# Analysis of the Influence of the Filler Material Composition of High Temperature Boilers under Operating Conditions

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**Abstract.** The presented work deals with the analysis of the influence of the material composition of the filler and structural components of high-temperature boilers on their operational properties, safety, and service life. High-temperature boilers operate under conditions of extreme thermal and chemical stress, which lead to gradual material degradation, corrosion, and the formation of microcracks. The study compares the properties of traditional non-alloyed steels with modern alloyed heat-resistant steels and evaluates their resistance to thermal shocks, cyclic oxidation, and mechanical wear. The work includes microstructural analysis of sampled tubes, hardness measurements, and identification of the materials' yield strength. The results demonstrate significant thermal effects on the material of the operated tubes, grain growth, and a decrease in hardness, indicating long-term overheating. Based on the performed analysis, optimized material solutions and operational measures are proposed to improve the reliability, energy efficiency, and service life of high-temperature boilers in industrial operation. In addition, the study highlights the importance of appropriate material selection and operating regimes in minimizing premature failures and unplanned shutdowns. The obtained findings provide practical recommendations for the design and modernization of high-temperature boiler systems operating under severe thermal conditions.

**Keywords:** diesel engine; alternative fuel; nitrogen oxides; carbon monoxide.

## INTRODUCTION

A high-temperature boiler is a pressure device designed for the recuperation of thermal energy from flue gases and its subsequent conversion into steam. High-temperature boilers are equipment intended for heat production at extreme temperatures, often above 500 °C, operating in an environment with high heat flux, pressure, and aggressive chemical media (e.g., flue gases containing sulfur, chlorine, nitrogen oxides) [1]. These conditions cause intense stress on structural and filler materials, leading to their gradual degradation.

The boiler filling (e.g., refractory materials, ceramic inserts, insulation) serves as thermal protection and reduces heat losses. The materials used must meet the following requirements:

- High thermal resistance – preservation of mechanical properties at elevated temperatures.
- Chemical stability – resistance to corrosion and aggressive components of flue gases.
- Low thermal conductivity – minimization of heat losses.

The most commonly used materials include refractory ceramic materials, fireclay, magnesite and aluminosilicate mixtures, or modern composites.

The boiler is constructed as a horizontal cylindrical body with elliptical end caps and is mounted on three fixed steel supports. The design enables operation under high pressures and temperatures. The main pressure parts of the boiler consist of the shell with its nominal and test pressure ratings, heat-exchange tubes, and a welded header joint. Inside the unit, there is a heat-exchange bundle consisting of 470 tubes with an outer diameter of Ø51 mm and a wall thickness of 5.7 mm, which are expanded between two tube sheets. The bundle is divided by baffles into three sections.

Flue gases enter through a ceramic-reinforced conical inlet and pass through the inside of the heat-exchange tubes. Water, serving as the heat-transfer medium, surrounds the tubes from the outside, enabling efficient heat transfer.

## Detection and evaluation of possible damage

Technical inspection prior to commissioning, as well as during extraordinary inspections, is performed by a specialist holding a license from the supervisory authority to conduct expert assessments in the field of industrial safety of technical equipment [2]. During the initial inspection, special attention must be paid to identifying possible defects originating from manufacturing, transportation, storage, or assembly of the equipment, such as dents, cracks, corrosion damage, or weld defects.

During regular external and internal inspections, it is essential to verify that no damage or wear of individual components has occurred as a result of operation. The most common types of damage include cracks in the base material or welded joints, material loss due to corrosion or erosion, deformations and bulges caused by pressure or thermal loading, leakages in flanged and threaded joints, loosened fastening elements, deterioration of surface coating, malfunction of measuring, control, and safety devices, as well as damage to insulation layers and supporting structures.

The most frequent types of damage include:

- Cracks, which most commonly occur at bends, edges, flange welds, welded covers, welded supports, and similar locations,
- Corrosion damage to the equipment walls and welded seams [3].

Inspection of the condition of the external and internal surfaces of the equipment in accessible areas must be carried out particularly in the regions of flange welds, at intersections of shell welds, and at the points where heat-exchange tubes are welded to the tube sheets. If defects are detected on the walls of any component of the equipment or if suspicious areas appear, wall-thickness measurements must be performed using a non-destructive testing method, as instructed by the person responsible for technical supervision or a specialist from an organization licensed by the supervisory authority [4]. Wall-thickness measurements are conducted from both the outside and the inside of the equipment.

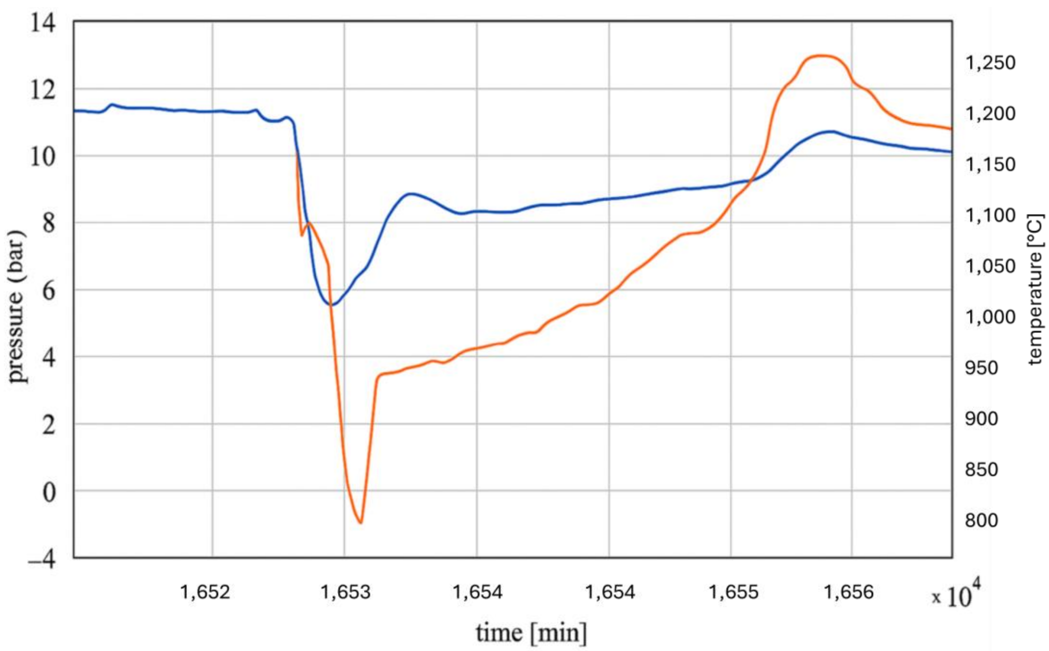


**Figure 1.** Flue gas temperature and steam pressure during testing

Another identified issue caused by non-stationary operation, see Figure 1, occurs during situations involving rapid heating. The temperature difference between the boiler shell and the tubes generates uneven thermal expansion of both components. The resulting stress may further increase with a larger temperature gradient (in cases of overheating). The stress level may reach the yield strength of the tube sheet material at the given operating temperature [5].

One of the main causes of failure may be the migration of water through the refractory lining, which leads to its gradual degradation. Possible consequences of such a failure include:

- microcracks at the joints between the tubes and the tube sheet,
- presence of corrosion lesions in the contact zones between the tube material and the tube sheet,
- significant degradation of the surface layer of the boiler shell, particularly in the flue-gas outlet region.

## Material Analysis of the Samples Taken from the Boiler Shell

Optimizing the material composition of boiler filling is essential from technical, economic, and environmental perspectives.
Its main benefits include:

- Extended service life of the equipment:
  Properly selected materials resist corrosion, thermal shock, and mechanical wear, reducing the frequency of repairs and component replacements.
- Reduced operating costs:
  Longer service life and lower maintenance needs result in reduced service and shutdown costs.
  Optimization also decreases fuel consumption thanks to improved thermal insulation.

In the presented analysis, tests were carried out on samples taken from non-operated tubes in as-manufactured condition and samples collected from operated tubes removed from the boiler during service. The microstructure was examined on three samples. For each sample, the microstructure was analyzed near the inner surface and in the middle of the wall thickness [6]. The microstructure near the outer surface was not analyzed because, due to the tube manufacturing process (rolling), it exhibits significantly different characteristics (larger, directionally oriented grains).

Based on the analyzed microstructures, it can be stated that the tested samples taken from the operated tubes (H) show visible changes in microstructure [7]. This change is manifested by an increase in grain size. Under stable operating conditions, the temperature of the tubes should not exceed 200–300 °C. However, the observed microstructural changes occur at temperatures close to the eutectoid transformation (600–720 °C). At these temperature levels, recrystallization occurs, leading to the growth of the most favorably oriented grains. This phenomenon is clearly visible in the microstructure of the operated tube on the hot side (Figure 2). Individual microstructures taken from the mid-wall thickness are shown in Figures 2, 3, and 4 with corresponding grain-size scales.

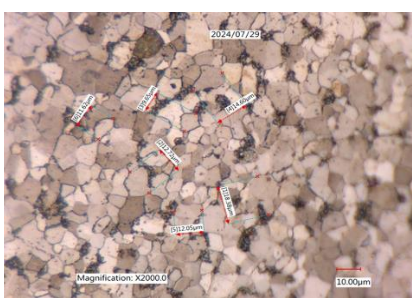


**Figure. 2** Microstructure 1

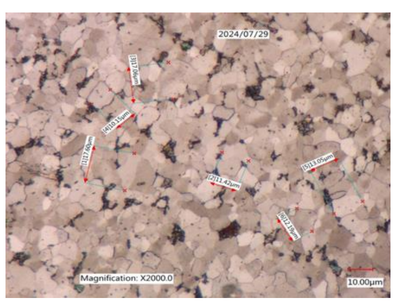


**Figure. 3** Microstructure 2

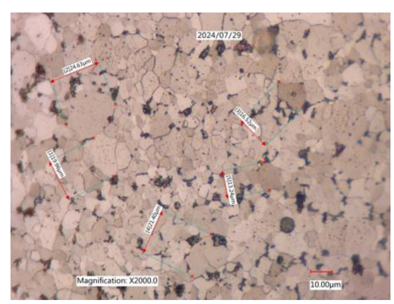


**Figure. 4** Microstructure 3

Another proposed step in the analysis is hardness testing of the examined samples. Hardness is measured using a microhardness tester. The hardness testing method used is HV 0.1 (test force 1 N). Hardness is measured uniformly across the wall thickness of each sample to avoid local anomalies. It is recommended to take six measurements on each sample in order to compare the average value. The measurements are shown in Figures 5 and 6.

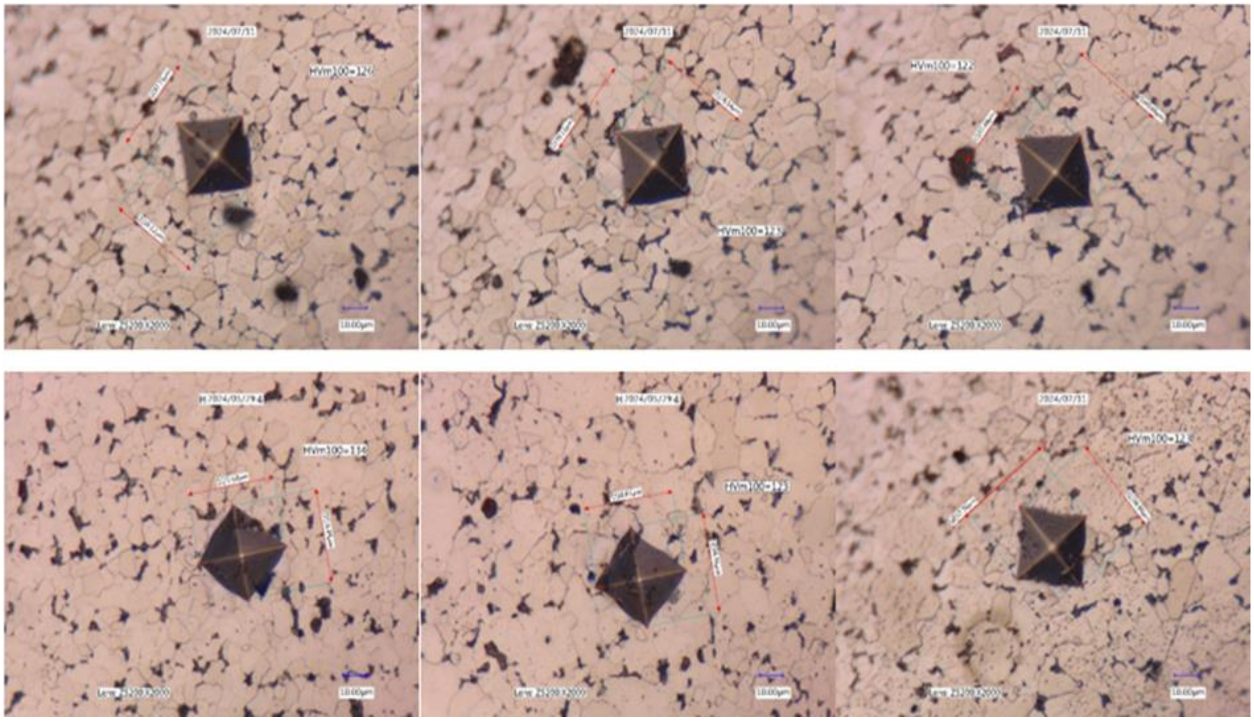

**Figure 5.** Indentation with Measurements on Sample 3

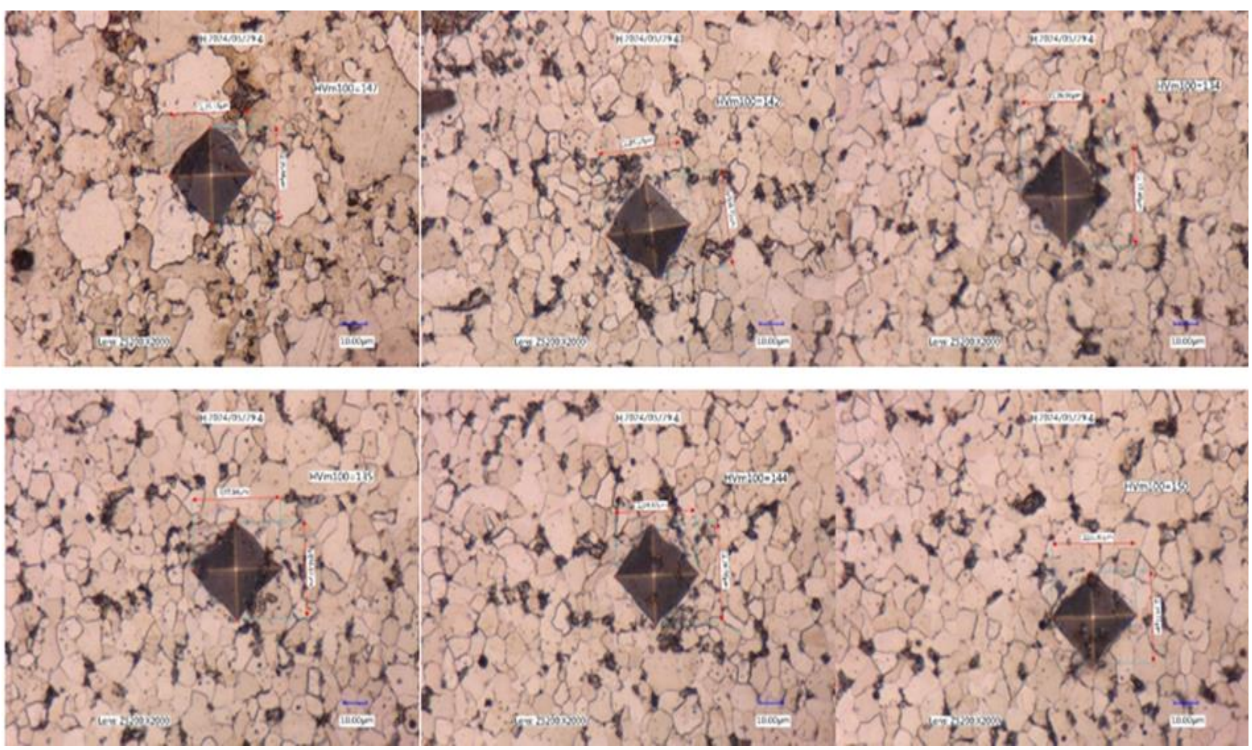

**Figure 6.** Indentation with Measurements on Sample 1

Recrystallization of grains (grain growth) and the reduction in hardness indicate heating of the material close to the eutectoid transformation temperature range (600–720 °C). Changes in material properties were observed outside the area of wall burn-through (approximately 5 cm from the defect). This suggests that the wall burn-through is not the result of an isolated phenomenon caused by local conditions, but rather excessive overheating of the cooling tubes.

Recrystallization, accompanied by grain growth and a decrease in hardness, is characteristic of long-term exposure to elevated temperatures, which leads to structural restoration and a reduction in internal stresses [8]. The observed changes in material properties located outside the burned-through area – approximately 5 cm from the defect-indicate that the thermal influence was not local but affected a wider region.

Based on these observations, it can be assumed that the wall burned-through is not the consequence of a singular event caused by localized conditions (e.g., local deposits or fouling), but rather the result of excessive overheating of the cooling tubes due to impaired circulation of the cooling medium or suboptimal control of operating parameters. This condition leads to gradual material degradation, reduced mechanical strength, and an increased risk of defect formation.

## OPTIMIZATION OF THE MATERIAL SOLUTION FOR THE HEATING BOILER

Heating boilers operate in environments characterized by high temperatures, elevated pressure, and aggressive chemical media. The material configuration of the boiler-particularly its filling and structural components-has a decisive impact on service life, efficiency, and operational safety [9]. Optimization of the material solution involves selecting and combining materials so that they meet requirements for thermal resistance, mechanical strength, corrosion stability, and economic efficiency.

Based on the analysis of the existing structural materials used in the boiler-specifically P235GH, P265GH, and P355GH-and on the evaluation of available statistics of operational failures (corrosion, fatigue-related microcracking, limited thermal stability), an optimized approach to material selection for critical parts of the equipment is proposed. This approach relies on the application of alloyed heat-resistant steels of the type 16Mo3, 13CrMo4-5, and 10CrMo9-10.

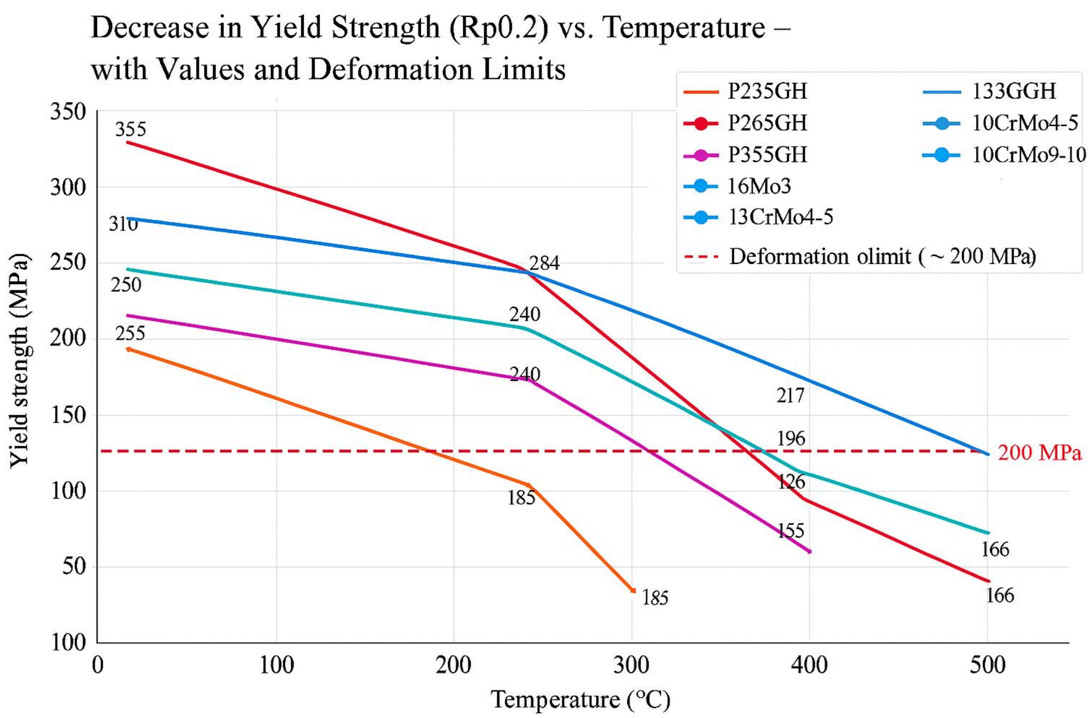


**Figure 7.** Comparison of Yield Strength of Materials

Figure 7 shows the calculation of plastic deformation (in %) for various steels at elevated temperatures. Individual values are provided directly in the graph. Plastic deformation in this context expresses the material's ability to deform without failure under applied stress. The comparison shows that alloyed steels such as 13CrMo4-5 and 10CrMo9-10 retain a high level of plastic deformability even at 500–600 °C. In contrast, non-alloyed steels such as P235GH and P265GH lose this capability significantly above 300 °C, which presents a risk for their use in high-temperature applications.

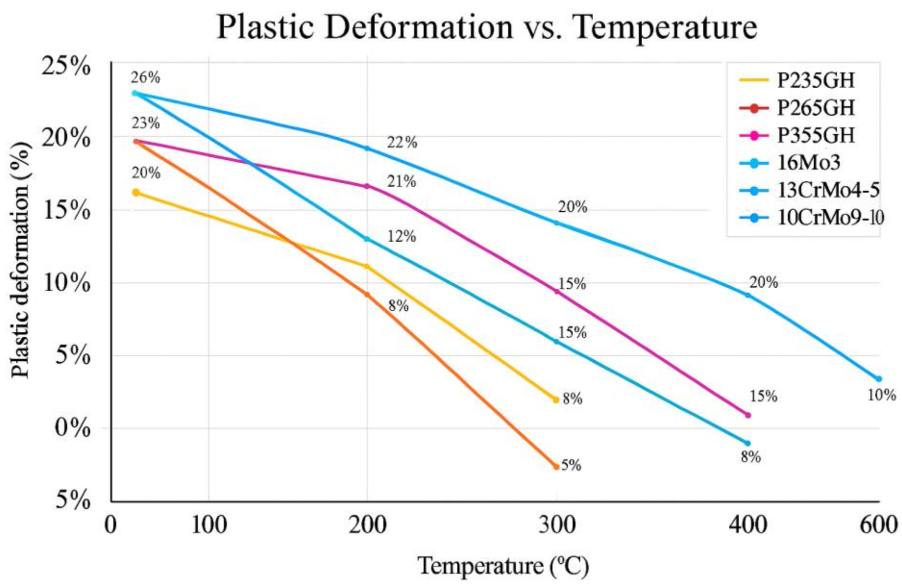


**Figure 8**. Plastic Deformation as a Function of Temperature

## RESULTS

The analysis of materials used in high-temperature boilers confirmed that their operation takes place under extremely demanding conditions combining high temperatures, chemically aggressive environments, and significant dynamic changes in operating regimes. The results showed that improper material selection has a decisive impact on the safety, reliability, and service life of boiler components.

The material concept based on non-alloyed steels, particularly P235GH and P355GH, was found to be unsuitable for long-term operation under high-temperature conditions. Progressive material degradation, intensive surface oxidation, and the formation of microcracks were observed in these materials, leading to frequent failures and a reduced operational lifetime.

The most pronounced negative properties were identified in steel P235GH. Mechanical testing revealed a sharp decrease in strength at temperatures above 350 °C, accompanied by a loss of plastic properties and accelerated surface oxidation. Creep loading at 400 °C and a stress level of 80 MPa demonstrated a significantly limited service life. Investigation of thermal fatigue under cyclic loading in the temperature range of 350–500 °C revealed the formation of microcracks, particularly in welded joints, with the number of cycles to failure being less than 5,000.

The results also demonstrated that non-stationary boiler operation represents one of the most critical factors influencing material degradation. Rapid start-ups, load fluctuations, and sudden pressure drops generate thermal shocks with temperature change rates of up to 100 °C/min, resulting in significant temperature gradients in the walls of tubes and other components. A particularly dangerous phenomenon was identified as a sudden pressure drop accompanied by instantaneous boiling of the cooling water and the formation of a boiling film, which reduces the heat transfer coefficient by up to 80 % and increases the local tube-wall temperature by up to 200 °C.

In contrast, the results confirmed significantly superior performance when alloyed high-temperature steels were used. Steel 13CrMo4-5 achieves an operational lifetime of approximately 100,000 hours at a temperature of 550 °C and a pressure of 50 MPa, while exhibiting a low corrosion rate even in aggressive environments. For even more demanding operating conditions, steel 10CrMo9-10 proved suitable, maintaining stable mechanical properties up to 600 °C and achieving a creep strength of 70 MPa at 550 °C.

## DISCUSSION OF RESULTS

The obtained results unequivocally confirm that the use of non-alloyed steels in high-temperature boilers represents a significant operational and safety risk. The observed degradation of materials P235GH and P355GH is a consequence of their limited thermal stability, low resistance to creep, and unfavorable behavior under cyclic thermal loading. Especially under non-stationary operating conditions, fatigue damage accumulates, leading to the premature occurrence of failures.

Temperature gradients arising during rapid changes in operating regimes play a significant role. Temperature cycling combined with high internal pressure causes local plastic deformation, which initiates microcracks, particularly in welded regions. The boiling-film phenomenon occurring during a sudden pressure drop represents an extremely dangerous operating condition, as it dramatically reduces cooling efficiency and accelerates material damage.

The discussion of the results also highlights the clear advantages of alloyed heat-resistant steels. Their higher strength at elevated temperatures, improved oxidation resistance, and significantly higher creep life enable reliable boiler operation even under prolonged high thermal loads. The implementation of steels such as 13CrMo4-5 and 10CrMo9-10 represents an effective approach to reducing failure frequency, increasing operational safety, and extending equipment service life.

Based on these findings, it can be concluded that modern solutions for high-temperature boilers should be founded on a transition from non-alloyed materials to alloyed high-temperature steels, as well as ceramic composites and advanced insulation systems. A key aspect is also the optimization of operating regimes aimed at minimizing thermal shocks and limiting non-stationary conditions. The combination of appropriate material selection and proper operational control constitutes a fundamental prerequisite for improving the reliability, safety, and energy efficiency of high-temperature boiler systems.

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## CONFLICT OF INTERESTS

The authors declare that there is no conflict of interests regarding the publication of this paper.

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