Journal of Information System and Technology Management
JISTM
EISSN: 0128-1666

Volume 10 Issue 41 (December 2025) PP. 14-22
DOI: 10.35631/JISTM.1041002

JOURNAL OF INFORMATION SYSTEM AND TECHNOLOGY MANAGEMENT (JISTM)
www.jistm.com

GLOBAL ACADEMIC EXCELLENCE

CORRELATION BETWEEN HARDNESS AND MICROSTRUCTURAL EVOLUTION OF P22 STEEL SUBJECTED TO ANNEALING

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Article Info:

Article history:
Received date: 30.09.2025
Revised date: 15.10.2025
Accepted date: 11.11.2025
Published date: 01.12.2025

To cite this document:

Shilan, S. T., & Tarmizi, A. A. T. A. (2025). Correlation Between Hardness and Microstructural Evolution of P22 Steel Subjected to Annealing. *Journal of Information System and Technology Management, 10* (41), 14-22.

DOI: 10.35631/JISTM.1041002

Abstract:

This study investigates the correlation between hardness and microstructural evolution in P22 carbon steel subjected to annealing. Brinell hardness testing revealed a reduction from 161.3 BHN in the as-received condition to 121.3 BHN after annealing, corresponding to an approximate 25% decrease. Optical microscopy of the as-received sample showed irregularly shaped grains with elongated, clustered carbide precipitates concentrated along grain boundaries, which contributed to higher hardness by impeding dislocation motion. In contrast, the annealed microstructure exhibited coarser, more homogeneous grains with spheroidized and uniformly dispersed carbides, consistent with thermal stability achieved through recovery and recrystallization. Complementary SEM analysis further revealed that machining induced grooves and work-hardened surface features present in the as received specimen disappeared after annealing, leaving a uniform recrystallized surface morphology. The combined hardness and microstructural observations demonstrate that annealing promotes softening by reducing dislocation density and redistributing carbides, thereby enhancing ductility at the expense of strength. These findings provide insight into the role of annealing in balancing mechanical performance and microstructural stability of P22 steel for high-temperature service applications.

Keywords:

P22 Carbon Steel, Annealing, Hardness, Heat Treatment, Microstructure

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Introduction

P22 carbon steel, a chromium–molybdenum alloy steel, is widely used in high-temperature and high-pressure piping systems such as power plants and petrochemical facilities due to its creep strength, oxidation resistance, and long-term stability (Shibli et al., 2004; Cao et al., 2021; Jaafar et al., 2022). The mechanical properties of such steels are strongly dependent on microstructural features, including grain size, dislocation density, and carbide distribution, which evolve during fabrication and subsequent thermal treatments (Honeycombe & Bhadeshia, 2006). Among heat treatment processes, annealing is particularly important for restoring ductility, relieving internal stresses, and refining grain morphology through recovery and recrystallization (Krauss, 2005).

Annealing, a common heat treatment for steels, promotes recovery, recrystallization, and grain growth, thereby reducing hardness while improving ductility and toughness (Callister & Rethwisch, 2014; Almula et al., 2023). This relationship between microstructure and mechanical response has been widely documented in alloy steels, where hardness reduction is consistently linked to grain coarsening and dislocation annihilation (Di Schino et al., 2020; Huang et al., 2023).

Recent studies have provided deeper insights into the microstructural and mechanical behaviour of P22 and related Cr–Mo steels under different thermal and service conditions. Xu et al. (2016) demonstrated that heat treatment strongly influences the microstructure and hardness of Cr–Mo steels, highlighting the importance of thermal history in determining performance. Building on this, Ghosh et al. (2023) applied advanced electron backscatter diffraction and transmission electron microscopy to reveal detailed deformation structures in P22 steel, including grain orientation and dislocation substructures formed at elevated temperatures. Investigations of dissimilar weldments involving P22 have further emphasized the sensitivity of hardness and microstructure to post-weld heat treatment, where microstructural inhomogeneity and hardness gradients were observed and mitigated through appropriate thermal processing (Kumar et al., 2022; Muralidharan et al., 2022; Tammasophon et al., 2021). More recently, Sarkar et al. (2024) reported that post-weld heat treatment markedly alters the microstructure and hardness distribution in 2.25 Cr–1Mo steels, reinforcing the strong correlation between thermal treatment parameters and mechanical response.

Microstructural changes during annealing typically reduce dislocation density and grain boundary energy, thereby lowering hardness and enhancing ductility (Callister & Rethwisch, 2014; Gladman, 1989). Hardness testing remains one of the most widely used methods for detecting such changes, owing to its simplicity and sensitivity to microstructural variations. However, despite progress in understanding thermal treatments of low-alloy steels, relatively few studies have explicitly addressed the direct correlation between hardness and grain structure evolution in annealed P22 steel pipe. Consequently, a direct evaluation of as-received versus annealed P22 steel is required to clarify structure–property correlations in this alloy system (Yang et al., 2024; Fortini et al., 2024).

This study aims to address this gap by examining the microstructure and hardness of P22 steel before and after annealing. The findings contribute to a better understanding of the structure–property relationship in P22 steel and provide guidance for optimizing its thermal processing for industrial applications.

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Literature Review

Fundamentals of Heat Treatment in Cr–Mo Steels

Cr–Mo steels, such as P22, are widely used in power generation and petrochemical applications because of their creep resistance and thermal stability. Their properties are strongly dependent on microstructural features that evolve during thermal processing. Classical metallurgical studies demonstrated that annealing promotes recovery, where dislocations rearrange to lower-energy configurations, and recrystallization, where new strain-free grains nucleate and grow (Honeycombe & Bhadeshia, 2006; Krauss, 2005). At longer durations or higher temperatures, grain growth occurs, leading to a reduction in strength but improved ductility.

Annealing also influences carbide precipitation and distribution, which contribute to strengthening in Cr–Mo steels (Callister & Rethwisch, 2014; Gladman, 1989). As carbides coarsen during prolonged annealing, the pinning effect on grain boundaries diminishes, allowing grains to enlarge. This process reduces hardness, reflecting diminished dislocation density and boundary strengthening. Thus, the fundamental mechanism of hardness reduction during annealing is well established: it is driven by microstructural coarsening and recovery of crystal defects.

Hardness and Microstructural Evolution Under Thermal Processing

Recent studies have expanded this understanding by quantifying the relationship between heat treatment conditions, microstructure, and hardness in a variety of steels. For instance, Di Schino et al. (2020) showed that a 7% Cr forging steel experienced significant microstructural refinement when subjected to optimized thermal treatments, with corresponding hardness variations. Huang et al. (2023) further demonstrated that in 5CrNiMoV steels, adjusting the tempering temperature and duration optimized carbide precipitation and hardness balance, confirming the sensitivity of hardness to both grain size and secondary phases.

In high-chromium steels such as X46Cr13, Przyszlak and Wróbel (2025) revealed that higher austenitizing temperatures increased hardness due to finer martensite formation upon cooling, while prolonged holding promoted grain coarsening and hardness reduction. Similarly, annealing studies on 28 wt% Cr cast iron with Mo/W additions indicated that prolonged exposure produced a homogenized microstructure, accompanied by lower hardness values (Wróbel et al., 2023). These results emphasize that both composition and thermal parameters govern the balance between hardness and microstructural evolution.

Research on 9% Cr heat-resistant steels such as T91 has confirmed analogous behavior. Jaafar et al. (2022) reported that heat treatment reduced hardness while stabilizing the ferrite–martensite microstructure, critical for high-temperature service. Yang et al. (2024) optimized annealing conditions in DH steels, observing that increased annealing temperatures promoted hole expansion properties by reducing hardness and refining the grain structure. Fortini et al. (2024) extended these findings at an industrial scale, showing that isothermal treatment of EN 100CrMo7 steel produced systematic reductions in hardness with increasing treatment severity, directly linked to grain coarsening.

Studies on P22 Steel and Related Weldments

Although P22 steel is a critical structural material, much of the recent literature has focused on its welding and post-weld heat treatment (PWHT) rather than direct annealing of pipe material. Kumar et al. (2022) studied dissimilar P22/P91 weldments, finding pronounced hardness

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gradients across the weld metal, heat-affected zone (HAZ), and base metal. PWHT at appropriate conditions successfully reduced these gradients by tempering martensitic regions and homogenizing the microstructure. Similarly, Tammasophon et al. (2021) examined TIG welds of P22/P91 steels with Inconel 625 filler, where PWHT reduced hardness in the HAZ and improved toughness.

Other studies reinforce the effect of PWHT on related steels. Du et al. (2021) reported that heat treatment modified both the hardness and carbide morphology of Cr12MoV steels, while Xu et al. (2016) showed that hardness reduction in Cr–Mo steels was highly dependent on the precise thermal cycle. Muralidharan et al. (2022) also confirmed that dissimilar weldments benefit from PWHT, with hardness and microstructural inhomogeneities mitigated by carefully designed thermal schedules. These findings collectively highlight the sensitivity of P22 and related steels to thermal treatment in terms of hardness and microstructural response.

Research Gap

Together, these studies highlight the importance of correlating hardness with microstructural features in P22 and related steels. However, despite the extensive research on thermal processing and weldments, limited work has focused specifically on the direct comparison of hardness and grain structure in P22 steel before and after annealing. Addressing this gap provides a valuable opportunity to deepen understanding of the annealing response in P22 steel pipe, with implications for its processing and application in high-temperature service environments.

Methodology

Material Preparation

The material investigated in this study was a section of P22 carbon steel hollow pipe (2.25 Cr–1Mo steel) obtained in the as-received condition. Samples were cut into small size hollow cylinder size as show in Figure 1 using a precision cutter to minimize thermal and mechanical distortion. The specimens were divided into two sets: (i) as-received condition, and (ii) annealed condition. The annealing treatment was performed in a muffle furnace at a controlled temperature (shown at Figure 2) followed by furnace cooling to room temperature.

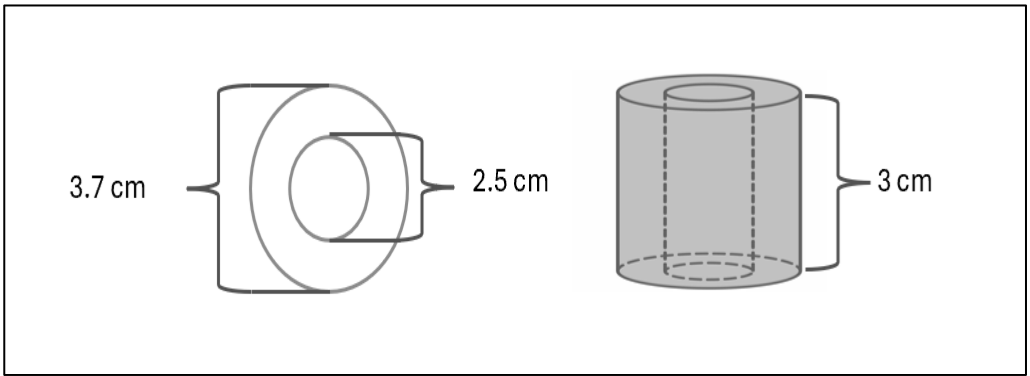

Figure 1: P22 Hollow Pipe Sample Dimension.

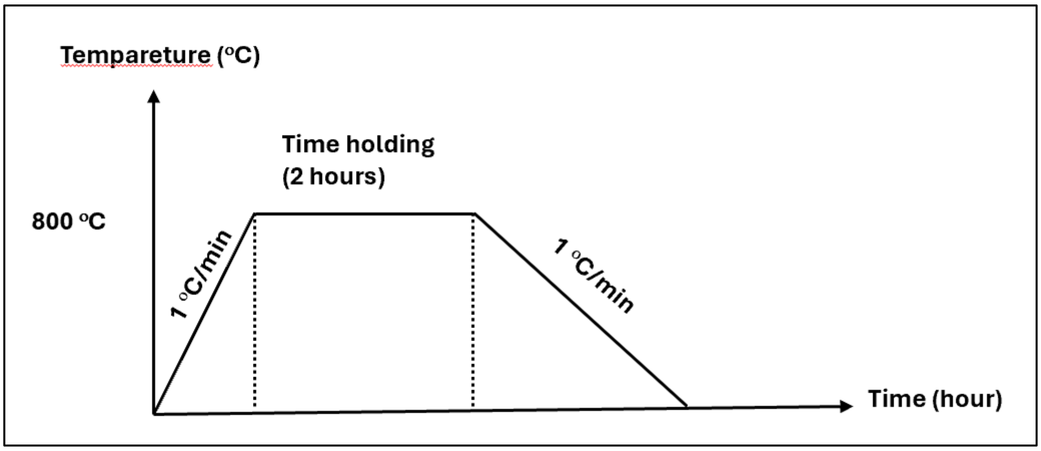

Figure 2: The Annealing Process for P22

Hardness Testing

Brinell hardness measurements were performed using a 2.5 mm diameter tungsten carbide ball indenter with a maximum load of 187.5 N applied for 10–15 seconds, following ASTM E10 standard. At least five indentations were made on each sample surface at randomly selected locations, with sufficient spacing between indents to avoid overlapping plastic zones. The Brinell hardness number (BHN) was calculated from the indentation diameters, and the average values were compared between initial and annealed specimens.

Metallographic Preparation and SEM Analysis

For microstructural examination, specimens were mounted in epoxy resin and sequentially ground with silicon carbide papers (grades 240–1200) followed by polishing with diamond suspensions down to 1 µm finish. Final polishing was carried out using colloidal silica to achieve a mirror-like surface. The samples were etched with a 3% Nital to reveal grain boundaries.

Microstructural characterization was performed using optical microscope and scanning electron microscopy (SEM) operated at 15–20 kV. Representative micrographs were recorded for both initial and annealed samples, focusing on grain morphology, distribution, and the presence of defects. Grain size and morphology changes were qualitatively compared with corresponding hardness results to establish structure–property correlations.

Result and Discussion

Hardness Evaluation

Table 1: Brinell Hardness Number (BHN) for P22 Sample

Sample	Test 1	Test 2	Test 3	Test 4	Test 5	Average
As received	158.4	163.7	161.3	159.6	163.5	161.3
After annealed	121.2	121.5	121.3	121.2	121.5	121.3

The Brinell hardness test provided a quantitative assessment of the mechanical response of P22 carbon steel before and after annealing. As shown in Table 1, the as received sample exhibited a hardness of 161.3 BHN, while the annealed sample recorded a significantly lower hardness of 121.3 BHN, corresponding to a reduction of approximately 25%.

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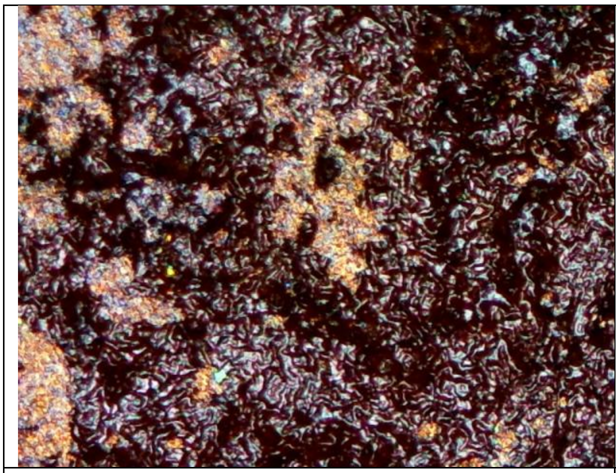
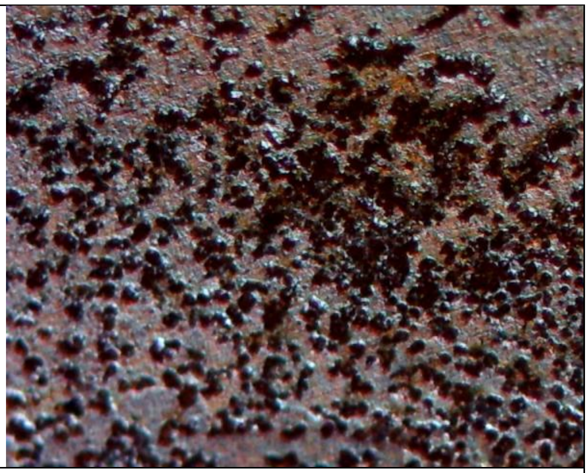
This decrease in hardness reflects the substantial microstructural changes induced by annealing. In the as received condition, the relatively higher hardness is attributed to the presence of finer grains, elevated dislocation density, and the heterogeneous distribution of carbide precipitates, which act as barriers to dislocation motion (Li et al., 2020; Olugbade et al., 2024). Such features strengthen the steel through a combination of grain boundary and precipitation hardening.

After annealing, the hardness reduction is consistent with the recovery and recrystallization processes that occur during thermal treatment. The observed microstructure supports this trend: coarser grains and spheroidized carbides were evident, suggesting reduced grain boundary area and fewer obstacles to dislocation movement. Consequently, the material softens as ductility improves, which is beneficial in applications where toughness and formability are required.

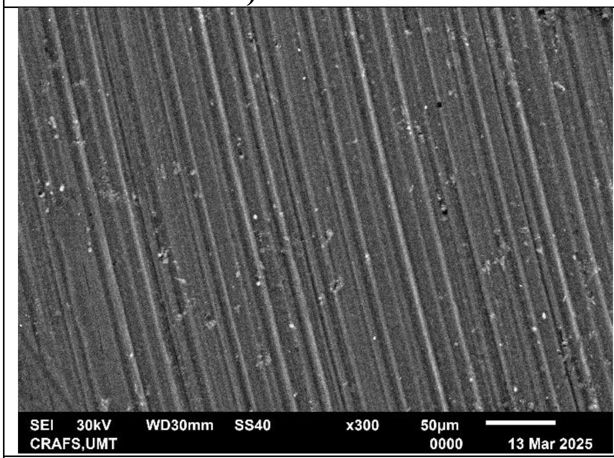
Microstructural Analysis



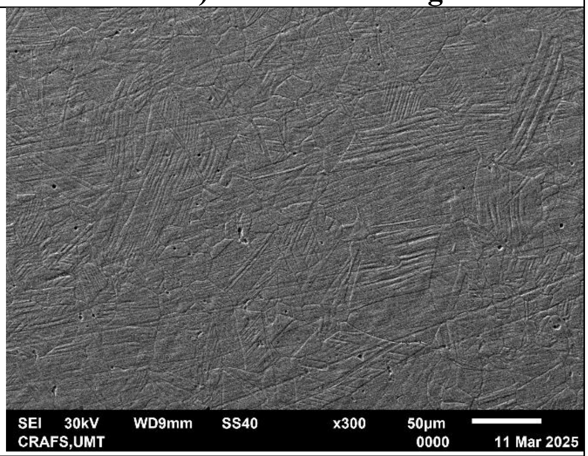
a) As received



b) After annealing



c) As received



d) After annealing

Figure 3: Micrograph of P22 using Optical Microscope x5 for (a) and (b); Scanning Electron Microscope x300 for (c) and (d)

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The optical micrograph of the as received sample (Figure 3a) showed a heterogeneous microstructure characterized by irregularly shaped grains and bright carbide precipitates concentrated along grain boundaries. These carbides appeared elongated and clustered, consistent with incomplete homogenization during prior fabrication processes. Such a morphology provides effective strengthening by restricting dislocation motion, explaining the higher hardness values observed in this condition (Zhou et al., 2019).

In comparison, the annealed sample (Figure 3b) displayed a coarser and more homogenized grain structure, with carbide precipitates appearing darker, more rounded, and evenly dispersed across the ferritic matrix. The transformation from elongated, clustered carbides to spheroidized carbides reflects the thermal stability achieved through annealing. This evenly dispersion also contribute to the precise hardness reading in Table1. Grain coarsening and carbide redistribution reduce grain boundary area and dislocation pinning points, leading directly to the observed decrease in hardness to 121.3 BHN.

The SEM micrographs further confirmed the significant transformation in surface morphology following annealing. In the as received condition (Figure 3c), the surface displayed prominent unidirectional grooves, indicative of prior mechanical processing such as grinding or turning. These features are typical of cold worked surfaces, where plastic deformation introduces surface roughness, residual stresses, and high dislocation density (Callister & Rethwisch, 2020). The presence of such striations suggests that the material retained work-hardened grains and machining-induced defects.

By contrast, the annealed specimen (Figure 3d) exhibited a uniform surface topography, free from machining grooves, with crisscrossed patterns suggestive of recrystallized grains and slip bands. The disappearance of machining marks confirms that annealing facilitated recovery and recrystallization, which relieved internal stresses, reduced dislocation density, and restored ductility (Porter et al., 2009). This observation is consistent with earlier reports on ferritic martensitic steels, where annealing promoted the development of strain-free grains and microstructural homogenization (Zhu et al., 2015).

These changes have important implications for the mechanical and functional performance of the steel. The as received condition, with its higher residual stress and surface roughness, may be more susceptible to stress corrosion cracking and fatigue initiation due to localized stress concentrations (Gegel, 1984). Meanwhile, the annealed condition is expected to offer improved dimensional stability, enhanced fatigue life, and better surface integrity, making it more suitable for high-temperature service environments such as those encountered in boiler and pressure vessel applications.

Correlation Between Hardness and Microstructure

The combined hardness and microstructural analyses establish a clear correlation between annealing, microstructural evolution, and mechanical response in P22 steel. The as received condition exhibited higher hardness due to grain boundary and precipitation strengthening effects, while the annealed condition demonstrated lower hardness consistent with recovery and grain growth. These findings align with established metallurgical principles for 2.25 Cr–1 Mo steels, in which annealing improves ductility and toughness at the expense of strength. The results thus provide direct evidence that the mechanical behaviour of P22 steel is closely governed by its microstructural stability under thermal treatment.

Conclusion

This study examined the effect of annealing on the hardness and microstructural features of P22 carbon steel using Brinell hardness testing and SEM analysis. The steel's initial hardness was relatively high, which can be attributed to finer grain structures, higher dislocation density, and non-uniform microstructural characteristics that were typically maintained from past processing. SEM micrographs confirmed the presence of irregular and relatively refined grains, supporting the observed higher hardness values.

Following annealing, a notable reduction of hardness from 161.3 BHN for as received condition to 121.3 BHN after annealing, representing a decrease of approximately 25%. The decrease in hardness was accompanied by distinct microstructural changes, as SEM analysis revealed grain coarsening, improved uniformity, and a reduction in microstructural defects. These transformations reflect recovery and partial recrystallization processes, in which dislocations rearrange and annihilate, while boundaries migrate to produce a more stable grain structure. The coarsening of grains reduced grain boundary strengthening, thereby accounting for the measured reduction in hardness.

The correlation between hardness reduction and microstructural transformation confirms that annealing enhances ductility and homogenization at the expense of strength in P22 steel. These findings are consistent with established metallurgical principles for Cr–Mo steels, highlighting the critical role of thermal processing in balancing mechanical performance and microstructural stability for high temperature applications.

Acknowledgements

This work was supported by the Pusat Asasi STEM, Universiti Malaysia Terengganu (UMT). The authors also acknowledge the technical assistance provided by the staff of the Central Laboratory, Faculty of Ocean Engineering Technology (FTKK) and the Nano Physics Laboratory, whose assistance was crucial to the experimental work's completion.

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Journal of Information System and Technology Management
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