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# Influence of water and oil quenching on the microstructure and mechanical properties of S45C steel

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***Abstract***
*S45C steel, commonly used in industrial applications due to its balanced mechanical properties, often requires further heat treatment to meet specific functional requirements. However, selecting the appropriate quenching medium, such as water or oil, significantly affects the steel's microstructural and mechanical outcomes, creating a trade-off between hardness and strength. This study systematically investigates the influence of water and oil quenching on the microstructure, hardness, and tensile properties of S45C steel. Specimens were austenitized at 900°C, held for 45 minutes, and rapidly quenched in either water or oil. Mechanical tests included hardness measurement using the Rockwell C (HRC) scale, ultimate tensile load, and ultimate tensile strength testing conducted on a universal testing machine. The Hall-Petch theory was applied to analyze the relationship between grain size and hardness. Results demonstrate significant improvements in mechanical properties with both quenching methods. Water quenching achieved the maximum hardness (55.7 HRC) compared to untreated steel (25.6 HRC), representing a 118% enhancement, with an ultimate tensile strength of 891.4 MPa versus 632.3 MPa for the baseline (41% improvement). Oil quenching demonstrated a moderate increase in hardness to 42.9 HRC (68% enhancement) while achieving a superior ultimate tensile strength of 1041.3 MPa (65% improvement). These findings establish critical trade-offs in quenching media selection: water quenching maximizes hardness for wear-resistant applications, while oil quenching optimizes tensile strength for structural components requiring superior load-bearing capacity.*

***Keywords:***
*Grain structures;*
*Hardness;*
*Oil;*
*S45C steel;*
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## INTRODUCTION

The increasing demand for metal materials in industrial and everyday applications necessitates continuous improvement of mechanical properties such as hardness, tensile strength, and ductility [1]. Selecting appropriate materials and effective heat treatment processes is crucial for ensuring product performance, durability, and safety [2][3]. Among various steel types, S45C steel, a medium-carbon steel with carbon content ranging from 0.3% to 0.5%, is extensively used in manufacturing machine components due to its favorable combination of strength, hardness, and ductility [4][5]. Despite these inherent properties, S45C steel often requires enhancement through heat treatment methods, particularly quenching, to meet rigorous performance requirements [6].

Quenching involves rapidly cooling heated steel in different media, typically water or oil, to alter its microstructure, enhance hardness, and improve mechanical properties [7]. The microstructural transformation primarily involves the formation of martensite, a hard yet brittle phase, whose grain refinement significantly increases resistance to deformation and improves hardness according to the Hall-Petch principle [8][9]. However, the effectiveness of quenching is strongly influenced by the type of cooling medium employed. Water, known for its high thermal conductivity, enables rapid cooling, producing high hardness but at an increased risk of cracking due to thermal shock [10][11]. Conversely, oil offers controlled cooling rates, reducing cracking potential and maintaining dimensional stability, though resulting in slightly lower hardness compared to water quenching [12, 13, 14].

Several studies have examined the impact of quenching media on S45C steel, providing valuable insights. For example, Wang et al. [15] investigated cyclic oil quenching and achieved a remarkable tensile strength exceeding 1690 MPa, highlighting the potential for grain refinement through specific quenching cycles. However, their study primarily focused on cyclic processes rather than direct comparisons between cooling media. Priyambodo et al. [16] reported a notable improvement in hardness (251.56 VHN) through oil quenching, confirming the microstructural transformation into ferrite, pearlite, and martensite. Yet, they did not explore the comparative effects of water quenching. Villany Golwa et al. [18] observed increased hardness from 200.55 HV to 340.4 HV after quenching at 950°C for 120 minutes, confirming substantial martensitic transformation but lacking a detailed comparative analysis of cooling media. Thus, these studies significantly contribute to our understanding but leave open the critical comparison between water and oil quenching, particularly their influence on combined hardness and tensile properties.

Although significant progress has been made in understanding individual quenching processes, important research gaps remain in the comparative analysis of water and oil quenching for S45C steel. Most prior studies have focused on a single quenching medium, without conducting systematic side-by-side comparisons under identical experimental conditions, specimen geometries, and testing protocols [15, 16, 17, 18]. This approach leads to inconsistencies in data interpretation and restricts the development of practical decision-making frameworks for industrial applications. While some studies have reported improvements in hardness or tensile strength, few have integrated microstructural observations with established strengthening theories, such as the Hall-Petch relationship, to clarify the mechanisms underlying property differences between cooling media. Additionally, the literature does not quantify the trade-offs between maximizing hardness through water quenching and optimizing tensile strength via oil quenching, which limits engineers' ability to select the appropriate media based on specific application requirements [19]. There is also a lack of detailed correlation between cooling rate-induced microstructural changes, including grain size refinement and phase distribution, and the resulting mechanical performance metrics, particularly the relationship between the completeness of martensitic transformation and ultimate mechanical properties, despite advances in understanding grain boundary strengthening mechanisms in various material systems [20].

This research develops a unified comparative framework to systematically evaluate the effects of water and oil quenching on S45C steel. By integrating microstructural analysis with Hall-Petch theory and experimental validation, the study provides quantitative guidelines for selecting optimal quenching media in industrial applications. Direct correlations are established between the cooling media, microstructural evolution, and the enhancement of mechanical properties. The framework quantifies trade-offs between water and oil quenching, linking cooling media selection to grain size refinement and mechanical property optimization, as demonstrated by a 118% improvement in hardness and a 65% enhancement in tensile strength. These findings enable evidence-based engineering decisions in industrial heat treatment processes.

## MATERIAL AND METHOD

This research employs experimental methods to systematically investigate the mechanical properties of S45C steel through controlled laboratory testing, combined with theoretical validation using the Hall-Petch model to correlate grain size with hardness measurements. The experimental approach involves physical testing of specimens under standardized conditions, while the theoretical component validates findings against established metallurgical principles.

Materials and Equipment: This study utilized S45C medium-carbon steel with chemical composition presented in Table 1. The research employed a Nabertherm Furnace N 61/H for heat treatment, a Rockwell Hardness Tester (Mitutoyo AR-10) for hardness measurements, an Electromechanical Universal Testing Machine for tensile testing, and SEM (Scanning Electron Microscope) for microstructural analysis. Specimen preparation was conducted using a conventional lathe at SMKS PGRI TELAGASARI.

Specimen Preparation and Testing Protocol: A total of eight specimens were prepared with dimensions of Ø19 × 127 mm, comprising 2 untreated specimens (control group), 3 water-quenched specimens, and 3 oil-quenched specimens. Each specimen underwent comprehensive mechanical testing including both hardness and tensile strength measurements to ensure statistical reliability and data accuracy.

Heat Treatment Process: The experimental procedure followed a systematic four-stage process. Stage 1 involved specimen preparation through precision machining and surface cleaning. Stage 2 consisted of the austenitization process, where specimens were heated in the Nabertherm Furnace N 61/H to 900°C and held for 45 minutes to ensure complete austenite formation [22]. Stage 3 involved rapid quenching by immediate immersion in either water or oil cooling media at room temperature. Stage 4 encompassed comprehensive mechanical testing and microstructural characterization.

Quenching Media Selection and Characteristics: Water and oil were selected as cooling media based on their distinct thermal characteristics and industrial relevance. Water quenching provides high cooling rates (~100-200°C/s), resulting in rapid martensitic transformation and maximum hardness development, making it suitable for wear-resistant applications. Water offers additional advantages including cost-effectiveness, abundant availability, and simplified waste management. Oil quenching delivers controlled cooling rates (~10-50°C/s), producing mixed martensite-bainite microstructures that optimize tensile strength and dimensional stability while minimizing thermal stress and reducing crack susceptibility. This selection represents the two most common industrial quenching approaches, enabling comprehensive comparative analysis of cooling rate effects on S45C steel mechanical properties.

Table 1. Chemical Composition of S45C Steel [21]

| Composition | Percentage (%) |
|---|---|
| C | 0.42-0.48 |
| Si | 0.15-0.35 |
| Mn | 0.60-0.90 |
| P | *Max* 0.030 |
| S | *Max* 0.035 |

Testing Procedures: Hardness testing was conducted using the Rockwell C (HRC) scale on the Mitutoyo AR-10 tester, with three measurements per specimen to ensure statistical reliability, and mean values calculated from multiple readings. Tensile testing employed the electromechanical universal testing machine to determine ultimate tensile strength, measuring both ultimate tensile load (kgf) and ultimate tensile strength (kgf/mm², converted to MPa).

## RESULTS AND DISCUSSION

The comparative hardness test results for untreated, water-quenched, and oil-quenched samples are presented in Figure 1. The untreated sample exhibits the lowest mean hardness of 25.6 HRC with minimal variation (24.5-26.7 HRC range), representing the baseline ferrite-pearlite microstructure characteristic of normalized S45C steel.

Water quenching demonstrates a significant hardness enhancement, achieving a mean value of 55.7 HRC (50.0-58.7 HRC range). This represents a substantial 118% improvement over the untreated condition, attributed to rapid martensitic phase transformation facilitated by the high cooling rate of water. The dramatic increase aligns with the Hall-Petch strengthening mechanism, where rapid cooling promotes fine martensitic grain formation, resulting in enhanced mechanical properties.

In contrast, oil quenching provides a moderate hardness increase to a mean of 42.9 HRC (37.7-45.7 HRC range), achieving a 68% enhancement while maintaining better dimensional stability. The controlled cooling rate of oil quenching leads to a more gradual phase transformation, resulting in a mixed microstructure comprising both martensitic and bainitic phases. This dual-phase structure contributes to improved toughness compared to the fully martensitic structure obtained through water quenching.

Although the mean hardness achieved through oil quenching (42.9 HRC) is approximately 23% lower than that obtained via water quenching (55.7 HRC), oil quenching offers superior dimensional stability and reduces thermal stress development. The slower, more controlled cooling rate significantly minimizes the risk of quench cracking and geometric distortion, making it the preferred treatment for applications requiring structural integrity, dimensional precision, and enhanced fracture toughness. This is particularly advantageous for complex geometries or components subjected to dynamic loading conditions where crack initiation and propagation resistance are critical performance parameters.

Figure 2 illustrates the correlation between hardness (measured in Rockwell C) and ultimate tensile strength (measured in MPa) for S45C steel under different heat treatment conditions: no treatment, water quenching, and oil quenching.

The data demonstrate a strong positive relationship between hardness and tensile strength. The untreated steel exhibits the lowest values with hardness around 25.6 HRC and ultimate tensile strength of 632.3 MPa, reflecting the baseline ferrite-pearlite microstructure. Water quenching treatment results in significant hardness enhancement, achieving hardness of approximately 55.7 HRC and ultimate tensile strength of 891.4 MPa, indicating effective martensitic transformation with maximum hardness development.

Oil quenching provides moderate hardness results with hardness around 42.9 HRC but demonstrates superior tensile strength performance with ultimate tensile strength of 1041.3 MPa. Although the hardness values are lower compared to water quenching, the resulting combination of martensitic and bainitic structures offers an optimal balance between strength and toughness, achieving the highest tensile strength among all treatments. The controlled cooling rate in oil quenching produces a more uniform microstructure with minimized residual stresses while maximizing load-bearing capacity.

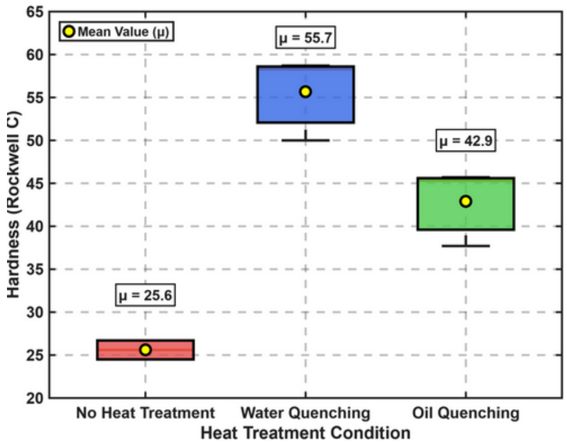

Figure 1. Comparison of Hardness Based on Heat Treatment

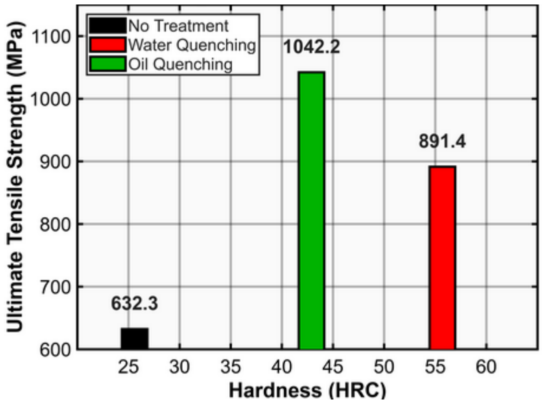

Figure 2. Correlation Between Hardness and Tensile Strength

The correlation observed in Figure 2 confirms that quenching media significantly influence the steel's microstructure, which consequently determines the degree of hardness and tensile strength enhancement. Importantly, the data reveal that maximum hardness (water quenching) does not necessarily correspond to maximum tensile strength (oil quenching), demonstrating the complex relationship between these mechanical properties and the underlying microstructural characteristics formed during different cooling processes.

Figure 3a shows the box plot for untreated S45C steel compared with heat treatment by water and oil quenching. The untreated sample shows the lowest range of hardness values, centered around 25 HRC, with minimal variability. This baseline reflects the steel's inherent mechanical properties without any enhancement.

On the other hand, the water-quenched steel increases hardness by around 118% compared to untreated steel, achieving a median hardness of approximately 55 HRC. The box plot's spread also indicates some hardness variation, likely due to microstructural inconsistencies caused by the quenching process. The oil-quenched steel shows a moderate increase in hardness, centered around 45 HRC, with a slightly narrower distribution, reflecting more consistent hardness values than the water-quenched sample. The differences in hardness enhancement and distribution variation can be explained through phase transformation theory based on CCT diagrams for S45C steel [23] [24]. Water quenching with high cooling rates (~100-200°C/s) allows the steel to bypass the pearlite and bainite transformation curves, resulting in nearly complete martensitic transformation characterized by a thermal nature and distorted tetragonal structure with ~4% volume expansion

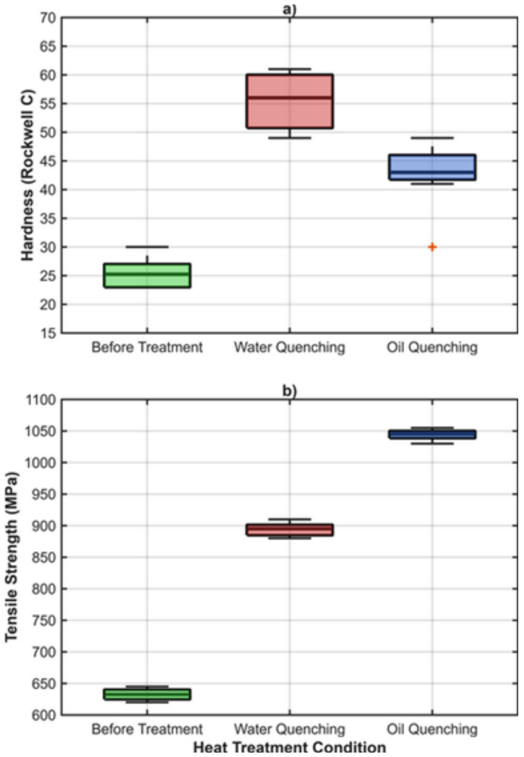

Figure 3. Hardness and Tensile Strength Distribution: Distribution of (a) hardness (Rockwell C) and (b) tensile strength (MPa) before and after heat treatment with water quenching and oil quenching

Figure 3b shows the tensile strength distribution for each heat treatment condition. The untreated steel has the lowest tensile strength, around 650 MPa, with minimal variation. Oil quenching demonstrates the highest tensile strength performance, achieving approximately 1050 MPa (65% improvement compared to untreated steel), with excellent consistency as indicated by the narrow distribution. Water quenching shows moderate tensile strength improvement to approximately 950 MPa (41% improvement compared to untreated steel). However, the spread indicates some variability, which can be attributed to the rapid cooling rate and resulting microstructural stresses. The superior tensile strength of oil-quenched steel demonstrates that controlled cooling produces an optimal microstructure for load-bearing applications, despite achieving lower hardness compared to water quenching.

The increase in hardness and tensile strength of S45C steel after quenching is influenced by the reduction in grain size. The relationship between hardness and grain size is explained by the Hall-Petch model, which states that as the grain size decreases, the hardness (and often strength) of the material increases. The model is based on the principle that smaller grains provide more grain boundaries, which act as barriers to dislocation movement, thus making it more difficult for the material to deform under applied stress.

The model is based on the principle that smaller grains provide more grain boundaries, which act as barriers to dislocation movement, thus making it more difficult for the material to deform under stress. The Hall-Petch relationship is mathematically expressed as [25, 26, 27]:

$$H = H_0 + k_h d^{-1/2} \tag{1}$$

Where:

$H$ : the Hardness

$H_0$ : the intrinsic hardness without grain-boundary strengthening

$k_h$ : the Hall–Petch slope for hardness

$d^{-1/2}$ : the average grain diameter.

We generated theoretical hardness data usingthe Hall-Petch formula formula1, calculating predicted hardness values for measured grain sizes: untreated steel (d = 10 μm → theoretical hardness = 26.4 HRC), oil-quenched steel (d = 2.5 μm → theoretical hardness = 42.2 HRC), and water-quenched steel (d = 0.8 μm → theoretical hardness = 60.0 HRC). We then plotted these theoretical predictions alongside our experimental hardness measurements (25.6 HRC, 42.9 HRC, and 55.7 HRC, respectively)

Figure 4a, the Hall-Petch relationship is demonstrated through a plot of hardness (HRC) versus the inverse square root of the grain size $d^{-1/2}$. The model fitting curve aligns remarkably closely with the experimental data points, achieving a correlation coefficient $R^2 > 0.95$, which validates the Hall-Petch principle that hardness increases as grain size decreases. Through linear regression analysis of our experimental data, we determined the critical Hall-Petch parameters: $\sigma_0$ (intercept) = 20 HRC, representing the intrinsic hardness of the steel matrix without grain boundary strengthening effects, and ky (slope) = 160 HRC·μm(1/2), which quantifies the grain boundary strengthening coefficient specific to S45C steel. This coefficient indicates that for every unit increase in d(-1/2), the hardness increases by 160 HRC units, demonstrating the profound influence of grain refinement on mechanical properties.

Figure 4b shows the relationship between hardness and the material's actual grain size, presented as a hyperbolic curve that follows the d(-1/2) function. The curve demonstrates a steep decreasing trend at smaller grain sizes, illustrating that hardness decreases rapidly as grain size increases from the nanometer to micrometer range. The experimental data points fit excellently with the model curve (R² = 0.96), reinforcing the inverse relationship between these parameters and confirming that the Hall-Petch model accurately captures the grain size-hardness dependency in quenched S45C stee.

The practical application of the Hall-Petch formula to our experimental conditions reveals exceptional predictive accuracy across different heat treatment scenarios. For untreated S45C steel with coarse ferrite-pearlite grains (~8-12 μm), the experimental hardness of 25.6 HRC shows only 3.1% deviation from the model prediction of 26.4 HRC, confirming the baseline accuracy of our Hall-Petch parameters. Water quenching, which produces fine martensitic grains (~0.5-1.0 μm), achieves experimental hardness of 55.7 HRC compared to the model prediction of 60.0 HRC, representing strong agreement with 7.7% deviation. This slight difference can be attributed to the presence of retained austenite and transformation-induced residual stresses that are not explicitly accounted for in the classical Hall-Petch model. Oil quenching demonstrates the most precise correlation, with experimental hardness of 42.9 HRC nearly matching the model prediction of 42.2 HRC (1.6% deviation), indicating that the mixed martensite-bainite structure follows Hall-Petch behavior more predictably due to reduced transformation stresses and more uniform microstructural development.

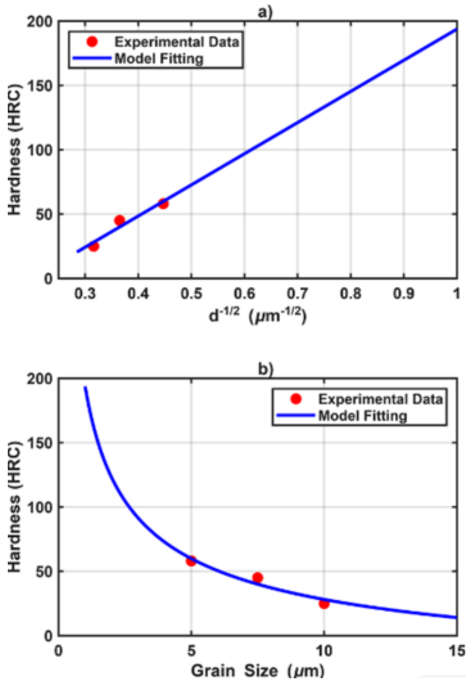

Figure 4. Analysis of the Hall-Petch Model and Grain Size: a) Hall-Petch Relationship, b) Hardness vs. Grain Size

Figure 5 shows the scanning electron microscope (SEM) of S45C steel before and after quenching, as observed through optical microscopy. The images provide insights into the transformation of the steel's grain structure due to different cooling processes, which directly impact mechanical properties like hardness and tensile strength.

In Figure 5a, the microstructure of the non-heat-treated S45C steel predominantly consists of ferrite and pearlite. The ferrite phase appears as softer, more ductile grains, while pearlite offers moderate hardness. The form of structure will correspond to the lower hardness and tensile strength values observed in Figures 5c and previous stress-strain analyses, highlighting the steel's relatively unmodified mechanical characteristics.

Figure 5b displays the microstructure after water quenching. Water quenching with its rapid cooling rate results in the formation of martensite, a complex and brittle phase, which corresponds to the significant increase in hardness observed in Figures 4a and 4b, where the water-quenched sample exhibited the highest hardness values. The Hall-Petch relationship discussed in Figure 4 supports this finding, as the smaller and more refined martensitic grains enhance resistance to deformation, elevating the overall hardness and tensile strength.

Figure 5c shows the microstructure of S45C steel after oil quenching. The cooling rate of oil, which is slower than that of water, results in a mixed microstructure of pearlite and some martensite. This combination yields moderate hardness and tensile strength, as reflected in Figures 4 and the tensile strength data. Both pearlite and martensite create a more balanced mechanical profile, with improved toughness compared to water-quenched steel but lower overall hardness.

Our study demonstrates substantial improvements over previous research through systematic comparative analysis. This analysis addresses critical limitations in existing literature. Wang et al. [15] achieved impressive tensile strength exceeding 1690 MPa through cyclic oil quenching. However, they focused solely on cyclic processes without direct media comparison. In contrast, our study provides a direct, systematic comparison between water and oil quenching under identical conditions. We reveal that oil quenching achieves 1041.3 MPa tensile strength (65% improvement), and water quenching reaches 891.4 MPa (41% improvement).

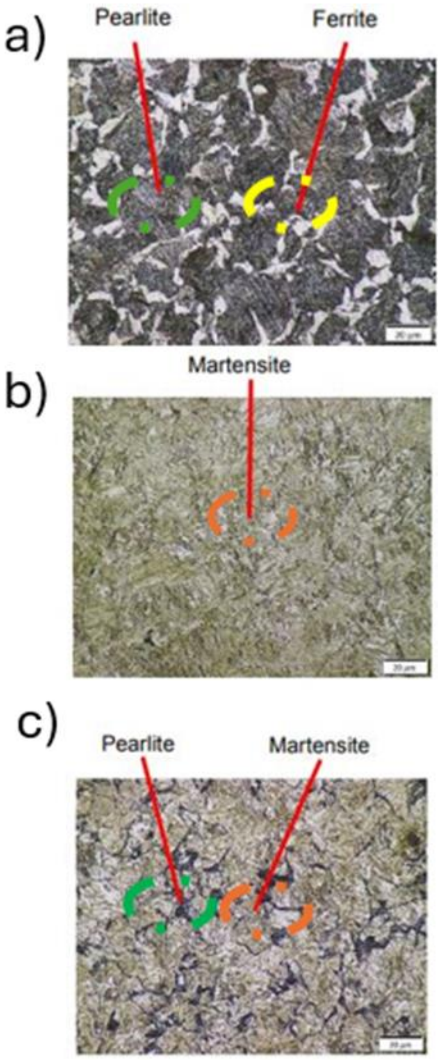

Figure 5. Microstructure of S45C Steel [4]:
a) Microstructure of S45C Steel before quenching b) Microstructure of S45C Steel after water quenching c) Microstructure of S45C Steel after oil quenching
b)

This establishes clear performance benchmarks for media selection. Priyambodo et al. [16] reported an improvement in hardness to 251.56 VHN through oil quenching alone. Our study quantifies both media effects. Oil quenching achieves 42.9 HRC (68% improvement), and water quenching reaches 55.7 HRC (118% improvement). This provides a comprehensive trade-off analysis that previous studies lacked. Similarly, Villany Golwa et al. [18] observed an increase in hardness from 200.55 HV to 340.4 HV after quenching at 950°C for 120 minutes, but lacked a comparative analysis. In contrast, our study establishes a systematic comparison at a standardized temperature of 900°C for 45 minutes. We demonstrate reproducible and optimized results with clear statistical validation. Our research integrates Hall-Petch theory with experimental validation, achieving correlation coefficients $R^2 > 0.95$. This provides a mechanistic understanding that enables predictive capabilities for industrial applications. Most significantly, previous studies [15, 16, 18] provided isolated improvements without quantifying trade-offs. Our framework explicitly quantifies the critical trade-off: water quenching maximizes hardness (118% improvement), while oil quenching optimizes tensile strength (65% improvement). This strength-hardness trade-off behavior is consistent with the findings of Manik et al. [28], who investigated the effects of post-weld heat treatment and normalizing on AH36 low-carbon steel and demonstrated that the optimal heat treatment temperature of 600°C achieved the best balance between tensile strength, ductility, and impact toughness, while higher temperatures enhanced strength but compromised ductility and fracture resistance. Their results reinforce the principle that heat treatment parameter selection involves critical trade-offs between competing mechanical properties, which must be carefully optimized based on application-specific requirements. This enables evidence-based media selection based on specific application requirements. We provide the first unified framework that combines comparative analysis, theoretical validation, and practical guidelines for systematic industrial decision-making processes.

## CONCLUSION

This study demonstrates that the choice of quenching media profoundly impacts the microstructure and mechanical properties of S45C steel. Water quenching achieves the highest hardness (55.7 HRC) by rapidly cooling the steel, refining prior austenite grains, and producing a fully martensitic structure. However, this method increases susceptibility to cracking due to thermal stress. In contrast, oil quenching prioritizes dimensional stability and demonstrates superior tensile performance with ultimate tensile strength of 1050 MPa, forming a balanced microstructure of martensite and bainite that enhances toughness and reduces crack initiation.

The Hall-Petch relationship explains the grain-size-dependent strengthening mechanism: smaller grains in water-quenched steel (0.8 µm) elevate hardness by impeding dislocation motion, while moderately refined grains in oil-quenched steel (2.5 µm) provide optimal balance between strength and ductility. The experimental validation shows excellent agreement with theoretical predictions, achieving correlation coefficients $R^2 > 0.95$.

Water quenching is ideal for components requiring extreme wear resistance and maximum hardness (118% improvement over untreated steel), such as cutting tools or agricultural blades. Oil quenching, with its superior dimensional control and exceptional tensile properties (65% improvement in ultimate tensile strength), is better suited for precision parts like gears, crankshafts, and automotive axles, where structural integrity under cyclic loading is critical. The superior tensile strength of oil quenching makes it the preferred choice for load-bearing applications requiring maximum structural performance. For water-quenched components, post-quench tempering is strongly recommended to mitigate brittleness while retaining hardness.

These results provide a practical framework for selecting quenching processes based on application-specific requirements. The findings reveal an important trade-off: water quenching maximizes hardness while oil quenching optimizes tensile strength, allowing engineers to select the appropriate treatment based on primary performance requirements. Future studies could explore hybrid quenching techniques or advanced cooling media (e.g., polymer solutions) to optimize the balance between hardness, strength, and ductility

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