Index

Abstract

This report investigates the effects of three heat treatment processes—annealing, normalizing, and quenching—on low-carbon steel (0.05–0.25% C) at varying temperatures (800°C, 900°C, 1000°C, and 1100°C). The primary objective was to understand how temperature and cooling rates influence phase transformations, microstructure evolution, and mechanical properties such as hardness.
During the experiment, samples were heated to target temperatures and subjected to the respective heat treatments. Microstructural analysis was conducted using optical microscopy after metallographic preparation, and mechanical properties were evaluated through Vickers hardness testing.
The results revealed that annealing produced coarse-grained structures dominated by ferrite and pearlite with relatively low hardness values. Normalizing resulted in refined microstructures with smaller grains and moderately increased hardness due to faster air cooling. Quenching produced martensitic structures with significantly higher hardness but reduced ductility due to rapid cooling.
The discussion highlights the relationship between microstructure and mechanical properties, emphasizing the role of grain size, phase distribution, and cooling rates in determining material behavior.

This study provides a comprehensive understanding of heat treatment processes and their impact on low-carbon steel, offering valuable insights for optimizing material performance in engineering applications.

Introduction

Heat treatment is a controlled process involving heating and cooling of metals and alloys to alter their microstructure and mechanical properties. It is widely employed to optimize characteristics such as hardness, ductility, toughness, strength, and machinability. In this experiment, three fundamental heat treatment processes—annealing, normalizing, and quenching—were investigated on low carbon steel samples containing approximately 0.05–0.25% carbon.

Annealing is a heat treatment process where steel is heated to a temperature slightly above its critical temperature range, held at that temperature for a specific duration, and then cooled slowly (usually within the furnace). This slow cooling allows atoms to diffuse properly, relieving internal stresses developed during previous manufacturing processes like casting, forging, or rolling. Annealing results in a softer and more ductile material with improved machinability and formability. It also refines grain structures and homogenizes chemical composition throughout the material.

Normalizing involves heating the steel above its upper critical temperature (typically 30–50°C above), holding it briefly at this elevated temperature to achieve uniformity in the microstructure, followed by air cooling at room temperature. The faster cooling rate compared to annealing leads to a finer grain size, uniform microstructure distribution (usually pearlite and ferrite), and improved mechanical properties such as strength and toughness. Normalizing is commonly performed to eliminate structural irregularities caused by prior processing steps.

Quenching is a rapid cooling process where steel heated above its critical temperature is quickly immersed in a quenching medium such as water, oil, or brine. This rapid cooling prevents diffusion-controlled transformations like pearlite formation, resulting instead in the formation of martensite—a hard, brittle microstructure. Quenching significantly increases hardness and strength but reduces ductility and toughness. To achieve desired mechanical properties and reduce brittleness after quenching, subsequent tempering (controlled reheating) is often performed.

In this experimental study, low carbon steel samples were heated separately to temperatures of 800°C, 900°C, 1000°C, and 1100°C. Each sample was subjected individually to annealing, normalizing, and quenching heat treatments. Following these treatments, optical microscopy was used for microstructural analysis of each sample. Additionally, Vickers hardness tests were conducted to quantitatively evaluate the effects of different heat treatments on hardness at varying temperatures.

Heat-treated low carbon steels find extensive applications across industries due to their enhanced mechanical properties. Typical applications include automotive components (gears, shafts), structural elements (beams, rails), machinery parts (bolts, fasteners), construction materials, pipelines, and various engineering components requiring specific combinations of strength, ductility, hardness, or toughness.

Material

The material selected for this experiment was **low carbon steel**, also commonly known as mild steel, with a carbon content ranging from approximately **0.05% to 0.25% C**. Low carbon steel is primarily composed of iron with small amounts of carbon and minor quantities of other alloying elements such as manganese and silicon. The carbon content in low carbon steels typically ranges below 0.25%, which imparts specific mechanical properties suitable for various engineering applications. Low carbon steel is produced primarily through basic oxygen furnaces (BOF) or electric arc furnaces (EAF), followed by casting and rolling into desired shapes and sizes[4]. Due to its relatively low carbon content, this steel exhibits excellent ductility and malleability, allowing it to be easily formed, machined, and welded without significant risk of cracking or brittleness[4].

Key Properties of Low Carbon Steel:

- **Ductility**: It can be easily shaped, stretched, or bent without fracturing, making it ideal for forming processes such as bending, drawing, or stamping[4].
- **Weldability**: Low carbon content minimizes the formation of cracks in heat-affected zones during welding processes, simplifying fabrication and assembly[4].
- **Density**: Typically around 7.85 g/cm^3, consistent with most ferrous alloys[4].
- **Thermal Conductivity**: Moderate thermal conductivity; suitable for applications where heat conduction is necessary but not critical[4].
- **Mechanical Properties**: Exhibits moderate strength and toughness combined with good ductility. These properties can be further enhanced through controlled heat treatments to achieve desired hardness and strength levels[4].

Low carbon steel is widely used across industries due to its favorable balance between cost, mechanical properties, machinability, and ease of fabrication. Typical applications include automotive body panels, structural components (such as beams and rails), machinery parts (fasteners, bolts), pipes for low-pressure systems, construction materials, furniture frames, and general-purpose engineering components where moderate strength combined with good ductility is essential

Experimental Procedure

Heat Treatment Procedure

The experimental procedure involved heating low carbon steel samples (0.05–0.25% C) to different set temperatures—800°C, 900°C, 1000°C, and 1100°C—followed by three distinct heat treatments: annealing, normalizing, and quenching. The detailed steps for each heat treatment are described below:

Annealing

1. Samples were heated to their respective temperatures (800°C, 900°C, 1000°C, and 1100°C) in a muffle furnace.
2. Upon reaching the desired temperature, samples were held at that temperature for approximately 30 minutes to ensure complete and uniform heating.
3. After soaking, the furnace was turned off, and samples were allowed to cool slowly inside the furnace to room temperature.

Normalizing

1. Samples were heated individually to the designated temperatures (800°C, 900°C, 1000°C, and 1100°C) and held at these temperatures for approximately 30 minutes.
2. After soaking at these elevated temperatures, samples were removed from the furnace and cooled in still air at room temperature until they reached ambient conditions.

Quenching

1. Samples were heated separately to each of the specified temperatures (800°C, 900°C, 1000°C, and 1100°C).
2. After holding at temperature for approximately 30 minutes to achieve uniform austenitization, samples were rapidly quenched in water maintained at room temperature.
3. Samples remained immersed until completely cooled.

Metallographic Sample Preparation

After heat treatment processes were completed, each sample underwent metallographic preparation for microstructural analysis. The following detailed procedure was employed:

Cutting and Mounting

- Small sections of treated samples were cut using a precision cutting machine.
- Each sample was mounted using standard mounting resin to facilitate handling during polishing.

Grinding and Polishing

The metallographic preparation involved two main stages: grinding/paper polishing followed by cloth polishing.

Grinding/Paper Polishing

- Samples were initially ground on rotating abrasive papers of progressively finer grit sizes (starting from coarse grit size such as 220 grit and progressing through intermediate sizes like 400-600-800-1000, and finally up to fine grit size of about 1200-1500-2000).
- During grinding, water was continuously applied as a lubricant and coolant to prevent overheating and maintain cleanliness of the sample surfaces.
- Each grinding step was performed until scratches from previous grit size disappeared completely before moving to finer grit paper.

Cloth Polishing

- After paper polishing, samples underwent fine polishing using a rotating polishing cloth wheel impregnated with diamond paste or alumina suspension (typically particle sizes of around 1 μm or smaller).
- Polishing continued until a mirror-like surface finish without scratches or irregularities was achieved on each sample surface.

Etching

- Polished samples were chemically etched using **Nital solution**, typically consisting of approximately **2–5% nitric acid diluted in ethanol**.
- Etching was done by immersing polished surfaces briefly (usually around 5–15 seconds) in Nital solution (commonly about 2–5% nitric acid in alcohol), followed immediately by rinsing with distilled water and drying carefully.
- Etching selectively attacked grain boundaries and phase interfaces to reveal microstructural features clearly under microscopic examination.

Optical Microscopy

- Prepared surfaces were examined under an optical microscope equipped with suitable magnification lenses.
- Micrographs were captured digitally for each sample clearly showing grain structures, phases present (ferrite, pearlite, martensite), grain size distributions, and other relevant microstructural details.

Hardness Testing Procedure (Vickers Hardness Test)

Vickers hardness testing was employed to quantitatively evaluate hardness changes resulting from different heat treatments.

Procedure:

1. The polished metallographic samples were placed on the stage of a Vickers hardness tester.

2. A diamond pyramid indenter with a square base angle of $136^{\circ}136^{\circ}$ was pressed into the sample surface under a standardized load (typically ranging from 10 kgf to 30 kgf depending upon material hardness).

3. The load was applied steadily for approximately 10–15 seconds before being released carefully.

4. After removing the load, indentation diagonals created on the sample surface were measured accurately using an optical microscope integrated within the hardness tester.

5. The average diagonal length (d) of indentation impression was measured precisely.
   The Vickers hardness number (HV) was calculated using the formula:
   where:

$$HV = \frac{1.8544 \times P}{d^2}$$

Figure 4.1: Formula for Hardness Number in Vickers Hardness Test

- HV is Vickers hardness number,
- P is applied load in kilograms-force (kgf),
- d is the average diagonal length of indentation impression measured in millimeters.

Results

1) 800°C

(a) Annealing

General Observations

The sample was heated to 800°C, held at this temperature for 30 minutes, and then cooled slowly inside the furnace. At 800°C, the steel was partially in the austenitic phase (γ-Fe) as this temperature is near the upper critical temperature (A3) for low-carbon steels. During slow cooling, the austenite transformed into ferrite and pearlite. The slow cooling rate allowed grain growth to dominate nucleation, resulting in a coarse-grained microstructure.

Microstructure Analysis

The microstructure observed under the optical microscope (Figure 1) reveals large equiaxed ferrite grains (light regions) and coarse pearlite colonies (dark regions). The lamellar spacing within the pearlite is wide due to the slow cooling process.

- **Phase Transformation**: At 800°C, the steel was partially austenitic. Upon slow cooling, the remaining austenite decomposed into ferrite and pearlite according to the Fe-C phase diagram. The extended cooling time allowed carbon atoms to diffuse out of the austenite matrix, forming cementite layers within pearlite colonies.

- **Grain Morphology**: The prolonged exposure to high temperatures and slow cooling favored grain growth over nucleation, resulting in larger ferrite grains and coarser pearlite colonies compared to samples treated at higher temperatures or subjected to faster cooling rates.

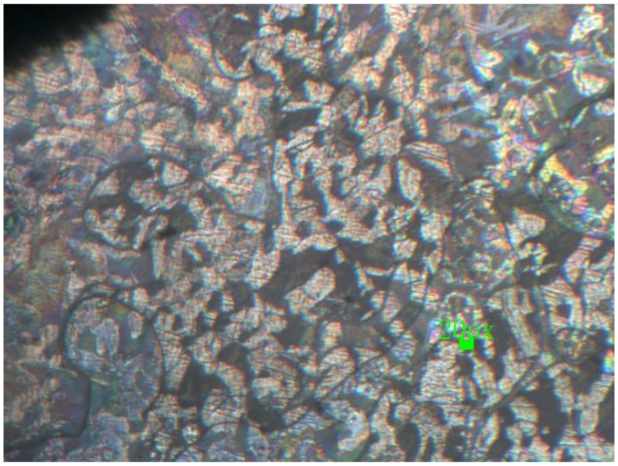

Figure 5.1.1.: Microstructure of the annealed sample at 800°C (10x magnification).

Hardness Test Results

The Vickers hardness test was conducted on the annealed sample using a load of 100 gf. The average hardness value obtained was **210 HV**, as shown in Figure 2. This hardness is consistent with the coarse-grained structure dominated by ferrite and pearlite phases.

- **Hardness Analysis**: The coarse-grained structure resulting from annealing at 800°C contributes to moderate hardness compared to finer-grained structures produced by other heat treatments or higher temperatures. Ferrite remains the dominant phase, contributing to ductility but limiting hardness.

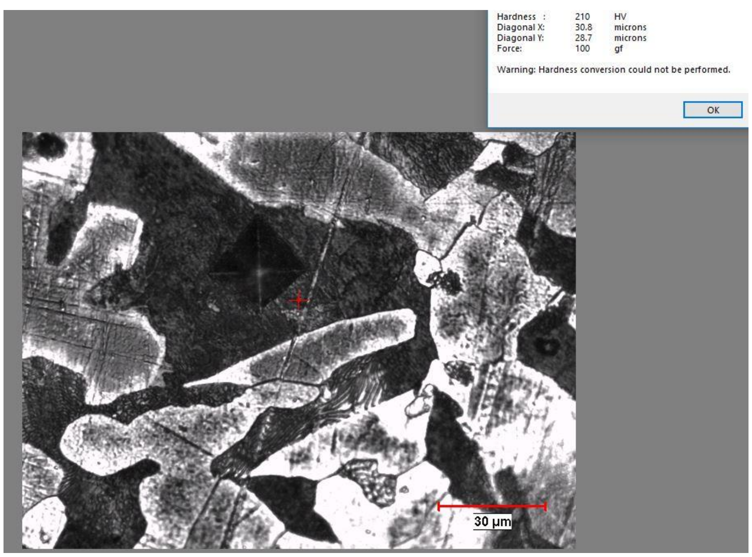

Figure 5.1.2 : Vickers Hardness Test Result for Annealed Sample at 800°C

(b) Normalizing

General Observations

The sample was heated to 800°C, held at this temperature for 30 minutes, and then cooled in still air at room temperature. At 800°C, the steel was partially in the austenitic phase (γ-Fe), as this temperature is near the upper critical temperature (A3) for low-carbon steels. During air cooling, the austenite transformed into ferrite and pearlite. The faster cooling rate compared to annealing limited grain growth and promoted nucleation, resulting in a more refined microstructure.

Microstructure Analysis
The microstructure observed under the optical microscope (Figure 1) reveals smaller ferrite grains (light regions) and finer pearlite colonies (dark regions) compared to the annealed sample. The lamellar spacing within the pearlite is tighter due to the increased cooling rate during normalizing.

- **Phase Transformation**: At 800°C, the steel was partially austenitic. Upon cooling, the remaining austenite transformed into ferrite and pearlite. The faster cooling rate during normalizing increased nucleation sites for ferrite and pearlite formation, leading to finer grains and a more uniform distribution of phases.
- **Grain Morphology**: Ferrite grains are smaller and more equiaxed, while pearlite colonies are finer with closely spaced lamellae. This refined structure enhances mechanical properties such as strength and toughness compared to annealed samples.

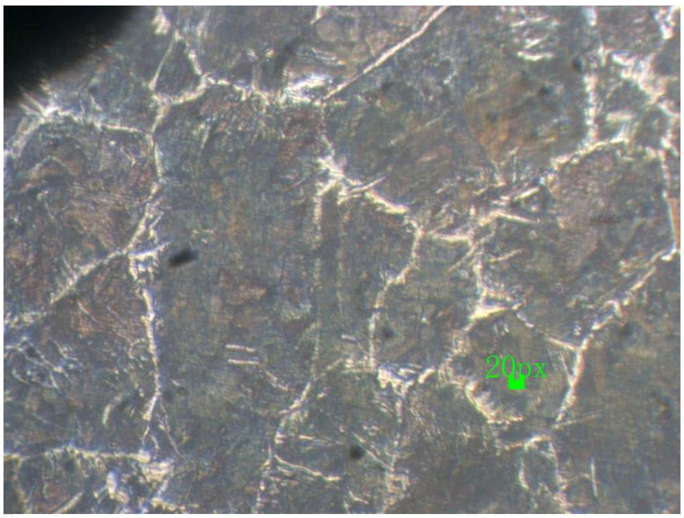

Figure 5.1.3: Microstructure of the normalized sample at 800°C (20x magnification)

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Hardness Test Results
The Vickers hardness test was conducted on the normalized sample using a load of 100 gf. The average hardness value obtained was **225 HV**, higher than that of the annealed sample (**210 HV**) at the same temperature. This increase in hardness is attributed to the refined grain structure and compact pearlite morphology produced by normalizing.

- **Hardness Analysis**: The refined microstructure resulting from normalizing contributes to improved hardness compared to annealing. The smaller grain size increases grain boundary area, which impedes dislocation movement and enhances hardness.

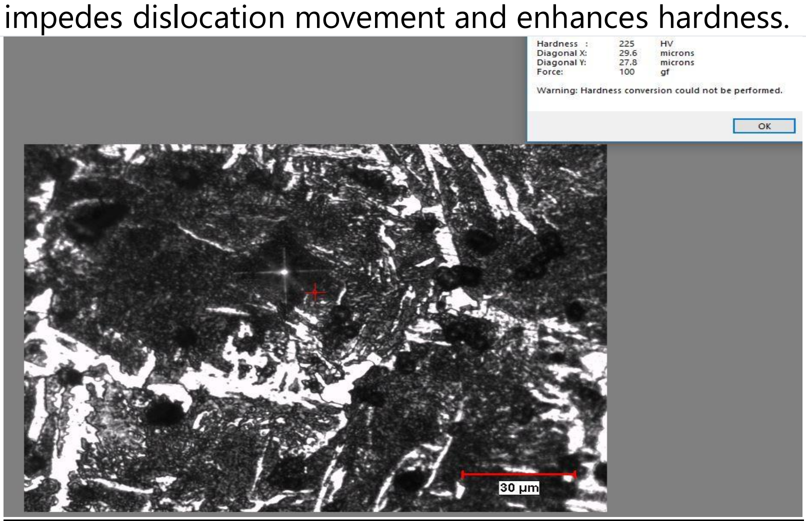

Figure 5.1.4: Vickers Hardness Test Result of Normalized Sample at 800°C

(c) Quenching

General Observations

The sample was heated to 800°C, held at this temperature for 30 minutes, and then rapidly cooled by immersion in water at room temperature. At 800°C, the steel was partially in the austenitic phase (γ-Fe), as this temperature is near the upper critical temperature (A3) for low-carbon steels. The rapid cooling during quenching suppressed diffusion-controlled transformations, resulting in the formation of martensite—a hard and brittle microstructure.

Microstructure Analysis

The microstructure observed under the optical microscope (Figures 1 and 2) reveals a predominantly martensitic structure characterized by needle-like or acicular morphology. The rapid cooling rate during quenching prevented the formation of ferrite and pearlite, instead transforming austenite directly into martensite.

- **Phase Transformation**: Austenite transformed into martensite due to the rapid cooling rate, bypassing equilibrium phase transformations such as ferrite and pearlite formation. The martensitic structure is formed through a shear transformation mechanism, which results in high internal stresses and dislocation density.

- **Grain Morphology**: The martensitic grains appear fine and needle-like, indicative of high hardness but low ductility.

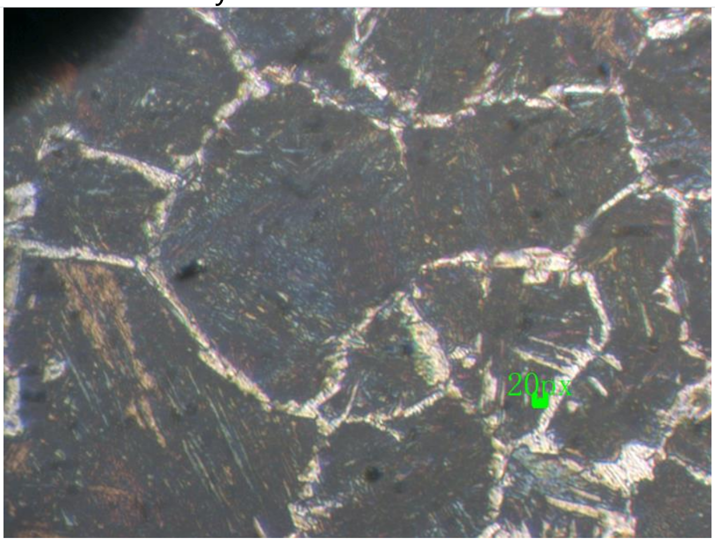

Figure 5.1.5: Microstructure of the quenched sample at 800°C (20x magnification).

Hardness Test Results

The Vickers hardness test was conducted on the quenched sample using a load of 100 gf. The average hardness value obtained was **437 HV**, significantly higher than those of annealed (**210 HV**) and normalized (**225 HV**) samples at the same temperature. This increase in hardness is attributed to the martensitic structure formed during quenching.

- **Hardness Analysis**: The martensitic structure contributes to extreme hardness due to its high dislocation density and internal stresses. However, this comes at the expense of ductility and toughness, making quenched steel brittle.

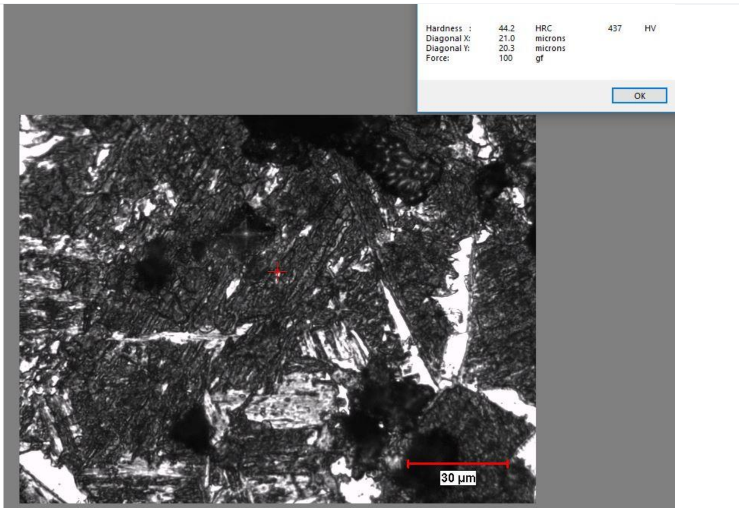

Figure 5.1.6: Vickers Hardness Test Result of quenched sample at 800°C.

Summary for 800°C

At 800°C, three distinct heat treatments—annealing, normalizing, and quenching—produced markedly different microstructures and mechanical properties:

1. **Annealing**:
- Produced a coarse-grained structure with large ferrite grains and coarse pearlite colonies due to slow cooling.
- Grain growth dominated nucleation, resulting in moderate hardness (**210 HV**) but improved ductility.
2. **Normalizing**:
- Produced a refined microstructure with smaller ferrite grains and finer pearlite colonies due to faster air cooling.
- Hardness was slightly higher (**225 HV**) compared to annealing, with improved strength and toughness.
3. **Quenching**:
- Produced a martensitic structure with needle-like morphology due to rapid cooling.
- Hardness was significantly higher (**437 HV**) than both annealed and normalized samples but accompanied by reduced ductility.

2) 900°C

(a) Annealing

General Observations

The sample was heated to 900°C, held at this temperature for 30 minutes, and cooled slowly inside the furnace. Annealing is characterized by slow cooling, which promotes grain growth over nucleation due to the extended time available for atomic diffusion. This results in a coarse microstructure dominated by equilibrium phases.

At 900°C, the steel initially existed in the austenitic phase (γ-Fe), as this temperature is above the upper critical temperature (A3) for low-carbon steels. Upon slow cooling, the austenite transformed into ferrite (α-Fe) and pearlite—a eutectoid mixture of ferrite and cementite (Fe_3C). The slow cooling allowed sufficient time for ferrite and pearlite grains to grow, resulting in a coarse-grained structure.

Microstructure Analysis
The microstructure observed under the optical microscope (Figure 1) reveals large equiaxed grains of ferrite (light regions) interspersed with coarse pearlite colonies (dark regions). The pearlite exhibits a lamellar structure with alternating layers of ferrite and cementite. This morphology is typical of annealed low-carbon steel and results from the slow cooling process, which favors grain growth over nucleation.

- **Phase Transformation**: During cooling, austenite decomposed into ferrite and pearlite as per the Fe-C phase diagram. The slow cooling rate ensured that nucleation sites were limited, allowing existing grains to grow larger.

- **Grain Morphology**: Ferrite grains are equiaxed due to recrystallization during annealing, while pearlite colonies are coarse due to extended diffusion times.

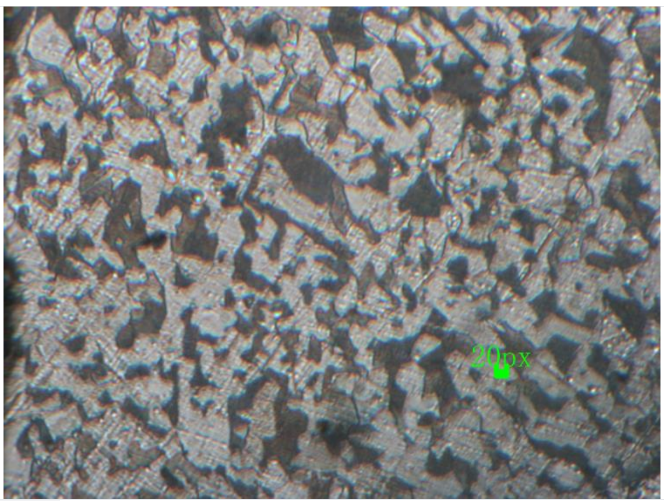

Figure 5.2.1: Microstructure of the annealed sample at 900°C (10x magnification).

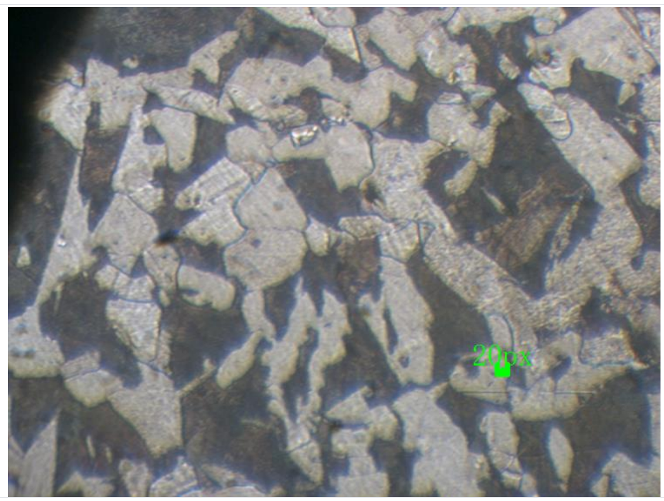

Figure 5.2.2: Microstructure of the annealed sample at 900°C (20x magnification).

Hardness Test Results
The Vickers hardness test was conducted on the annealed sample using a load of 50 gf. The average hardness value obtained was **153 HV**, as shown in Figure 2. This relatively low hardness is consistent with the microstructure dominated by soft ferrite and coarse pearlite. Ferrite contributes significantly to ductility but minimally to hardness, while pearlite adds moderate hardness due to its lamellar structure.

- **Hardness Analysis**: The slow cooling during annealing resulted in reduced dislocation density and stress relief within the grains, leading to lower hardness values compared to other heat treatments like quenching or normalizing.

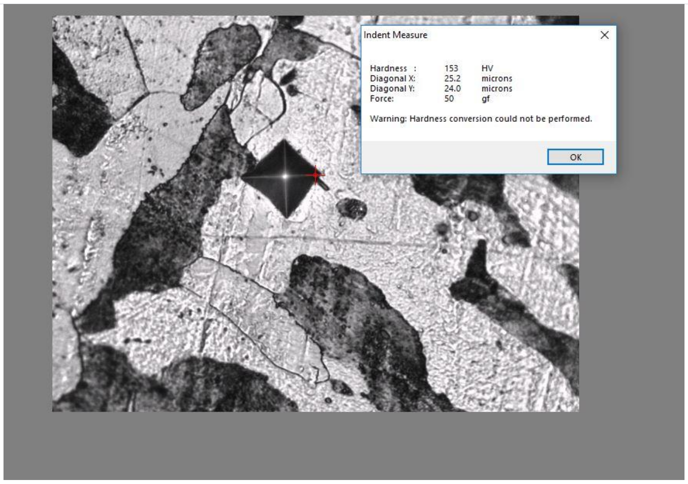

Figure 5.2.3: Vickers Hardness Test Result of annealed sample at 900°C

(b) Normalizing

General Observations
The sample was heated to 900°C, held at this temperature for 30 minutes, and then cooled in still air at room temperature. Normalizing is performed to refine the grain structure, eliminate residual stresses, and achieve a more uniform microstructure. Cooling in air results in faster cooling compared to annealing, which promotes nucleation over grain growth.
At 900°C, the steel was entirely in the austenitic phase (γ-Fe). Upon cooling, the austenite transformed into ferrite and pearlite. Due to the faster cooling rate during normalizing compared to annealing, nucleation dominated over grain growth, resulting in finer pearlite colonies and smaller ferrite grains.

Microstructure Analysis
The microstructure observed under the optical microscope (Figures 2 and 3) shows a refined structure consisting of ferrite (light regions) and pearlite (dark regions). The pearlite colonies are finer compared to those observed in annealed samples due to the increased cooling rate during normalizing. The lamellar structure of pearlite is more compact, and ferrite grains are smaller and more uniformly distributed.

- **Phase Transformation**: During cooling, austenite decomposed into ferrite and pearlite as per the Fe-C phase diagram. The faster cooling rate during normalizing led to increased nucleation sites for ferrite and pearlite formation, resulting in finer grains.

- **Grain Morphology**: Ferrite grains are smaller and more uniformly distributed compared to annealed samples, while pearlite colonies exhibit a finer lamellar structure due to faster cooling.

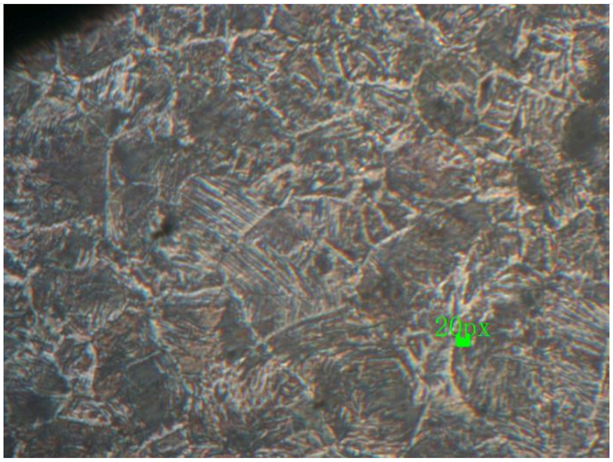

Figure 5.2.4: Microstructure of the normalized sample at 900°C (10x magnification).

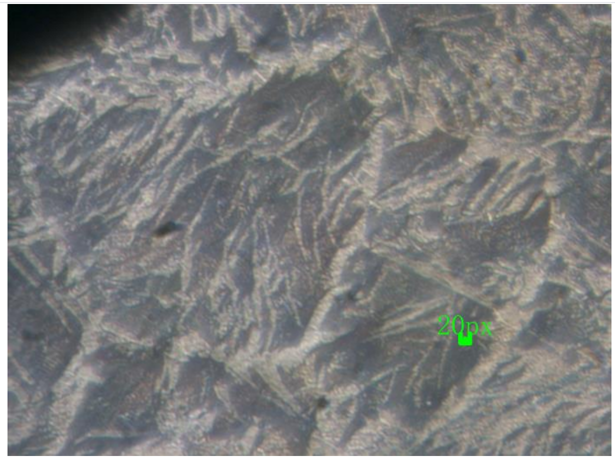

Figure 5.2.5: Microstructure of the normalized sample at 900°C (20x magnification).

Hardness Test Results

The Vickers hardness test was conducted on the normalized sample using a load of 100 gf. The average hardness value obtained was **216 HV**, as shown in Figure 4. This higher hardness compared to annealed samples is attributed to the finer grain structure and compact pearlite morphology produced by normalizing.

- **Hardness Analysis**: The faster cooling rate during normalizing increased dislocation density and refined grain size, both of which contribute to improved hardness. The presence of finer pearlite colonies also enhances hardness due to their compact lamellar structure.

Figure 5.2.6: Vickers Hardness Test Result of normalized sample at 900°C .

This detailed analysis includes all necessary observations, microstructural transformations, and hardness test results for the normalized sample at 900°C. Please confirm if this format meets your expectations before proceeding with further heat treatments or temperatures.

(c) Quenching

General Observations

The sample was heated to 900°C, held at this temperature for 30 minutes, and then rapidly cooled by immersion in water at room temperature. Quenching is characterized by rapid cooling, which suppresses diffusion-controlled transformations and results in the formation of martensite—a hard and brittle microstructure.

At 900°C, the steel was entirely in the austenitic phase (γ-Fe). Upon quenching, the rapid cooling prevented the decomposition of austenite into ferrite and pearlite, instead transforming it into martensite. Martensite is a supersaturated solid solution of carbon in iron, formed due to the shear transformation mechanism.

Microstructure Analysis

The microstructure observed under the optical microscope (Figures 3 and 4) reveals a predominantly martensitic structure with needle-like or acicular morphology. The rapid cooling during quenching resulted in high internal stresses and dislocation density within the grains, contributing to the hardness of the material.

- **Phase Transformation**: Austenite transformed directly into martensite due to the rapid cooling rate, bypassing the formation of equilibrium phases like ferrite or pearlite.
- **Grain Morphology**: The martensitic structure is characterized by its fine, needle-like appearance, indicative of high hardness but low ductility.

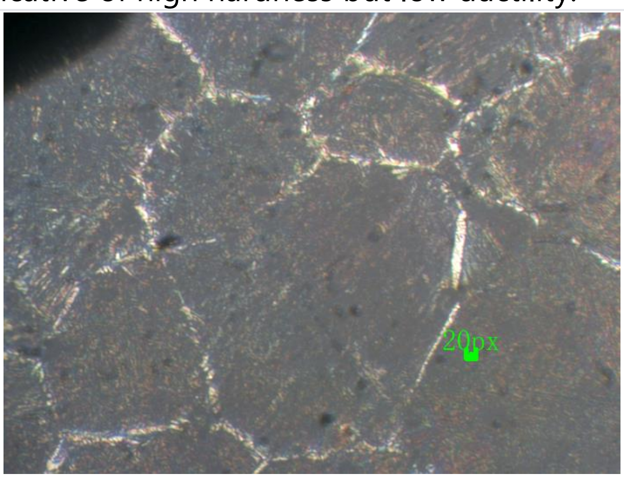

Figure 5.2.7: Microstructure of the quenched sample at 900°C (20x magnification).

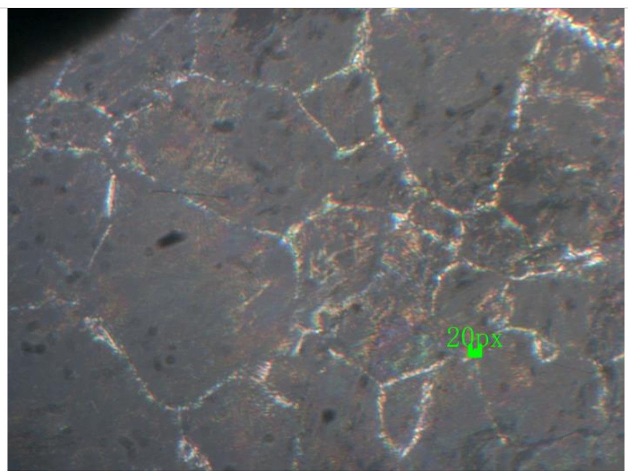

Figure 5.2.8: Microstructure of the quenched sample at 900°C (20x magnification).

Hardness Test Results

The Vickers hardness test was conducted on the quenched sample using a load of 100 gf. The average hardness value obtained was **563 HV**, as shown in Figure 5. This significantly higher hardness compared to annealed and normalized samples is attributed to the martensitic structure formed during quenching.

- **Hardness Analysis**: The martensitic structure contributes to extreme hardness due to its high dislocation density and internal stresses. However, this comes at the expense of ductility and toughness, making quenched steel brittle.

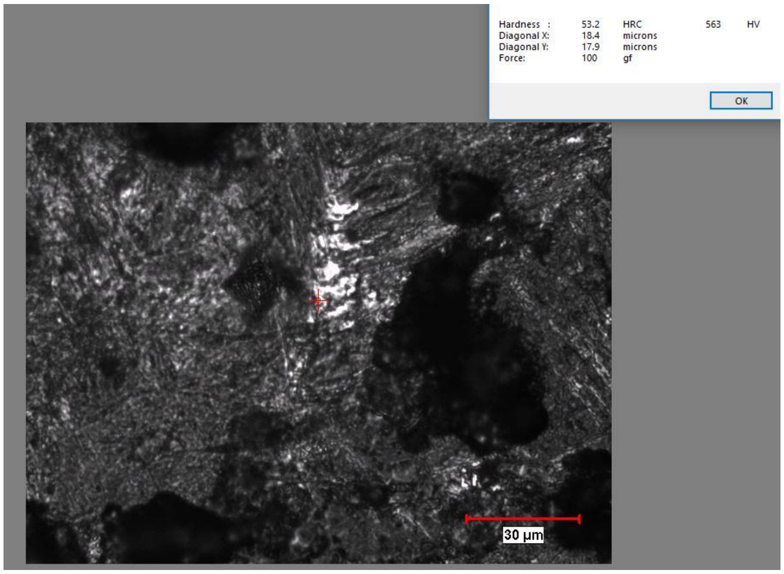

Figure 5.2.9: Vickers Hardness Test Result of quenched sample at 900°C .

Summary for 900°C

At 900°C, three distinct heat treatments—annealing, normalizing, and quenching—resulted in markedly different microstructures and mechanical properties:

1. **Annealing**:
- Produced a coarse-grained structure consisting of ferrite and pearlite due to slow cooling.
- Grain growth dominated nucleation, resulting in large ferrite grains and coarse pearlite colonies.
- Hardness was relatively low (**153 HV**) due to the dominance of soft ferrite.
-

2. **Normalizing**:
- Produced a refined microstructure with smaller ferrite grains and finer pearlite colonies.
- Faster cooling promoted nucleation over grain growth.
- Hardness increased (**216 HV**) compared to annealing due to finer grain structure.

3. **Quenching**:
- Produced a martensitic microstructure with needle-like morphology.
- Rapid cooling suppressed equilibrium phase transformations, resulting in high internal stresses.
- Hardness was significantly higher (**563 HV**) but accompanied by reduced ductility.

In summary, annealing resulted in a soft and ductile material suitable for machining or forming processes, normalizing improved strength and toughness with moderate hardness, while quenching maximized hardness at the expense of ductility.

3) 1000°C

(a) Annealing

General Observations

The sample was heated to 1000°C, held at this temperature for 30 minutes, and cooled slowly inside the furnace. At this temperature, the steel was fully in the austenitic phase (γ-Fe), as it is well above the upper critical temperature (A3) for low-carbon steels. During slow cooling, the austenite transformed into ferrite and pearlite. The slow cooling rate allowed grain growth to dominate nucleation, resulting in a coarse-grained microstructure with large ferrite grains and coarse pearlite colonies.

Microstructure Analysis

The microstructure observed under the optical microscope (Figures 1 and 2) reveals large equiaxed ferrite grains (light regions) interspersed with coarse pearlite colonies (dark regions). The pearlite exhibits a lamellar structure, but the spacing between lamellae is relatively wide due to the slow cooling process.

- **Phase Transformation**: Upon slow cooling, austenite decomposed into ferrite and pearlite according to the Fe-C phase diagram. The extended cooling time allowed carbon atoms to diffuse out of the austenite matrix, forming cementite layers within pearlite colonies.
- **Grain Morphology**: The prolonged cooling time favored grain growth over nucleation, leading to larger ferrite grains and coarser pearlite colonies compared to samples treated at lower temperatures or subjected to faster cooling rates.

Figure 5.3.1: Microstructure of the annealed sample at 1000°C (10x magnification).

Hardness Test Results

The Vickers hardness test was conducted on the annealed sample using a load of 100 gf. The average hardness value obtained was **233 HV**, higher than that of the annealed sample at 900°C.

- **Hardness Analysis**: The coarse-grained structure resulting from annealing at 1000°C contributes to reduced hardness compared to finer-grained structures produced by other heat treatments or lower annealing temperatures. Ferrite remains the dominant phase, contributing to ductility but limiting hardness.

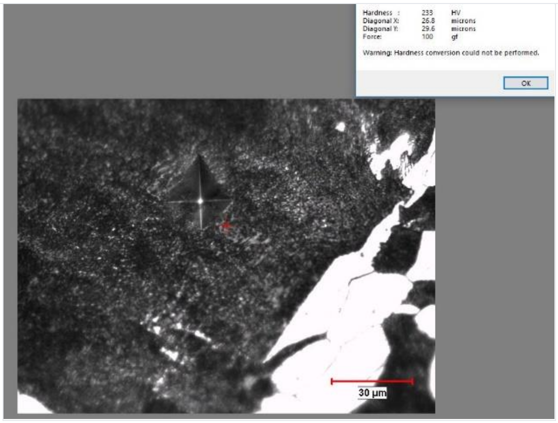

Figure 5.3.2: Vickers Hardness Test Result of annealed sample at 1000°C .

(b) Normalizing

General Observations

The sample was heated to 1000°C, held at this temperature for 30 minutes, and then cooled in still air at room temperature. At 1000°C, the steel was fully in the austenitic phase (γ-Fe). During air cooling, the austenite transformed into ferrite and pearlite. The faster cooling rate compared to annealing limited grain growth and promoted nucleation, resulting in a more refined microstructure.

Microstructure Analysis

The microstructure observed under the optical microscope (Figures 1 and 2) consists of smaller ferrite grains (light regions) and finer pearlite colonies (dark regions) compared to the annealed sample. The pearlite exhibits a more compact lamellar structure due to the faster cooling rate during normalizing.

- **Phase Transformation**: Upon cooling, austenite decomposed into ferrite and pearlite as per the Fe-C phase diagram. The faster cooling rate during normalizing increased nucleation sites, leading to finer grains and a more uniform distribution of phases.
- **Grain Morphology**: The ferrite grains are smaller and more equiaxed, while the pearlite colonies are finer with closely spaced lamellae. This refined structure enhances mechanical properties like strength and toughness compared to annealed samples.

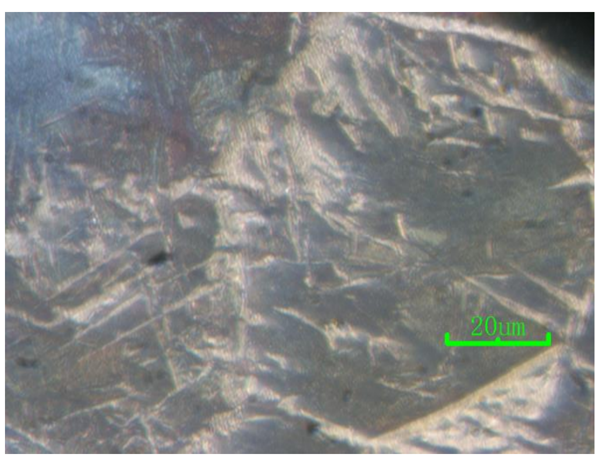

Figure 5.3.3: Microstructure of the normalized sample at 1000°C (20x magnification).

Hardness Test Results

The Vickers hardness test was conducted on the normalized sample using a load of 100 gf. The average hardness value obtained was **210 HV**, lower than that of the annealed sample at 1000°C. This increase in hardness is attributed to the slight-finer grain size and compact pearlite morphology produced by normalizing.

- **Hardness Analysis**: The refined microstructure resulting from normalizing contributes to improved hardness compared to annealing. The smaller grain size increases grain boundary area, which impedes dislocation movement and enhances hardness.

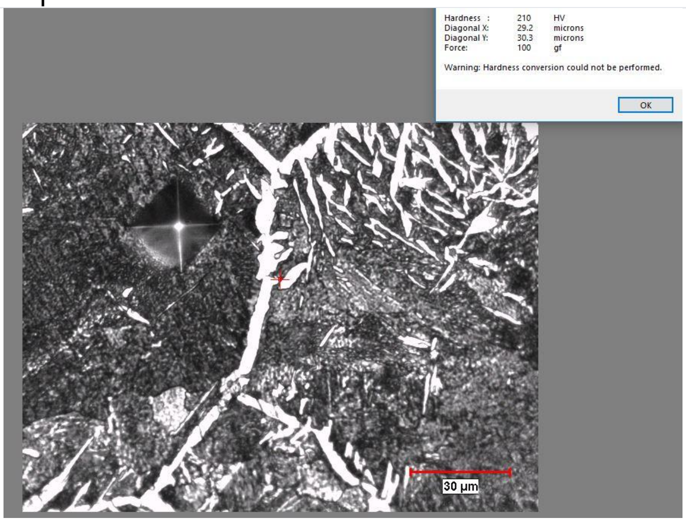

Figure 5.3.4: Vickers Hardness Test Result of normalized sample at 1000°C .

(c) Quenching

General Observations

The sample was heated to 1000°C, held at this temperature for 30 minutes, and then rapidly cooled by immersion in water at room temperature. At this temperature, the steel was entirely in the austenitic phase (γ-Fe). The rapid cooling during quenching suppressed diffusion-controlled transformations, resulting in the formation of martensite—a hard and brittle microstructure.

Microstructure Analysis

The microstructure observed under the optical microscope (Figure 1) reveals a predominantly martensitic structure characterized by needle-like or acicular morphology. The rapid cooling rate during quenching prevented the formation of ferrite and pearlite, instead transforming austenite directly into martensite.

- **Phase Transformation**: Austenite transformed into martensite due to the rapid cooling rate, bypassing equilibrium phase transformations such as ferrite and pearlite formation. The martensitic structure is formed through a shear transformation mechanism, which results in high internal stresses and dislocation density.
- **Grain Morphology**: The martensitic grains appear fine and needle-like, indicative of high hardness but low ductility.

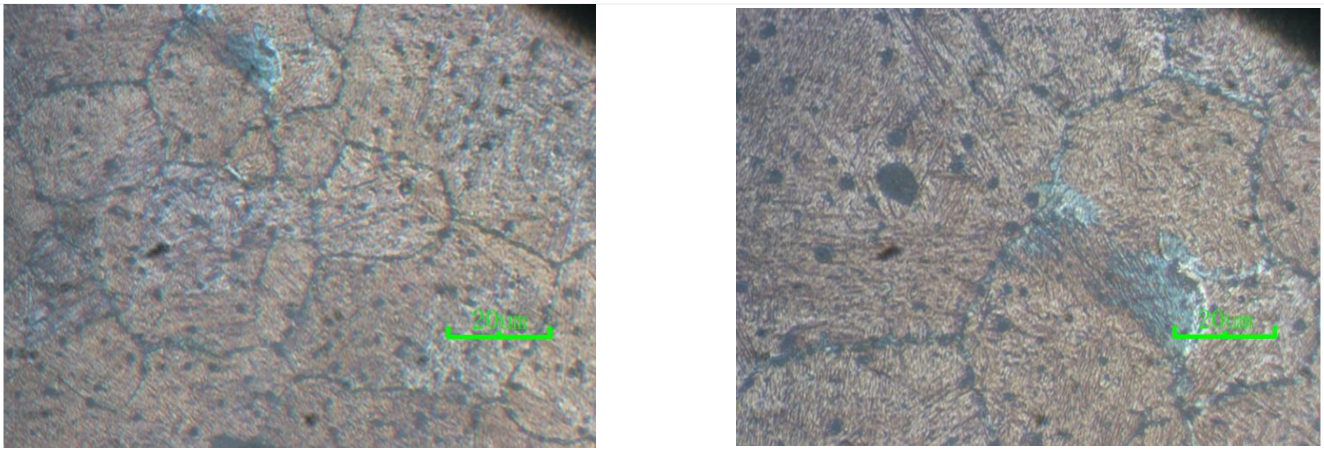

Figure 5.3.5: Microstructure of the quenched sample at 1000°C (10x magnification),(20x magnification)

Hardness Test Results

The Vickers hardness test was conducted on the quenched sample using a load of 100 gf. The average hardness value obtained was **578 HV**, significantly higher than those of annealed (**233 HV**) and normalized (**210 HV**) samples at the same temperature. This increase in hardness is attributed to the martensitic structure formed during quenching
.

- **Hardness Analysis**: The martensitic structure contributes to extreme hardness due to its high dislocation density and internal stresses. However, this comes at the expense of ductility and toughness, making quenched steel brittle.

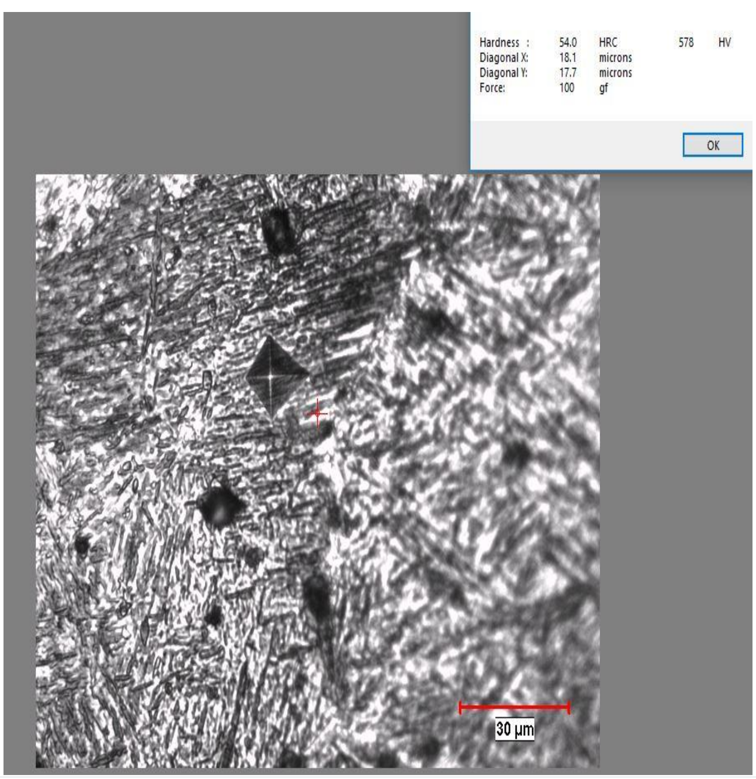

Figure 5.3.6: Vickers Hardness Test Result of quenched sample at 1000°C .

Summary for 1000°C

At 1000°C, three distinct heat treatments—annealing, normalizing, and quenching—produced vastly different microstructures and mechanical properties:

1. **Annealing**:
- Produced a coarse-grained structure with large ferrite grains and coarse pearlite colonies due to slow cooling.
- Grain growth dominated nucleation, resulting in reduced hardness (**233 HV**) but improved ductility.

2. **Normalizing**:
- Produced a refined microstructure with smaller ferrite grains and finer pearlite colonies due to faster air cooling.
- Hardness was moderate (**210 HV**) compared to annealing, with improved strength and toughness.

3. **Quenching**:
- Produced a martensitic structure with needle-like morphology due to rapid cooling.
- Hardness was significantly higher (**578 HV**) than both annealed and normalized samples but accompanied by reduced ductility.

4) 1100°C

(a) Annealing

General Observations

The sample was heated to 1100°C, held at this temperature for 30 minutes, and then cooled slowly inside the furnace. At 1100°C, the steel was fully in the austenitic phase (γ-Fe), as this temperature is well above the upper critical temperature (A3) for low-carbon steels. During slow cooling, the austenite transformed into ferrite and pearlite. The slow cooling allowed significant atomic diffusion, resulting in a coarse-grained microstructure dominated by grain growth.

Microstructure Analysis

The microstructure observed under the optical microscope (Figures 1 and 2) shows large equiaxed ferrite grains (light regions) and coarse pearlite colonies (dark regions). The lamellar spacing within the pearlite is wide, a characteristic of slow cooling at high temperatures.

- **Phase Transformation**: Upon slow cooling, austenite decomposed into ferrite and pearlite as per the Fe-C phase diagram. The extended cooling time allowed carbon atoms to diffuse out of the austenite matrix, forming cementite layers within pearlite colonies.
- **Grain Morphology**: The prolonged exposure to high temperatures and slow cooling favored grain growth over nucleation, resulting in significantly larger ferrite grains and coarser pearlite colonies compared to samples treated at lower temperatures or subjected to faster cooling rates.

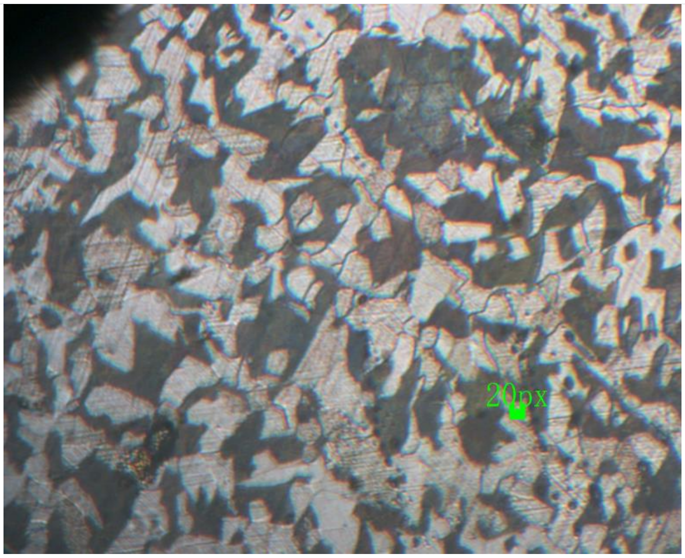

Figure 5.4.1: Microstructure of the annealed sample at 1100°C (10x magnification).

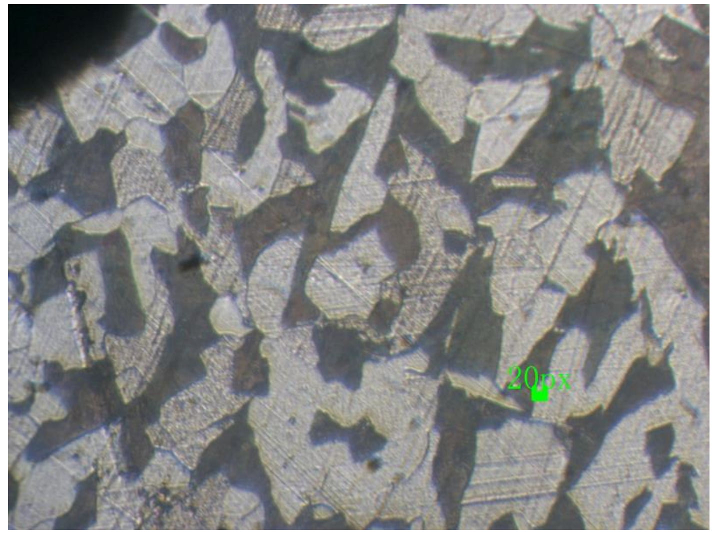

Figure 5.4.2: Microstructure of the annealed sample at 1100°C (20x magnification).

Hardness Test Results

The Vickers hardness test was conducted on the annealed sample using a load of 100 gf. The average hardness value obtained was **222 HV**, as shown in Figure 3. This hardness is slightly lower than that of annealed samples at lower temperatures due to increased grain size, which reduces grain boundary strengthening effects.

- **Hardness Analysis**: The coarse-grained structure resulting from annealing at 1100°C contributes to reduced hardness compared to finer-grained structures produced by other heat treatments or lower annealing temperatures. Ferrite remains the dominant phase, contributing to ductility but limiting hardness.

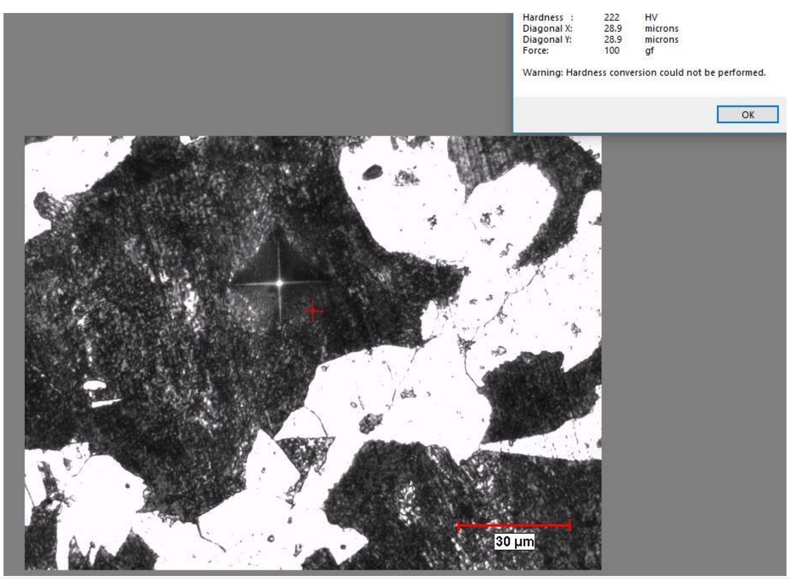

Figure 5.4.3: Vickers Hardness Test Result of annealed sample at 1100°C .

(b) Normalizing

General Observations
The sample was heated to 1100°C, held at this temperature for 30 minutes, and then cooled in still air at room temperature. At this temperature, the steel was fully in the austenitic phase (γ-Fe). The faster cooling rate during normalizing compared to annealing limited grain growth and promoted nucleation, resulting in a more refined microstructure.

Microstructure Analysis
The microstructure observed under the optical microscope (Figures 1 and 2) shows smaller ferrite grains (light regions) and finer pearlite colonies (dark regions) compared to the annealed sample. The pearlite exhibits a compact lamellar structure due to the increased cooling rate during normalizing.

- **Phase Transformation**: Upon cooling, austenite decomposed into ferrite and pearlite as per the Fe-C phase diagram. The faster cooling rate during normalizing increased nucleation sites for ferrite and pearlite formation, leading to finer grains and a more uniform distribution of phases.

- **Grain Morphology**: Ferrite grains are smaller and more equiaxed, while pearlite colonies are finer with closely spaced lamellae. This refined structure enhances mechanical properties such as strength and toughness compared to annealed samples.

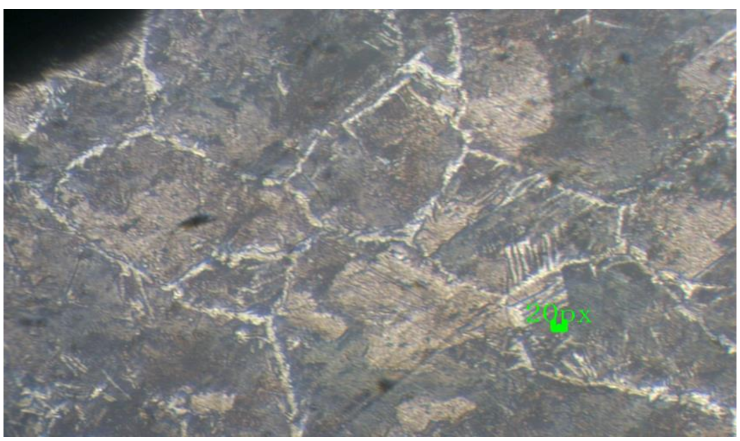

Figure 5.4.4: Microstructure of the normalized sample at 1100°C (20x magnification).

Hardness Test Results
The Vickers hardness test was conducted on the normalized sample using a load of 100 gf. The average hardness value obtained was **251 HV**, higher than that of the annealed sample at 1100°C (**222 HV**). This increase in hardness is attributed to the refined grain structure and compact pearlite morphology produced by normalizing.

- **Hardness Analysis**: The refined microstructure resulting from normalizing contributes to improved hardness compared to annealing. The smaller grain size increases grain boundary area, which impedes dislocation movement and enhances hardness.

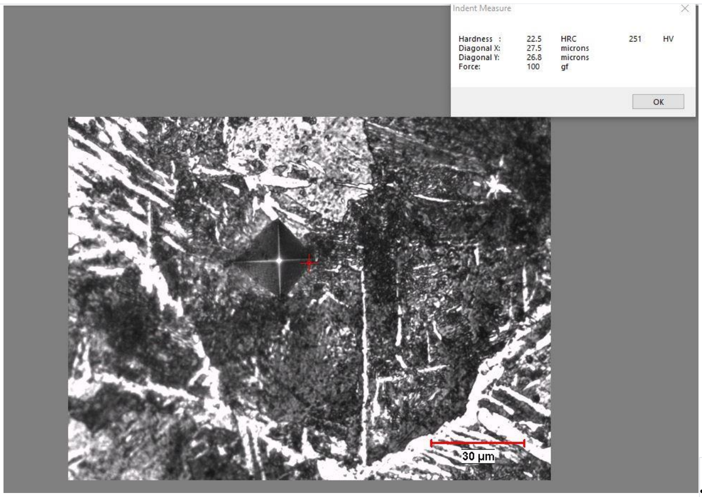

Figure 5.4.5: Vickers Hardness Test Result of normalized sample at 1100°C .

(c) Quenching

General Observations

The sample was heated to 1100°C, held at this temperature for 30 minutes, and then rapidly cooled by immersion in water at room temperature. At this temperature, the steel was fully in the austenitic phase (γ-Fe). The rapid cooling during quenching suppressed diffusion-controlled transformations, resulting in the formation of martensite—a hard and brittle microstructure.

Microstructure Analysis

The microstructure observed under the optical microscope (Figure 1) reveals a predominantly martensitic structure characterized by needle-like or acicular morphology. The rapid cooling rate during quenching prevented the formation of ferrite and pearlite, instead transforming austenite directly into martensite.

- **Phase Transformation**: Austenite transformed into martensite due to the rapid cooling rate, bypassing equilibrium phase transformations such as ferrite and pearlite formation. The martensitic structure is formed through a shear transformation mechanism, which results in high internal stresses and dislocation density.

- **Grain Morphology**: The martensitic grains appear fine and needle-like, indicative of high hardness but low ductility.

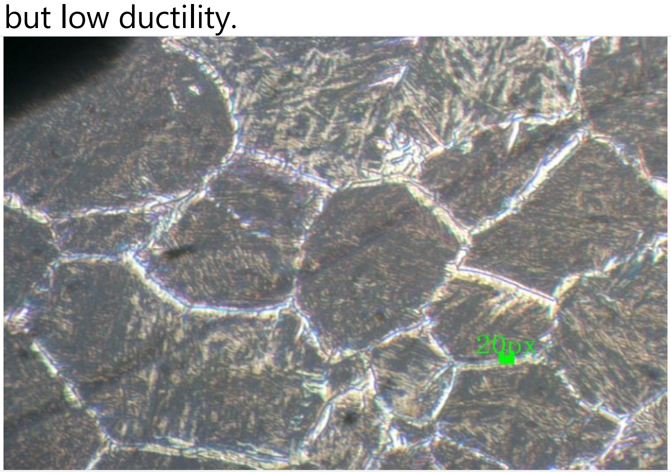

Figure 5.4.6: Microstructure of the quenched sample at 1100°C (20x magnification).

Hardness Test Results

The Vickers hardness test was conducted on the quenched sample using a load of 100 gf. The average hardness value obtained was **463 HV**, as shown in Figure 2. This significantly higher hardness compared to annealed (**222 HV**) and normalized (**251 HV**) samples at the same temperature is attributed to the martensitic structure formed during quenching.

- **Hardness Analysis**: The martensitic structure contributes to extreme hardness due to its high dislocation density and internal stresses. However, this comes at the expense of ductility and toughness, making quenched steel brittle.

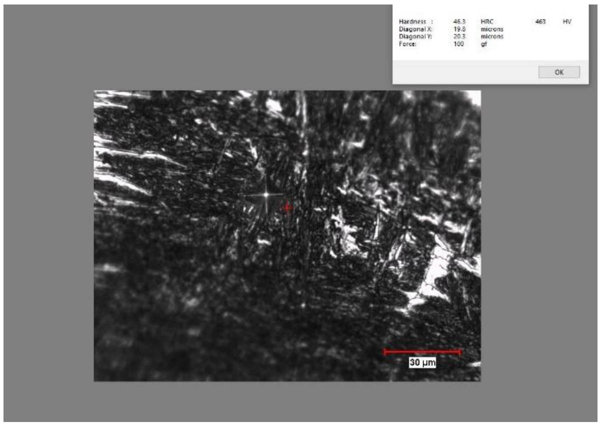

Figure 5.4.7: Vickers Hardness Test Result of quenched sample at 1100°C .

Summary for 1100°C

At 1100°C, three distinct heat treatments—annealing, normalizing, and quenching—produced vastly different microstructures and mechanical properties:

1. **Annealing**:
- Produced a coarse-grained structure with large ferrite grains and coarse pearlite colonies due to slow cooling.
- Grain growth dominated nucleation, resulting in reduced hardness (**222 HV**) but improved ductility.
2. **Normalizing**:
- Produced a refined microstructure with smaller ferrite grains and finer pearlite colonies due to faster air cooling.
- Hardness was moderate (**251 HV**) compared to annealing, with improved strength and toughness.
3. **Quenching**:
- Produced a martensitic structure with needle-like morphology due to rapid cooling.
- Hardness was significantly higher (**463 HV**) than both annealed and normalized samples but accompanied by reduced ductility.

In summary, annealing resulted in a soft and ductile material suitable for machining or forming processes; normalizing enhanced strength and toughness with moderate hardness; while quenching maximized hardness at the expense of ductility.

Discussion

1. Effect of Heat Treatment on Phase Transformations

1.1 Annealing Process and Its Impact on Microstructure

- **Transformation Mechanism**: During annealing, steel samples heated above the critical temperature (A3) formed austenite (γ-Fe). The slow cooling allowed sufficient time for carbon atoms to diffuse, resulting in the formation of equilibrium phases—ferrite (α-Fe) and pearlite (lamellar mixture of ferrite and cementite).
- **Grain Growth Dominance**: The extended cooling period during annealing significantly influenced grain development. The slow cooling kinetics provided ample time for atomic diffusion, resulting in larger grain sizes. This phenomenon occurred because the system was given sufficient time to reduce its total grain boundary area, minimizing the overall energy state.
- **Temperature Effect on Grain Size**: Annealing at higher temperatures (1000°C and 1100°C) resulted in larger grain sizes compared to lower temperatures (800°C and 900°C). This is attributed to increased atomic mobility at elevated temperatures, facilitating more extensive grain growth.
- **Pearlite Morphology**: The lamellar spacing in pearlite increased with annealing temperature due to enhanced carbon diffusion at higher temperatures. At 1100°C, the pearlite exhibited the widest lamellar spacing, indicating the most extensive diffusion of carbon during the slow cooling process.

1.2 Normalizing Process and Its Impact on Microstructure

- **Transformation Dynamics**: During normalizing, the austenite formed at high temperatures transformed into ferrite and pearlite during air cooling. The relatively faster cooling rate compared to annealing restricted diffusion time, resulting in more nucleation sites and less grain growth.
- **Microstructural Refinement**: Air cooling promoted a balance between nucleation and growth, leading to finer and more homogeneous grain structures. This refinement was consistent across all temperature ranges but was particularly pronounced at intermediate temperatures (900°C and 1000°C).
- **Temperature Influence on Normalization**: At higher temperatures (1100°C), despite the faster cooling rate compared to annealing, grain growth was still significant due to the higher initial temperature. This resulted in a moderately refined structure that was still coarser than samples normalized at lower temperatures.
- **Pearlite Morphology in Normalized Samples**: Normalized samples consistently exhibited finer pearlite colonies with reduced lamellar spacing compared to annealed samples. This refinement enhances mechanical properties by increasing the number of interfaces that impede dislocation movement.

1.3 Quenching Process and Its Impact on Microstructure

- **Martensitic Transformation**: During quenching, rapid cooling suppressed diffusion-controlled transformations, preventing the formation of equilibrium phases (ferrite and pearlite). Instead, austenite transformed directly into martensite through a diffusionless, shear-type transformation.

- **Cooling Rate Effect**: The water quenching provided cooling rates that exceeded the critical cooling rate required for martensitic formation in low carbon steel. This resulted in the characteristic needle-like or acicular martensite morphology observed in all quenched samples.
- **Temperature Effect on Martensite Formation**: Samples quenched from higher temperatures (1000°C) exhibited a more pronounced martensitic structure with higher internal stresses compared to those quenched from lower temperatures (800°C). This is attributed to increased austenite grain size at higher temperatures before quenching.
- **Carbon Supersaturation**: The martensitic structure formed during quenching represents a supersaturated solid solution of carbon in iron, with carbon atoms trapped in interstitial positions. This distorts the crystal lattice, creating high internal stresses and contributing to increased hardness.

2. Relationship Between Microstructure and Mechanical Properties

2.1 Hardness Variation Across Heat Treatments

- **Annealing and Hardness**: Annealed samples exhibited the lowest hardness values among all heat treatments, ranging from 153 HV (900°C) to 233 HV (1000°C). This is attributed to the coarse ferrite-pearlite microstructure with minimal grain boundary strengthening and low dislocation density.

- **Normalizing and Hardness**: Normalized samples showed intermediate hardness values, ranging from 210 HV (1000°C) to 251 HV (1100°C). The refined grain structure increased grain boundary area, enhancing hardness through the Hall-Petch relationship, where grain boundary strengthening is inversely proportional to the square root of grain size.

- **Quenching and Hardness**: Quenched samples demonstrated significantly higher hardness values, ranging from 437 HV (800°C) to 578 HV (1000°C). This substantial increase is attributed to the martensitic microstructure with high dislocation density, lattice distortion, and internal stresses.

- **Temperature Effect on Hardness**: For annealed samples, hardness values did not show a linear relationship with temperature due to competing mechanisms of grain growth and phase transformations. For quenched samples, hardness peaked at 1000°C (578 HV) and decreased at 1100°C (463 HV), suggesting potential austenite grain growth effects or incomplete martensitic transformation at higher temperatures.

2.2 Structural Mechanisms for Property Changes

- **Dislocation Movement Inhibition**: The refined microstructure in normalized samples impeded dislocation movement through increased grain boundaries, contributing to moderate hardness improvements without the brittleness associated with martensite[6].
- **Lattice Distortion Effects**: In quenched samples, the tetragonal distortion of the martensitic lattice significantly restricted dislocation movement, resulting in the observed hardness increase but also introducing brittleness[2 7].
- **Carbon Distribution Influence**: The distribution and morphology of carbon-rich phases (primarily cementite) strongly influenced mechanical properties. In annealed samples, the coarse pearlite with

widely spaced cementite lamellae contributed minimally to hardness. In normalized samples, the finer pearlite with closely spaced cementite lamellae provided moderate hardening effects[26].

- **Grain Boundary Effects**: The inverse relationship between grain size and yield strength (Hall-Petch relationship) was evident across the heat treatments. Normalized samples with finer grains exhibited improved strength compared to annealed samples with coarser grains at the same temperature[68].

3. Influence of Temperature on Heat Treatment Effectiveness

3.1 Annealing Temperature Effects

- **Lower Temperature Annealing (800°C)**: Annealing at 800°C produced a moderately coarse microstructure with a hardness of 210 HV. At this temperature, which is near the A3 line for low carbon steel, incomplete austenitization may have occurred, resulting in a mixed microstructure with varying grain sizes.
- **Intermediate Temperature Annealing (900°C-1000°C)**: These temperatures, well above the A3 line, ensured complete austenitization. The 900°C annealed sample showed the lowest hardness (153 HV), suggesting optimal stress relief and grain growth, while the 1000°C sample showed increased hardness (233 HV), potentially due to more complex phase transformations or element segregation effects.
- **High Temperature Annealing (1100°C)**: Annealing at 1100°C resulted in very coarse grains due to excessive grain growth at this elevated temperature. However, the hardness (222 HV) was similar to the 1000°C sample, suggesting a plateau effect where additional grain growth beyond a certain point has diminishing effects on hardness reduction

.

3.2 Normalizing Temperature Effects

- **Lower Temperature Normalizing (800°C)**: Normalizing at 800°C produced a moderately refined microstructure with a hardness of 225 HV. The transformation was likely incomplete due to the proximity to the A3 temperature, resulting in a mixed microstructure.
- **Optimal Normalizing Temperature (900°C-1000°C)**: These temperatures produced well-refined microstructures with balanced hardness values (216 HV and 210 HV respectively). This range appears optimal for normalizing low carbon steel while maintaining controlled grain size during cooling.
- **High Temperature Normalizing (1100°C)**: Normalizing at 1100°C resulted in the highest hardness among normalized samples (251 HV). This suggests that despite some grain growth at this temperature, the faster cooling rate effectively refined the microstructure, potentially through increased nucleation sites for pearlite formation

.

3.3 Quenching Temperature Effects

- **Lower Temperature Quenching (800°C)**: Quenching from 800°C resulted in a hardness of 437 HV, the lowest among all quenched samples. This is attributed to potentially incomplete austenitization and smaller austenite grain size before quenching, resulting in a less pronounced martensitic structure.

- **Optimal Quenching Temperature (900°C-1000°C)**: Quenching from these temperatures produced the highest hardness values (563 HV and 578 HV respectively). These temperatures ensure complete austenitization without excessive austenite grain growth, resulting in optimal martensitic transformation during quenching.
- **High Temperature Quenching (1100°C)**: Quenching from 1100°C resulted in reduced hardness (463 HV) compared to lower temperatures, despite the formation of martensite. This could be attributed to excessive austenite grain growth at this temperature, resulting in coarser martensite plates with potentially higher retained austenite content.

Conclusion

This comprehensive study on the effect of different heat treatments at varying temperatures on low carbon steel has demonstrated the profound influence of thermal processing on microstructure and mechanical properties. The experiment successfully validated the established principles of heat treatment while providing quantitative data on the relationship between processing parameters, microstructural evolution, and resulting hardness.

Annealing produced coarse-grained structures with low hardness values, making it suitable for applications requiring maximum ductility and machinability. Normalizing resulted in refined microstructures with moderate hardness values, offering a good balance between strength and toughness. Quenching generated martensitic structures with significantly higher hardness values, albeit with reduced ductility.

The temperature effect was notable across all heat treatments, with optimal ranges identified for specific property requirements. For annealing, 900°C yielded the softest structure; for normalizing, 1100°C produced the highest hardness; and for quenching, 1000°C resulted in maximum hardness.

These findings have significant implications for industrial applications, providing guidance on heat treatment selection and parameter optimization for low carbon steel based on specific property requirements. Future work could focus on investigating the impact of tempering on quenched samples, exploring the effect of holding time variations, and examining the correlation between microstructure and other mechanical properties such as tensile strength, toughness, and fatigue resistance.

References

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