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INFLUENCE OF LONG-TERM ANNEALING ON MICROSTRUCTURE AND CREEP PROPERTIES OF P92 STEEL WELDED JOINTS

The study presents an analysis of the relationship between microstructural evolution and creep properties degradation in welded joints made of P92 (X10CrWMoVNb9-2) steel subjected to long-term annealing. The investigated material consisted of butt-welded pipe joints exposed to thermal ageing at 600°C and 650°C for up to 10,000 h.

Microstructural observations were performed using scanning electron microscopy (SEM), while creep behaviour was evaluated using both constant-load tests with strain measurement and accelerated creep rupture tests. The results indicate that degradation processes are strongly temperature-dependent and are particularly intensified in the heat-affected zone (HAZ), where fracture initiation consistently occurs.

The dominant degradation mechanisms include coarsening of $M_{23}C_6$ carbides, dissolution of MX precipitates and recovery of the tempered martensitic structure. These changes lead to a significant increase in creep rate, reaching up to 25.7 times compared to the initial state, and a reduction in creep rupture strength of up to 34%.

A strong correlation between microstructure and creep behaviour was confirmed, indicating that microstructural analysis can be effectively used to assess the residual life of welded joints in high-temperature applications.

Keywords: P92, annealing; SEM analysis; creep testing; microstructural degradation

1. Introduction

The increasing efficiency requirements of modern power generation systems operating under supercritical and ultra-supercritical conditions necessitate the use of advanced materials with high creep resistance [1-4]. In such conditions, the durability of pressure components is primarily governed by time-dependent deformation processes, particularly creep [5-7]. The modelling of strain and stress state under creep conditions further confirms the importance of these processes in high-temperature service [8].

Steel grade P92 (X10CrWMoVNb9-2) belongs to a group of 9-12% Cr martensitic steels and is widely applied in high-temperature installations due to its excellent mechanical properties and resistance to creep. However, welded joints represent the weakest elements of such systems due to their heterogeneous microstructure and susceptibility to degradation [2,9-13].

Particularly critical is the heat-affected zone (HAZ), where microstructural instability during long-term service leads to deterioration of mechanical properties. Previous studies indicate that microstructural changes such as precipitate coarsening and martensite recovery significantly influence creep resistance [14-17].

The aim of this work is to establish a direct relationship between microstructural evolution and creep properties degradation in P92 welded joints subjected to long-term annealing.

2. Research material

The material used in this study consisted of circumferential welded joints made of P92 (X10CrWMoVNb9-2) steel pipes intended for high-temperature pressure applications in modern power units. The investigated joints were designed to reflect the geometry and technological conditions typical for critical components such as main steam pipelines operating under supercritical parameters. Depending on the source material, pipe dimensions in the range of approximately Ø76,1-88,9 mm and wall thickness of 17,5-20,0 mm were considered.

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The welded joints were produced using a combined welding procedure to ensure high structural integrity. The root pass was performed using the Gas Tungsten Arc Welding (GTAW, process 141) technique with a non-consumable tungsten electrode and solid filler wire under an inert shielding atmosphere of pure argon. Subsequent filling passes and the final weld face were deposited using Shielded Metal Arc Welding (SMAW, process 111) with covered electrodes. Such a hybrid welding approach is commonly applied in the fabrication of high-pressure pipeline systems due to its reliability and ability to produce high-quality joints.

During welding, strict technological parameters were maintained. The interpass temperature was controlled within the range of approximately 200-300°C. After welding, the joints were subjected to post-weld heat treatment involving heating to a temperature between 750 and 770°C, holding for 180 minutes, followed by controlled cooling at a rate of about 100-300°C/h. These conditions were selected to achieve optimal microstructural stability and mechanical performance in the initial condition.

The chemical composition of both the base material and welding consumables was consistent with the requirements of relevant standards, including EN 10216-2 for pipes, ISO 3580 for covered electrodes, and EN ISO 21952 for welding wires.

3. Methodology

The objective of the experimental programme was to compare the evolution of the heat-affected zone (HAZ) microstructure in welded joints of P92 steel in the as-received condition and after thermal exposure simulating service conditions of high-pressure steam pipelines. To this end, circumferential welds were sectioned longitudinally and specimens were prepared for both microstructural examination and long-term ageing.

The samples were divided into reference material (initial state) and groups subjected to isothermal exposure at elevated temperature. Annealing was carried out in laboratory furnaces at the Łukasiewicz – Upper Silesian Institute of Technology under controlled conditions. Four time-temperature variants were considered: 3,000 h and 10,000 h at 600°C, representing typical operating conditions, as well as 3,000 h and 10,000 h at 650°C, corresponding to accelerated degradation conditions beyond nominal service limits.

For microstructural analysis, metallographic specimens were prepared from transverse sections of the welded joints in a manner enabling clear identification of weld regions. Standard preparation procedures were applied, including mechanical grinding, polishing and chemical etching. Observations were performed using a high-resolution scanning electron microscope (SEM, JEOL JSM-7200F) equipped with EDS and EBSD detectors, which allowed for detailed characterization of phase morphology, precipitate distribution in both, the initial and aged conditions.

The influence of thermal exposure on mechanical performance was evaluated by means of creep testing conducted in accordance with PN-EN ISO 204:2018 standard. The experiments were performed using single-specimen creep testing systems equipped with automated control and measurement units for temperature and deformation. The apparatus enabled stable testing conditions with temperature deviations not exceeding ±0.5°C in the main operating range, ensured by a multi-point thermocouple system. Load application was achieved through lever-based mechanisms, while specimen elongation was continuously monitored using high-precision extensometers with inductive displacement sensors.

Two complementary testing approaches were adopted. In the first, creep deformation was recorded continuously at 600°C under a constant stress of 120 MPa, allowing determination of steady-state creep rates. In the second approach, accelerated creep rupture tests were carried out at 650°C under stresses ranging from 80 to 140 MPa, without continuous strain measurement, in order to determine time to failure and evaluate creep rupture strength.

Based on the experimental results, extrapolation procedures were applied to estimate creep rupture strength for extended service durations of 10,000 and 100,000 hours. The obtained values were compared with the properties of the material in the initial condition as well as with standard reference data for seamless pipes intended for high-temperature applications. This combined methodology enabled a direct assessment of the relationship between microstructural evolution during annealing and the degradation of creep resistance.

4. Results

Creep behaviour of welded joints made of P92 steel was evaluated through a series of long-term and accelerated tests, with particular attention paid to the influence of prior thermal exposure on deformation kinetics and failure mechanisms. Tests performed at 600°C under an applied stress of 120 MPa revealed that all specimens, regardless of their initial or annealed condition, failed within the heat-affected zone (HAZ), confirming this region as the most critical in terms of structural integrity.

The preferential failure of the HAZ is closely related to its microstructural instability under prolonged exposure to elevated temperature. In the Fig. 1, observations of the microstructure of the heat-affected zone in the initial state are presented. Detailed observations of heat affected in after annealed-state (Figs. 2 and 3) indicate that high-temperature annealing, especially at 650°C for extended durations, promotes intensive coarsening of carbide precipitates. In particular, $M_{23}C_6$ particles grow along prior austenite grain boundaries and martensitic laths, while fine MX precipitates gradually dissolve. These processes are accompanied by partial recovery of the tempered martensitic structure, leading to a decrease in dislocation density and formation of localized softened regions. As a result, the HAZ becomes the weakest part of the welded joint.

The quantitative results of creep deformation tests with continuous strain measurement are summarized and illustrated in Fig. 4. The reference (initial) condition exhibited a steady-

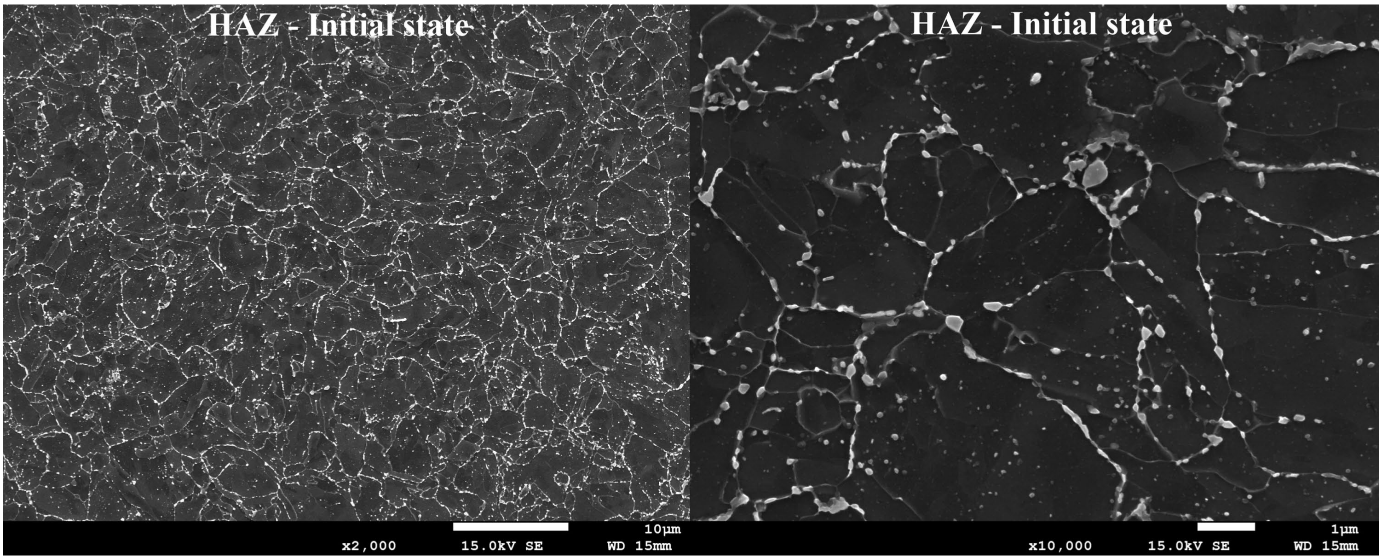

Fig. 1. Microstructure of HAZ in initial state – SEM images

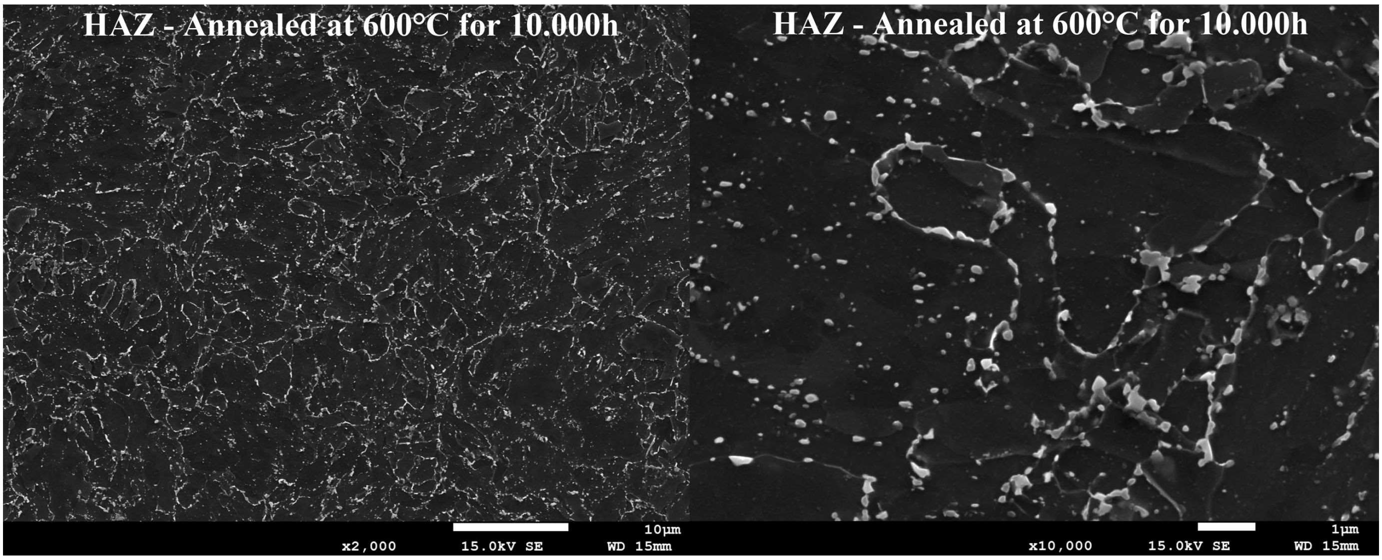

Fig. 2. Microstructure of HAZ after annealing at 600°C for 10.000 h – SEM images

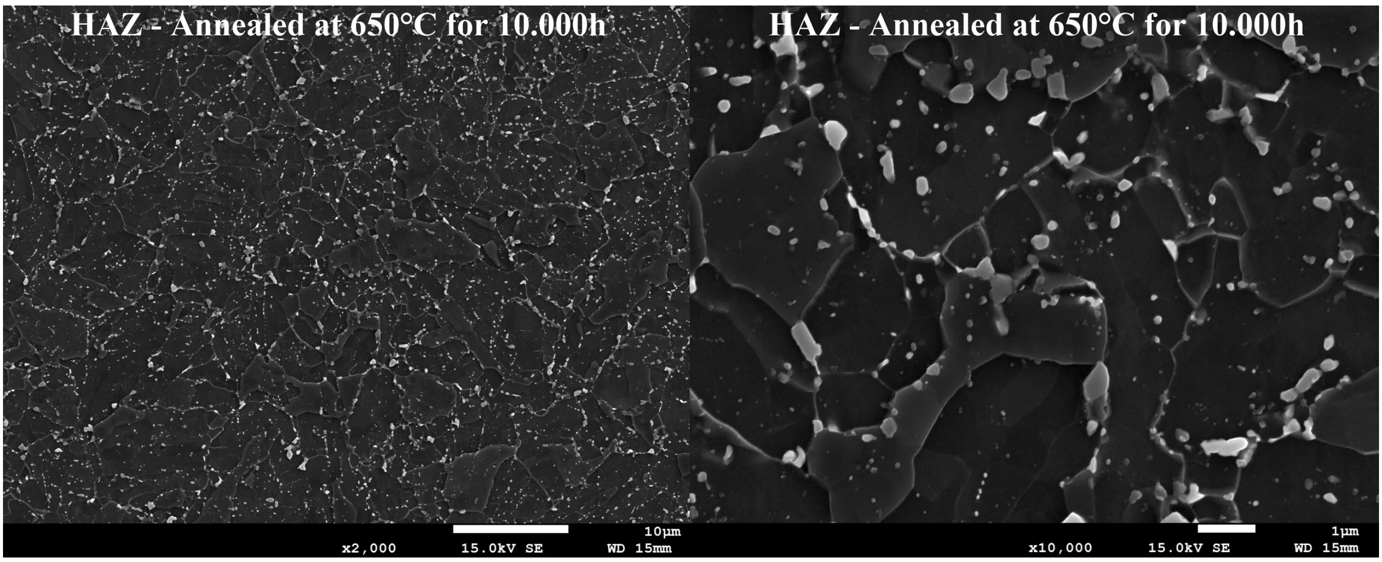

Fig. 3. Microstructure of HAZ after annealing at 650°C for 10.000 h – SEM images

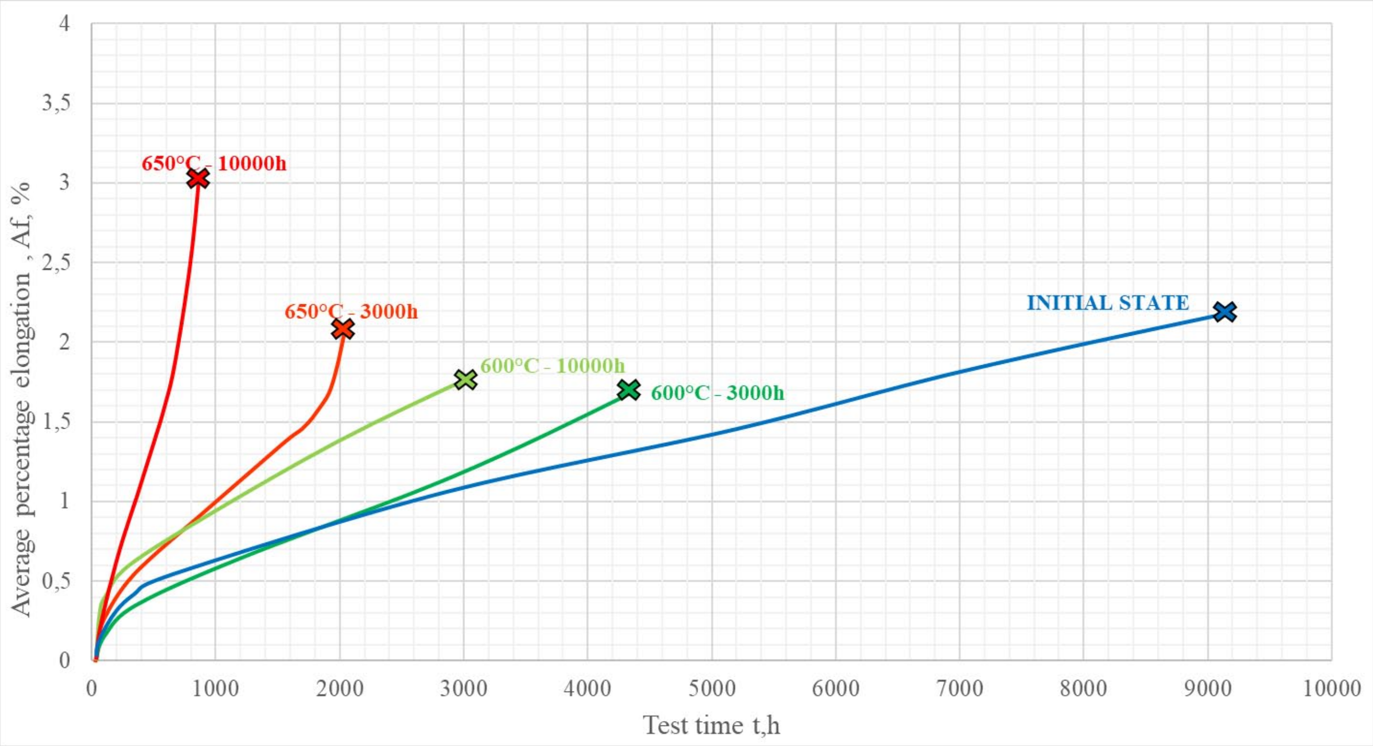

Fig. 4. Creep curves with elongation measurement for different annealing conditions, creep tests at 600°C / 120 MPa

state creep rate of 16.3×10^{-5} %/h. Thermal exposure at 600°C resulted in a moderate increase in creep rate: after 3,000 hours the value rose to 41.9×10^{-5} %/h, while after 10,000 hours it reached 42.9×10^{-5} %/h, corresponding to approximately 2.6-fold acceleration.

A significantly stronger effect was observed for specimens annealed at 650°C. After 3,000 hours, the creep rate increased to 78.3×10^{-5} %/h (approximately 4.8 times higher than the baseline), whereas prolonged exposure for 10,000 hours resulted in a dramatic increase to 418.8×10^{-5} %/h. This corresponds to more than a 26-fold acceleration of the creep process, indicating advanced degradation of the material.

The obtained creep curves clearly demonstrate that both temperature and exposure time have a pronounced effect on deformation behaviour. Increasing annealing parameters leads to faster attainment of steady-state creep and a reduction in time to failure, reflecting progressive deterioration of material properties.

To further assess durability loss, accelerated creep rupture tests were conducted at 650°C under stress levels ranging from 80 to 140 MPa. The results are presented in in the form of logσ versus log t relationships in Fig. 5.

Based on the experimental data, mathematical relationships were established and used for extrapolation of creep rupture strength to long-term service conditions of 10,000 and 100,000 hours. The calculated values provide a quantitative measure of degradation as a function of annealing time and temperature.

Comparative analysis shows a systematic reduction in creep strength with increasing exposure severity. For specimens annealed at 600°C, the reduction in creep rupture life was estimated at approximately 13% after 3,000 hours and 17% after 10,000 hours. In contrast, exposure at 650°C resulted in significantly greater degradation, reaching 25% and 34% for 3,000 and 10,000 hours, respectively.

The obtained values were also compared with standard creep strength data specified for base material in EN 10216-2 [18,19]. For example, at 650°C and 10,000 hours, the standard value of raw material pipe 88 MPa contrasts with the experimentally determined welded joint strength of 62 MPa, corresponding to approximately 70% of the base material performance. A similar trend was observed for 100,000-hour extrapolation, where the joint retained about 82% of the nominal strength.

The combined results of microstructural observations and mechanical testing clearly demonstrate that degradation processes are strongly dependent on annealing conditions. Specimens exposed to 650°C exhibit significantly higher susceptibility to creep damage due to accelerated microstructural evolution, including precipitate coarsening and matrix recovery.

Accelerated creep tests provided a reliable basis for estimating long-term performance and confirmed that the extent of degradation increases with both temperature and time of exposure. Among all investigated variants, the most severe deterioration was observed for specimens annealed at 650°C for 10,000 hours.

Importantly, fracture consistently occurred in the HAZ for all tested conditions, highlighting the critical role of this region in determining the service life of welded joints [20]. This observation confirms that detailed characterization of HAZ microstructure is essential for reliable life assessment of high-temperature components [14].

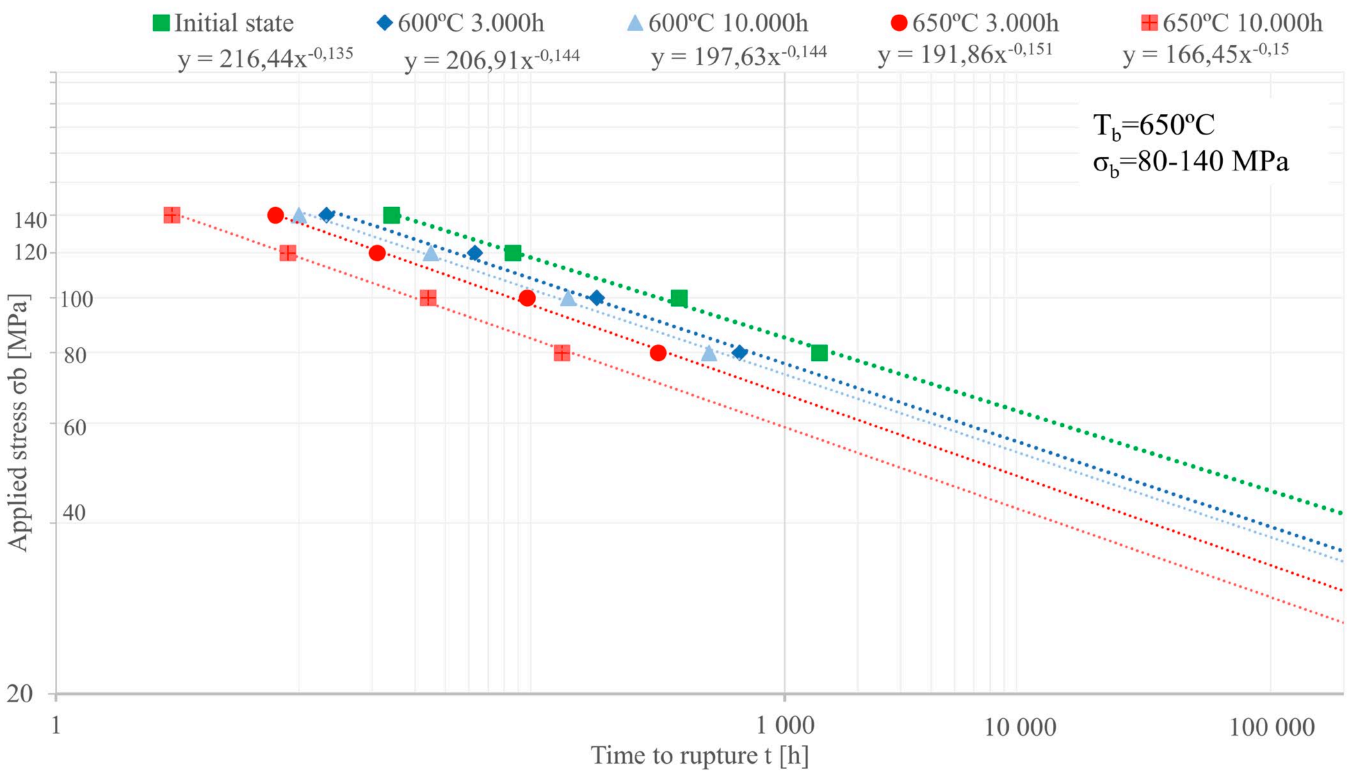

Fig. 5. Accelerated creep rupture tests at 650°C under stress levels ranging from 80 to 140 MPa

5. Conclusions

- No voids, microcracks or discontinuities were detected in the heat-affected zone (HAZ), indicating that the observed degradation of creep properties is primarily controlled by microstructural evolution rather than damage accumulation.
- Long-term annealing at 600°C for 10,000 h resulted in only minor microstructural changes, mainly limited to slight precipitate evolution along prior austenite grain boundaries and martensitic laths, which corresponds to a moderate increase in creep rate and limited reduction in creep life.
- Significantly more pronounced degradation was observed after annealing at 650°C, confirming that elevated temperature strongly accelerates diffusion-controlled processes affecting creep resistance.
- Coarsening and coalescence of precipitates, particularly $M_{23}C_6$ carbides, reduce the effectiveness of strengthening mechanisms, leading to a substantial increase in creep rate.
- Microstructural changes occurring in the HAZ, including partial recovery of the martensitic structure and reduction in dislocation density, are responsible for local weakening and determine the preferential fracture location.
- Increasing annealing temperature and time leads to a systematic acceleration of creep deformation and a corresponding reduction in time to rupture.
- The most severe degradation of creep properties was observed for specimens annealed at 650°C for 10,000 h, highlighting the critical role of temperature in long-term material stability.
- The results confirm a strong correlation between microstructural evolution and creep behaviour, indicating that microstructural analysis can be effectively used for predicting the service life of welded joints operating under creep conditions.

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