

STUDY OF MICROSTRUCTURE CHANGES CAUSED BY LONG-TERM THERMAL AGING OF SELECTED NUCLEAR POWER PLANT COMPONENTS

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Abstract

The long-term global trend in energy consumption indicates that the gradual shutdown of nuclear power units after reaching their planned service life may increase the risk of power outages. One effective way to mitigate this risk is to extend the operation of nuclear units beyond their originally designed lifetime. A crucial prerequisite for reliable long-term operation is a detailed understanding of degradation processes occurring in structural materials, particularly microstructural changes induced by prolonged thermal exposure and the associated changes in the mechanical and physical properties of nuclear power plant materials. The present study focuses on secondary phase precipitation in austenitic steels 08CH18N10T and 08CH18N12T exposed to real operating conditions for 28 years. The results were systematically compared with those obtained for a reference, non-operated material to identify possible differences in the extent and character of precipitation. Experimental observations performed using transmission electron microscopy (TEM) were complemented by quantitative statistical analysis of microstructural parameters. The obtained results indicate a high degree of microstructural stability of the investigated steel even after prolonged thermal exposure. No significant differences in either the nature or the number of precipitates were observed between the operated and reference materials, confirming the material's good resistance to long-term thermal ageing and supporting its suitability for extended operation of nuclear facilities.

Keywords: Austenitic steel 08CH18N10T, austenitic steel 08CH18N12T, nuclear power plant materials, long-term thermal ageing, secondary phase precipitation

1. INTRODUCTION

Austenitic steels are widely used engineering materials due to their favorable combination of properties. They are applied across various industries, particularly in the chemical, petrochemical, and energy sectors, as well as in cryogenic applications, heat exchangers, automotive exhaust systems, aerospace structures, and other fields [1]. In applications where materials are exposed to elevated temperatures, attention must be paid to sensitization, involving precipitation of chromium carbides ($M_{23}C_6$) along grain boundaries and localized chromium depletion, reducing corrosion resistance in these regions. To suppress this effect, stabilizing elements – particularly titanium or niobium – are added to certain austenitic steels. These elements exhibit a higher affinity for carbon than chromium and preferentially form stable carbides such as TiC or NbC, thereby preventing the formation of chromium carbides ($M_{23}C_6$) and enhancing the steel's resistance to sensitization during long-term service at elevated temperatures [1-3].

Austenitic steels are widely used as structural materials in primary circuit components of nuclear power plants. In VVER-440 reactors, they are exposed to typical operating pressures ranging from 12.26 MPa to 13.73 MPa and temperatures between 267 °C and 300 °C, with a maximum temperature of 325 °C [4]. The operating conditions of nuclear power plants are thus characterized by long-term exposure to elevated temperatures and

pressures which, in combination with a corrosive environment, impose both thermal and mechanical loading on the material. Under cyclic loading, it is difficult to observe any gradual changes in the material's microstructure, and failure may occur abruptly, without clear indications of impending degradation [5].

These conditions can lead to progressive material degradation, such as low-temperature precipitation of secondary phases or changes in mechanical properties. The aim of this paper is to analyse the microstructural characteristics and microhardness of austenitic steel used in primary circuit components and to compare the material state before and after long-term operation.

2. MATERIALS AND METHODS

2.1 Sample Information

Within this study, two pairs of samples from the Jaslovské Bohunice Nuclear Power Plant in the Slovak Republic were analysed. The first pair (MCP-0 and MCP-28) comes from main circulation piping (MCP) made of 08CH18N12T steel; MCP-0 is as-received (unexposed), while MCP-28 was taken after 28 years of operation from the decommissioned V1 unit. The second pair (PSL-0 and PSL-28) originates from the pressurizer surge line (PSL), made of 08CH18N10T steel; PSL-0 represents the unexposed condition for unit EBO3, whereas PSL-28 was obtained after 28 years of operation from V1.

An overview of sample designations, materials, origin, and operational condition is provided in **Table 1**. These samples enable comparison of microstructural and mechanical changes induced by long-term operation of a VVER-440 reactor.

Table 1 Sample Designation

No.	Material	Origin	Operational Status
MCP-0	08CH18N12T	Main circulation piping	Initial State (NPP V1)
MCP-28	08CH18N12T	Main circulation piping	Operated for 28 years (NPP V1)
PSL-0	08CH18N10T	Pressurizer surge line	Initial State (NPP EBO3)
PSL-28	08CH18N10T	Pressurizer surge line	Operated for 28 years (NPP V1)

The indicative chemical compositions of the investigated steels are summarized in **Table 2** and **Table 3**.

Table 2 Guideline Chemical Composition of Steel 08CH18N12T [6]

Element content (wt%)									
C	Si	Mn	Cr	Ni	Ti	Co	S	P	Cu
max. 0.08	max. 0.80	max. 2.0	17.0- 19.0	11.0- 13.0	5xC- 0.60	max. 0.050	max. 0.020	max. 0.035	max. 0.30

Table 3 Guideline Chemical Composition of Steel 08CH18N10T for Piping [7]

Element content (wt%)									
C	Si	Mn	Cr	Ni	Ti	Co	S	P	N
max. 0.08	max. 0.80	max. 1.50	17.0- 19.0	9.0- 11.0	5xC- 0.60	max. 0.050	max. 0.020	max. 0.035	max. 0.050

2.2 Optical Microscopy

The microstructure of the steel samples was examined using optical microscopy. Prior to analysis, the specimen surfaces were prepared using standard metallographic procedures consisting of multi-stage grinding

with SiC papers (P280, P600, P1200), followed by polishing with diamond suspensions (9 µm, 3 µm). To reveal the microstructure, electrolytic etching was performed in a 10% solution of oxalic acid in distilled water.

2.3 Microhardness Measurement

Vickers microhardness (HV5) was measured using a QATM QNESS 10A instrument. Ten indentations were performed on each specimen. The average microhardness and standard deviation were calculated from the measured values. The obtained microhardness values were used to assess potential changes in mechanical properties associated with microstructural evolution during long-term service exposure.

2.4 Transmission Electron Microscopy (TEM)

Specimens intended for TEM observation were first mechanically thinned to a thickness of 90 µm, followed by punching of 3 mm diameter discs. The discs were subsequently further thinned by electrochemical polishing using a TenuPol-5 system. An electrolyte consisting of 30 vol.% HNO₃ and 70 vol.% CH₃OH was used at a voltage of 15 V and a temperature of -20 °C. TEM investigations were performed at an accelerating voltage of 200 kV. Microstructures were examined in bright-field (BF) and dark-field (DF) imaging modes, enabling detailed analysis of grain boundary precipitates and particle morphology. The analysis was complemented by selected area electron diffraction (SAED) for identification of individual structural constituents.

2.5 Quantitative Analysis of Precipitate Distribution

Since long-term service exposure of austenitic steels is expected to manifest primarily through precipitation and evolution of secondary phases, especially in terms of their size, distribution, and number density, the experimental work was extended to include their quantitative evaluation. Morphological and stereological parameters were defined to describe the precipitate population in the microstructure. Stereological methods were used for statistical evaluation, enabling quantification of precipitate size and spatial distribution from two-dimensional microscopic images [8]. The evaluated parameters were calculated using equations (1–4):

$$D = \frac{L_N}{N} \quad (\text{nm}) \quad (1)$$

$$N_A = \frac{N}{A} \quad (\text{nm}^{-2}) \quad (2)$$

$$N_V = \frac{N_A}{t} \quad (\text{nm}^{-3}) \quad (3)$$

$$L = \frac{1}{\sqrt{N_V \cdot D}} - \sqrt{\frac{2}{3}} D \quad (\text{nm}) \quad (4)$$

where D is the average particle size, L_N is the total measured particle length (sum of particle sizes), N is the number of particles, N_A is the number of particles per unit area, A is the analysed area, N_V is the number of particles per unit volume, t is the TEM foil thickness (100 nm), and L represents the mean interparticle spacing.

Image analysis for quantitative evaluation of precipitate size distribution was performed using ImageJ software.

3. RESULTS

3.1 Optical Microscopy

The optical microscopy images (**Figure 1**) present a comparative overview of the microstructure of the investigated steels in the unoperated and 28-year operated conditions, revealing a fully austenitic matrix with no evident macroscopic degradation or significant differences attributable to long-term thermal exposure.

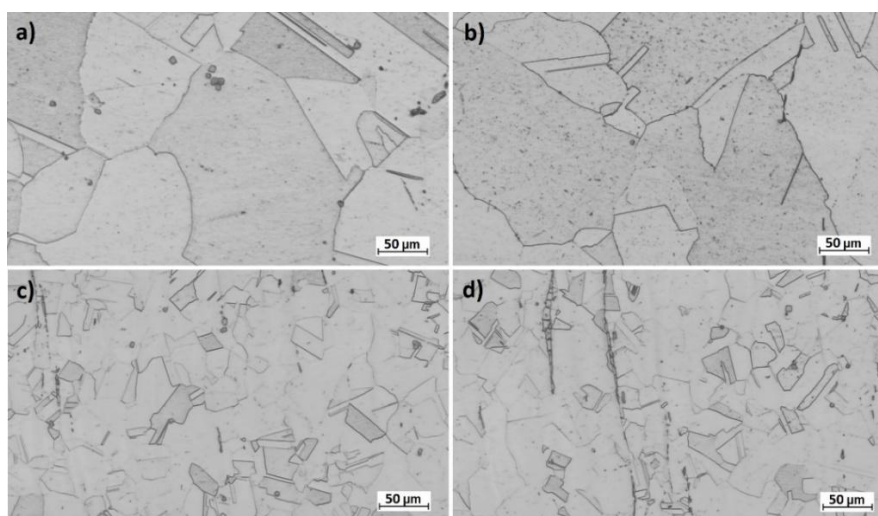


Figure 1 Optical microstructures of 08CH18N12T and 08CH18N10T steels in unoperated and long-term operated conditions, a) MCP-0, b) MCP-28, c) PSL-0, d) PSL-28

The MCP samples (a, b) exhibit a coarse-grained heterogeneous austenitic microstructure with stabilized carbides distributed within the matrix. Larger particles can be attributed to titanium carbides, while fine dispersed features likely correspond to additional carbide precipitates. The PSL samples (c, d) are characterized by a predominantly austenitic microstructure with a relatively finer grain size compared to the MCP material, with elongated features corresponding to δ -ferrite locally observed, as well as the presence of carbide particles. No significant differences in grain morphology, carbide distribution, or overall microstructural characteristics were identified between the unoperated and 28-year operated conditions in either material, indicating that long-term thermal exposure did not result in observable microstructural degradation at the optical microscopy level.

3.2 Microhardness Measurement

The Vickers microhardness (HV5) results are shown in **Figure 2**. The 08CH18N12T steel exhibited a slight decrease from approximately 144 HV5 (MCP-0) to 135 HV5 (MCP-28), though this difference is not statistically significant considering the error bars. In the case of 08CH18N10T steel, the values remained nearly unchanged at about 170 HV5 for both the initial (PSL-0) and operated (PSL-28) conditions. Overall, the results indicate good mechanical stability of both steels after long-term operation, with no significant hardening or softening.

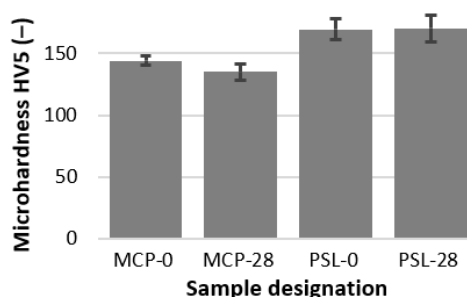


Figure 2 Vickers microhardness (HV5) of investigated steels in unoperated and 28-year operated conditions

3.3 Transmission Electron Microscopy (TEM) and Quantitative Analysis of Precipitate Distribution

Transmission electron microscopy (TEM) was used to study secondary phase precipitation in the investigated austenitic steels after long-term thermal exposure, focusing on particle morphology and distribution at the nanoscale. Representative TEM images are shown in **Figure 3**.

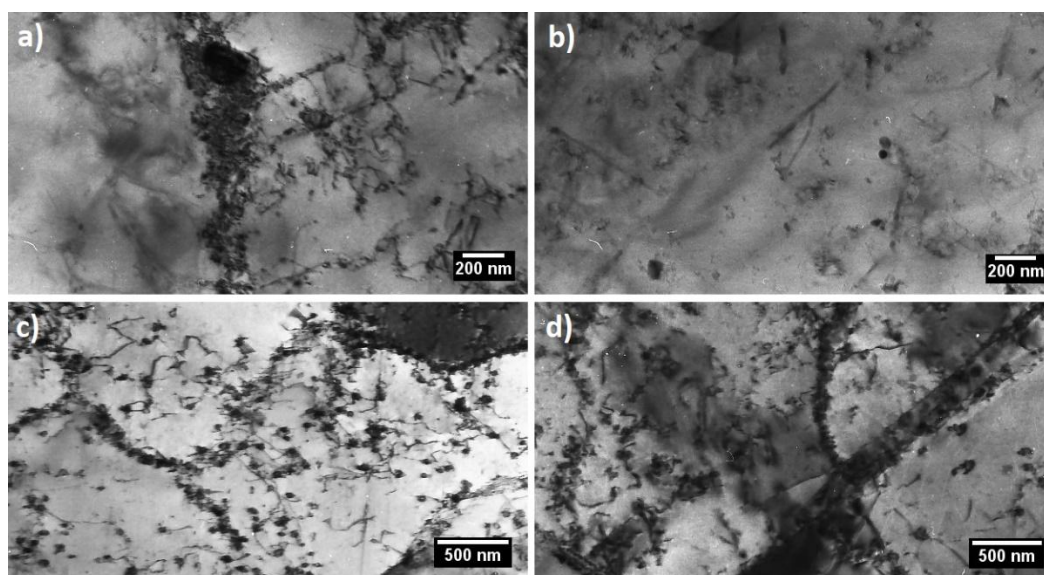


Figure 3 TEM microstructural images of 08CH18N12T and 08CH18N10T steels in unoperated and long-term operated conditions, a) MCP-0, b) MCP-28, c) PSL-0, d) PSL-28

To describe precipitation behavior in more detail, a quantitative analysis of precipitate size and distribution was performed based on TEM image processing. Particle size distributions were obtained and are presented in **Figure 4**. The results show a broad size range with no significant shift between unoperated and operated conditions, indicating that long-term thermal exposure did not cause substantial precipitate coarsening.

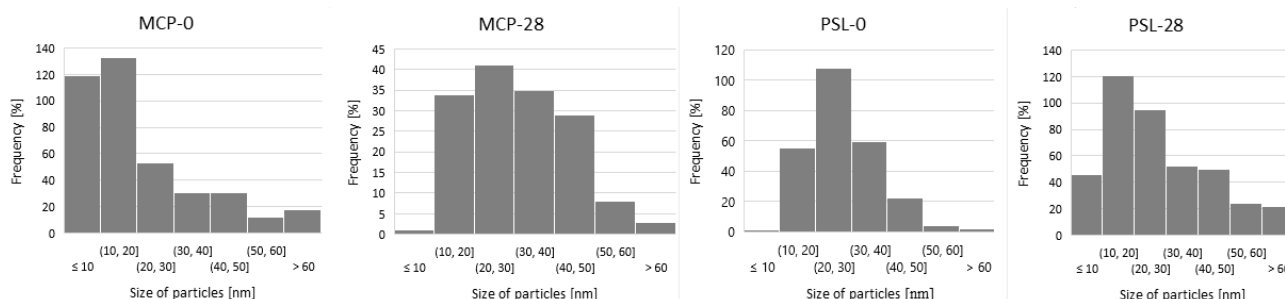


Figure 4 Particle size distribution histograms of precipitates (TEM analysis)

The quantitative stereological parameters derived from the TEM analysis are summarized in **Table 4**. The average precipitate size (D) ranges from approximately 21 nm to 31 nm, depending on the material and condition. A slight increase in particle size was observed in some operated samples; however, this change remains within the range of statistical uncertainty. The number density of particles (N_A and N_V) remains comparable for all investigated states, confirming that no significant change in precipitation intensity occurred during long-term operation.

Table 4 Precipitate size and distribution parameters obtained by TEM

Samopale	D (nm)	N_A (nm ⁻²)	N_V (nm ⁻³)	L (nm)
MCP-0	21 ± 16	$(3.98 \pm 0.20) \times 10^{-5}$	$(3.98 \pm 0.20) \times 10^{-7}$	329 ± 149
MCP-28	31 ± 12	$(3.03 \pm 0.25) \times 10^{-5}$	$(3.03 \pm 0.25) \times 10^{-7}$	299 ± 76
PSL-0	28 ± 10	$(1.98 \pm 0.13) \times 10^{-5}$	$(1.98 \pm 0.13) \times 10^{-7}$	405 ± 88
PSL-28	28 ± 20	$(2.16 \pm 0.10) \times 10^{-5}$	$(2.16 \pm 0.10) \times 10^{-7}$	380 ± 160

The calculated mean interparticle spacing L further supports the conclusion of a stable precipitate distribution, with only minor variations between unoperated and operated conditions. These findings are consistent with the microhardness results and optical microscopy observations, all indicating negligible microstructural degradation. The parameter D exhibits high standard deviation values, indicating a wide scatter in precipitate sizes due to microstructural heterogeneity; therefore, particle size distribution histograms provide a more representative description than the average value alone. The relatively high standard deviation of the interparticle spacing L is caused by the propagation of uncertainties from both particle size D and number density N_v , as well as by the inherent heterogeneity of precipitate distribution in the microstructure.

4. CONCLUSION

This study evaluated microstructural changes in austenitic steels 08CH18N12T and 08CH18N10T after 28 years of service under VVER-440 operating conditions. Optical microscopy, transmission electron microscopy (TEM), and microhardness measurements consistently revealed no significant microstructural degradation. Both materials retained a fully austenitic structure without evidence of grain boundary deterioration, phase transformation, or other instabilities. TEM analysis confirmed a stable distribution of secondary phases, with no significant changes in precipitation intensity, particle size, or morphology compared to the unoperated condition. Microhardness values showed only minor variations within experimental scatter, indicating negligible influence of long-term operation on mechanical properties. Overall, the investigated steels exhibit a high degree of microstructural stability and resistance to thermal ageing, supporting their suitability for long-term application and potential lifetime extension of nuclear power plant primary circuit components.

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