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# Microstructural and Mechanical Properties Assessment of P91 Main Steam Pipes

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ABSTRACT

*This study investigates the microstructural and mechanical property changes in P91 steel used in the main steam pipe of a 700 MW sub-critical power plant after 130,000 hours of operation at 548°C and 19.4 MPa. P91 steel, valued for its high-temperature strength and corrosion resistance, is a critical material in thermal power plants. This research evaluates the effects of prolonged high-temperature exposure on the material's microstructure, hardness, and tensile strength by comparing samples of the original (virgin) P91 material with those subjected to long-term operation. Tensile and hardness tests, following ASTM E8M and E21 standards, and microstructural analysis using optical microscopy were conducted. Results indicate a reduction in hardness from 224 HV in the virgin sample to 214 HV in the exposed sample, which remains within the acceptable range for P91 (196 HV to 265 HV) but signifies some softening due to microstructural changes. Tensile testing revealed a decrease in maximum tensile strength from 705.9 MPa in the virgin sample to 671.6 MPa in the exposed sample, alongside a slight increase in elongation at break (21.3 mm in the exposed sample vs. 20.5 mm in the virgin sample). Microstructural analysis showed coarser tempered martensitic grains and increased precipitate size and density in the exposed material, consistent with thermal aging effects. These findings highlight the gradual degradation of mechanical properties, including reduced hardness and plasticity, underscoring the importance of regular monitoring to ensure the long-term reliability of power plant components. This study contributes to a better understanding of P91 steel's durability and structural integrity under prolonged operational stress, supporting predictive maintenance and material performance assessment in high-stress environments.*

*Keywords: P91 alloy; microstructure stability; mechanical properties; hardness; power plant*

## INTRODUCTION

Originally developed in the 1970s by Oak Ridge National Laboratory and Combustion Engineering, United States of America, P91 steel was engineered from P9 steel into a more robust 9Cr-1Mo grade to enhance thermal efficiency and reduce $CO_2$ emissions from thermal power plants, thereby supporting environmental sustainability (Abe 2014). Enhanced by additives like vanadium, niobium, and nitrogen, P91 steel boasts superior mechanical properties, including a yield strength of 415 MPa, a tensile strength of 585 MPa, and a maximum hardness of 260 HV at room temperature, ensuring reliability under extreme conditions. Its use is crucial in temperatures ranging from 540 to 650°C, conditions under which it maintains integrity and performance essential to power plant operation (Abe 2014).

For a power plant to function effectively and without interruptions, all its equipment and components must continue to work properly. One of the most common reasons for unexpected problems in power plants is pipeline leaks. For power plants that rely on fossil fuels, the reliability of pipes, superheaters, heat exchangers, turbines, and other equipment is essential to maintaining a consistent and uninterrupted power supply. These components are all critical to the operation of the power plant, and the failure of any one of them can result in a complete shutdown of the entire system. Within the pipeline system, the P91 main steam pipe (MSP) is particularly critical, as it transmits high-temperature, high-pressure steam (Fardeen Malik et al. 2023; Xu et al. 2020).

Energy plants operate in cycles, and routine operations such as start-up and shut-down can cause thermal effects like temperature gradients. These effects can lead to the water hammer phenomenon, which can cause fatigue damage to the piping system (Ghaffar et al. 2017). This damage can accumulate over time, leading to system failures and power generation disruptions, as reported in both local and international power plants (Choi & Han 2021). The main steam pipe system is designed to deliver steam safely and efficiently throughout the power generation process. Failures in this system can significantly impact the power plant's smooth operation, affecting both safety and power generation capacity. Several factors contribute to these pipe failure incidents, including continuous exposure to high pressure and temperature, leading to aging and fatigue(Ghaffar et al. 2017). Additionally, fluctuations in the operational load of the boiler unit can influence these failure occurrences.

Engineering components and their structures are among the most crucial aspects that must be carefully and meticulously designed to ensure no losses occur, based on fundamental factors such as user safety, manufacturing costs, maintenance, and production time in engineering applications(Mubasyir et al. 2025). Proper design and material selection play a vital role in determining the longevity and efficiency of power plant components, particularly those subjected to extreme conditions(Mubasyir et al. 2025)

P91 steel, an alloy with high chromium (9%) and molybdenum (1%), is widely recognized for its high-temperature strength, corrosion resistance, and excellent heat transfer properties, making it ideal for components subjected to high pressure in power generation, such as steam pipes and turbines (Dak & Pandey 2020). However, the microstructure of P91 steel evolves during prolonged exposure to high temperatures. Initially, finely distributed precipitates, which help pin dislocations and provide creep strength, begin to coarsen over time. MX carbonitride precipitates, crucial for maintaining creep resistance, gradually dissolve, reducing their ability to impede dislocation motion. Simultaneously, the growth of the Z-phase at the expense of MX particles further accelerates creep degradation (Zhao et al. 2018).

Recent studies have analyzed P91 steel degradation at exposure durations of 50,000–100,000 hours (Siefert & David 2014; Wang et al. 2021; Zhao et al. 2018), providing insights into its microstructural evolution and mechanical performance. However, research focusing on extended service durations remains limited. The present study addresses this gap by extending the analysis to 130,000 hours, offering a comprehensive assessment of the long-term degradation mechanisms in P91 steel. This extended exposure provides a deeper understanding of the material's behavior under prolonged high-temperature conditions, particularly in terms of creep resistance, carbide evolution, and mechanical stability. By evaluating these microstructural and mechanical changes, this study contributes to optimizing maintenance strategies, extending the service life of steam pipes, and ensuring the reliability of power plant components operating under extreme conditions.

Despite the extensive use of P91 steel in power plants, its long-term microstructural degradation and mechanical property evolution require further investigation. Previous studies have examined P91 steel after shorter service durations, typically within 50,000–100,000 hours, providing insight into its initial aging behavior. However, there remains a knowledge gap in understanding how prolonged exposure up to 130,000 hours affects its integrity, particularly regarding creep resistance, carbide evolution, and mechanical stability. This study aims to bridge that gap by analyzing the microstructural and mechanical changes in P91 steel after 130,000 hours of service, offering a new perspective on its long-term performance and reliability in high-temperature environments. The findings of this study can provide valuable insights for extending the lifespan of steam pipes, optimizing maintenance strategies, and ensuring operational safety in power plants.

## METHODOLOGY

This investigation explores the microstructural and mechanical properties of P91 steel after 130,000 hours of operation under high temperature and pressure, comparing them with those of an unused (virgin) P91 steel sample. The investigation focuses solely on the base metal, excluding any welded regions, to ensure that the analysis reflects only the effects of prolonged thermal exposure. The methodology involves sample preparation, microstructural analysis through optical microscopy, and mechanical testing, including hardness and tensile tests, utilizing advanced equipment to ensure accuracy.

Figure 1 illustrates the arrangement of the main steam pipeline in the power plant. This diagram illustrates the main steam flow path in the boiler component, which spans nine levels starting from the ground level (G), followed by levels 0.5, 1, 2, 3, 4, 5, 6, 7, 8, and up to level 9. The H-pipe component is located at level 0.5, while the final superheater header is positioned at level 8. From this header, there are two main pipes known as the MSPH-pipeline, branching out as the Left pipe and Right pipe. The steam flow moves in the direction indicated in the diagram, from the boiler and ultimately towards the steam turbine. This multi-level arrangement is designed to optimize the steam flow path within the boiler system to ensure high operational efficiency and flow stability before reaching the turbine.

The microstructural and mechanical properties of P91 main steam pipes in a subcritical power plant after 130,000 hours of service under high pressure and high temperature were analyzed. The pipe selected for this study is shown in Figure 2. The pipe has an internal diameter of 350 mm, an external diameter of 445 mm, and a wall thickness of 95 mm, and was operated at a temperature of 548°C and a pressure of 19.4 MPa. The chemical composition of the used P91 steel is listed in Table 1.

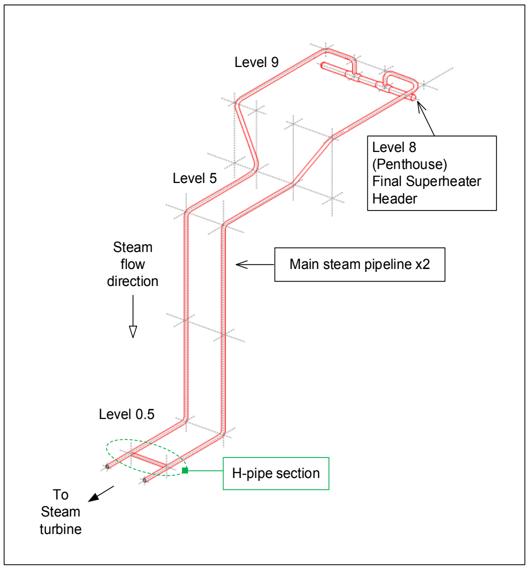


FIGURE 1. Ilustrate the arrangement of main stem pipeline in power plant.

FIGURE 2: Main Steam H-Pipe.

TABLE 1. ASTM Chemical compositions of the P91 studied (mass %)

| Element | C | Mn | P | S | Si | Cr | Mo | V | N | Ni | Al | Co |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Composition (mass %) | 0.08% - 0.12% | 0.3% - 0.6% | max - 0.020% | max - 0.010% | 0.20% - 0.50% | 8.00% - 9.50% | 0.85% - 1.05% | 0.18% - 0.25% | 0.030% - 0.070% | 0.40% Max | 0.02% Max | 0.06% - 0.10% |

## SAMPLE PREPARATION FOR MICROSTRUCTURAL ANALYSIS AND HARDNESS TESTING

The study utilized two types of P91 steel samples: a service-exposed P91 steel pipe that had been in operation for 130,000 hours and a virgin, unused P91 steel sample for comparison, with both samples prepared for microstructural analysis and hardness testing using identical procedures to ensure consistency in the material examination. To preserve surface integrity and protect the edges, both service-exposed and virgin samples were cold-mounted following the Standard Guidelines for Metallographic Specimen Preparation(ASTM 2011). Cold mounting also facilitated handling irregularly shaped specimens and filled porous regions. After mounting, the samples underwent grinding using silicon carbide paper with progressively finer grits (120, 350, and 1,000) to ensure a flat and smooth surface. The samples were then polished with non-metallic polishing cloths impregnated with diamond paste of decreasing grain sizes (9 µm, 6 µm, and 1 µm) to achieve a mirror-like finish. This step was essential for both microstructural observation and hardness testing. To reveal the true microstructure of the P91 steel, the polished samples were etched using Villella's reagent for approximately 5 seconds, as recommended for P91 steel examination(C. Pandey & Mahapatra 2016). This process exposed the tempered martensitic structure, grain boundaries, and precipitates such as $M_{23}C_6$ and MX.

## MICROSTRUCTURAL EXAMINATION

The microstructural examination was conducted using an optical microscope to analyze the structural differences between the virgin and service-exposed P91 steel samples. The analysis focused on identifying changes in martensitic structure, grain growth, and precipitate distribution. Microstructural images were captured using a Carl Zeiss Axio Imager 2, optical microscope with a magnification of 500x. These magnifications were used to observe the tempered martensitic lath structure, grain refinement, and potential carbide precipitation, as well as any abnormal microstructures that may have developed after long-term service. This analysis helped to determine the presence of untempered and tempered martensite, as well as any grain growth or other microstructural abnormalities.

## HARDNESS TESTING

The same samples used for microstructural analysis were also subjected to hardness testing. Sample preparation, including mounting, grinding, polishing, and etching, was done to ensure smooth and reflective surfaces, which are crucial for accurate micro-hardness measurements. The hardness of the samples was measured using a Future Tech Micro Vickers Hardness Tester. A consistent load of 300 gf was applied for 15 seconds on the surface of each polished specimen using a diamond pyramid-shaped indenter with a square base. The test involved making indentations at ten random points across each specimen, with indentation spacing ranging from 0.25 mm to 3 mm. The average hardness values were recorded for each sample to assess differences in mechanical integrity between the service-exposed and virgin P91 steel samples. Both the microstructural images and hardness values were analysed to assess the effects of long-term exposure to high temperature and pressure on the service-exposed P91 steel. The optical microscope provided detailed observations of martensitic structures and grain boundaries, while the hardness data were used to evaluate material degradation and changes in mechanical properties.

## TENSILE TEST

Tensile tests were conducted on both service-exposed and unused P91 steel samples using the Shimadzu Universal Testing Machine 500kN, in accordance with ASTM E8M and E21 standards (Products 2021). The test was conducted at room temperature for both samples. The test involved applying uniaxial tensile loads until failure, and key parameters such as yield strength, ultimate tensile strength, and elongation were recorded. The tensile test results have been analysed to assess mechanical degradation and strength loss in samples exposed to service due to prolonged operation under high temperatures and pressure.

## RESULT AND DISCUSSION

### MICROSTRUCTURE ANALYSIS

The comprehensive microstructural analysis of P91 steel, both in its virgin form and after 130,000 hours of operation, provides critical insights into the effects of prolonged high-temperature service on the material's integrity and performance. In its original state, the P91 steel exhibits a fine, uniform tempered martensitic structure with clearly defined grain boundaries and a homogeneous distribution of small precipitates, as shown in Figure 3. a(i), a(ii). The microstructure shows clearly defined grain boundaries and a homogeneous distribution of small precipitates.

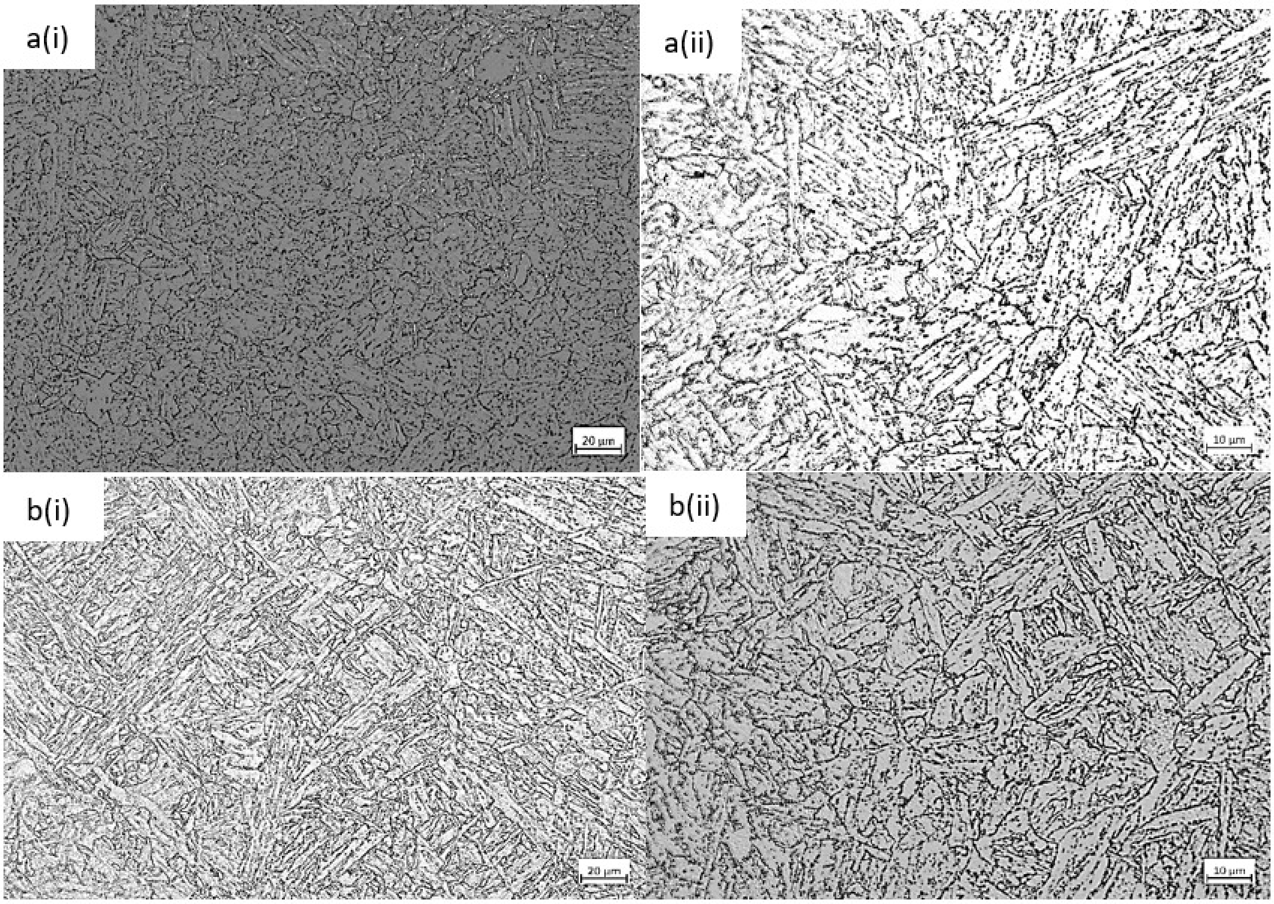


FIGURE 3. Microstructure of P91 Material: (a) Virgin P91 Material at 500× Magnification (a(i)) and 1000× Magnification (a(ii)); (b) P91 Material After 130,000 Hours of Operation at 500× Magnification (b(i)) and 1000× Magnification (b(ii))

After 130,000 hours of operation under high-temperature (548°C) and high-pressure (19.4 MPa) conditions, the microstructure of the P91 steel demonstrates significant changes, as observed in Figure 3 b(i) and b(ii). The martensitic laths have become coarser, with an increased size and density of precipitates along the grain boundaries and within the grains. These precipitates, primarily composed of $M_{23}C_6$ carbides and potentially Laves phases, have grown in size due to the prolonged thermal exposure. Such coarsening is a common phenomenon in ferritic steels, as noted in studies on 12Cr-2W, where grain boundary precipitate growth significantly affects creep behavior (Kimura et al. 2006). The observed presence of medium-grained, tempered martensitic structures enriched with larger precipitates suggests a degree of degradation, yet remains within operational tolerance.

The microstructural changes observed in P91 steel after prolonged operation have direct implications on its mechanical stability and creep resistance. Grain coarsening reduces the grain boundary area available to impede dislocation movement, leading to a decline in creep resistance. This is particularly critical for components exposed to high-temperature and stress conditions, where material longevity depends on maintaining microstructural stability. The increased size and density of $M_{23}C_6$ carbides and Laves phases at the grain boundaries may serve as strengthening agents initially; however, excessive precipitate growth can lead to embrittlement and reduce the material's ability to accommodate strain, thereby affecting its long-term mechanical stability. Additionally, carbide formation and precipitate coarsening significantly influence the creep rupture strength of the material, as they dictate the steel's ability to withstand prolonged stress without premature failure. These transformations highlight the necessity of understanding microstructural evolution to predict material performance over time and optimize its service life.

Based on the microstructural analysis of P91 after 130,000 hours of operation at a temperature of 548°C and pressure of 19.4 MPa, several key features were observed that can be classified according to VGB guidelines. VGB, originally known as the "Vereinigung der Großkessel-Besitzer" (Association of Large Boiler Owners), is a prominent technical association that serves the global energy industry, with its roots in Germany. At an initial stage, the presence of small voids or microvoids at grain boundaries was identified, although no large creep voids were observed, indicating a low level of damage. Based on the VGB classification (Table 2), this sample qualifies for a Category 2A rating, which reflects "creep exposure without significant cavity presence." This VGB-based assessment provides essential guidance that, despite early signs of creep damage, the microstructure of P91 remains within an acceptable level for continued use, with indications of low-level microstructural degradation (Hu 2012). Compared to the virgin P91 sample, the operated material shows grain coarsening with an average grain size of around 25 μm and the presence of carbide rows along the boundaries of the martensitic laths. This change highlights the structural transformation that occurs due to prolonged pressure and high-temperature exposure, as noted in the VGB classification, which states that microvoid formation at grain boundaries becomes more prominent with increased secondary creep exposure.

Research by Chandan Pandey and Mahapatra (2016) supports these observations, showing that in P91 steel, secondary phase precipitates and grain coarsening increase with prolonged exposure. Their findings indicated that the size and number of precipitates rose as tempering time extended from 720 hours to over 2230 hours, a progression that aligns well with the changes observed in the service-exposed P91 sample (Chandan Pandey et al. 2016). Furthermore, Hui Jin Lin's research (2013) on similar martensitic steels highlighted the presence of tempered martensitic features with faint austenite grain boundaries and low carbide levels in virgin materials, contrasting with the coarser grain structure and increased carbide content in service-exposed samples (H. Li & Mitchell 2013). This structure aligns with the typical microstructure of ferritic-martensitic steels like P91, which are designed to maintain stability and high creep resistance at elevated temperatures. These fine precipitates contribute to the material's initial hardness and resistance to deformation, critical factors for its application in power plants.

TABLE 2. VGB Standard for the Global Energy Industry (Originally "Vereinigung der Großkessel-Besitzer")

| Rating Class | Microstructural/Damage conditon | Demarcation criterion |
|---|---|---|
| 1 | Creep-expose, no creep pores | |
| 2a | Scattered creep pores | Up to 150 pores per mm2 |
| 2b | Numerous creep pores, no orientation | More than 150 pores per mm2 |
| 3a | Numerous creep pores, with orientation | Note 1: In the analyses performed so far on 9-12% Cr-steels, the formation of linear microporosity and grain boundary separations, leading to the formation of macrocracks, was not identified until immediately before the failure of the steel, which is why rating classes 3a and 3b must not be used for the material group. |
| 3b | Linear creep porosity, scattered grain boundry separations | At least two successive grain boundaries, each with at least three pores |
| 4 | Micro-cracks | More Than one grain boundary length |
| 5 | Large creep macro-cracks. | |

The observed microstructural evolution of the P91 material after 130,000 hours indicates a moderate level of degradation that impacts its hardness and ductility. The increase in precipitate size and density, along with grain boundary coarsening, weakens the grain boundary strength and contributes to reduced hardness. Despite these changes, the material maintains most of its mechanical properties within acceptable limits, reflecting the durability of P91 steel in high-stress environments. The coarsening of subgrains and precipitates points to creep-fatigue damage, but this does not signify severe degradation; instead, it suggests manageable changes that can be accommodated within standard operational guidelines (Armaki et al. 2011).

These microstructural changes emphasize the importance of predictive maintenance and regular assessment to ensure the long-term reliability of P91 steel in high-temperature environments. The progressive increase in precipitate size and grain coarsening may lead to a decline in ductility and toughness over time, necessitating careful monitoring (Chandan Pandey et al. 2016). Implementing a systematic evaluation of creep resistance through hardness testing, creep rupture tests, and microstructural analysis will provide valuable insights into the steel's remaining service life and performance trends (Eccc - Wg1.1 2005) .

The microstructural findings from this study demonstrate that while long-term exposure to high temperatures and pressure induces measurable microstructural changes, such as increased grain and precipitate sizes, P91 steel retains substantial structural integrity. This resilience is evident in the material's ability to remain within hardness and tensile strength tolerances. These results underscore the importance of predictive maintenance strategies, including microstructural analysis, hardness testing, and tensile testing, to assess material degradation over time. Industry standards recommend inspection intervals of every 3 to 5 years to detect early signs of aging, ensuring continued operational reliability (Standard 2000). Additionally, considering the manufacturer-recommended service life of P91 steel is approximately 25 years, systematic evaluations and predictive maintenance approaches are crucial for prolonging its usability. This study highlights the significance of understanding microstructural changes to predict material performance and maintain structural integrity within demanding power plant environments.

## HARDNESS

The hardness testing findings for P91 steel samples, encompassing both a virgin sample and a service-exposed sample subjected to 130,000 hours of high-temperature and high-pressure conditions, reveal notable distinctions. The virgin sample demonstrated a hardness of 224 HV, aligning with the standard hardness of P91 steel in its as-received state, which typically measures around 247 HV. In comparison, the service-exposed sample exhibited a reduced hardness of 214 HV, suggesting a moderate decline due to prolonged operational exposure. This reduction correlates with observed microstructural changes, such as grain boundary coarsening and increased precipitate size and density, which contribute to decreased hardness and ductility over time. Nevertheless, these values remain within the specified hardness range for P91 steel, as defined by the American Society of Mechanical Engineers (ASME 2021), which sets a range between 196 HV and 265 HV. These findings indicate that, while some degradation is evident, the P91 steel retains the majority of its mechanical properties, demonstrating durability in high-stress environments.

The observed hardness reduction in the service-exposed sample underscores the effects of long-term exposure to operating conditions. According to standard practices, hardness is routinely monitored during each outage opportunity, with results reported if approach the minimum threshold established by the manufacturer. The reduced hardness is a common expectation for in-service materials subjected to extended high-temperature exposure, as prolonged thermal exposure can lead to microstructural degradation.

Comparatively, results from prior studies, such as the Li & Mitchell (2013) study, reported a significant hardness decline to 145 HV for P91 boiler tube material exposed to 600°C. However, those findings relate to boiler tube material, which has a smaller cross-sectional size than the main steam pipe examined in this study, potentially contributing to the greater hardness reduction observed. In this study, hardness values were reported as the average of five indentations, following ASTM A1038, over a 650 $mm^2$ area per spot, whereas the Li & Mitchell (2013) study reports only the lowest reading without specifying the indentation count or test area size per result. This methodological difference likely contributes to the discrepancies between the hardness findings at 77,000 hours reported in the Li & Mitchell (2013) study and the results observed at 130,000 hours in the current study.

The decline in hardness in the service-exposed sample is primarily attributable to microstructural changes, including grain coarsening and the depletion of interstitial carbon (C) and nitrogen (N) from the matrix. The hardness of P91 steel is influenced by critical factors such as the presence and density of fine precipitates (MX-type), grain size, and the concentrations of C and N in solution (Chandan Pandey et al. 2016). Extended exposure to elevated temperatures leads to the dissolution or coarsening of these fine precipitates, thereby diminishing the material's hardness and mechanical strength.These findings demonstrate the importance of understanding hardness evolution in P91 steel to assess material integrity for components under prolonged operational stress, helping to ensure that the material remains within safe hardness limits throughout its service life.

## TENSILE TESTING

The tensile test results for P91 steel, as shown in Table 3 and Figure 5, reveal notable differences in mechanical properties between the virgin and 130,000-hour service-exposed samples. Both samples display similar elastic behavior up to the yield point, indicating comparable resistance to initial loading. However, the maximum tensile strength of the service-exposed sample is slightly lower (671.6 MPa) compared to the virgin material (705.9 MPa), suggesting minor degradation due to prolonged service. This aligns with findings from Li & Chen (2020), showing that P91 steel maintains much of its tensile strength even after extended high-temperature exposure.

TABLE 3. Tensile test results for virgin and 130,000-hour service-exposed P91 Steel samples.

| Parameter | Virgin Sample | 130,000-Hour Service-Exposed sample |
|---|---|---|
| Maximum Load (kN) | 85.2 | 82.4 |
| Maximum Stress (MPa) | 705.9 | 671.6 |
| Maximum Elongation(mm) | 11.5 | 12.0 |
| Maximum Time (sec) | 345.2 | 361.5 |
| Break Load (kN) | 47.7 | 48.00 |
| Break Stress (MPa) | 394.8 | 391.2 |
| Break Elongation (mm) | 20.5 | 21.3 |
| Break Time (sec) | 615.83 | 640.13 |
| Yield Load (kN) | 65.7 | 61.2 |
| Yield Strength (MPa) | 544.2 | 499.1 |
| Yield Time (sec) | 150.22 | 130.29 |
| Strain % | 14.02 | 14.56 |

In terms of ductility, the service-exposed sample has a marginally higher elongation at break (21.3 mm) than the virgin sample (20.5 mm). While this may indicate a slight increase in total elongation, previous studies (M. Li & Chen 2020; Ma et al. 2018) attribute long-term thermal aging to embrittlement, driven by microstructural changes such as the formation of secondary phases (e.g., $M_{23}C_6$ carbides and Laves phase). Figure 5 supports this, with the stress-strain curve of the service-exposed sample (red) showing a lower stress response at comparable strain levels and reduced capacity for further plastic deformation before fracture. The reduced maximum stress and slightly altered break behavior in the service-exposed sample, as marked in Figure 5, underscore the cumulative effect of prolonged exposure on P91 steel's strength and ductility.

The observed reduction in tensile strength and changes in ductility have direct implications for maintenance strategies and lifespan predictions of P91 steel components in power plants. The relatively minor strength degradation suggests that P91 retains its load-bearing capacity over long-term operation; however, the embrittlement risk necessitates periodic inspection to assess fracture susceptibility. Industrial practices recommend condition monitoring through non-destructive testing (e.g., hardness measurements, metallographic analysis) at service intervals of 3 to 5 years to detect early signs of creep or embrittlement.

Additionally, the increase in elongation may indicate softening due to prolonged thermal exposure, which can influence operational decisions regarding component replacement or refurbishment (Egner et al. 2020). Predictive maintenance models incorporating mechanical property trends and microstructural evolution can improve remaining life estimation, optimizing power plant reliability and reducing unplanned shutdowns. These findings support the need for proactive maintenance strategies, including creep rupture testing and carbide stability analysis, to extend the operational lifespan of P91 steel components in high-temperature environments

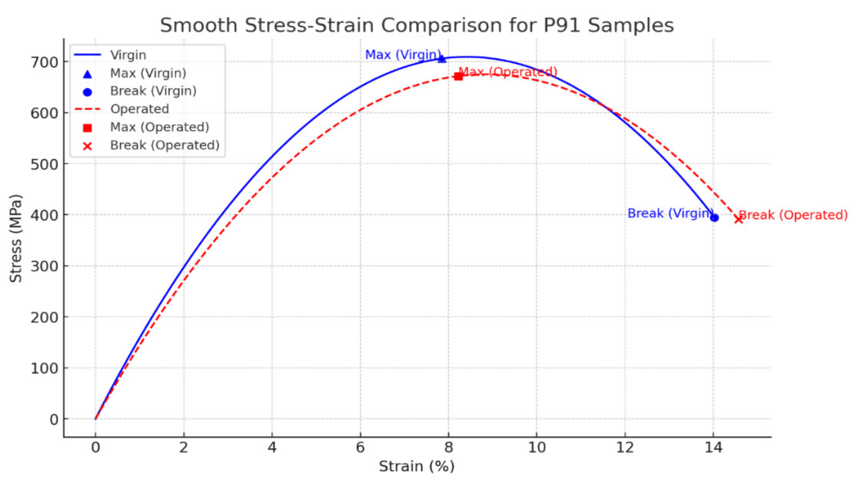


FIGURE 5. Comparison of Tensile Strength between Virgin P91 Material and P91 Material after 130,000 Hours of Operation.

## SUMMARY DISCUSSSION

Table 4 summarizes the comparative analysis of virgin P91 steel and the same material after 130,000 hours of high-temperature service, highlighting significant changes in microstructure, hardness, and tensile properties. The microstructure of virgin P91 steel is characterized by tempered martensite with indistinct prior austenite grain boundaries and minimal carbide presence, reflecting its initial stability and creep resistance. However, after 130,000 hours of service at 548°C and 19.4 MPa, the microstructure undergoes notable transformations, including martensitic coarsening, an increase in precipitate size and density, and secondary phase formation. These aging effects indicate long-term microstructural degradation, which influences the material's mechanical properties and service life. Hardness testing reveals a reduction from 224 HV in the virgin sample to 214 HV in the service-exposed sample, suggesting precipitate coarsening and microstructural softening, which gradually diminishes the material's resistance to deformation. Tensile testing results indicate a decline in maximum tensile strength from 705.9 MPa to 671.6 MPa, alongside a slight increase in elongation at break from 20.5 mm to 21.3 mm. This marginal increase in ductility, likely due to microstructural realignment, does not fully counterbalance the overall reduction in mechanical robustness. This study extends beyond previous research by analyzing P91 steel after an exceptionally long operational period of 130,000 hours, whereas most existing studies have focused on shorter exposure durations. The findings bridge the gap in long-term material performance data, providing a more comprehensive understanding of the progressive effects of prolonged thermal aging on P91 steel. Unlike prior studies that primarily examined early-stage degradation, this research quantifies microstructural and mechanical changes at an advanced stage of service exposure, allowing for more accurate lifespan predictions and maintenance planning for high-temperature power plant components. These findings collectively emphasize the gradual yet significant impact of long-term high-temperature service on the mechanical and structural integrity of P91 steel. The study provides critical insights for power plant operators by reinforcing the need for structured inspection intervals, predictive maintenance, and lifespan assessment to ensure continued operational safety and efficiency.

TABLE 4. Comparative summary of virgin and 130,000 hour of operation P91 steel properties

| Testing | Finding | |
|---|---|---|
| | Virgin P91 | 130,000 hours of operation P91 |
| Microstructure Analysis | Microstructure typical of tempered martensite with prior austenite grain boundaries not very apparent and minimal carbide presence. | Exhibits coarser tempered martensitic growth and the formation of larger and more numerous precipitates. |
| Hardness Testing | Hardness value remains at 224 Hv. | Hardness decreased to 214 Hv, indicating softening due to prolonged service exposure. |
| Tensile Testing | Higher tensile strength (705.9 MPa) and baseline elongation at break (20.5 mm), indicating higher ductility and strength in virgin state. | Slightly reduced tensile strength (671.6 MPa) and a minor increase in elongation at break (21.3 mm), suggesting microstructural changes with a slight increase in total elongation but reduced plasticity, consistent with embrittlement due to long-term high-temperature exposure. |

## CONCLUSION

This study provides a comprehensive analysis of the long-term effects of high-temperature and high-pressure exposure on P91 steel by comparing its microstructural, hardness, and tensile properties in both virgin and 130,000-hour service-exposed states. The findings reveal that while P91 steel retains substantial mechanical integrity after prolonged exposure, gradual degradation is evident in its microstructure, hardness, and tensile strength over time. In its virgin state, P91 steel exhibits a fine, tempered martensitic structure with minimal carbide presence, supporting initial hardness and high creep resistance. However, prolonged service leads to microstructural coarsening, with larger and more numerous precipitates, including $M_{23}C_6$ carbides and potential Laves phases, forming due to thermal aging. This correlates with a reduction in hardness from 224 HV to 214 HV, indicating minor material softening associated with grain coarsening and precipitate growth

Tensile testing results further confirm the impact of long-term exposure, showing a slight decrease in tensile strength from 705.9 MPa to 671.6 MPa and a minor increase in elongation at break from 20.5 mm to 21.3 mm. While this increase in elongation suggests limited plastic deformation adjustments, the overall trend indicates a gradual reduction in ductility over time. These findings emphasize the importance of regular inspection and maintenance of P91 steel components in high-stress environments, such as power plants, to manage material aging and ensure continued reliability. Despite these changes, P91 steel maintains most of its mechanical properties within acceptable operational limits, demonstrating considerable durability and resilience in high-temperature applications. This study highlights the significance of microstructural analysis in predicting long-term material performance, reinforcing P91 steel's suitability for extended service in demanding industrial environments

## DECLARATION OF COMPETING INTEREST

None

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