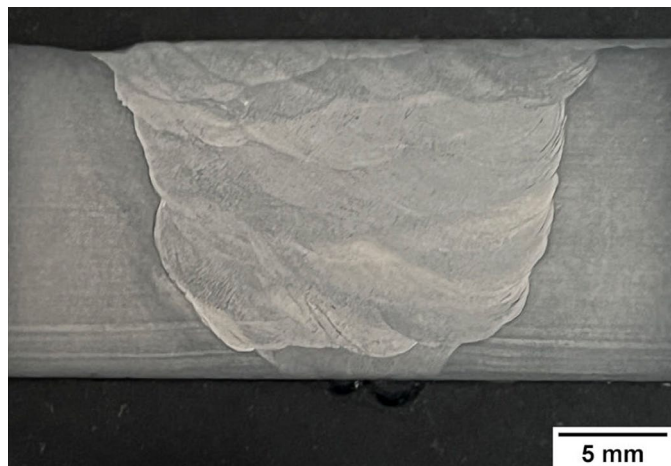


Fig. 1. Metallographic specimen of welded joint for microstructural analysis

To confirm the presence of precipitates, element distribution maps were created using scanning electron microscopy with an EDS analyser, which allows for rapid determination of chemical composition both at specific points and in areas of varying sizes.

The quantitative analysis of the precipitates was carried out using the image analysis system which provided image data such as: pixel size (14.7 nm), resolution (800 $\times$ 600 px), quantity and surface area of individual precipitates. For each of them, the diameter of the precipitate expressed in nm, minimum and maximum values, average size of the precipitate and standard deviation were calculated.

The mechanical characteristics of the welded connection were evaluated using a Zwick Z250 universal testing apparatus with a maximum capacity of 250 kN. The specimens were examined in compliance with the PN-EN ISO 6892-1:2016-09 standard. The assessment of mechanical properties was conducted on samples of the welded joint in the as-received condition, as well as on specimens after heat treatment for 3,000 h at 650°C and for 10,000 h at 650°C. The mechanical evaluations were performed at ambient temperature ($T = 25^\circ\text{C}$).

4. Study results

In this article, the description of microstructural changes was limited to the heat affected zone. The examined X10CrW-

MoVNb9-2 steel pipes in the as-delivered condition (supplied after normalization and tempering, i.e., +NT) are characterized by a martensitic structure with a predominant share of tempered lath martensite (Fig. 2). Based on the obtained images, it can be confirmed that the heat-affected zone of the joint in its initial state is characterized by a slightly more refined structure compared to the base material zone. The microstructure of the heat-affected zone exhibits fine grain size, areas of visible ferrite grains, and martensitic laths. There are regions with varied distribution of precipitates and non-uniform grain size distribution. Numerous precipitates in the initial state of X10CrWMoVNb9-2 steel consist of finely dispersed MX-type carbides (MC and MN) and $M_{23}C_6$, which is confirmed by publications [6,7,15-17]. MX precipitates are found mainly within martensite laths, on dislocations, and at subgrain boundaries, while $M_{23}C_6$ carbides are predominantly located at prior austenite grain boundaries and martensite lath boundaries. A detailed atlas of structural changes

with the division into zones of the welded joint was discussed in [18,19,21]. To confirm the presence of precipitates, chemical distribution maps were created EDS analyzer (Fig. 3). The surface concentration images of chromium indicate the distribution of $M_{23}C_6$ carbides, while the concentration images of niobium and vanadium show the distribution of finely dispersed MC carbides within the grain.

Based on the obtained images after annealing at 650°C for 3000 h (Fig. 4), it can be concluded that the microstructure of the steel undergoes more significant changes compared to the initial state shown in Fig. 2. In the case of samples annealed for 10000 h at 650°C (Fig. 5), the increase in precipitate size and the disappearance of the lath microstructure of tempered martensite are more apparent. Moreover, in the microstructure, numerous precipitates of varying sizes can be observed, locally arranging themselves into continuous networks along the boundaries of former austenite grains and martensite laths.

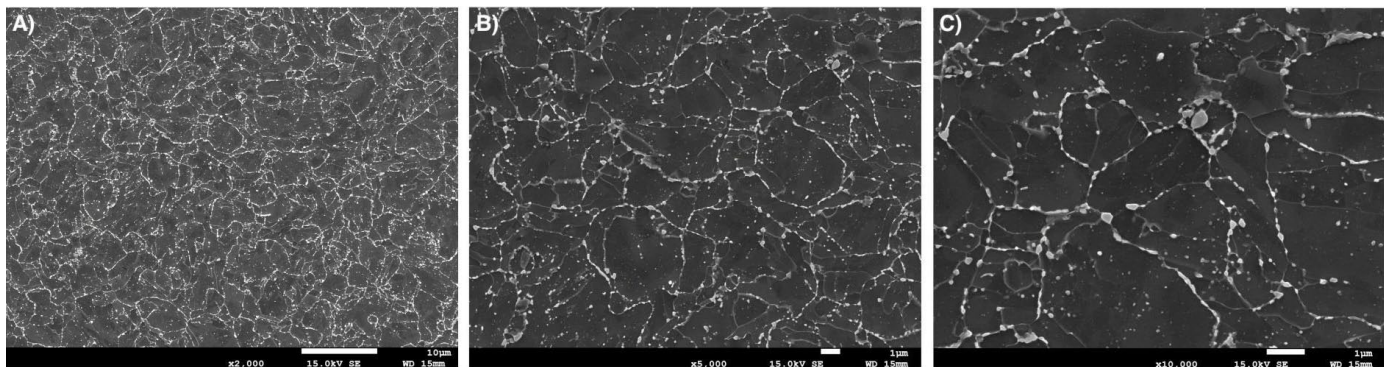


Fig. 2. Microstructure of heat affected zone of the tested joint in the delivery condition, A) mag 2.000×, B) mag 5.000× and C) mag 10.000×

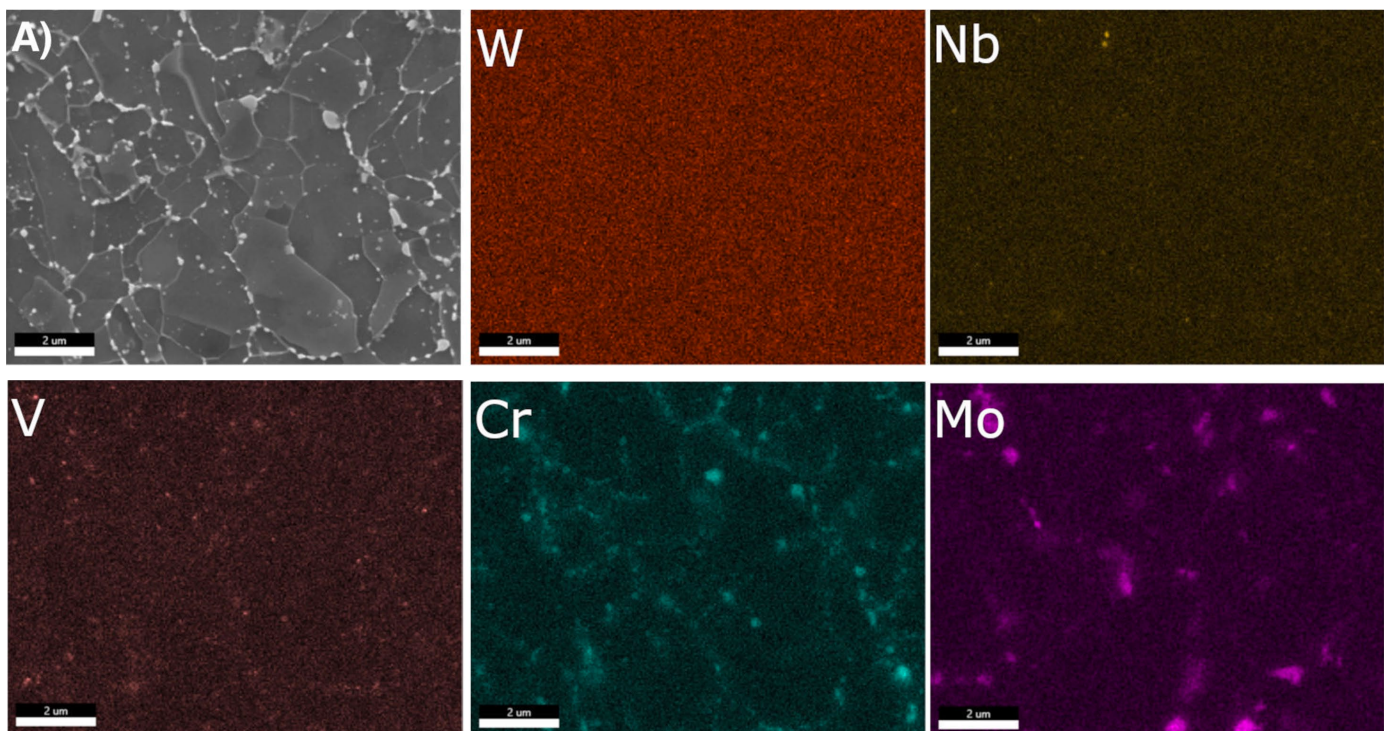


Fig. 3. Chemical composition maps of heat affected zone in the delivery condition, A) – analysed microstructure, W – concentration of tungsten, Nb – concentration of niobium, V – concentration of vanadium, Cr – concentration of chromium, Mo – concentration of molybdenum

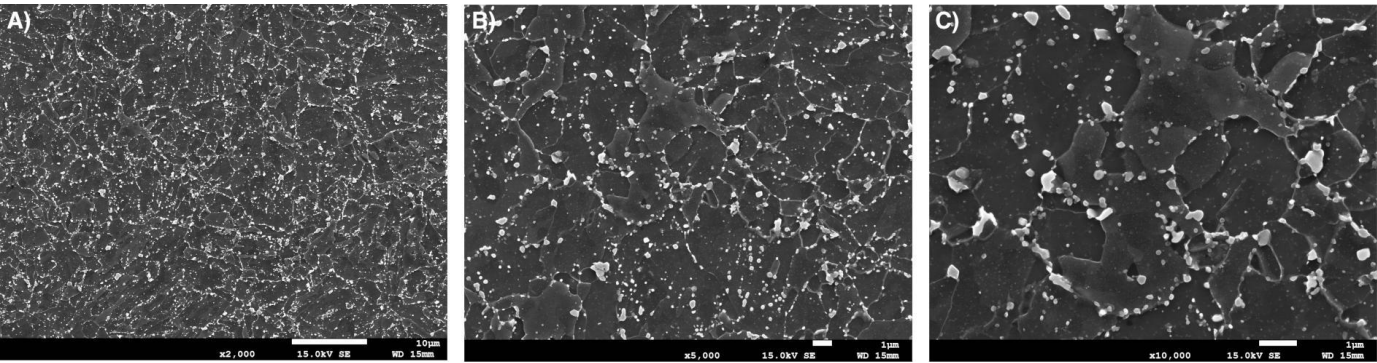


Fig. 4. Microstructure of heat affected zone after annealing for 3,000 h at 650°C, A) mag 2.000×, B) mag 5.000× and C) mag 10.000×

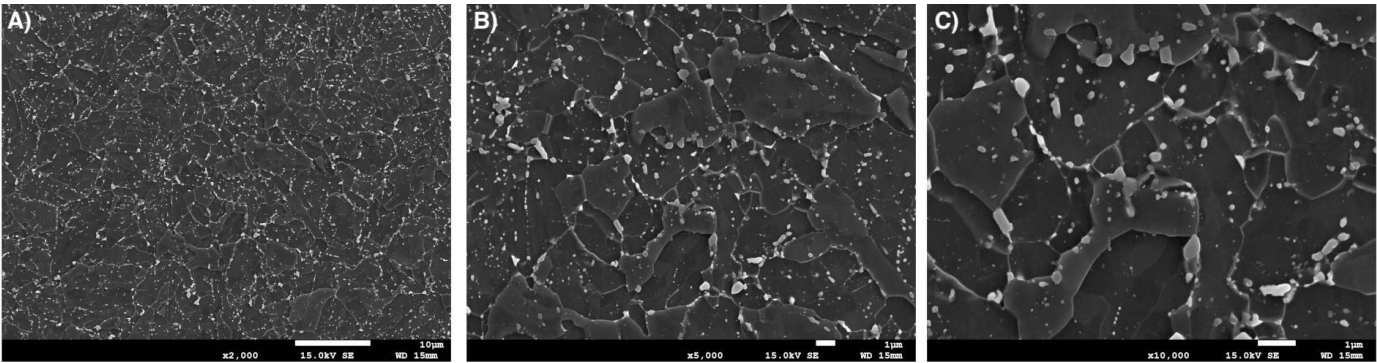


Fig. 5. Microstructure of heat affected zone after annealing for 10,000 h at 650°C, A) mag 2.000×, B) mag 5.000× and C) mag 10.000×

To identify the precipitates and their distribution in the material structure after annealing at 650°C for 3000 and 10000 h, EDS element distribution maps were created, like those for the initial state. The analysis of precipitates in the heat-affected zone

of the joint after annealing at 650°C for 10000 h is presented in Fig. 6.

Analysing the elemental maps of MX precipitates, niobium and vanadium, it can be concluded that the number of secondary

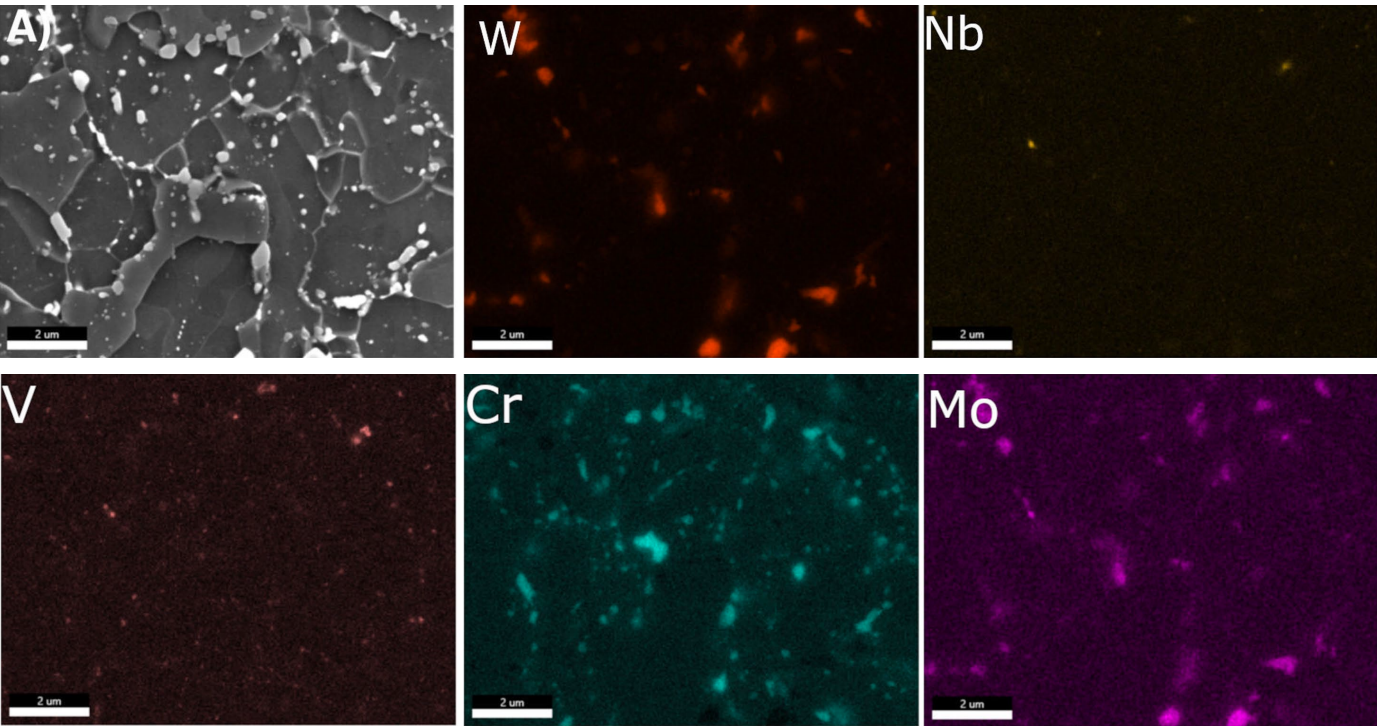


Fig. 6. Chemical composition maps of heat affected zone after annealing for 10,000 h at 650°C, A) – analysed microstructure, W – concentration of tungsten, Nb – concentration of niobium, V – concentration of vanadium, Cr – concentration of chromium, Mo – concentration of molybdenum

precipitates rich in vanadium (probably VN-type precipitates) has increased. A growth of secondary particles is also noticeable, which indicates an ongoing process of microstructural degradation.

The distribution areas of elements forming $M_{23}C_6$ precipitates, chromium, molybdenum, tungsten are also presented in Fig. 6. Comparing the chromium concentration to the initial state, an increase in locations where chromium accumulates can be observed, along with a noticeable growth in the size of these clusters. One can also discern densification of elements forming Laves phases in locations where the concentration of primarily molybdenum and tungsten overlap. The annealing temperature increased to 650°C accelerated diffusion and precipitation processes, resulting in visible effects in the form of more advanced phenomena, such as: continuous chains of precipitates along prior austenite grain boundaries and martensite laths. A locally stronger concentration of individual elements is also evident.

The quantitative analysis of the precipitates using the image analysis system is presented in Fig. 7. The analysis of image in the program provided image data such as quantity and surface area of individual precipitates.

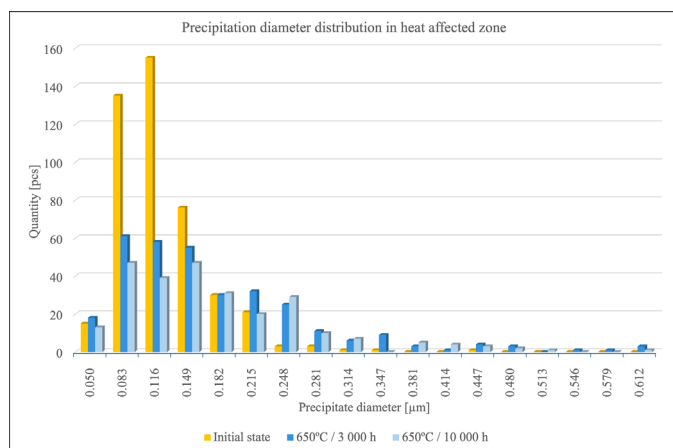


Fig. 7. Results of diameter measurements in heat affected zone of weld

Annealing of the joint at 650°C causes a decrease in the minimum diameter of precipitates and a significant increase in the observed maximum precipitate size (up to 605 nm after annealing for 10000 h). Extending the annealing time at 650°C increases the growth dynamics, with an average of 47% larger precipitates observed. The initially noticeable dynamic process of precipitate growth gradually slows down over time, which is a characteristic effect for P92 steel [3,4,6,14,20,21].

Strength properties were tested using a static tensile test in all sample configurations – in the initial state, after annealing for 3,000 h at 650°C and for 10,000 h at 650°C. The results are presented in Fig. 8. All the tested samples achieved minimum values given in the PN-EN 10216-2 for offset yield determined at 0.2% plastic elongation (min. $R_{p0.2}$ = 440 MPa) and tensile strength (min. R_m = 620 MPa).

To achieve high strength properties and creep resistance in high-chromium martensitic steels, including the studied P92

steel, various strengthening mechanisms are utilized, including precipitation hardening. In the initial state of P92 steel, two types of particles are observed that significantly influence the material's strengthening: $M_{23}C_6$ carbides and MX precipitates. During operation at elevated temperatures, secondary phases precipitate, which usually negatively affect the material's performance properties. It can be seen also in the results of tensile tests presented in Fig. 8.

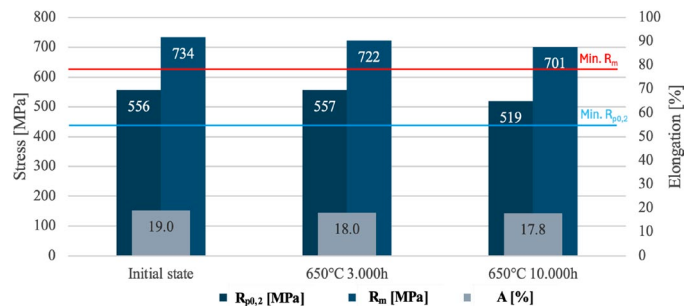


Fig. 8. Tensile testing results

For samples annealed at 650°C for 3000 h, a decrease in tensile strength of 1.6% was recorded, while the yield strength value remained constant. The results of mechanical properties for the joint annealed for 10000 h at 650°C indicate a greater dynamic of property decline, with a 7% decrease in yield strength and a 4% decrease in tensile strength. Despite the discussed decrease in $R_{p0.2}$ and R_m values for all material states, the welded joint after annealing still meets the requirements for the base material according to the PN-EN 10216-2 standard.

5. Conclusions

- The X10CrWMoVNb9-2 (P92) steel undergoes significant microstructural changes during annealing at 650°C, with more pronounced effects observed after longer exposure times (10,000 h vs. 3,000 h).
- Annealing at 650°C leads to an increase in secondary precipitates, particularly vanadium-rich (likely VN-type) precipitates, growth of existing particles and Laves phase forming. This indicates ongoing microstructural degradation.
- In the initial state, MX-type carbides are found within martensite laths and at subgrain boundaries, while $M_{23}C_6$ carbides are located at prior austenite grain boundaries and martensite lath boundaries. After prolonged annealing, precipitates form continuous chains along these boundaries.
- The quantitative image analysis of precipitates in P92 steel reveals a complex evolution of particle size distribution during long-term annealing at 650°C. While the minimum precipitate diameter decreases, there is a significant increase in the maximum precipitate size, reaching up to 605 nm after 10,000 h of annealing. This indicates a simultaneous process of new precipitate nucleation and substantial growth of

existing particles. This precipitate evolution likely impacts the material's mechanical properties and microstructural stability during long-term high-temperature service.

- Mechanical property changes after annealing at 650°C results in a gradual decrease in mechanical properties. After 10,000 h, there's a 7% decrease in yield strength and a 4% decrease in tensile strength compared to the initial state.
- Despite the observed microstructural changes and decrease in mechanical properties, the welded joint after annealing still meets the requirements for the base material according to the PN-EN 10216-2 standard.

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