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Degradation Behaviour of P235GH, P265GH and P355GH Steels in High-Temperature Boiler Applications

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The study focuses on the evaluation of the degradation behaviour of structural materials used in a heat exchanger boiler exposed to elevated thermal, pressure, and cyclic loading conditions. The research is aimed at non-alloy pressure steels P235GH, P265GH, and P355GH employed in critical boiler components. The objective of the study was to analyse the effect of temperature in the range of 250–600 °C on the residual mechanical properties, plastic deformation, and fatigue behaviour of these materials. The results indicate that at temperatures above 300–400 °C, a significant degradation of mechanical properties occurs. The residual strength of P235GH steel decreases by more than 60 % at 400 °C, while the plastic deformation of P235GH and P265GH steels is reduced to 5–8 %, representing a critical threshold from the perspective of fatigue damage. Steel grade P355GH exhibits higher thermal stability; however, at 400 °C its yield strength decreases to approximately 195 MPa. Based on the obtained results, an optimised material concept was proposed utilising heat-resistant Cr–Mo steels 16Mo3, 13CrMo4-5, and 10CrMo9-10, which retain 50–100 % higher plastic deformation and significantly greater creep resistance at temperatures of 500–600 °C compared to the original materials.

Keywords: Optimization, Boiler, Failure, Materials, Degradation

1 Introduction

The operation of water-tube and shell boilers in energy and industrial installations is long-term affected by the combined action of high temperatures, pressures, and the chemically aggressive environment of flue gases and boiler water. These conditions lead to the accumulation of multiple degradation mechanisms in structural materials, which gradually reduce the safety margin of critical components and increase the risk of failures. Suwarno et al. analysed failures of heat exchanger tubes in waste heat boilers and demonstrated that locally increased heat fluxes combined with deposit formation result in pronounced material overheating and accelerated degradation of mechanical properties [1]. Similarly, Ardy et al. identified combined thermal and corrosive loading as the dominant damage mechanism in boiler bank-wall tubes, leading to premature wall thinning and crack initiation [2].

The reduction of strength properties of steels at elevated temperatures represents one of the primary life-limiting factors for pressure components. Li et al., in their review of mechanical properties of structural steels at high temperatures, showed that a significant decrease in yield strength, elastic modulus, and fatigue resistance already occurs in the temperature range of 300–450 °C, fundamentally changing the failure mechanism from instantaneous to time-dependent [3]. This effect is particularly critical for non-alloy pressure steels, where the loss of strength is frequently accompanied by increased plasticity and enhanced susceptibility to creep damage.

Surface degradation due to corrosion also contributes significantly to the deterioration of mechanical performance, as it reduces the effective load-bearing cross-section and promotes stress localisation. Li et al. experimentally demonstrated that corrosion of low-carbon steels not only leads to material loss but also to reduced ductility and accelerated crack initiation under cyclic loading [4]. Under boiler operating conditions, this effect is often combined with thermal transients and pressure fluctuations, resulting in a further reduction of component service life.

For medium- and high-temperature boiler components, low-alloy Cr–Mo steels are therefore commonly applied; however, these materials are not immune to long-term degradation. Gwoździk et al. investigated microstructural changes in 10CrMo9-10 and 13CrMo4-5 steels after long-term service and identified carbide coarsening, micropore formation, and toughness degradation as the main manifestations of creep damage [5]. The degradation state of these materials has been further assessed using small-scale mechanical testing, with Majchrowicz et al. confirming the high sensitivity of creep resistance in Cr–Mo steels to thermal history and local stress concentrators [6]. From a mechanistic standpoint, Jakubowska et al. showed that the accumulation of plastic strain associated with precipitate stability during long-term exposure is a decisive factor governing the creep behaviour of low-alloy steels [7].

In addition to bulk degradation, surface oxidation and deposit-induced corrosion play a critical role. Maciejczyk et al. demonstrated that the chemical composition of ash deposits significantly influences the rate of high-temperature corrosion of boiler steels [8]. In the case of 16Mo3 steel, Boissonnet et al. found that the presence of water vapour accelerates oxidation and reduces the protective character of oxide layers [9]. Furthermore, Kendall et al. highlighted the importance of temperature regime and tube geometry in the modelling of oxidation processes, which has a direct impact on the assessment of local overheating and wall degradation [10].

The aim of this study is to analyse the degradation mechanisms of pressure steels P235GH, P265GH, and P355GH used in a heat exchanger boiler under conditions of elevated temperatures and cyclic thermo-mechanical loading, to quantify the reduction in their mechanical properties, and to identify the dominant strength-degrading mechanisms. Based on the obtained findings, a material optimisation of key boiler components is proposed, with particular emphasis on improving thermal stability, creep resistance, and long-term operational reliability.

2 Materials and methods

The evaluation of metallic materials used in the heat exchanger boiler focused on three non-alloy pressure steels, P235GH, P265GH, and P355GH, which represent the primary structural materials for the boiler shell, heat exchanger tubes, and tube sheets. The objective of the assessment was to evaluate their suitability for long-term operation at temperatures of 250–400 °C and pressures up to 1.8 MPa, as well as their resistance to cyclic thermal and mechanical loading typical of non-stationary heat exchanger boiler operation.

The investigated steels belong to the group of low-carbon materials intended for pressure equipment in accordance with EN 10028-2. Their chemical composition is primarily optimised with respect to weldability and basic strength; however, the absence of alloying elements enhancing creep resistance significantly affects their behaviour at elevated temperatures. The basic chemical composition of the individual materials is presented in Table 1.

From a microstructural perspective, all three steels were characterised by a ferritic–pearlitic microstructure, which is typical for non-alloy pressure steels processed by normalising or controlled rolling.

2.1 Materials and Methods – Experimental Procedure

Experimental verification of the degradation behaviour of the investigated steels was carried out on real material samples extracted from an industrial heat exchanger boiler operating under long-term service conditions. The aim of the experimental program was to compare the microstructural condition and mechanical properties of materials in the as-received state and after service exposure.

The presented results are based on a combination of experimental, operational, and literature data. The experimental data were obtained from the analysis of samples extracted from a real high-temperature boiler operating under industrial conditions, and were supplemented by operational records, including:

Flue gas temperature:

- maximum values: up to 1300 °C (boiler inlet),
- typical operating range: 900–1200 °C.

Steam pressure:

- nominal operating pressure: approximately 14 bar (1.4 MPa).

Dynamics of operating regime changes:

- temperature change rate reaching up to ≈ 100 °C/min.

The boiler operated under the following conditions:

- maximum flue gas temperature: up to 1300 °C,
- operating temperature of structural components: 200–300 °C (design range),
- steam pressure: approximately 14 bar (1.4 MPa).

2.2 Sampling and Specimen Preparation

The experimental analysis was performed on three sets of samples:

The experimental part was carried out on samples of steel tubes from a high-temperature boiler. Three types of samples were analysed:

- U (unused) – a tube in the as-manufactured condition (not exposed to operation).

Reference samples taken from non-operated tubes in the as-manufactured condition. These samples served as a baseline for evaluating changes in microstructure and mechanical properties caused by service exposure.

- H (hot side) – a tube taken from a region subjected to high thermal loading.

Samples extracted from tubes subjected to the highest thermal loading in the flue gas inlet region. The sampling was performed approximately 50 mm from the location of a local through-wall burnout, which made it possible to analyse material affected by extreme thermal stress but not yet completely structurally failed. These samples represent a critical state of material degradation.

- C (cold side) – a tube from a less thermally loaded section.

Samples obtained from the colder part of the unit, where the thermal load was significantly lower. They were used for comparison with the hot zone and for identifying the degradation gradient across the equipment.

The samples were extracted from a real operating unit; in the case of damaged tubes, the H sample was taken approximately 5 cm from the burnout location.

The geometry of the specimens corresponded to the wall thickness of the service tubes (approximately 5.7 mm), and for each sample the following regions were analysed near the inner surface, and at the mid-thickness of the wall.

The operating conditions of the boiler corresponded to long-term exposure to temperatures in the range of 250–400 °C combined with cyclic thermal and pressure loading. Sampling locations were selected to reflect different levels of thermal and mechanical degradation. Metallographic specimens were prepared using standard procedures, including sectioning, mounting, grinding, polishing, and etching using a suitable reagent to reveal the ferritic–pearlitic microstructure.

2.3 Microstructural Analysis

Microstructural observations were conducted on three representative samples (U, C, H) using a Keyence VHX digital metallographic microscope. To ensure representative evaluation, each sample was analysed at two characteristic locations: near the inner surface of the tube, which is directly exposed to the working medium and thermal loading, at the mid-thickness of the wall, representing the bulk material behaviour.

- conducted using a Keyence VHX metallographic microscope,
- evaluation of grain size and microstructural changes,
- comparison between reference and service-exposed samples.

The outer surface layer was intentionally excluded from the analysis due to its altered microstructure resulting from manufacturing processes (rolling and surface deformation effects), which could distort the interpretation of operational degradation.

Based on the observations, a noticeable microstructural evolution was identified in the H samples, indicating the effect of prolonged exposure to elevated temperatures and local overheating conditions.

2.4 Hardness Measurement

Hardness measurements were carried out to quantify changes in mechanical properties due to thermal exposure. Testing was performed on:

- unused reference samples (U),
- service-exposed samples from the hot side (H).

The C samples were not subjected to hardness testing, as the failure mechanism was localized on the hot side, and the cold side was not considered critical for degradation assessment.

Hardness was measured using a microhardness tester with the Vickers method HV 0.1, applying a test load of 1 N. To minimise the influence of local heterogeneities, hardness indentations were distributed uniformly across the wall thickness of each specimen. This approach ensured statistical relevance of the results and enabled identification of potential gradients in mechanical properties across the material thickness.

Tab. 1 *Chemical composition of investigated steels according to EN 10028-2 (wt.%) and measured values from spectral analysis*

Steel grade	C	Mn	Si	P	S	Al
P235GH	≤0.16	0.60–1.20	≤0.35	≤0.025	≤0.015	≥0.020
P235GH spectral analysis	0.12	0.92	0.24	0.012	0.006	0.028
P265GH	≤0.20	0.80–1.40	≤0.40	≤0.025	≤0.015	≥0.020
P265GH spectral analysis	0.17	1.12	0.29	0.014	0.007	0.025
P355GH	≤0.22	1.00–1.70	≤0.50	≤0.025	≤0.015	≥0.020
P355GHspectral analysis	0.19	1.42	0.33	0.016	0.008	0.023

For steel grade P265GH, primarily used for the boiler shell, the assessment focused on its stability at sustained operating temperatures of approximately 300–350 °C, as well as on the risk of strength degradation at higher temperatures and the influence of cyclic heating on the initiation of microcracks and local deformations. The evaluation also included its corrosion resistance in the boiler water environment and under condensation cycles.

Steel P235GH, applied in heat exchanger tubes, was evaluated with respect to its limiting temperature resistance of approximately 300 °C, its sensitivity to short-term temperature excursions to the range of 350–400 °C, and its susceptibility to creep deformation and corrosion damage during long-term operation. Consideration was also given to its lower fatigue resistance under pressure shocks and cyclic loading conditions.

The most highly loaded material examined was steel grade P355GH, used for the tube sheet, for which its higher yield strength, suitability for operation up to 400 °C, and ability to withstand higher pressures were assessed. The material behaviour under short-term overheating to approximately 450 °C was analysed, as well as the risks associated with long-term exceedance of temperature limits leading to embrittlement, microcrack formation, and reduced corrosion resistance.

All three materials were evaluated using a comparative approach, focusing on the identification of dominant degradation mechanisms, operational limits, and potential risks under combined thermo-mechanical cycling typical of heat exchanger boiler operation. This approach provided the basis for the subsequent analysis of results and the proposal of material optimisation strategies.

3 Results

The limiting temperatures of 300 °C, 350 °C, and 400 °C represent transitional regions between stable and degradative material behaviour for steel grade P265GH. Haţiegan et al. experimentally demonstrated that at temperatures up to approximately 300 °C, structural steels retain more than 90 % of their residual strength, as the microstructure remains stable and time-dependent deformation mechanisms are not yet activated [11].

At temperatures around 350 °C, a more pronounced reduction in strength characteristics occurs due to the activation of creep processes and a decrease in yield strength, resulting in a reduction of residual strength to approximately 70–80 %. This temperature is therefore considered the upper limit for safe long-term operation of non-alloy pressure steels.

At temperatures ≥ 400 °C, accelerated degradation of mechanical properties is observed, with residual strength falling below 50 % of the original value. Haţiegan et al. emphasise that within this temperature range, the simultaneous activation of creep deformation, plastic instability, and surface oxidation occurs, leading to a significant loss of load-bearing capacity and a high risk of failure of pressure components in Fig. 1.

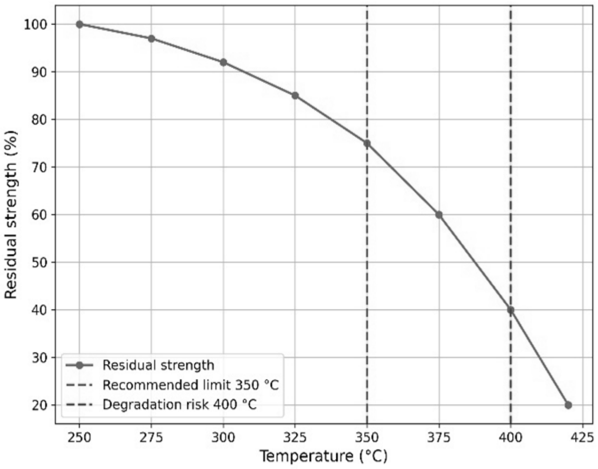

***Fig. 1** Effect of temperature on the residual strength of P265GH steel*

The results of the analysis indicate that the mechanical properties of steel grade P235GH significantly deteriorate at elevated temperatures, as illustrated in Fig. 2. Up to a temperature of 300 °C, the material retains residual strength at a level of approximately 90 %, which represents the upper limit of stable material behaviour. At a temperature of 350 °C, the residual strength decreases to approximately 60 %, indicating a substantial reduction in the safety margin due to microstructural instability and the onset of creep-controlled deformation processes. At 400 °C, the residual strength drops below 30–40 %, which represents a critical condition from the perspective of long-term operation of pressure components.

The safety margin of the material at different pressure levels is depicted in Fig. 3. At the nominal operating pressure of 1.8 MPa, the safety margin of P235GH steel decreases to approximately 20 %, indicating that even minor pressure increases or the simultaneous action of elevated temperature lead to an unacceptable risk of failure. At pressures ≥ 2.0 MPa, the safety margin falls below 10 %, corresponding to a condition close to the limit state of material failure.

Based on the combined effects of temperature and pressure presented in Figs. 2 and 3, it can be concluded that steel P235GH is suitable only for service up to approximately 300 °C and at relatively low pressure levels. For the operation of heat exchanger tubes in the boiler at higher temperatures and pressures, the material does not provide a sufficient safety margin and represents an increased risk of operational failure.

The influence of combined cyclic and thermal loading on the residual strength of steel P235GH is shown in Fig. 4. At a temperature of 300 °C, the material retains approximately 85 % of its original strength after 10^5 loading cycles. Increasing the temperature to 350 °C leads to a reduction of residual strength after the same number of cycles to approximately 75 %, while at 400 °C the residual strength decreases further to approximately 65 %.

At a high number of cycles (10^6), the degradation becomes significantly more pronounced. The residual strength of P235GH steel decreases to approximately 35 % at 300 °C, 25 % at 350 °C, and only 15 % at 400 °C, indicating a high sensitivity of the material to fatigue damage under the combined action of cyclic loading and elevated temperature. These results confirm that cyclic loading significantly accelerates the degradation of mechanical properties of P235GH even at temperatures that are still considered acceptable from the standpoint of static strength.

It can be concluded that the decrease in residual stress is smaller at higher temperatures due to the activation of recrystallization and relaxation processes, which were also experimentally confirmed by microstructural analysis. In the samples taken from the hot side (H), grain coarsening and recrystallization were observed, indicating that the material was exposed to temperatures in the range of approximately 600–720 °C.

At such temperatures, the yield strength of the material decreases significantly, enabling local plastic deformation even at lower stress levels. As a result, stress redistribution occurs in the material and partial “smoothing” of stress gradients is achieved.

At the same time, due to cyclic thermal loading (repeated heating and cooling), an effect of gradual stabilization of the stress state is observed. The material undergoes a series of plastic deformations, which lead to a reduction of stress gradients between individual regions. This phenomenon in the analyzed boiler was further intensified by non-stationary operation with rapid changes in pressure and temperature.

Another important factor is the formation of a boiling film during pressure drops, which reduces the heat transfer coefficient and causes local overheating of the tube wall. This leads to a sudden increase in material temperature followed by plastic deformation, which contributes to further stress relaxation.

From a mechanical perspective, this effect is further supported by a decrease in material hardness. Experimental results showed an approximately 12% reduction in hardness in the service-exposed samples, which is directly associated with a decrease in strength and an increased ability of the material to undergo plastic deformation and thereby redistribute stresses. From a mechanical point of view, this phenomenon is further supported by the observed decrease in material hardness. Experimental measurements confirmed a reduction in hardness of approximately 12% in the service-exposed samples compared to the reference material. This decrease in hardness is closely related to a reduction in the material’s strength, particularly its yield strength, which determines the onset of plastic deformation.

As the hardness decreases, the material becomes more susceptible to plastic deformation under both applied and residual stresses. This increased deformability enables the material to accommodate internal stresses more effectively through localized plastic flow. As a result, stress concentrations are reduced and the overall stress distribution within the material becomes more homogeneous.

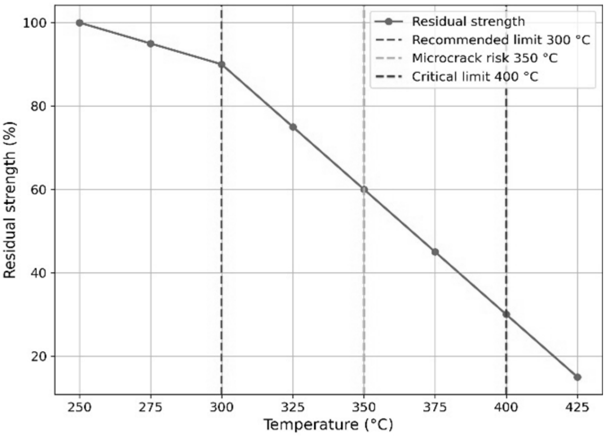

Fig. 2 *Effect of temperature on the residual strength of P235GH steel*

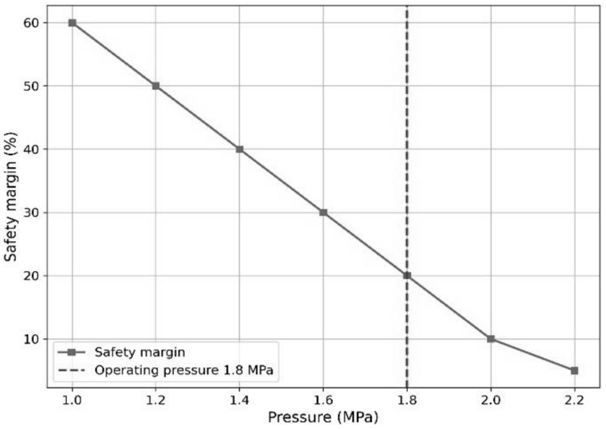

Fig. 3 *Safety margin of P235GH steel at different pressure levels (operating pressure 1.8 MPa)*

The influence of short-term thermal loading on the residual strength of steel grade P355GH is illustrated in Fig. 5. Up to a temperature of approximately 400 °C, the material retains more than 85–90 % of its original strength, which corresponds to its safe operational limit. Short-term temperature excursions to approximately 450 °C result in a reduction of residual strength to around 50 %; however, without an immediate loss of material integrity. This behaviour indicates the ability of P355GH steel to tolerate short-term thermal peaks.

A comparison of the results presented in Fig. 4 and Fig. 5 reveals a significant difference in the behaviour of the investigated materials. While P355GH steel exhibits high resistance to short-term thermal overload, P235GH steel is substantially more sensitive to combined cyclic and thermal loading, under which rapid degradation of mechanical properties occurs.

At the same time, it is evident that long-term operation of P355GH steel at temperatures exceeding 400 °C leads to pronounced material degradation. This degradation manifests as the onset of creep softening, loss of toughness, formation of microcracks in overheated regions, and an increased rate of oxidation. Under prolonged exposure to these mechanisms, the tube sheet may be progressively weakened, fatigue crack initiation may occur, and in extreme cases, leakage or failure of the boiler pressure parts may develop.

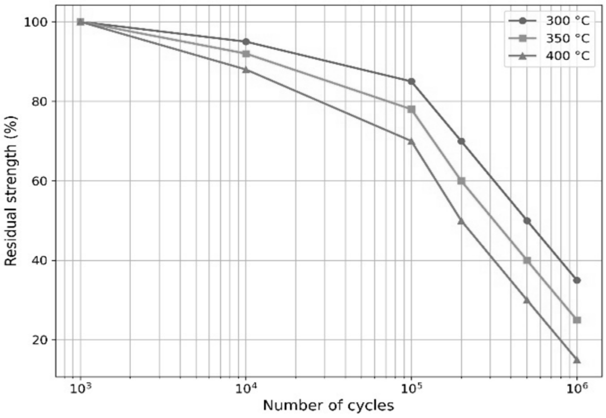

***Fig. 4** Effect of cyclic loading and temperature on the residual strength of P235GH steel*

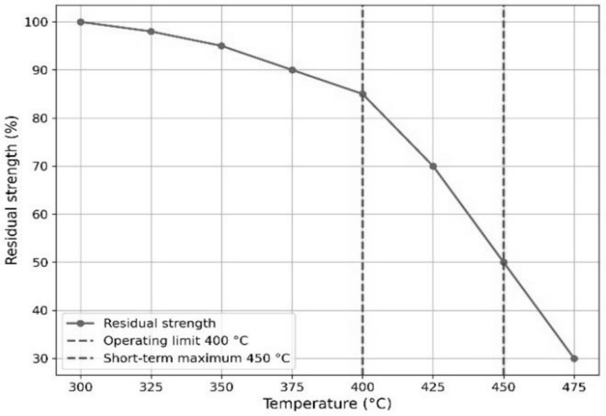

***Fig. 5** Effect of temperature on the residual strength of P355GH steel*

4 Optimisation of the Material Solution for the Heat Exchanger Boiler

Based on a comprehensive analysis of the original structural materials used in the heat exchanger boiler (P235GH, P265GH, and P355GH), an optimised approach to material selection for the most thermally loaded components of the equipment was proposed. This approach is based on replacing non-alloy steels with alloyed heat-resistant steels 16Mo3, 13CrMo4-5, and 10CrMo9-10, which provide significantly higher thermal stability and long-term strength reserves at elevated temperatures.

Figure 6 illustrates the decrease in yield strength $R_{p0.2}$ as a function of temperature for both the original and the proposed materials, where the dashed line represents the limiting value of plastic deformation (~200 MPa). The results clearly show that the non-alloy steels P235GH and P265GH exhibit the most rapid strength degradation—at temperatures as low as 300 °C, their yield strength falls below the critical threshold of 200 MPa. At 400 °C, P265GH reaches a value of approximately 106 MPa and P235GH approximately 141 MPa, which fundamentally limits their applicability in long-term thermally loaded boiler components.

Steel grade P355GH demonstrates higher thermal stability; however, at 400 °C its yield strength decreases to approximately 195 MPa, i.e., only marginally above the safe operating limit. This material is therefore suitable primarily for medium-temperature regions; nevertheless, under long-term exposure to elevated temperatures, a gradual degradation of strength properties must be anticipated.

In contrast, the heat-resistant steels 16Mo3, 13CrMo4-5, and 10CrMo9-10 maintain significantly higher yield strength levels even at temperatures of 400–600 °C. Steel 13CrMo4-5 achieves a yield strength of approximately 217 MPa at 500 °C, while 10CrMo9-10 retains a value of around 186 MPa even at 600 °C, confirming their high suitability for long-term high-temperature service.

The results presented in Fig. 6 clearly confirm that optimisation of the material solution towards alloyed heat-resistant steels represents an effective approach to increasing the service life, operational reliability, and safety of the T-601B boiler in its most thermally stressed regions.

Figure 7 illustrates the dependence of plastic deformation of the analysed steels on temperature. Plastic deformation represents the ability of a material to absorb stress without fracture and is a key parameter particularly in regions exposed to cyclic thermal loading and local overheating. The non-alloy steels P235GH and P265GH exhibit a pronounced decrease in plastic deformation already at temperatures above 300 °C. At 400 °C, their plastic deformation reaches only approximately 5–8 %, significantly increasing the risk of microcrack initiation, local embrittlement, and damage during operational or accidental thermal peaks. These results confirm the limited suitability of these materials for long-term service at elevated temperatures.

Steel grade P355GH retains higher deformability compared to P235GH and P265GH; however, at temperatures exceeding 450 °C its plastic deformation decreases below 10 %, indicating an increased risk of creep damage and thermal degradation during prolonged exposure.

In contrast, the alloyed heat-resistant steels 16Mo3, 13CrMo4-5, and 10CrMo9-10 exhibit consistently higher levels of plastic deformation even at temperatures of 500–600 °C, where values of approximately 10–12 % are maintained. This ability to accommodate plastic strain at high temperatures confirms their high thermal stability and resistance to creep damage, making them suitable for application in the most thermally stressed boiler components.

The results presented in Fig. 7 thus clearly support the proposed replacement of the original non-alloy steels with heat-resistant alloyed materials in regions exposed to combined thermal and pressure loading.

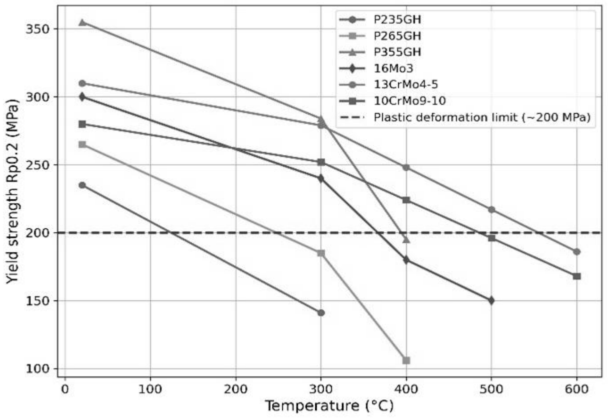

Fig. 6 *Temperature dependence of yield strength ($R_{p0.2}$) of original and proposed boiler steels*

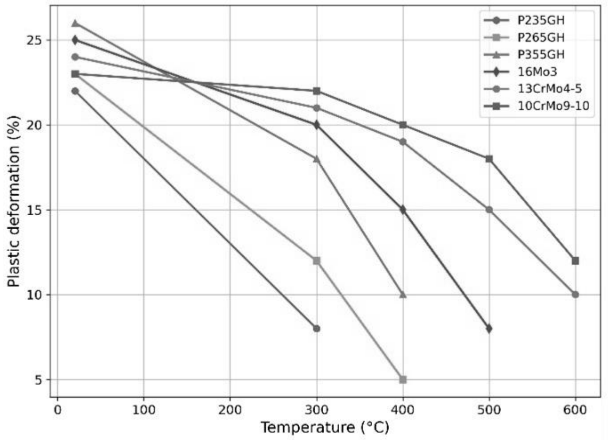

Fig. 7 *Temperature dependence of plastic deformation of investigated boiler steels*

5 Discussion

The results presented in this study confirm that the operational limitations of non-alloy pressure steels P235GH, P265GH, and P355GH at elevated temperatures are primarily determined by the combined effects of yield strength reduction, decreased plastic deformation, and the activation of creep mechanisms. Haţiegan et al. experimentally demonstrated that the temperature range of 300–400 °C represents a boundary between stable behaviour and pronounced degradation of mechanical properties for structural steels, which is in good agreement with the findings of this study [11]. The most significant degradation was observed for steel P235GH, where the thermal effect is further exacerbated by its low resistance to cyclic loading. Suwarno et al., in their analysis of boiler tube failures, showed that the combination of local overheating and cyclic pressure fluctuations leads to accelerated microcrack initiation and premature failure of components manufactured from non-alloy steels [12]. These observations correspond well with the experimental results reported in the present work. In contrast, alloyed Cr–Mo steels exhibit significantly higher stability of mechanical properties at elevated temperatures. Gwoździk et al. demonstrated that steels 13CrMo4-5 and 10CrMo9-10 retain a favourable microstructure during long-term operation due to stable carbide precipitates and a slower accumulation of creep strain [13]. These mechanisms explain the higher yield strength and plastic deformation observed for these materials in this study. For components subjected to extreme thermal loading, steel grade 10CrMo9-10 appears to be the most suitable material. Majchrowicz et al. confirmed its high creep stability using small-scale mechanical testing, which enables the assessment of material condition after long-term service exposure [14]. At the same time, it is evident that plastic deformation represents a critical indicator of operational safety. Jakubowska et al. emphasised that the ability of a material to accumulate plastic strain at elevated temperatures significantly contributes to delaying creep rupture [15]. In this context, the proposed material optimisation does not merely represent an increase in strength, but rather a fundamental improvement in the long-term reliability and safety of the heat exchanger boiler.

6 Conclusion

The aim of this study was to comprehensively evaluate the suitability of the original structural materials used in the heat exchanger boiler (P235GH, P265GH, and P355GH) for long-term operation under elevated temperature and pressure conditions and based on experimental and analytical results, to propose an optimised material concept for the most thermally stressed components of the equipment. Based on the obtained results, the following main conclusions can be drawn:

- Non-alloy steels P235GH, P265GH, and P355GH exhibit pronounced operational limitations at temperatures above 300–400 °C. At a temperature of 350 °C, the residual strength of P235GH decreases by approximately 40 %, and at 400 °C its yield strength falls below 150 MPa. Steel P265GH reaches a yield strength of only approximately 106 MPa at 400 °C, while P355GH retains about 195 MPa at this temperature, which is only marginally above the safe operating threshold.
- The plastic deformation of non-alloy steels decreases sharply with increasing temperature. At 400 °C, steels P235GH and P265GH exhibit only 5–8 % plastic deformation, representing a critical limit in terms of microcrack initiation, local embrittlement, and fatigue fracture. In contrast, heat-resistant steels 13CrMo4-5 and 10CrMo9-10 maintain plastic deformation levels of 10–12 % even at temperatures of 500–600 °C, corresponding to approximately 50–100 % higher values compared to non-alloy materials.
- Cyclic thermal and pressure loading significantly accelerates degradation of the original materials. Non-stationary boiler operation, characterised by temperature change rates of up to 100 °C/min, leads to the accumulation of plastic deformation and a reduction in the fatigue life of critical regions, particularly in the vicinity of welded joints. Under combined cyclic loading and a temperature of 400 °C, the residual strength of P235GH decreases to approximately 15–20 % of its original value after 10^6 cycles.
- Local overheating and deteriorated heat transfer were identified as key degradation mechanisms. Sudden pressure drops lead to the formation of a boiling film, reducing heat transfer by up to 80 % and causing local material temperature increases of up to +200 °C. This phenomenon was identified as the primary trigger for rapid degradation of steels P235GH and P355GH under heat exchanger boiler operating conditions.
- Heat-resistant Cr–Mo steels provide substantially higher strength and creep reserves. Steel 16Mo3 exhibits a creep strength of approximately 60 MPa at 550 °C after 100,000 h, representing an improvement of 40–60 % compared to P235GH. Steel 13CrMo4-5 shows creep resistance in the range of 80–110 MPa at 600 °C, while 10CrMo9-10 maintains long-term stability up to 600 °C with creep strength values of 70–130 MPa.
- Based on the results, a targeted material optimisation of the heat exchanger boiler was recommended:
    - P235GH → 16Mo3 (tube systems and thermally exposed piping),
    - P265GH → 13CrMo4-5 (medium-temperature heat exchangers and steam sections),
    - P355GH → 10CrMo9-10 (tube sheets and high-pressure sections).

The implementation of the proposed material and operational measures provides substantial benefits in terms of safety, reliability, and economic efficiency. The transition to heat-resistant steels, combined with controlled thermal cycling, pressure management, and monitoring of the working medium quality, enables an extension of the boiler service life up to 100,000 operating hours and a reduction of maintenance costs by approximately 40–60 %. At the same time, the proposed solution significantly reduces the risk of emergency failures and ensures stable and safe operation of the heat exchanger boiler even under demanding thermal and chemical operating conditions.

The relationship between operating conditions, material response, and degradation mechanisms was identified in the study as a clear cause–effect sequence, where elevated temperatures in the range of 300–400 °C and non-stationary operation with cyclic thermal and pressure loading lead to the activation of creep processes, a reduction in yield strength, and the loss of microstructural stability. These factors result in the progressive degradation of mechanical properties, manifested by a significant decrease in residual strength and plastic deformability, thereby increasing the material's susceptibility to fatigue damage and microcrack initiation. At the same time, local operational phenomena, such as sudden pressure drops and the formation of a boiling film, reduce heat transfer and cause local overheating of the material, which accelerates recrystallisation, grain growth, and hardness reduction. This process is accompanied by stress redistribution and a gradual loss of load-bearing capacity, while the combined effect of temperature, cyclic loading, and the chemical environment leads to dominant material degradation and an increased risk of failure of critical boiler components.

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