Microstructural Characterization of AISI 1045 Steel after Quenching with Various Cooling Media

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***Abstract*— AISI 1045 steel is a medium-carbon steel widely used for machine components due to its favorable combination of strength, toughness, and machinability. Its mechanical properties can be enhanced through heat treatment, specifically quenching using various cooling media. This study aims to analyze the effect of different cooling media on the microstructural changes of AISI 1045 steel following the quenching process. An experimental method was employed using three cooling media variations: 25% NaCl solution, SAE 10W-30 oil, and distilled water. Specimens were heated to an austenitizing temperature of 850°C with a 60-minute holding time, followed by quenching for 5 minutes in each respective medium. Microstructural characterization involved metallographic preparation comprising grinding, polishing, and etching with 5% nital solution followed by observation under a metallographic microscope at 200× and 400× magnifications. Observations revealed that the raw material was dominated by ferrite and pearlite structures. After quenching, a martensitic structure formed, with the quantity and distribution varying according to the cooling medium used. The 25% NaCl solution produced the most dominant and relatively uniform martensitic structure, followed by distilled water, whereas SAE 10W-30 oil resulted in a lower proportion of martensite, with ferrite and pearlite remaining dominant. These differences indicate that the cooling rate characteristics of the quenching media influence phase transformation and the resulting microstructure of AISI 1045 steel. Based on the observations, the 25% NaCl solution provided the most intensive cooling effect compared to distilled water and SAE 10W-30 oil.**

Keywords—AISI 1045, Cooling Media, Martensite, Microstructure, Quenching.

I. INTRODUCTION

Steel is a widely used material in manufacturing and mechanical engineering due to its combination of mechanical properties, manufacturability, and relatively good availability[1]. AISI 1045 steel is a type of carbon steel frequently utilized for machine components. Classified as a medium-carbon steel with a carbon content of approximately 0.45%, it possesses characteristics suitable for various components requiring strength and resistance to mechanical loading [1], [2]. Applications of AISI 1045 steel include shafts, gears, bolts, machine components, and various structural parts that demand a combination of strength and toughness [2], [3]. The mechanical properties of AISI 1045 steel are significantly influenced by the microstructure formed during manufacturing and heat treatment processes. Heat treatment is a common method used to control microstructure and enhance the mechanical properties of steel [3], [4]. One widely applied heat treatment method is quenching, which involves rapidly cooling the material after it has been heated to a specific temperature. The primary objective of quenching is to alter the microstructure through phase transformation, thereby increasing the material's hardness and strength [2], [3], [4]. In medium-carbon steels like AISI 1045, heating into the austenitic range followed by rapid cooling can result in the formation of martensite, the extent of which depends on the cooling rate [4], [5]. The faster the cooling process, the greater the likelihood of forming a martensitic structure, whereas slower cooling rates can yield mixed structures such as martensite, bainite, or ferrite-pearlite [5], [6]. The quenching medium is a critical factor determining the heat transfer rate during the quenching process. Each type of medium possesses distinct heat transfer characteristics, resulting in varying cooling rates [6], [7]. Water, oil, and brine solutions differ in terms of thermal conductivity, viscosity, heat capacity, and the characteristics of vapor layer formation on the workpiece surface. These differences cause the phase transformation process in the steel to proceed with distinct characteristics [6], [7], [8]. The choice of quenching medium must be tailored to the material properties and the desired final characteristics.

Varying the quenching medium affects not only hardness but also the shape, size, and distribution of phases within the microstructure [4], [6], [7]. A medium with a very high cooling rate can produce a larger volume of martensite, but under certain conditions, it may also increase the risk of residual stress, distortion, or even cracking in the material [8], [9]. A quenching medium with a slower cooling rate can produce a softer structure resulting from different phase transformations [10], [11]. Consequently, microstructural characterization is essential to understand the relationship between cooling conditions and material structural changes following quenching [9], [10], [12]. Microstructure is closely linked to the mechanical properties of steel; variations in phase proportions and morphology, grain size, and the distribution of constituents such as ferrite, pearlite, bainite, and martensite can alter the material's strength, hardness, ductility, and toughness [11], [13]. Metallographic examination after quenching serves as a crucial method for evaluating the effectiveness of the heat treatment [13], [14]. By observing the microstructure, one can conduct an in-depth analysis of how

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different quenching media affect material characteristics. Although quenching is widely applied to medium-carbon steel, the choice of quenching medium remains a critical factor in achieving material properties tailored to specific application requirements [14], [15]. Variations in process conditions, quenching media, heating temperatures, holding times, and the material's initial state can lead to distinct microstructural characteristics [13], [15], [16]. Experimental research is required to specifically investigate microstructural changes in AISI 1045 steel after quenching with various media under controlled treatment conditions. This study aims to characterize the microstructure of AISI 1045 steel following quenching with different media, focusing on the microstructural changes resulting from these variations.

The findings are expected to provide insights into the influence of cooling characteristics on phase formation and microstructural morphology in AISI 1045 steel, thereby serving as a basis for selecting appropriate quenching media to achieve desired material properties for engineering component applications.

II. RESEARCH METHODOLOGY

This study employs an experimental method to analyze microstructural changes in AISI 1045 steel following quenching heat treatment using various cooling media. The primary variable is the type of cooling medium: NaCl solution, SAE 10W-30 oil, and distilled water [15], [16]. These three media were used to determine the effect of cooling rate characteristics on the microstructure of the AISI 1045 steel. The material used was AISI 1045 steel in the form of round bars, which were prepared into test specimens [16], [17]. The specimens underwent quenching heat treatment with consistent heating conditions and holding times across all cooling media variations. Following the quenching process, the specimens were sectioned and prepared for microstructural examination through grinding, polishing, and etching stages. The resulting observations were then used to identify morphological changes and the phases formed within the material.

A. Research Materials

The primary material used in this study is AISI 1045 steel. A round bar form was selected because it is widely used for machine components requiring strength and the ability to withstand mechanical loads [16], [17]. The AISI 1045 steel specimens were prepared in accordance with the requirements for microstructural and mechanical testing. Three variations of quenching media were used:

1. NaCl solution, used as a brine-based cooling medium.
2. SAE 10W-30 oil, used as an oil-based cooling medium with a slower cooling rate than water.
3. Distilled water, used as a water-based cooling medium with very low mineral content.

The use of these three media is intended to produce different cooling conditions, allowing for a comparison of the AISI 1045 steel's microstructural changes following the quenching process [18].

B. Preparasi Spesimen

AISI 1045 steel round bar specimens were cut and prepared to meet research requirements, ensuring uniform dimensions. Dimensional uniformity was necessary so that each specimen would undergo relatively identical heat treatment and cooling processes, thereby allowing for a more objective analysis of how different cooling media affect microstructural changes [17], [18], [19]. Following the cutting process, specimen surfaces were inspected and cleaned to remove dirt, oil, oxides, and other contaminants that could potentially influence the heating and cooling stages [17], [20], [21]. Thorough cleaning was performed to ensure no foreign material remained on the specimen surfaces. Subsequently, each specimen was labeled according to its treatment group to prevent errors during the experiment.



Fig. 1. AISI 1045 steel specimen for microstructure testing.

Specimens meeting the criteria for dimensions, shape, and surface cleanliness were grouped according to the type of quenching medium used. Three treatment groups were established: Q1 using a 25% NaCl solution, Q2 using SAE 10W-30 oil, and Q3 using distilled water. Each specimen had uniform dimensions to ensure consistency throughout the treatment process [20], [22], [23]. Subsequently, all specimens were prepared for quenching heat treatment under identical heating conditions. Heating was carried out until the predetermined austenitizing temperature was reached, followed by a holding period [23], [24]. Once the temperature and holding time were achieved, the specimens were immediately transferred to the quenching medium corresponding to their treatment group to obtain distinct microstructural characteristics.

C. Preparation of Cooling Media

The quenching media were prepared prior to the quenching proces[17]s. An NaCl solution was created by mixing NaCl with water according to the concentration specified in the research design. SAE 10W-30 oil was used in its ready-to-use state, while distilled water served as the quenching medium without the addition of other substances [21], [22]. Each quenching medium was placed in a container with sufficient capacity to fully submerge the specimen. The volume of the quenching medium was kept relatively consistent across all treatments to ensure that variations in heat absorption capacity would not act as a confounding factor during the quenching process.

D. Heat Treatment and Quenching Process

AISI 1045 steel specimens were heated in a heat treatment furnace to the austenitizing temperature determined by the research design [21], [22]. Once this temperature was reached, the specimens were held for a specific duration to ensure uniform heating and the formation of the austenite phase [20], [21], [22]. Following the holding period, the specimens were removed from the furnace and immediately cooled using a quenching medium corresponding to the specific treatment variation [24], [25]. The cooling process involved immersing the specimens in the quenching medium until their temperature approached that of the medium. Three quenching treatment groups were employed in this study, as detailed in Table 1.

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TABLE I. COOLING MEDIA

Code	Treatment	Quenching Medium
Q1	Quenching	25% NaCl Solution
Q2	Quenching	SAE 10W-30 Oil
Q3	Quenching	Distilled Water

All treatment parameters including heating temperature, holding time, specimen dimensions, and cooling duration were kept constant across all test groups, with the type of cooling medium serving as the sole variable. These parameters were controlled to minimize the influence of extraneous factors and to ensure a more objective comparison of the microstructural changes in AISI 1045 steel [26], [27]. Once the specimens reached the target cooling state, they were removed from the cooling medium and cleaned of any residual medium adhering to their surfaces. Subsequently, the specimens were dried to prevent surface corrosion or contamination [24], [27], [28]. The dried specimens were then labeled according to their treatment group and prepared for the stages of metallographic preparation and microstructural characterization.

E. Specimen Preparation for Microstructure Testing

Microstructural testing was conducted after the quenching process. All treatment parameters with the exception of the cooling medium were kept constant to ensure an objective comparison between specimens [28]. Following the cooling process, the specimens were dried and sectioned at predetermined locations to obtain a representative area for observation [24], [29], [30]. Subsequently, the specimens underwent metallographic preparation involving grinding, polishing, and etching stages.

Grinding was performed to level the specimen surface and remove material layers damaged during the cutting process. This step was carried out in stages using abrasive paper of appropriate grit sizes until a flat surface was achieved and cutting-induced scratches were minimized [31], [32]. After grinding, the specimens underwent polishing to remove fine surface scratches and produce a smooth, glossy finish. A well-polished surface is essential for obtaining clear microstructural images and minimizing visual interference during observation.

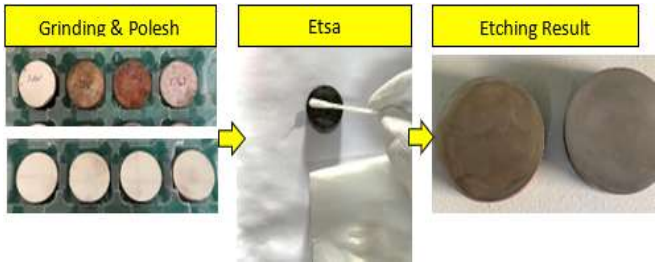


Fig. 2. Specimen grinding, polishing, and etching process.

The polished specimens were then subjected to etching to reveal grain boundaries and phase characteristics on the material surface. The etchant used was a mixture of nitric acid (HNO_3) and 96% ethanol, with an HNO_3 concentration of 5%. This solution was applied to the specimen surface for a specific duration, after which the specimen was immediately cleaned and dried [33], [34]. Etching time was carefully controlled to ensure optimal observation results; insufficient etching could render grain boundaries and phase characteristics indistinct, while excessive etching could lead to over-etching, thereby degrading the quality of the microstructural images [28], [29], [30].

Upon completion of the preparation stages, the specimens were examined using a metallographic microscope [31], [32], [34]. Observations were conducted at the same magnification for each cooling medium variation, allowing for a consistent comparison of the AISI 1045 steel's microstructural characteristics. The observation results were used to analyze changes in morphology and phase distribution resulting from quenching in NaCl solution, SAE 10W-30 oil, and distilled water [34], [35].

F. Microstructure Observation

Microstructural observation was conducted using a metallographic microscope after the specimens had undergone all preparation stages [35], [36]. Observations were performed on etched specimen surfaces to capture microstructural images for each cooling medium variant. The parameters observed included morphology, relative grain size, phase distribution, and microstructural characteristic changes resulting from the different cooling media [36], [37]. Microstructural images from each specimen were compared to determine the influence of the cooling medium type on the structure formed after quenching.

Observations were carried out at a consistent or predetermined magnification across all specimen groups to ensure the validity of the comparison. The observational data consisting of microstructural imageswere analyzed by comparing the microstructural characteristics of AISI 1045 steel across the different cooling media [37], [38]. The analysis focused on changes in morphology and phase distribution resulting from varying cooling rates. The microstructural observation results were then correlated with the characteristics of each cooling medium [38], [39]. Cooling media with differing heat transfer capabilities were expected to produce different cooling rates, thereby influencing the phase transformation of austenite during the quenching process [40]. The analysis involved comparing the microstructures of specimens cooled using NaCl solution, SAE 10W-30 oil, and distilled water. These results were used to identify the cooling medium that produced the most significant microstructural changes in AISI 1045 steel.

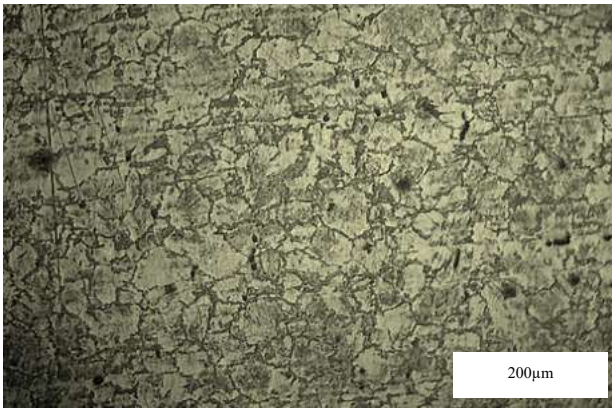
III. RESEARCH METHODOLOGY

A. Microstructure test results

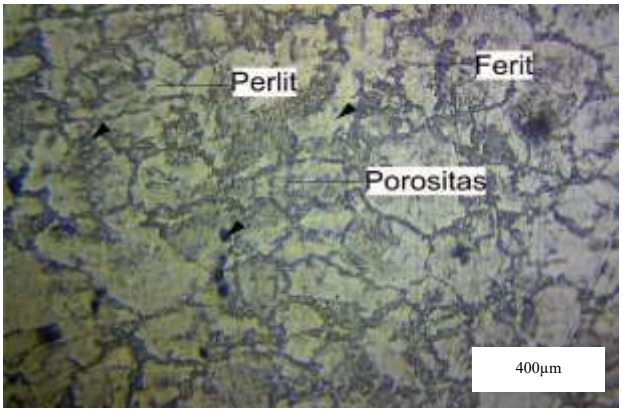
Fig. 3 displays the microstructural observations of the AISI 1045 steel raw material prior to quenching heat treatment. Observations were conducted using a metallographic microscope at 200× magnification for image (a) and 400× for image (b). Examining the initial condition aimed to establish a baseline for the material's microstructure before it underwent changes resulting from heating and rapid cooling [38], [40]. The raw material's microstructure image serves as a reference for comparison with specimens subjected to quenching using various cooling media.

The observations reveal that the initial microstructure of the AISI 1045 steel consists of ferrite and pearlite phases distributed across the specimen surface. Ferrite generally appears as lighter regions, whereas pearlite appears darker and exhibits a distinct morphology [37], [38]. The distribution of these two phases is characteristic of the microstructure of medium-carbon steel in its initial state. At 400× magnification, the morphology and boundaries between microstructural regions are more clearly discernible than at 200× magnification. This initial state provides the basis for

evaluating microstructural changes following the quenching process [36], [37], [38]. Comparisons between the raw material and the treated specimens are made based on morphology, phase distribution, and changes in structural characteristics. Thus, the observations of the raw material serve as a reference for analyzing the influence of different cooling media on the microstructural transformation of AISI 1045 steel after quenching.



(a)



(b)

Fig. 3. Microstructure of raw material at 200X and 400X magnification.

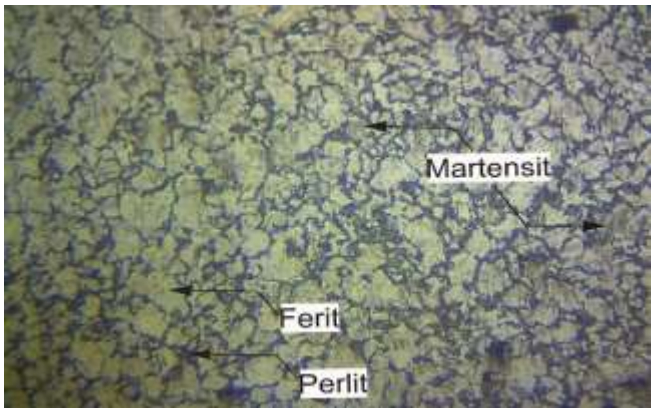
Fig. 3 shows the microstructure of the AISI 1045 steel raw material specimen in its untreated state, etched using Nital (5% nitric acid + 95% ethanol). The micrograph reveals that pearlite and ferrite are distributed throughout the raw material. Fundamentally, AISI 1045 steel is characterized by high toughness and significant hardness. In the image, the light-colored regions represent ferrite, while the dark regions represent pearlite [35], [36]. The micrograph shows pearlite particles that are coarse, irregular in shape, and appear somewhat dull black, whereas the ferrite particles appear as white, island-like formations with irregular distribution; ferrite is a soft microstructural constituent present in the steel prior to high-temperature treatment [32], [34]. Black spots are also visible, indicating porosity or material voids which are classified as porosity defects. These pores appear as small black holes at the grain boundaries between particles; they result from high impurity levels in the molten metal and the entrapment of gases released during solidification [29], [30]. Additionally, during the sintering manufacturing process, incomplete particle bonding can create micro-cracks that manifest as porosity visible during microstructural analysis. Thus, the results indicate that the raw material microstructure consists of pearlite and ferrite phases.

B. Microstructure test results for 25% NaCl brine medium

The microstructural observations of AISI 1045 steel following a quenching process using a 25% NaCl solution as the cooling medium are presented in Figure 4. Observations were conducted using a metallographic microscope at 200× magnification for image (a) and 400× for image (b). The microstructural images reveal changes in the material's structural characteristics resulting from heating and rapid cooling in the 25% NaCl solution [28], [29]. Different magnifications were employed to more clearly observe the morphology, distribution, and characteristics of the phases formed.



(a)



(b)

Fig. 4. Microstructure of 25% NaCl brine solution at 200X and 400X magnification.

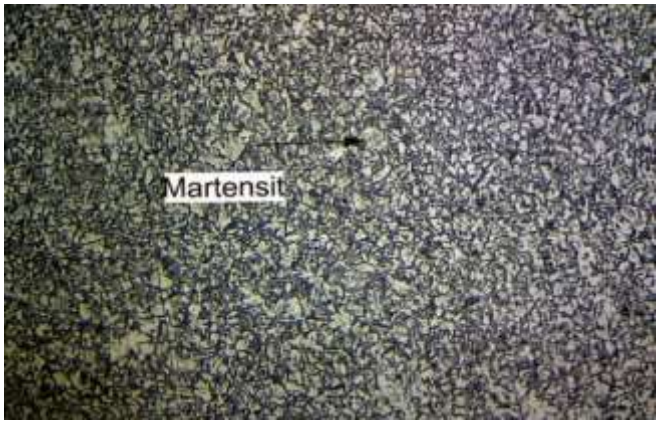
Fig. 4 shows the specimen after heating, quenching in a 25% brine solution for 5 minutes, and etching with nital (5% nitric acid + 95% ethanol). Martensite particles appear as irregular, linear features in shades of gray and black, whereas ferrite and pearlite particles are sparse and irregularly distributed [31], [33]. The formation of martensite during quenching with a 25% NaCl solution differs significantly from the raw material specimen; the micrograph is clearly dominated by martensite particles. Thus, it can be concluded that the microstructure resulting from quenching in a 25% NaCl solution consists of martensite, pearlite, and ferrite. The formation of martensite during quenching with a 25% NaCl solution differs significantly from the raw material specimen; the micrograph is clearly dominated by martensite particles [34], [35]. In steel quenched with water or brine (2.5–25.0% concentration), the microstructure is predominantly martensitic. The higher the salt concentration, the finer the resulting martensite structure [36]. Based on this theory, the research results are consistent with established principles. This indicates that a higher salt concentration accelerates the

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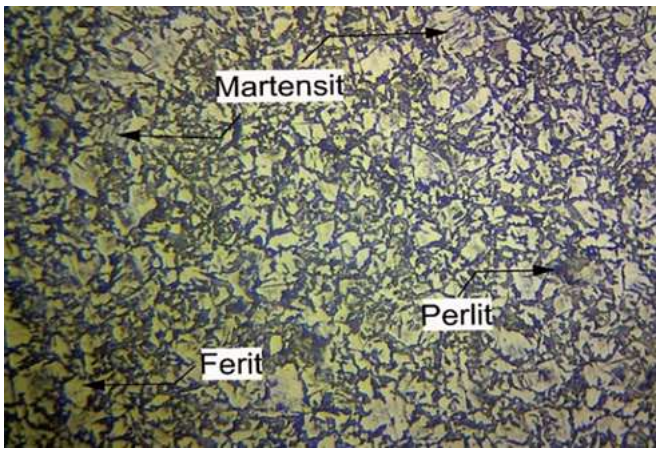
cooling process during quenching. This martensitic structure renders the steel harder and more brittle.

C. Microstructure images of the sample cooled in SAE 10W-30 oil.

On AISI 1045 steel with an observation scale of 200 µm in visual (a) and 400 µm in visual (b), the resulting microstructure can be seen in Figure 5. Observations were made to determine the initial condition of the material's microstructure before heat treatment [24]. The microstructure of AISI 1045 steel in its initial condition generally consists of ferrite and pearlite phases distributed on the surface of the specimen [22], [23], [24]. The difference in magnification provides a clearer picture of the morphology, distribution and shape of the grains in the material. The results of observations of the microstructure of these initial conditions are then used as a comparison to analyze changes in the microstructure of AISI 1045 steel after the heat treatment and quenching processes using various cooling media.



(a)



(b)

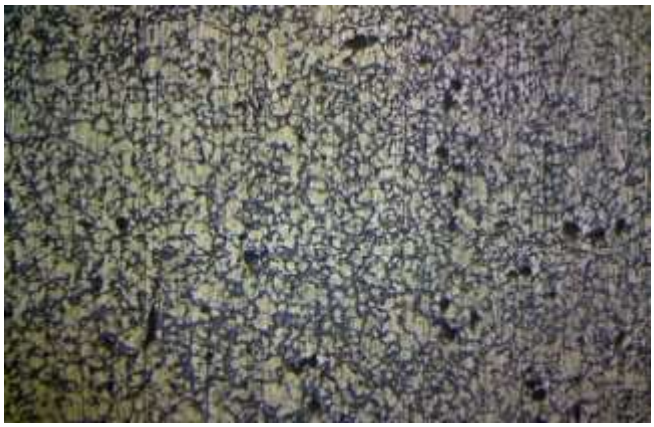
Fig. 5. Microstructure of SAE 10W-30 oil at 200X and 400X magnification.

Fig. 5 shows the microstructure of the AISI 1045 steel specimen after heating and quenching in SAE 10W-30 oil for 5 minutes, followed by etching with a nital solution consisting of 5% nitric acid (HNO_3) and 95% ethanol[26], [27]. Observations reveal that the microstructure is dominated by ferrite and pearlite phases; ferrite appears as lighter-colored regions, while pearlite appears darker [29], [31]. In addition to these two phases, martensite is present, exhibiting a needle-like or linear morphology with an uneven distribution. Thus, the microstructure resulting from quenching in SAE 10W-30 oil consists of ferrite, pearlite, and martensite.

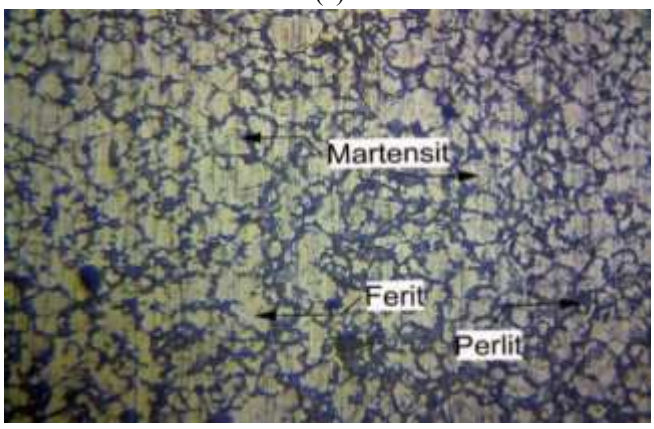
Compared to the raw material, the formation of martensite indicates a microstructural change resulting from the quenching process [26], [32]. The quantity and distribution of martensite in the SAE 10W-30 oil medium are lower than in specimens quenched in a 25% NaCl solution. This difference is attributed to the heat transfer characteristics and cooling rates of the respective media. The 25% NaCl solution provides faster cooling, resulting in a higher martensite fraction, whereas SAE 10W-30 oil has a relatively lower cooling rate, allowing a portion of the austenite to transform into ferrite and pearlite [21], [22], [23]. The microstructural images also reveal indications of small-scale porosity on the specimen surface.

D. Microstructure images of the sample cooled in distilled water

Observations of the microstructure of AISI 1045 steel in its raw material state are presented in Figure 6. These observations were conducted using an optical microscope at a scale of 200 µm for image (a) and 400 µm for image (b). The resulting microstructure reflects the material's initial characteristics prior to heat treatment and cooling. In this state, the microstructure of the AISI 1045 steel is generally dominated by ferrite and pearlite phases distributed throughout the material matrix [13], [14]. Ferrite appears as relatively bright regions, whereas pearlite appears darker, exhibiting distinct shapes and distribution patterns. This initial microstructure serves as a baseline for comparing structural changes following quenching processes that utilize various cooling media.



(a)



(b)

Fig. 6. Microstructure of distilled water at 200X and 400X magnification.

Fig. 6 shows the specimen after heating, quenching in distilled water for 5 minutes, and etching with Nital (5% nitric

acid + 95% ethanol). The image reveals the formation of martensite particles appearing as slightly finer, darkish streaks alongside small areas of pearlite (black) and ferrite (white) [21], [22]. The process involved heating to 850°C to achieve a fully austenitic structure, followed by a 60-minute holding time. Martensite formed during rapid cooling from the austenite phase (specifically between 200°C and 400°C), while ferrite formed during slow cooling below 700°C. The micrograph shows that the martensite structure dominates over the ferrite and pearlite structures [24], [26]. Thus, it can be concluded that the microstructure resulting from quenching in distilled water consists of martensite, pearlite, and ferrite. When compared to quenching in a 25% NaCl solution and SAE 10W-30 oil, the martensite content in the distilled water-quenched sample falls between the levels observed in the NaCl solution and the oil [29], [30]. The highest and most uniform martensite distribution was observed in the sample quenched in 25% NaCl solution, followed by the distilled water sample, with the SAE 10W-30 oil sample showing the least. Based on the extent of martensite distribution, the material quenched in 25% NaCl solution was the hardest and most brittle, followed by the distilled water sample, and finally the SAE 10W-30 oil sample [32], [34]. Micrographs obtained from the various specimens demonstrate that the quenching process altered the microstructural characteristics; specifically, the formation of martensite increased the material's hardness relative to the raw material. The results of all the tests above demonstrate that variations in quenching media influence changes in the microstructural characteristics of AISI 1045 steel.

E. Hardness Test Results

Hardness testing was conducted to determine changes in the mechanical properties of AISI 1045 steel following heat treatment and quenching using various cooling media. The tests employed the Vickers method with a load of 100 kgf. Each specimen was tested at three points, and the average value was subsequently calculated. As shown in Table II, the raw material (R) exhibited an average hardness of 215.15 HVN.

TABLE II. VICKERS HARDNESS TEST RESULTS FOR THREE SPECIMENS UNDER DIFFERENT QUENCHING MEDIA AND TEST AREAS

Material Code	Quenching Medium	Test Area	Hardness Value (HVN) – Specimen 1	Hardness Value (HVN) – Specimen 2	Hardness Value (HVN) – Specimen 3
R	Raw Material	Point 1	216.00	211.71	217.10
		Point 2	213.20	221.12	212.80
		Point 3	219.30	213.20	211.90
		Average	**216.17**	**215.34**	**213.93**
Q1	25% NaCl Solution	Point 1	566.80	409.30	438.20
		Point 2	568.20	399.60	436.60
		Point 3	573.30	434.40	515.30
		Average	**569.43**	**414.43**	**463.36**
Q2	SAE 10W-30 Oil	Point 1	243.70	285.10	262.70
		Point 2	249.80	277.50	257.30
		Point 3	255.50	284.00	253.00
		Average	**249.67**	**282.20**	**257.67**
Q3	Distilled Water	Point 1	365.50	330.10	375.80
		Point 2	360.90	374.00	344.50
		Point 3	325.20	354.00	387.20
		Average	**350.53**	**352.70**	**369.16**

Following the quenching process, all cooling media resulted in increased hardness, albeit to varying degrees. The 25% NaCl solution (Q1) yielded the highest average value at 482.41 HVN, representing an increase of approximately 124.22% compared to the raw material. Distilled water (Q3) resulted in an average of 357.46 HVN (an increase of approximately 66.15%), while SAE 10W-30 oil (Q2) produced an average of 263.18 HVN (an increase of approximately 22.33%). 1,152 The order of hardness values obtained was Q1 (25% NaCl) > Q3 (distilled water) > Q2 (SAE 10W-30 oil) > R (raw material). These differences indicate that the type of quenching medium influences the quenching results. The 25% NaCl solution provides a higher cooling rate, thereby increasing the likelihood of forming a martensitic structure, which possesses high hardness. Distilled water also results in relatively rapid cooling, whereas SAE 10W-30 oil has a lower cooling rate, resulting in a smaller increase in hardness. The use of different quenching media results in varying changes in the hardness of AISI 1045 steel. The 25% NaCl solution yields the greatest increase in hardness, while SAE 10W-30 oil produces the smallest increase. These results demonstrate a relationship between cooling characteristics, microstructural changes, and the increase in material hardness following the quenching process. To strengthen the analysis, the hardness results can be correlated with microstructural observations, allowing for a more comprehensive explanation of the relationship between phase formation and mechanical properties.

IV. CONCLUSION

Based on the experimental results, variations in quenching media significantly influenced the microstructural characteristics of AISI 1045 steel. The raw material initially exhibited a microstructure dominated by ferrite and pearlite. After quenching, martensite was formed in all specimens, although its morphology and distribution varied depending on the cooling medium. The 25% NaCl solution produced the highest and most uniform martensite distribution, indicating the most intensive cooling rate among the investigated media. Distilled water produced an intermediate martensitic structure, while SAE 10W-30 oil resulted in the lowest martensite distribution and a relatively greater presence of ferrite and pearlite. These differences demonstrate that the cooling rate of the quenching medium plays an important role in determining the phase transformation and microstructural morphology of AISI 1045 steel. Based on the observed martensite distribution, the 25% NaCl solution is expected to produce the highest hardness and brittleness, followed by distilled water and SAE 10W-30 oil. Therefore, the selection of an appropriate quenching medium should consider the desired balance between hardness, strength, toughness, and resistance to quenching-related defects.

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