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REMAINING LIFE ASSESSMENT OF LONG-TERM EXPLOITED St.35.8/II BOILER SCREEN TUBES VIA AN INTEGRATED MICROSTRUCTURAL DEGRADATION AND CREEP MODEL

PROCENA PREOSTALOG VEKA DUGOTRAJNO EKSPLOATISANIH KOTLOVSKIH EKRANSKIH CEVI OD ČELIKA St.35.8/II PRIMENOM INTEGRISANOG MODELA PUZANJA I OŠTEĆENJA MIKROSTRUKTURE

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Keywords
- St.35.8/II boiler steel
- remaining life assessment
- Wedel-Neubauer classification
- in-situ replica metallography
- hardness anomaly

Abstract

This paper presents a comprehensive methodology for the remaining life assessment of carbon steel St.35.8/II boiler screen tubes after an extreme operating lifetime of 306,581 hours. The assessment is carried out using non-destructive in-situ plastic replica metallography and Brinell hardness tests. The investigated boiler screen tubes located at an elevation height of 10 m are directly exposed to the highest heat flux inside the furnace where actual tube wall temperatures exceed the nominal fluid parameters of 300 °C and enter the creep regime and exhibit advanced microstructural degradation. This is characterised by progressive-to-complete spheroidisation of pearlite colonies and continuous accumulation of secondary carbide networks along ferrite grain boundaries. Measured in-situ hardness on these degraded regions reaches up to 174 HB, which is attributed to a combination of secondary phase carbide dispersion and surface work-hardening artifacts introduced during in-situ mechanical grinding preparation. Conversely, optical microscopy examination of surface replicas up to 500× magnification reveals no oriented creep cavitation pores, formally classifying the tubes as Class 0 (undamaged condition) according to the conventional Wedel-Neubauer creep classification scheme. The study highlights a critical safety limitation where traditional models based solely on cavitation underestimate the risk of premature brittle failure in low-carbon boiler steels. Consequently, a modified engineering assessment model incorporating carbide morphology parameters is proposed to prevent catastrophic intergranular failure.

Ključne reči
- kotlovski čelik St.35.8/II
- procena preostalog veka
- Vedel-Nojbauerova klasifikacija
- metalografija replika in-situ
- anomalija tvrdoće

Izvod

Ovaj rad predstavlja sveobuhvatnu metodologiju za procenu preostalog veka trajanja kotlovskih ekranskih cevi od ugljeničnog čelika St.35.8/II nakon ekstremnog radnog veka od 306.581 sati. Procena je sprovedena korišćenjem in situ plastične replike metalografije bez razaranja i Brinel ispitivanja tvrdoće. Ispitivane kotlovske ekranske cevi se nalaze na visini od 10 m i direktno su izložene najvećem toplotnom fluksu unutar kotla, gde stvarne temperature zidova cevi prelaze nominalne parametre od 300 °C i ulaze u režim puzanja i pokazuju uznapredovalu mikrostrukturnu degradaciju. Ovo je okarakterisano progresivnom do potpunom sferoidizacijom perlitnih kolonija i kontinuiranim nagomilavanjem sekundarnih karbidnih mreža na granicama feritnih zrna. Izmerena in situ tvrdoća u ovim degradiranim oblastima dostiže do 174 HB, što se pripisuje kombinaciji disperzije sekundarne faze karbida i artefakata površinskog očvršćavanja uvedenih tokom faze mehaničke pripreme brušenja. S druge strane, optičko-mikroskopsko ispitivanje površinskih replika do 500× ne otkriva orijentisane kavitacione pore puzanja, što prema konvencionalnoj Vedel-Nojbauerovoj šemi klasifikacije puzanja formalno klasifikuje cevi kao Klasa 0 (neoštećeno stanje). U radu se ističe kritično bezbednosno ograničenje gde se tradicionalnim modelima, zasnovanim isključivo na kavitaciji, potcenjuje rizik od prevremenog krtog loma kod niskougljeničnih kotlovskih čelika. Shodno tome, predložen je modifikovani model inženjerske procene koji sadrži parametre morfologije karbida kako bi se sprečio katastrofalni interkristalni lom.

INTRODUCTION

The reliable operation of evaporator and screen tubes in utility boilers is a critical factor for the structural integrity and availability of thermal power plants. Carbon steels, specifically St.35.8/II according to standard DIN 17175 (equivalent to P235GH according to EN 10216-2), have been extensively utilised in the construction of boiler components due to their optimal balance of weldability, thermal conductivity, and mechanical properties under moderate pressures and temperatures /1/. However, when these non-alloyed steels are subjected to extreme service intervals exceeding 300,000 operational hours, they undergo irreversible microstructural aging mechanisms that degrade their elevated-temperature load-bearing capacity, /2-4/.

The Wedel-Neubauer model correlates successive stages of creep damage evolution - specifically the nucleation and growth of isolated creep cavities - with the life fraction consumption ($E = t/t_r$, where t denotes accumulated operating hours and t_r is the time to rupture). This classification framework defines five distinct microstructural states, /5/:

- Class 1 (undamaged, E = 0-0.14): the base metal exhibits no detectable microstructural signs of creep damage, indicating structurally safe operating conditions.
- Class 2 (isolated cavities, E = 0.05-0.47): discrete, micro-sized cavities initiate along the grain boundaries, manifesting as isolated micro-voids within the matrix.
- Class 3 (oriented cavities, E = 0.27-0.53): cavities undergo preferential alignment, forming structured rows oriented parallel to the principal tensile stress axis.
- Class 4 (linked cavities/microcracks, E = 0.29-0.84): cavitation progresses to localised coalescence, where adjacent micro-voids interlink to initiate microcracking.
- Class 5 (macrocracks, E > 0.84): advanced macro-scale cracking becomes prominent, placing the component under an imminent risk of catastrophic structural failure.

Conventionally, high-temperature remaining life assessment relying on non-destructive surface replica metallography uses Wedel-Neubauer /5/ or VGB-TW 507 guidelines /6/. These models are fundamentally based on quantifying the nucleation, orientation, and coalescence of creep cavities (micro-voids) along grain boundaries. While these cavitation-centric models are highly effective for low-alloy creep-resistant steels (e.g., 1Cr0.5Mo or 2.25Cr1Mo) /7/, their direct application to plain carbon steels operates under significant engineering limitations. In low-carbon boiler tubes exposed to local thermal overheating inside the furnace zone, the primary degradation path is often dominated by pearlite spheroidisation and carbide migration rather than typical cavitation /8, 9/. The paper addresses this gap by analysing screen tubes after 306,581 hours of operation, revealing a metallurgical paradox where zero creep cavitation is observed, yet severe microstructural embrittlement has occurred.

MATERIALS AND METHODS

The investigation is conducted on seamless boiler screen tubes made of St.35.8/II steel according to DIN 17175 /1/. The boiler operates under a nominal pressure of 40 bar with a nominal fluid temperature of approximately 300 °C. Five distinct inspection points, designated as R1 through R5, are chosen along the evaporator circuit at different elevation heights (7 m and 10 m) to capture the influence of varying thermal fluxes.

In-situ surface metallography is executed in compliance with ISO 3057 /10/ using the plastic replica technique. Surface preparation /11/ included localised grinding, followed by polishing and chemical etching. Cellulose acetate replicas are examined under laboratory conditions using a light optical microscope. The cellulose acetate replicas are examined in the laboratory using an optical microscope up to 500× magnification. Microscopic analysis of replicas is conducted using a ‘METAVAL’ optical microscope at magnifications of 100× and 500×. Concurrently, hardness measurements are performed directly in-situ at each replica location using a calibrated portable digital TKM 359-S tester operating on the Ultrasonic Contact Impedance (UCI) principle /12/, converting the indentation parameters to Brinell hardness numbers (HB) according to SRPS ISO 6506-1, /13/.

IN-SITU METALLOGRAPHIC REPLICA TECHNIQUE

Surface replication constitutes a non-destructive testing (NDT) methodology enabling the high-resolution characterisation of the microstructural topography of critical engineering components directly in-situ. To ensure the reliability of the metallurgical assessment, the analytical protocol is systematically divided into localised surface preparation and direct single-stage replication phases.

Surface preparation protocol

Components operating under long-term high-temperature exploitation invariably develop robust surface oxidation scales, corrosion products, or localised decarburised layers. To expose the underlying representative bulk microstructure, these degraded layers must be thoroughly removed. Initial coarse grinding is executed using a portable rotary grinder, applying optimised mechanical pressure to mitigate grinding-induced artifacts, such as localised frictional overheating or superficial plastic deformation.

Following the initial ablation of the oxide scale, sequential mechanical polishing is performed using portable field metallographic equipment to replicate rigorous laboratory standards. The surfaces are sequentially ground using silicon carbide (SiC) abrasive disks of progressive grit sizes, followed by diamond paste polishing down to a 1 μm finish on lint-free polishing cloths. Structural features were subsequently developed via chemical etching using a 3 % nital solution tailored to the low-carbon steel matrix.

Direct single-stage plastic replication

Among available replication methodologies (direct single-stage versus indirect multi-stage variants), this investigation utilises the direct plastic replica technique due to its non-destructive nature, exceptional field adaptability, and minimal processing time. Unlike carbon or oxide replicas which can alter or damage the specimen surface upon removal, plastic-based extraction preserves the integrity of a component for subsequent inspection intervals.

The replication sequence involves the application of a high-purity cellulose acetate film, which is briefly softened using an organic solvent (acetone) and uniformly pressed onto the etched metallographic site (as schematically illustrated in Fig. 1. Upon complete solvent evaporation, the hardened polymer film, containing a high-fidelity negative topographic imprint of the microstructure, is carefully peeled. In the laboratory, these replicas are examined using a light optical microscope (LOM) at magnifications up to 500× to assess phase morphology, pearlite degradation, and grain boundary carbide distribution. Schematic mechanism of the single-stage plastic surface replication process and microstructural feature transfer is presented in Fig. 1.

At the top, the application of the polymer film over the etched specimen surface is shown, containing characteristic microstructural relief (carbides, grain boundaries, cracks, and pearlite colonies); (middle) cross-sectional profile of film conformation to the surface topography during replication; (bottom) mechanical peeling of the film, resulting in a high-fidelity negative topographic imprint (carbide, crack, and pearlite images) for subsequent light optical microscopy.

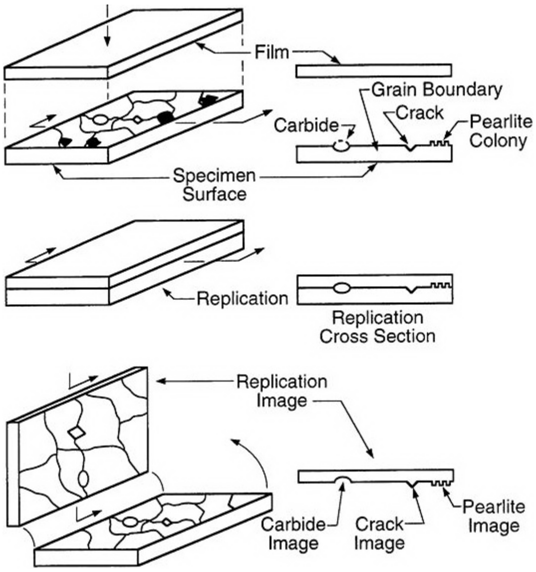
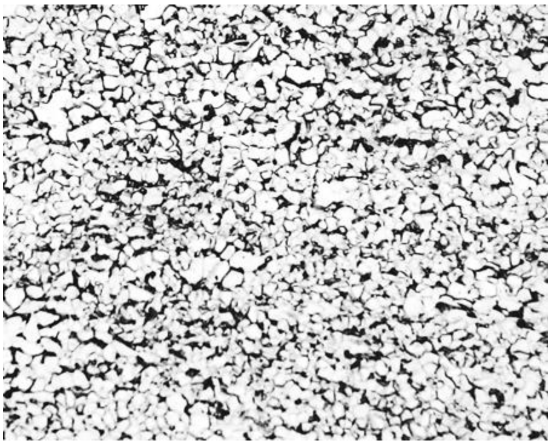


Figure 1. Schematic of the plastic replication mechanism.

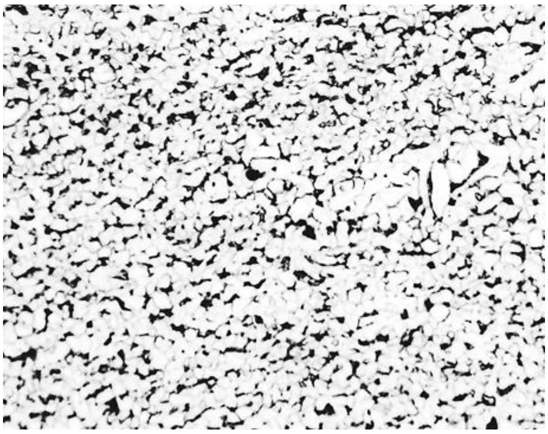
RESULTS AND DISCUSSION

Metallographic evaluation of in-situ plastic replicas taken from boiler screen tubes after 306,581 hours of operation provide critical insights into the localised phase degradation. A detailed view of morphological transformations within the ferrite-pearlite matrix and progressive accumulation of secondary phases along the boundaries for replica points R1 to R5 is compiled and presented in Fig. 2.



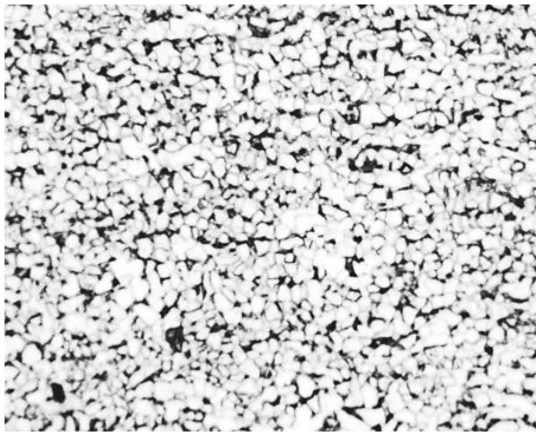
a) Replica R1. Original magnification 100×

b) Replica R1. Original magnification 500×

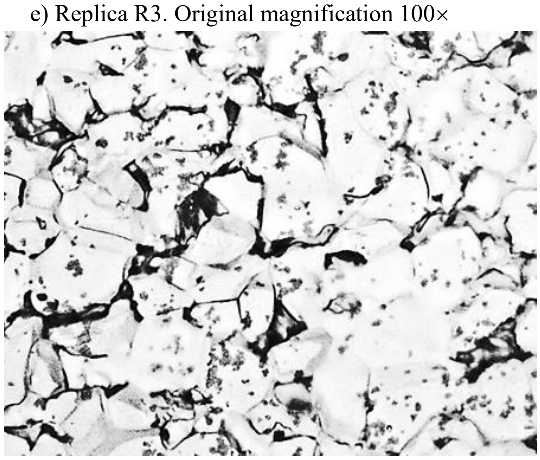


c) Replica R2. Original magnification 100×

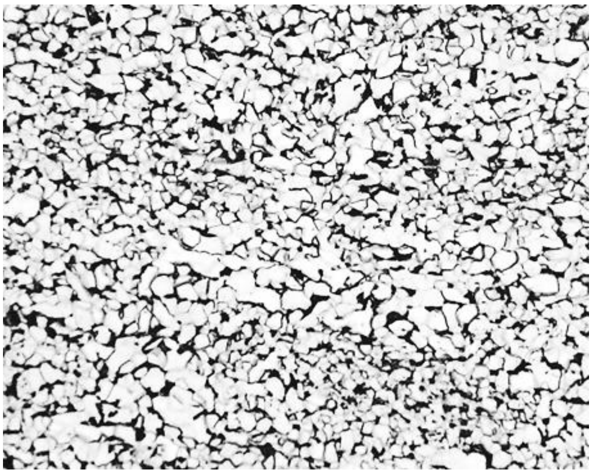
d) Replica R2. Original magnification 500×



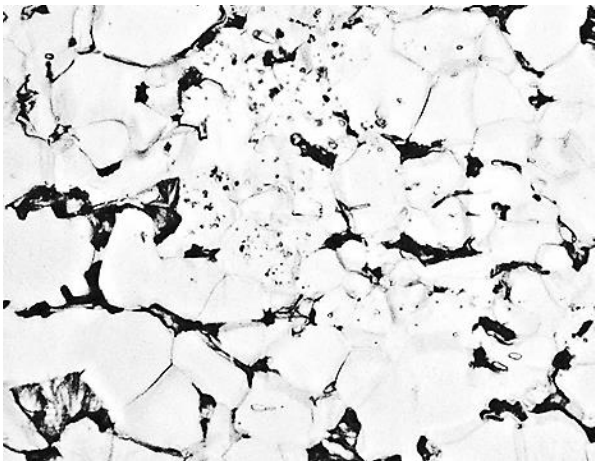
e) Replica R3. Original magnification 100×



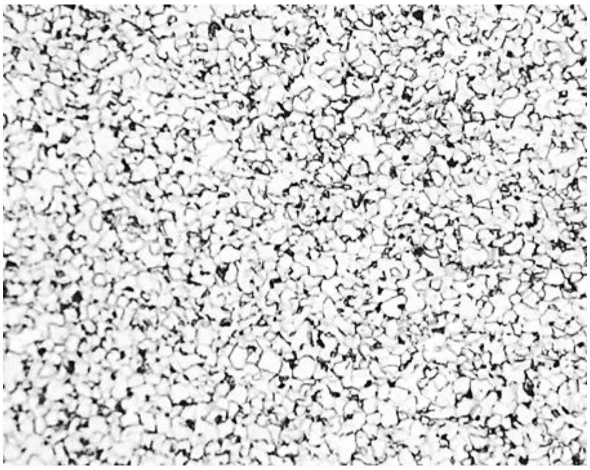
f) Replica R3. Original magnification 500×



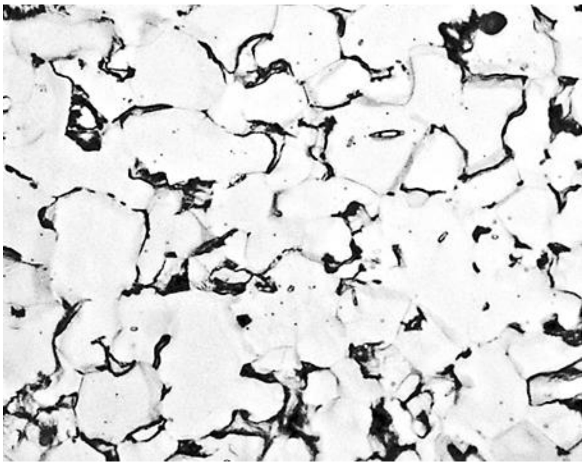
g) Replica R4. Original magnification 100×



h) Replica R4. Original magnification 500×



j) Replica R5. Original magnification 100×



k) Replica R5. Original magnification 500×

Figure 2. Microstructures of St.35.8/II boiler screen tubes recorded from surface plastic replicas at 100× and 500×: a, b) replica R1; c, d) replica R2; e, f) replica R3; g, h) replica R4; j, k) replica R5.

Based on the visual qualitative indexing of micro-photographs in Fig. 2, structural degradation damage is quantified and correlated with the measured in-situ hardness data. A comprehensive summary of the experimental results, contrasted against the standard cavitation-based Wedel-Neubauer creep classification and the newly proposed engineering structural safety assessment, is summarised in Table 1.

The thermodynamic parameters present a fundamental paradox. At a nominal operating fluid temperature of 300 °C, plain carbon steels are mechanically restricted to the time-independent elastic-plastic regime, as creep cavitation processes typically initiate above 370-400 °C /14, 15/. However, the screen tubes located at the 10 m elevation level are subjected to direct radiative furnace flames and localised high heat flux. Combined with internal magnetite insulation scale, the historical tube metal temperature significantly exceeds the nominal 300 °C threshold, driving the material well into the creep regime, /16/.

Despite this thermal exposure, optical microscopy up to 500× magnification (Fig. 2) fails to detect oriented creep cavities, which nominally restricts all evaluation points to Class 0 ('undamaged'). This indicates that standard creep cavitation models fail to reflect the imminent failure state of carbon steels. Under prolonged overheating, the lamellar cementite within the pearlite colonies fully decomposes and migrates toward the grain boundaries /8, 17/. This results in a heavy, brittle intergranular carbide network, providing a low-energy pathway for catastrophic intergranular brittle fracture without any pre-existing cavitation, /18/.

Table 1. Summary of in-situ hardness measurements, Wedel-Neubauer creep classification, and proposed structural actions.

Replica ID	Location/elevation	In-situ hardness (HB)	Wedel-Neubauer creep class	Proposed structural assessment & actions
R1	Tube 1 / 7 m (furnace side)	159	Class 0 (Undamaged)	Stable matrix, initial pearlite spheroidisation. No immediate action required.
R2	Tube 1 / 7 m (support side)	161	Class 0 (Undamaged)	Heat-affected zone (HAZ) exposure. Structure structurally acceptable.
R3	Tube 2 / 10 m (support side)	166	Class 0 (Undamaged)	Advanced spheroidisation. Monitor during scheduled overhaul.
R4	Tube 2 / 10 m (furnace side)	174	Class 0 (Undamaged)	CRITICAL! Continuous intergranular carbide network. Immediate tube replacement required.
R5	Tube 3 / 10 m (furnace side)	164	Class 0 (Undamaged)	High risk; semi-continuous carbide boundary decoration. Enhanced inspection interval.

In the metallurgy of boiler steels, the localised hardness peak of 174 HB at location R4 represents a structural response linked to advanced phase degradation and severe secondary carbide distribution along the grain boundaries which directly alters the local indentation resistance. Furthermore, such elevated *in-situ* hardness numbers in heavily aged low-carbon steels can be influenced by the shallow surface work-hardening layer introduced during portable mechanical grinding preparation. Consequently, these elevated hardness measurements must not be misinterpreted as a macroscopic strengthening of the component, as the grain matrix interior itself has become depleted of carbon and significantly softened.

CONCLUSIONS

Long-term exploitation of St.35.8/II boiler screen tubes for 306,581 hours led to advanced microstructural degradation driven by localised furnace overheating, despite moderate nominal fluid parameters (300 °C, 40 bar).

Traditional creep remaining life assessment criteria (Wedel-Neubauer) that rely exclusively on cavitation classification, fail to detect the damage, yielding a false-negative 'Class 0 (undamaged)' rating across all locations due to the complete absence of micro-voids.

The actual degradation mechanism is characterised by pearlite spheroidisation and the continuous precipitation of a brittle intergranular carbide network at the 10 m elevation furnace zone (R4), which severely embrittles the structure.

The anomalous in-situ hardness spike up to 174 HB is a localised artifact caused by the indentation tool intercepting grain boundary carbide phases, coupled with grinding-induced surface work hardening.

Immediate replacement of the tube sections corresponding to location R4 is strongly recommended, and a modified metallurgical assessment framework incorporating carbide network continuity must be implemented to ensure structural integrity.

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