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Investigating the effects of partitioning temperature fluctuations on the mechanical properties of ASTM A36 carbon steel using Q-P-T heat treatment: an experimental study

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Abstract

In the continuum of time and technological advancement, the use of metals, specifically carbon steel, has significantly increased as primary materials in various operational and industrial domains, including tool fabrication and automotive components. To meet the evolving demands of industries, precise heat treatment processes have been developed to enhance the metallic properties. This study specifically focused on the application of the Quenching-Partitioning-Tempering (Q-P-T) method to ASTM A36 steel. The study investigated different partitioning temperatures, namely 300°C, 350°C, and 400°C, with 15-minute intervals. A comprehensive set of mechanical tests, including hardness, tensile, and microstructural analyses, were conducted to assess the response of the material to the treatment. The results reveal significant findings: a partitioning temperature of 300°C yields the highest hardness value of 164 Vickers Hardness Number (VHN). Furthermore, the tensile tests demonstrate that a partitioning temperature of 300°C is optimal, achieving a maximum stress value of 515.73 MPa. Conversely, a partitioning temperature of 400°C exhibits the highest strain value at 21.08% and the highest elastic modulus value at 11.47 GPa. Microstructural evaluations highlighted the presence of pearlite and ferrite phases, with the partitioning temperature of 300°C displaying the highest proportion of pearlite phase at 38.5%. This meticulous investigation expands our understanding of metallurgy and underscores the intricate relationship between partitioning temperatures and the mechanical properties of ASTM A36 steel. It provides valuable insights for material design and application methodologies and facilitates advancements in industrial practices.

Keywords:
ASTM A36, heat treatment, mechanical testing, Q-P-T.

1 Introduction

With time and technological advances, metals have assumed a pivotal role as primary materials or raw elements in advanced engineering applications [1]–[3]. Steel, which is renowned for its cost-effectiveness and malleability, has emerged as the predominant metal in the industrial sector. Their versatility enables the production of a diverse range of products, driving their popularity in commercial and residential settings. Iron, another ubiquitous material in modern engineering, serves as a foundational component for a myriad of applications, ranging from structural supports to advanced machinery components [4]–[6]. The indispensability of iron underscores its integral role in modern engineering endeavors; indeed, the very existence of complex machinery and infrastructure hinges upon the availability and adaptability of iron.

The evolution of metallurgy has also highlighted the indispensable role of carbon steel in meeting the demanding requirements of modern engineering [7]–[9]. Carbon steel, a derivative of steel alloyed with carbon, is a cornerstone material that is renowned for its exceptional strength, durability, and versatility. Its unique properties make it a preferred choice across diverse industries, including automotive, aerospace, construction, and manufacturing. In structural engineering, carbon steel serves as a fundamental component for constructing high-rise buildings, bridges, and other critical infrastructure due to its robustness and reliability. Furthermore, in the automotive sector, the exceptional formability and weldability of carbon steel makes it ideal for producing vehicle frames, chassis, and safety components [10]. Its widespread use in industrial machinery, pipelines, and equipment underscores its significance in facilitating efficient operation across various sectors. Thus, the enduring utility and indispensability of carbon steel underscores its pivotal role in shaping the modern world of engineering and technology [11].

Moreover, as it delves deeper into the realm of modern engineering, the demand for materials with exceptional strength, durability, and versatility has increased. In response to these requirements, the ASTM A36 specification stands as a cornerstone in material engineering, offering a standardized framework for ensuring the reliability and performance of structural components across diverse industries. Known for its superior weldability, machinability, and formability, ASTM A36 steel has emerged as a preferred choice for engineers and designers seeking to optimize structural designs and streamline manufacturing processes [12]–[15]. Its adaptability to various fabrication techniques allows for the creation of intricate and robust components, essential for the realization of ambitious engineering projects. From skyscrapers to bridges, industrial machinery to automotive frames, ASTM A36 steel's versatility knows no bounds, making it a staple material in the arsenal of modern engineering solutions [16]–[18]. In the following discourse, the nuanced specifications and applications of ASTM A36 steel shall be explored, shedding light on its pivotal role in shaping the landscape of contemporary engineering practices.

As engineering demands evolve and projects become increasingly sophisticated, the quest for materials with enhanced mechanical properties intensified [19]–[21]. Although ASTM A36 steel offers commendable versatility and reliability, there is a compelling need to augment its mechanical characteristics to meet the rigorous demands of modern applications. Heat treatment presents a viable avenue for enhancing the mechanical properties of ASTM A36 steel, thereby expanding its utility across a broader spectrum of engineering endeavors. By subjecting ASTM A36 steel to controlled heating and cooling processes, engineers can tailor its microstructure and properties to achieve desired attributes such as increased strength, hardness, and toughness. This strategic approach empowers engineers to optimize the performance and durability of structural components, ensuring their resilience in the face of dynamic operational conditions [22]–[24]. In the ensuing discussion, the principles of heat treatment and its transformative impact on ASTM A36 steel should be explored, illuminating the path towards unlocking its full potential in the realm of modern engineering.

Heat treatment is a pivotal method for modifying the mechanical characteristics of steel. Hardening, quenching, partitioning, and tempering all constitute forms of heat treatment

[25]–[27]. Three of these, which are carried out continuously and in multiple cycles, are called the Q-P-T method. Hardening a metal involves heating it beyond its critical temperature (known as the austenite region), maintaining it for a specific duration (referred to as the hold time), and subsequently rapidly cooling it. Quenching, a heat-treatment technique, necessitates an exceptionally rapid cooling period. The toughness and hardness properties of the material are intricately determined and influenced by the austenite temperature during the heat treatment process, particularly during quenching [28]–[30].

The subsequent step, known as partitioning, aims to augment the carbon content of the retained austenite while reducing the solubility of carbon in the martensite [31]–[33]. This process renders the austenite more stable as the carbon dioxide steel reaches ambient temperature. In the tempering process, the steel is heated slightly below its critical temperature and held in the furnace toensure a consistent temperature level [34]–[36]. Subsequently, the steel was cooled to mitigate its hardness and tensile strength while enhancing its ductility and toughness.

Mechanical quality testing encompasses a variety of methods, including tensile, hardness, and microstructural analysis [37], [38]. Tensile strength assessment involves the application of opposing force loads along a straight line to evaluate the resistance of the material to deformation. Hardness testing is the most reliable method for assessing material hardness andoffers insights into its mechanical properties. The term "microstructure" pertains to the microscopic description of distinct phases discernible through metallographic methods. These testing methodologies play a crucial role in comprehensively evaluating the mechanical characteristics of materials and informing engineering decisions.

The existing literature on the Quenching-Partitioning-Tempering (Q-P-T) process presents a detailed investigation of its effects on various steel types. Y. Li *et al.*, investigates ultra-low carbon medium manganese Q-P-T steel [39], highlighting the role of hierarchical nanometer-sized precipitates in enhancing strength and ductility while also causing inter-granular cracks and reduced impact toughness. X. Liu *et al.*, examines low carbon bainitic steel [40], demonstrating that tempering temperature significantly influences yield strength, tensile strength, and elongation, with optimal properties achieved at 340°C. J. Zhang *et al.*, focuses on high carbon steel, developing a Q-P-T-LE thermo-kinetic model to predict the effects of carbide precipitation on retained austenite and overall steel properties [41], providing improved accuracy over existing models. P. Xu *et al.*, explores hydrogen embrittlement susceptibility in high-strength steels [42], showing that NbC carbide precipitation enhances hydrogen resistance and yield strength but has minimal impact on ductility. In light of the extensive investigations conducted by Y. Li et al., X. Liu et al., J. Zhang et al., and P. Xu et al., it becomes evident that while substantial progress has been made in understanding the Quenching-Partitioning-Tempering (Q-P-T) process across various steel types, crucial gaps still persist.

Despite significant advancements in understanding the Quenching-Partitioning-Tempering (Q-P-T) process and its effects on various types of steel, a critical gap remains concerning the specific impact of partitioning temperature fluctuations on mechanical properties. Current research predominantly explores ultralow carbon, low carbon bainitic, and high carbon steels, leaving a gap in the systematic investigation of partitioning temperature variations within the Q-P-T process itsel [39]–[42]. Although some studies have examined the influence of tempering temperature, there is a lack of detailed experimental research focused on how partitioning temperature fluctuations affect key mechanical traits such as yield strength, tensile strength, elongation, and hardness. Moreover, existing studies often integrate experimental work with modeling; however, a comprehensive experimental study isolating the effects of partitioning temperature variations is lacking. This research aims to address these gaps by thoroughly examining the Q-P-T process, specifically the role of partitioning temperature fluctuations, through a focused experimental approach, thereby providing clearer insights into optimizing mechanical performance in practical applications.

Regarding to gap matter, in this research ASTM A36 low carbon steel was used as the research object. ASTM A36 low-carbon steel was produced using a heating process at a temperature of 920°C. It was held for 60 min before the cooling process using oil at a temperature of 300°C. Then, the partition process was performed with temperature variations of 300ºC, 350ºC, and 400ºC with a closed time of 15 min, before the process cooled the oil to room temperature. The final stage was to provide a tempering heat treatment of 200ºC and hold for 60 min, followed by cooling with air to room temperature. Treatment with variations in the partitioning temperature was used to determine the effect on mechanical property testing, namely tensile tests, hardness tests, and microstructure.

The purpose of this study is to investigate the effect of heat treatment, particularly partitioning at different temperatures, on the mechanical properties of ASTM A36 low-carbon steel. By subjecting the steel to controlled heating, cooling, and tempering processes, the researchers aim to enhance its mechanical characteristics such as strength, hardness, and toughness. This study seeks to contribute to the understanding of how variations in partitioning temperature during heat treatment impact the material's properties, as evaluated through tensile tests, hardness tests, and microstructural analysis.

2 Materials and Methods

2.1 Research Materials

In this study, ASTM A36 steel plates with the chemical compositions listed in Table 1 were utilized as the primary material for investigation. The specimens were subjected to controlled heating using Thermo Scientific Thermolyne Benchtop Muffle Furnaces FB1410M-33, a gas furnace system renowned for its precision and reliability in achieving the desired thermal conditions. Turalik 48 ISO VG 46 oil was used as the cooling medium before commencement of the testing procedures.

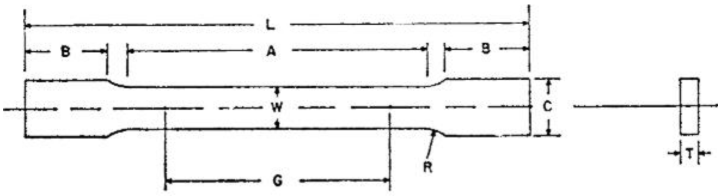
Table 1. Chemical composition for ASTM A36 steel plate (40 CFR 160.035-3 (b) (2)), (product analysis max wt%)

C	Si	Mn	P	S	Cu
0.26	0.40	-	0.04	0.05	0.20

For the scientific equipment, thermal identification of the specimens was conducted using the Seek Shotpro Thermal Imaging Camera, which provides accurate thermal imaging capabilities essential for assessing temperature variations and thermal profiles. Tensile testing was performed using a hydraulic universal tensile testing machine (TARNO), a robust and versatile system capable of accurately measuring the mechanical properties of materials under tension (Table 2). This research will employ Tensile testing was performed using specimens prepared according to ASTM E8 standard dimensions, as shown in Fig. 1. Hardness testing was conducted using the CARSON MOPAO3 M22011907 hardness tester at certain points on the samples, as shown in Fig. 2. The hardness tool used was renowned for its accuracy and efficiency in determining material hardness.

Table 2. ASTM A36 steel plate standard physical and mechanical properties (40 CFR 160.035-3 (b) (2))

Density (g/cc)	Tensile strength, ultimate (MPa)	Elongation at break (%)		Modulus of elasticity (GPa)	Poissons ratio
		In 200 mm	In 50 mm		
7.80	400-550	20	23	200	0.26



Dimensions	
	Standard Specimens
	Sheet-Type, 12.5 mm [0.500 in.] Wide
	mm [in.]
G—Gauge length	50.0 ± 0.1 [2.000 ± 0.005]
W—Width	12.5 ± 0.2 [0.500 ± 0.010]
T—Thickness	thickness of material
R—Radius of fillet, min	12.5 [0.500]
L—Overall length, min	200 [8]
A—Length of reduced section, min	57 [2.25]
B—Length of grip section, min	50 [2]
C—Width of grip section, approximate	20 [0.750]

Fig. 1. ASTM E8 standard dimensions.

Microstructure phase identification was carried out using an Insize Metallurgical Microscope 5102-M600, which offers superior magnification capabilities of up to 200×, enabling detailed examination and analysis of microstructural features. These advanced testing methodologies and equipment were instrumental in conducting a comprehensive analysis of the ASTM A36 steel specimens, facilitating the characterization and understanding of their thermal, mechanical, and microstructural properties.

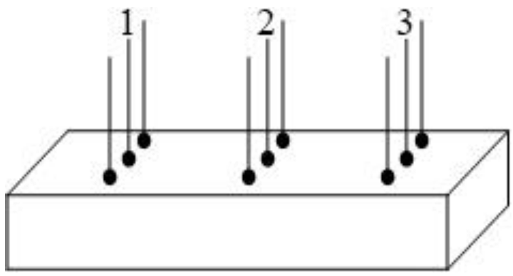


Fig. 2. Test point of the hardness test samples.

2.2 Research Methods

The Quenching-Partitioning-Tempering (Q-P-T) heat treatment method is a sophisticated approach aimed at enhancing the mechanical properties of steel, particularly ASTM A36 low-carbon steel. Quenching is the initial step in the Q-P-T process. This involves heating the steel beyond its critical temperature, also known as the austenite region. During this phase, the material undergoes a structural transformation, transitioning from its original form to austenite, which is a face-centered cubic crystalline structure [43]. The steel was then held at this elevated temperature for a specific duration, referred to as the hold time, to ensure uniform heating throughout the material. Subsequently, the steel is rapidly cooled, typically using a quenching medium such as oil. This rapid cooling process effectively "freezes" the steel microstructure and locks in the austenitic phase.

Partitioning is the second phase of the Q-P-T process, and is critical for enhancing the properties of the material. During partitioning, the steel was subjected to controlled heating at temperatures slightly below those of the austenite region. This temperature range allows the redistribution of carbon atoms within the steel microstructure [44]. The goal of partitioning is to increase the carbon content of the retained austenite, while reducing the solubility of carbon in the marten site phase. This redistribution of carbon atoms results in a more stable austenitic phase at ambient temperature. Partitioning is typically performed for a specified duration at various temperatures to achieve the desired microstructural changes.

Tempering is the final step in the Q-P-T process and is essential for refining the material's mechanical properties. During tempering, the steel is reheated to a temperature slightly below its critical temperature and held at this temperature for a specific period. This controlled heating allows for the relaxation of internal stresses within the material and the precipitation of fine carbide particles [45]. Consequently, the hardness and tensile strength of the steel were mitigated, while its ductility and toughness were enhanced.

The Q-P-T heat treatment method offers a systematic approach to modifying the microstructure and mechanical properties of steel, such as ASTM A36 low carbon steel. This methodological approach is instrumental in optimizing the performance and durability of structural components. The Q-P-T heat treatment process employs a furnace as the primary equipment with a multicycle process, as shown in Fig. 3. ASTM A36 metal specimens underwent a meticulous thermal treatment regimen, commencing with heating to a precise temperature of 920°C under controlled furnace conditions for 60 min for the first process, as shown in Fig. 4.

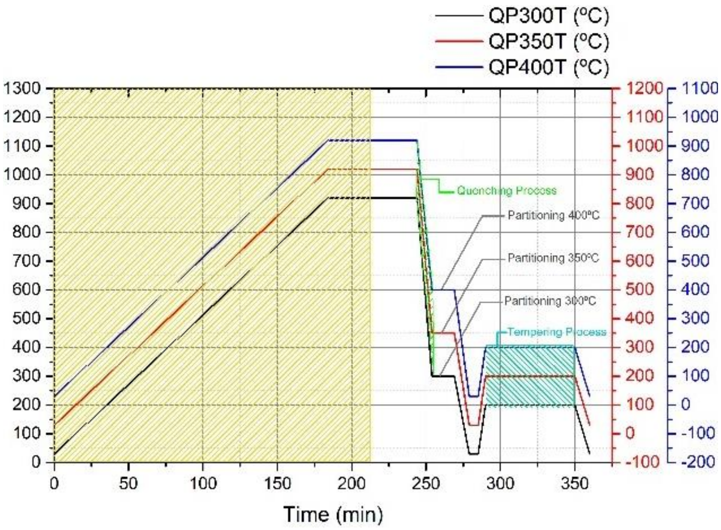


Fig. 3. Q-P-T process of all samples along with temperature and time variable.

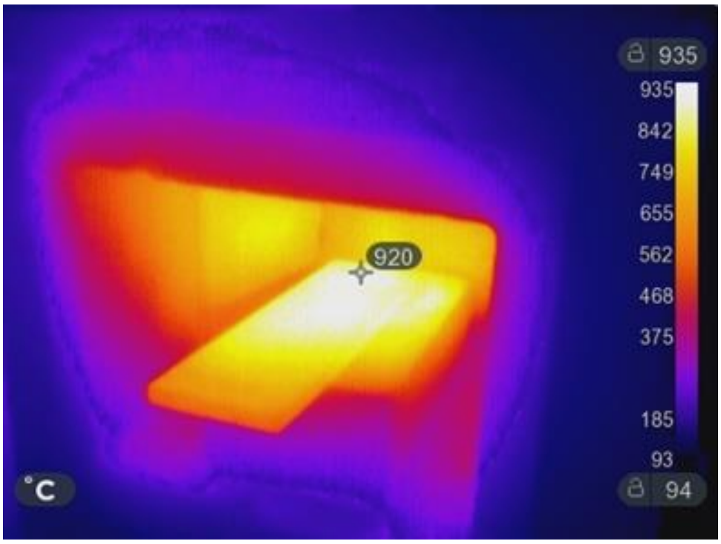


Fig. 4. Holding process in 920°C before quenched.

Following this, the samples underwent a quenching process, whereby they were rapidly cooled using oil to achieve a quenching temperature of 300°C, as shown in Fig. 5.

Subsequently, the partitioning phase ensues, wherein the specimens are subjected to varying temperatures of 300°C, 350°C, and 400°C, each with distinct holding times of 15 min. Turalik 48 oil was used as the cooling medium to facilitate gradual cooling to ambient temperature. Following partitioning, a tempering stage was initiated, entailing the exposure of the samples to a temperature of 200ºC for 60 min, as shown in Fig. 6.

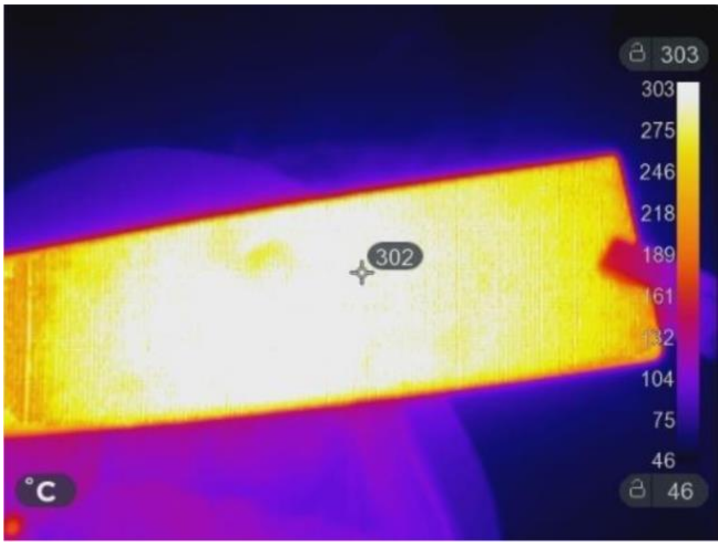


Fig. 5. Quenching process until 300°C.

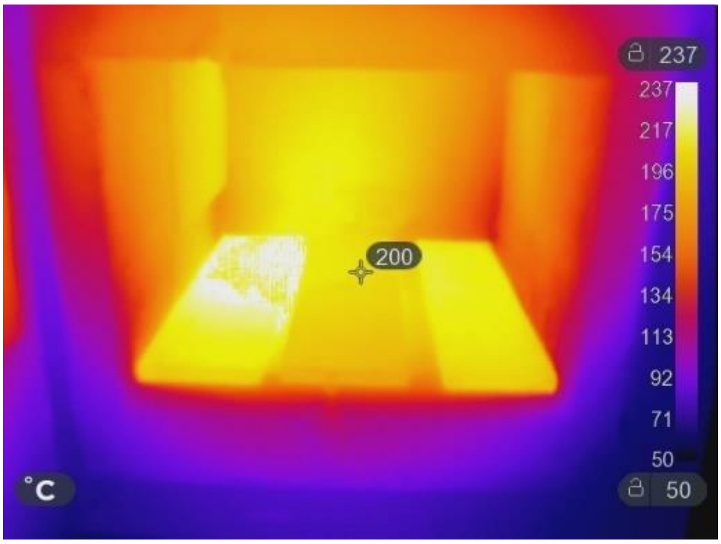


Fig. 6. Tempering process of the samples to a temperature of 200ºC for 60 minutes.

The partitioning temperature, which is slightly below the critical temperature, is crucial for promoting the diffusion of carbon atoms between the austenite and martensite phases [30]. The selection of partitioning temperatures (300, 350, and 400°C) reflects a deliberate exploration of different temperature regimes to study the effects of temperature on carbon redistribution and microstructural evolution. By varying the partitioning temperature, the optimal temperature range can be investigated to achieve the desired mechanical properties, such as hardness and strength, while minimizing the formation of undesirable phases or microstructural defects.

Holding the steel at the critical temperature for a specific duration, known as the holding time, ensures that the material reaches thermal equilibrium and allows the completion of phase transformations. This duration was essential for uniform heating throughout the steel volume. The holding time allows sufficient duration for the diffusion of carbon atoms between the austenite and martensite phases [3]. Longer holding times provide more time for carbon atoms to migrate within the steel microstructure, facilitating a more uniform distribution of carbon and promoting the formation of stable carbide precipitates in the austenitic phase [34]. This carbon redistribution is essential for achieving the desired mechanical properties, such as hardness, strength, and toughness, by optimizing the concentration and distribution of the strengthening phases within the steel matrix.

An adequate holding time ensures that the steel remains at the partitioning temperature for a sufficient duration to stabilize the desired phase (e.g., austenite) and minimize the formation of undesirable phases. The steel was heated to 920°C, which likely corresponded to the critical temperature for austenitic phase transformation. A holding time of 60 min ensured sufficient time for the steel to reach thermal equilibrium and undergo complete phase transformations.

The cooling rate and medium (e.g., oil) employed during the quenching and subsequent cooling stages influence the transformation kinetics and microstructural evolution of steel [19]. Quenching involves rapid cooling to "freeze" the microstructure of the steel in the desired phase state (e.g., martensite). The selection of an appropriate quenching medium and cooling rate ensures the suppression of undesired phase transformations and the retention of the desired microstructural features. The steel was quenched in oil to 300°C before partitioning, followed by cooling to room temperature. This controlled cooling process is critical for stabilizing the steel microstructure and preventing the formation of undesirable phases, such as pearlite.

The samples were then air cooled to room temperature. This multi-step heat treatment process is carefully orchestrated to manipulate the microstructure of ASTM A36 steel, enhance its mechanical properties, and optimize its performance in engineering applications.

3 Results and Discussion

3.1 Hardness Test

Based on the graphical representation in Fig. 7, the analysis of the hardness value data revealed significant insights. The Q-P-T Heat Treatment (HT) specimen exhibited the highest hardness value, registering a Vickers Hardness Number (VHN) 164 when subjected to a partitioning temperature variation of 300°C for 15 min. Conversely, both the raw material specimen and the Q-P-T method Heat Treatment (HT) specimen, which underwent partitioning at 400°C for 15 min, demonstrated the lowest hardness value of 146.33 VHN.

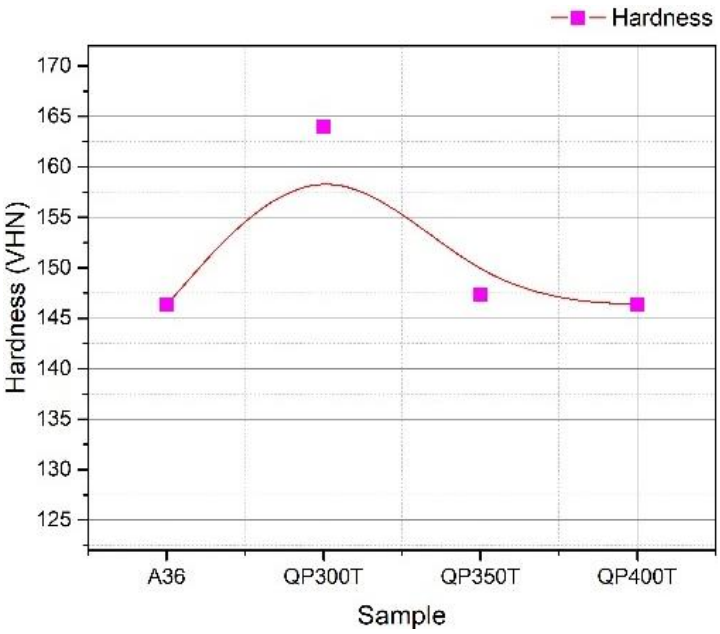


Fig. 7. Hardness values among samples reveal the impact of partitioning temperature.

The phenomenon of achieving the highest hardness value at 300°C during the partitioning phase, followed by a decrease in hardness at higher temperatures, can be understood through the interactions between the microstructure of the steel and the carbon atoms within it. During the partitioning process, steel is heated to temperatures slightly below its critical temperature, allowing for the redistribution of carbon atoms between the austenite and martensite phases [34]. At 300°C, the partitioning process was optimized, leading to an increased concentration of carbon atoms in the retained austenite phase. The higher carbon content in the austenitic phase promotes the formation of fine carbide precipitates, which act as strengthening agents within the steel matrix [46]. Therefore, if a higher carbon content is formed in the structure, a smaller ferrite structure is produced. In contrast, more cementite was formed when combined with ferrite to form pearlite. This was also related to the microstructure test results shown in Fig. 11, where the highest percentage of pearlite occurred in the QP300T sample. As a result, the steel exhibited increased hardness owing to the strengthening effect of the carbide precipitates.

However, as the partitioning temperature increased beyond 300°C, several factors come into play that contributed to the decrease in hardness. At higher partitioning temperatures, there is a greater diffusion of carbon atoms between the austenite and martensite phases. This increased carbon redistribution could lead to the formation of larger carbide precipitates or even the dissolution of some carbides, thereby reducing the overall strengthening effect on the steel matrix [47]. Higher partitioning temperatures could also promote the coarsening of the steel's microstructure. This coarsening refers to the growth of austenitic grains and the enlargement of carbide precipitates. Larger grain sizes and carbide particles are generally associated with decreased hardness because they are less effective in impeding dislocation movement within the material. At elevated temperatures, the stability of the austenitic phase may decrease, leading to its partial transformation into other phases such as ferrite. This is also related to the microstructure test result in Fig. 10, where the higher the temperature of partitioning, the more ferrite is formed and the more pearlite is reduced. This phase transformation could result in a reduction in the overall hardness of the steel.

These findings underscore the influence of partitioning temperature variations on the hardness properties of the specimens, highlighting the effectiveness of the Q-P-T method in enhancing material hardness [3], [48], as shown in Table 3. The observed differences in hardness values elucidate the intricate interplay between heat treatment parameters and resultant material characteristics, offering valuable insights for optimizing heat treatment processes to achieve desired mechanical properties.

Table 3. Comprehensive analysis of mechanical properties across all samples

Sample	Hardness (VHN)	UTS (MPa)	Elongation (%)	PSE (MPa.%)	Pearlite (%)	Ferrite (%)
A36	146.33	432.92	21.3	9221.196	30.9	69.1
QP300T	164	515.73	18	9283.14	38.5	61.5
QP350T	147.33	449.9	16.9	7603.31	29.1	70.9
QP400T	146.33	365.58	21.08	7706.426	20.9	79.1

3.2 Tensile Test

3.2.1 Ultimate Tensile Strength (UTS)

Drawing insights from the graphical representation in Fig. 8, the analysis of stress value data offers valuable findings. The Q-P-T method Heat Treatment (HT) specimen, subjected to a partitioning temperature variation of 300°C for 15 minutes, exhibited the highest maximum stress value, reaching 515.73 MPa. In contrast, the Q-P-T method Heat Treatment (HT) specimen, undergoing partitioning at 400°C for 15 minutes, displayed the lowest maximum tension value at 365.58 MPa. This discrepancy in stress values underscores the notable impact of partitioning temperature variations on the mechanical response of the specimens.

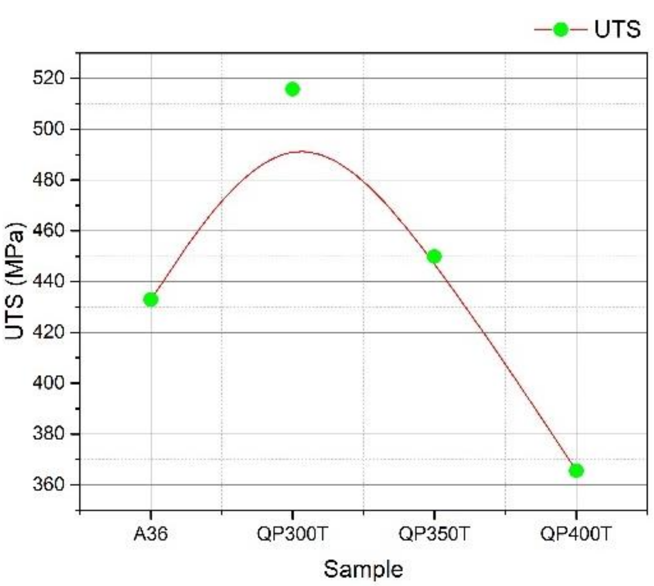


Fig. 8. Comparison of Ultimate Tensile Strength (UTS) values illustrates the influence of partitioning temperature.

The observed trend of the highest stress value at a partitioning temperature of 300°C, followed by a decrease at higher temperatures, could be attributed to the intricate interplay between microstructural changes and mechanical properties during the partitioning phase of the Q-P-T heat treatment method. At a partitioning temperature of 300°C, the steel undergoes controlled heating, allowing for the redistribution of carbon atoms between the austenite and martensite phases. The 300°C partitioning temperature likely optimizes the diffusion of carbon atoms, leading to the formation of fine and densely distributed carbide precipitates within the austenitic phase. These carbide precipitates act as effective strengthening agents, hindering dislocation movement and thereby increasing the material's resistance to deformation, resulting in higher stress values [49]–[51].

At higher partitioning temperatures (e.g., 400°C), the kinetics of carbide precipitation and carbon redistribution may be altered. The increased temperature could promote the growth and coarsening of carbide precipitates or even their dissolution, leading to a less effective strengthening effect on the steel matrix [51]. Additionally, higher partitioning temperatures may accelerate the diffusion of carbon atoms, leading to a more homogeneous distribution but potentially reducing the overall concentration of strengthening precipitates. The variation in partitioning temperature directly influences the mechanical properties of the steel, including its tensile strength and hardness. While the 300°C partitioning temperature optimally balances carbide precipitation and carbon redistribution, resulting in enhanced mechanical properties, higher temperatures may lead to a deterioration of these properties due to changes in microstructure and phase stability.

The graphical representation in Fig. 8 provides empirical evidence of the relationship between partitioning temperature variations and stress values. The specimen subjected to partitioning at 300°C exhibited the highest maximum stress value, indicating superior mechanical performance compared with the specimens treated at higher temperatures. The observed trend of decreasing stress values at higher partitioning temperatures suggests that the optimal mechanical response of the steel, characterized by higher stress values, is achieved at a partitioning temperature of 300°C. This finding underscores the critical role of partitioning temperature variations in influencing the mechanical properties of steel during the Q-P-T heat treatment process.

The effectiveness of the Q-P-T method in influencing stress properties is evident, emphasizing its potential for enhancing material strength [26]. These observed variations in the ultimate tensile strength values provide valuable insights into the interdependence between the heat treatment parameters and the resulting mechanical characteristics, contributing to a broader understanding of material behavior under different thermal conditions.

3.2.2 Elongation (E)

Based on the elongation data depicted in graphical form in Fig. 9, notable findings emerge. The raw-material specimen exhibited the highest elongation value of 21.3%. However, through various iterations of the heat treatment process, the specimen displaying the highest yield strain value was the Heat Treatment (HT) Q-P-T method with a partitioning temperature variation of 400ºC for 15 min, registering at 21.08%. Conversely, the Q-P-T Heat Treatment (HT) specimen, subjected to a partitioning temperature variation of 350°C for 15 min, exhibited the lowest strain value of 16.9%. These observations underscore the influence of heat-treatment parameters, particularly partitioning-temperature variations, on the elongation properties of the specimens.

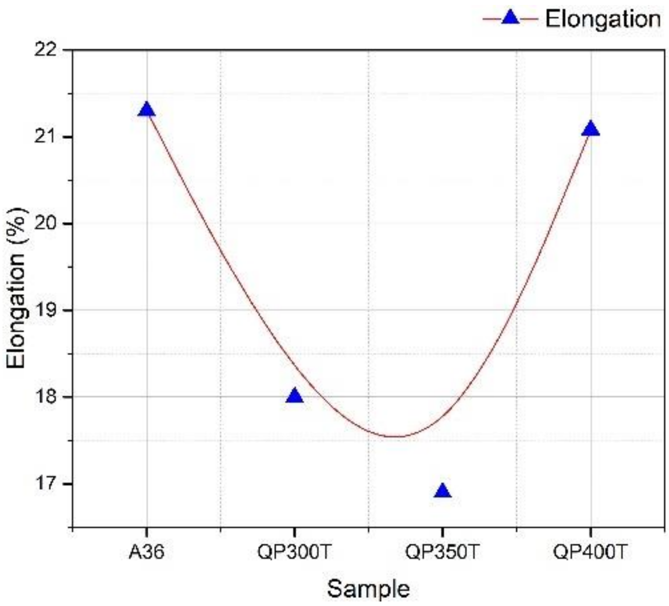


Fig. 9. Elongation values plotted for all samples demonstrate the impact of partitioning temperature.

The phenomenon of the trend changes in strain due to heat treatment temperature could be attributed to the complex interplay between the microstructural changes induced by the heat treatment process and their subsequent effects on material ductility [52]. When subjected to heat treatment, steel undergoes various structural transformations, such as the formation of different phases like ferrite and pearlite, as well as changes in grain size and distribution. These alterations directly influence the mechanical properties of the material, including its ductility, which is measured by factors such as elongation [47].

From the elongation value, it can be observed that the raw material specimen that did not undergo any heat treatment exhibited the highest elongation value. This could be attributed to the inherent properties of the steel in its untreated state. However, changes in elongation values were observed as the material underwent the Q-P-T heat treatment process with varying partitioning temperatures.

The specimen treated with a partitioning temperature variation of 400°C for 15 minutes shows a slightly lower elongation value compared to the untreated specimen, indicating a decrease in ductility. Conversely, the specimen treated at a partitioning temperature of 350°C for 15 minutes exhibits the lowest elongation value, suggesting even lower ductility. These changes in ductility could be explained by considering the microstructural alterations induced by the heat treatment process [19]. At higher partitioning temperatures, there may be increased diffusion of carbon atoms and changes in phase composition, which could lead to the formation of microstructural features that limit ductility, such as larger grain sizes or the presence of brittle phases [3]. Conversely, at lower partitioning temperatures, the diffusion of carbon atoms may be less pronounced, allowing for the formation of microstructural features that enhance ductility, such as finer grain sizes or a more homogeneous distribution of phases.

The substantial difference in elongation values highlights the intricate relationship between heat treatment processes and the resulting material ductility [34], [53]. These findings contribute to the broader understanding of material behavior under varying thermal conditions and underscore the importance of optimizing heat treatment methodologies to achieve desired mechanical properties.

3.2.3 Product of Strength and Elongation (PSE)

Analyzing the Product of Strength and Elongation (PSE) values provides invaluable insights into the mechanical behavior of the materials under different heat treatment conditions, as shown on Fig. 10. The baseline measurement of A36 sample, the raw material without heat treatment, sets a reference point with a PSE value of 9221.196 MPa.

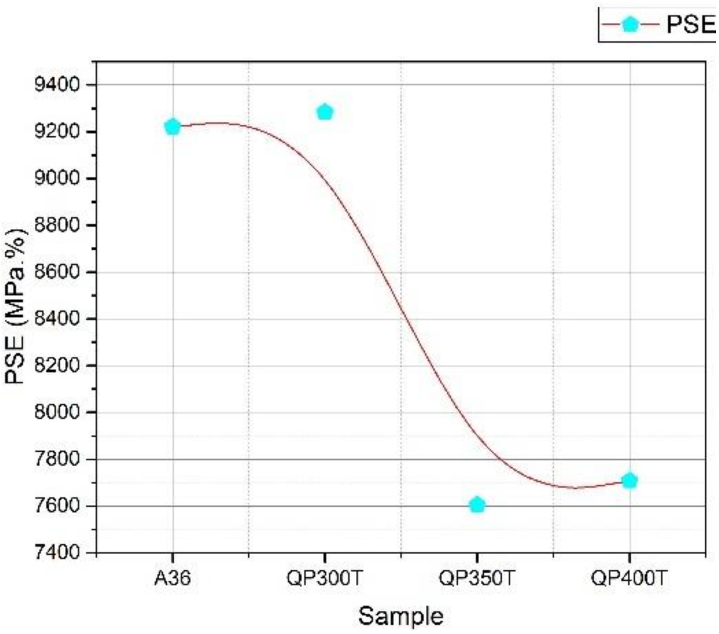


Fig. 10. Product of Strength and Elongation (PSE) values highlights the effect of partitioning temperature.

The QP300T sample, subjected to a partitioning temperature of 300ºC for 15 minutes, shows a slightly improved PSE value of 9283.14 MPa, indicating enhanced strength and elongation compared to the untreated material. However, the observation on QP350T and QP400T samples treated with partitioning temperatures of 350ºC and 400ºC for 15 minutes, respectively, a decline in PSE values is noted, reaching 7603.31 MPa and 7706.426 MPa.

These findings suggest that excessive partitioning temperatures may compromise material properties, resulting in reduced strength and elongation. However, the ideal partitioning temperature for A36 can increase the strength and elongation of the material [6], [25], [34]. It underscores the critical role of optimizing heat treatment parameters to achieve desired mechanical characteristics. These insights are pivotal for engineering applications where balancing strength and elongation is essential for material performance and reliability.

3.3 Microstructure Test

The microstructural analysis of the Heat Treatment (HT) process utilizing the Q-P-T method with varying partitioning temperatures provides critical insights into the transformation of the material's grain structure and the formation of distinct phases, namely pearlite and ferrite, as shown on Fig. 12 for A36 sample. The microstructural images of the steel samples were treated with varying partitioning temperatures using a microscope equipped with a camera. Ensure that the images are of high quality and adequately represent the microstructure of the samples. In this research, the captured images are imported into JMat Pro image analysis software. Use image processing tools to enhance contrast, adjust brightness, and remove any artifacts or noise that may interfere with the analysis. Utilize the software's tools to identify and distinguish between ferrite and pearlite phases within the microstructural images. This involved applying filters or thresholding techniques to isolate specific features characteristic of each phase. Once the phases are identified, quantify the percentage of ferrite and pearlite present in each image. This could be achieved by manually delineating regions corresponding to each phase or using automated segmentation algorithms to partition the image into distinct phase regions. Then, the percentage of ferrite and pearlite was calculated in each sample by dividing the area occupied by each phase by the total area of the microstructural image.

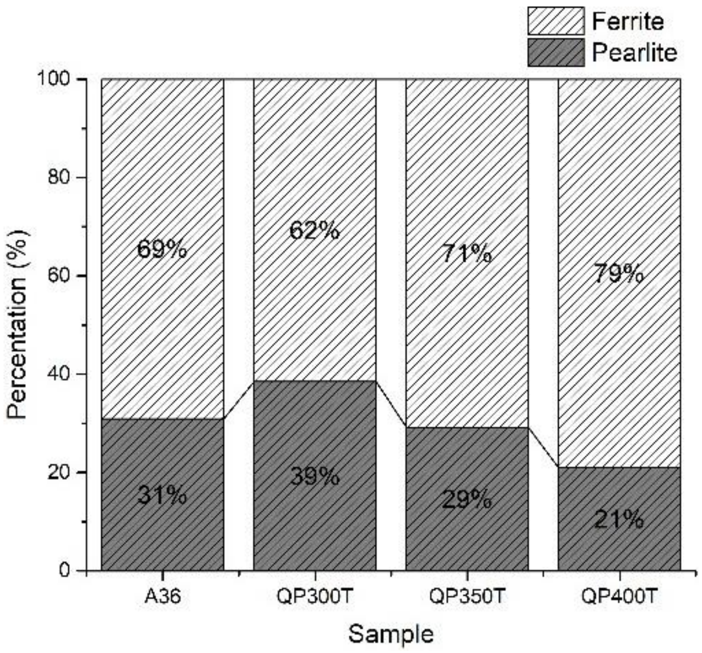


Fig. 11. The distribution of microstructure phase percentages across all samples.

Pearlite, characterized by its dark appearance, is a composite microstructure consisting of alternating layers of ferrite and cementite [19], [54]. Cementite, a hard and brittle phase, was interspersed within the softer ferrite matrix. The formation of pearlite is influenced by the cooling rate and carbon content of the steel. Slower cooling rates during heat treatment allowed for the diffusion of carbon atoms, facilitating the formation of pearlite, as shown in Fig. 13 for the QP300 sample.

On the other hand, ferrite, appearing light in color, is a pure iron phase known for its ductility and high electrical conductivity. It forms at lower temperatures during the cooling process and is primarily responsible for the ductile behavior of steel [55], [56].

The observed dominance of the ferrite phase in the microstructural analysis indicates that the cooling process during heat treatment favored the formation of ferrite over pearlite. This suggests a relatively faster cooling rate, which may have limited the diffusion of carbon atoms and hindered the formation of pearlite, as shown on Fig. 14 for QP350T sample.

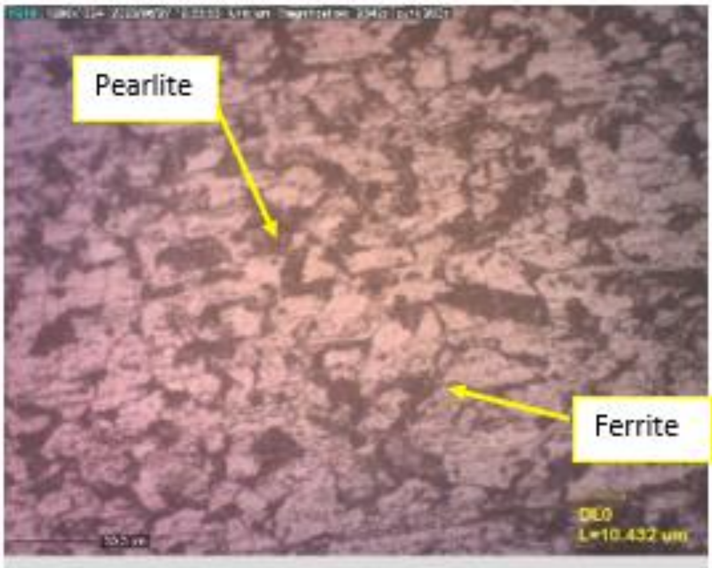


Fig. 12. The micrograph displays untreated ASTM A36 sample.

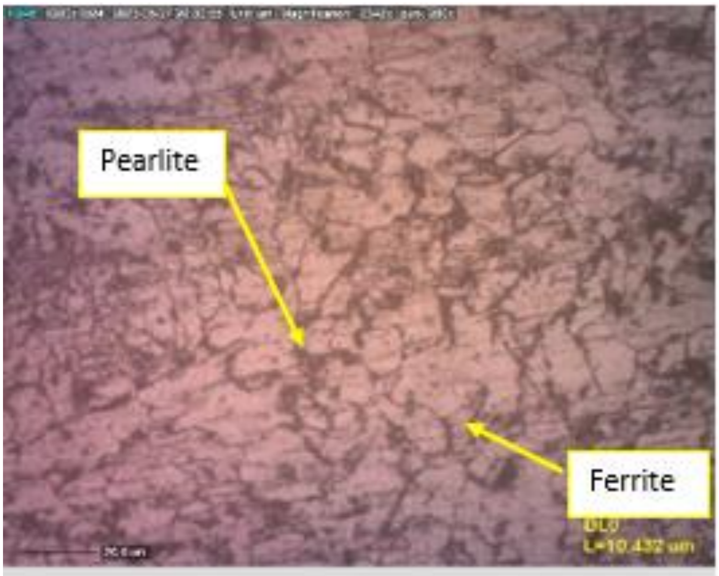


Fig. 13. The micrograph depicts the sample treated at a partitioning temperature of 300°C.

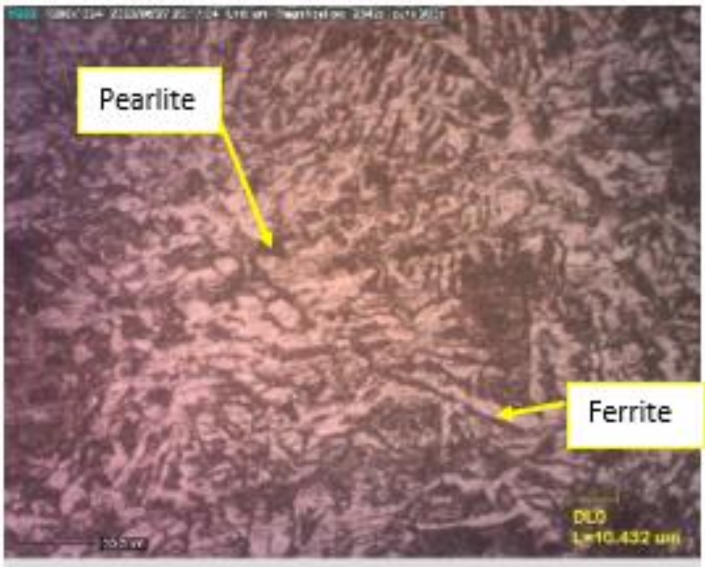


Fig. 14. The micrograph illustrates the sample subjected to a partitioning temperature of 350°C.

The analysis of microstructure percentage data further supports these observations, as shown on Fig. 11. The specimen treated with the Q-P-T method at a partitioning temperature of 300°C for

15 minutes exhibited the highest pearlite phase percentage at 38.5%. This suggests that at lower partitioning temperatures, there is sufficient time for carbon diffusion and the formation of pearlite. Conversely, specimens treated at 400℃ for 15 minutes displayed the lowest pearlite phase percentage at 20.9%, indicating that higher partitioning temperatures may have limited the formation of pearlite due to faster diffusion kinetics or other phase transformations [55], as shown on Fig. 15.

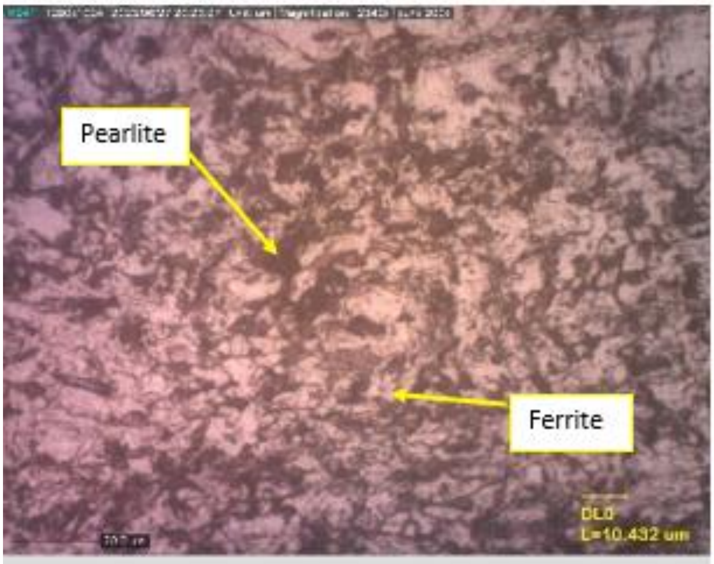


Fig. 15. The image captures the sample treated at a partitioning temperature of 400°C.

The microstructural analysis provides valuable insights into the intricate relationship between heat treatment parameters, grain structure evolution, and phase formation in steel alloys. These findings contribute to the optimization of heat treatment processes and the design of materials with tailored mechanical properties for specific engineering applications.

4 Conclusion

The relationship between partitioning temperature and material properties in steel specimens is crucial for understanding heat treatment effects. Higher partitioning temperatures result in softer material with lower hardness values and increased elasticity, while lower temperatures yield greater hardness and enhanced tensile stress, promoting ductility. Specimens treated at 300℃ exhibited the highest hardness value of 164 VHN and maximum stress value of 515.73 MPa, indicating superior mechanical performance. Conversely, specimens treated at 400℃ displayed higher elongation values, suggesting increased ductility. Variations in partitioning temperature also impact the microstructure, with higher temperatures favoring a softer material dominated by the ferrite phase, while lower temperatures yield harder material characterized by a higher percentage of pearlite.

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