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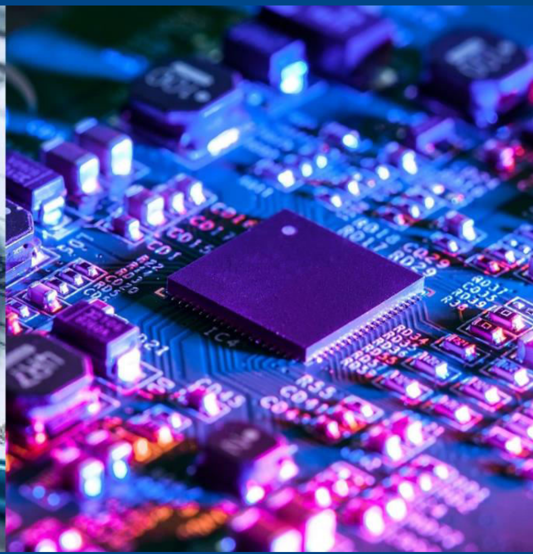

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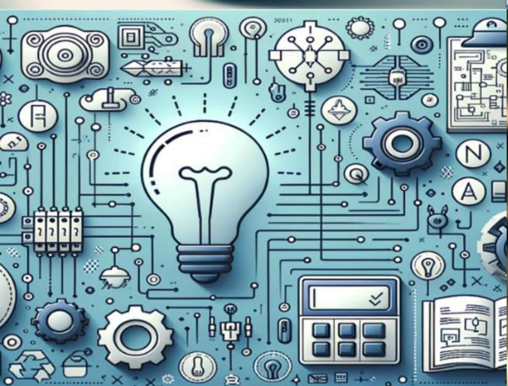

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Effect of Heat Treatment on the Mechanical Properties of Low Carbon Steel

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ABSTRACT: The effect of various heat treatment processes on the mechanical properties of low carbon steel (E250) was investigated. Annealing, normalizing, and hardening are the most important heat treatment processes used to modify the mechanical properties of engineering materials. The samples were prepared and heat-treated at 900 °C, followed by cooling in different media. The mechanical properties of both treated and untreated samples were evaluated using standard testing methods. The results indicate that heat treatment significantly influences the mechanical properties of low carbon steel. The hardened samples exhibited the highest tensile strength and hardness, but showed the lowest percentage elongation. The normalized samples showed moderate tensile strength and hardness, higher than the untreated samples but lower than the hardened samples, with improved percentage elongation compared to hardened samples. The annealed samples exhibited the lowest tensile strength and hardness but the highest percentage elongation.

KEYWORDS: low carbon steel, E250, heat treatment, mechanical properties, tensile strength, percentage elongation, hardness

I. INTRODUCTION

Heat treatment is a controlled process of heating and cooling metals to change their physical and mechanical properties without altering their shape. It is widely used for engineering materials, especially steels, to improve performance. The main heat treatment processes include annealing, normalizing, hardening, and tempering. In general, heat treatment involves three main stages: heating the material to a required temperature, holding it at that temperature for a specific period, and then cooling it to room temperature under controlled conditions. Annealing is carried out by heating the metal and then cooling it slowly, usually inside the furnace. This process reduces tensile strength and hardness while increasing ductility, making the material easier to machine and shape. Normalizing involves heating the metal to a higher temperature and then allowing it to cool in air. This produces a finer structure and improves strength and hardness compared to annealed steel. Hardening is done by heating the steel to its austenitizing temperature followed by rapid cooling, such as quenching in water, oil, or salt solutions. This process increases hardness, tensile strength, and wear resistance. However, it also reduces ductility.

Steel plays an essential role in everyday life, as it is present in a wide range of applications. Steel is a ferrous alloy primarily composed of iron and carbon, with carbon content typically ranging from about 0.02% to 2.1% by weight. It may also contain alloying elements such as nickel, chromium, cobalt, molybdenum, and tungsten to enhance specific mechanical and chemical properties. Steel is extensively used in building construction, infrastructure (such as bridges), tools and equipment, machinery, ships, vehicle components, and weapons. Carbon steel is classified into three categories based on its carbon content. Low carbon steels (also known as mild steels) contain up to 0.3% carbon, medium carbon steels contain between 0.3% to 0.6% carbon, and high carbon steels contain more than 0.6% carbon.

Global crude steel production reached about 1.8 billion tonnes in 2025. Global crude steel production in 2025 is shown in Figure 1. According to the World Steel Association, China was the largest producer with 960.8 million tonnes, which accounts for more than half of global output. India ranked second with 164.9 million tonnes, reflecting its rapid industrial growth. The United States produced 82 million tonnes, followed by Japan with 80.7 million tonnes, while Russia contributed 67.8 million tonnes. These top five countries together account for a major share of total steel production. The data clearly shows that steel production is highly concentrated in a few leading nations. This

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concentration highlights the strategic role of steel in economic growth, construction, and industrialization across the world.

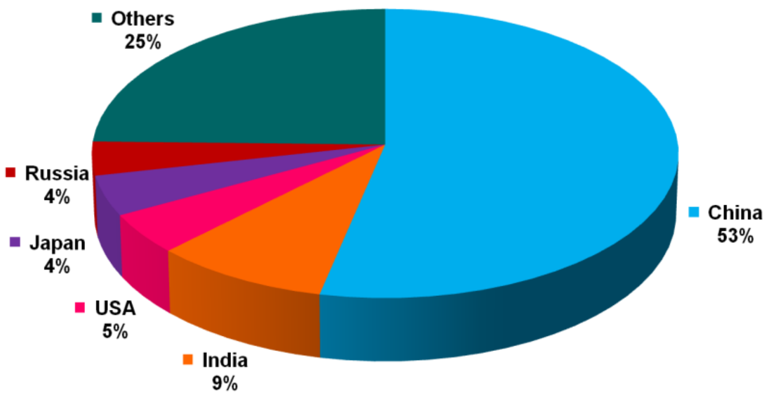

Figure 1: Global crude steel production in 2025

II. LITERATURE REVIEW

T. J. Prasanna Kumar et al [1] investigated the effect of carbon content (0.15%, 0.40%, and 0.80%) on the mechanical properties and microstructure of steel. The results showed that yield strength, ultimate tensile strength and hardness increase with increasing carbon content. However, percentage elongation decreased significantly, indicating reduced ductility. This is due to the transformation of microstructure from ferrite to pearlite and cementite. Thus, higher carbon content improves strength and hardness but reduces ductility.

M. M. Blaoui et al [2] studied the effect of heat treatment parameters, including austenitization temperature, cooling rate, holding time, and heating rate, on the microstructure and mechanical properties of C45 steel. The properties evaluated were tensile strength, yield strength, elongation, and hardness. The specimens were cooled using different media such as water, oil, and air. The results indicated that the microstructure and hardenability of C45 steel are significantly influenced by the cooling rate, austenitization temperature, holding time, and heating rate. Among the cooling media, water quenching produced the highest tensile strength, yield strength, and hardness, along with the lowest elongation. This is attributed to the high cooling rate, which promotes the transformation of a large amount of austenite into martensite. Furthermore, it was observed that increasing the holding time leads to a decrease in tensile strength, yield strength, and hardness.

Ch. Tirumala Prasad et al [3] investigated the effect of different cooling methods on the hardness of AISI 1040 steel. The specimens were heat-treated at temperatures of 750 °C and 850 °C, followed by cooling using three different methods: air cooling, water quenching, and furnace cooling. The results revealed that hardness is strongly influenced by both the heat treatment temperature and the cooling rate. Among the cooling methods, water quenching produced the highest hardness values, while furnace cooling resulted in the lowest hardness. It was also observed that the maximum hardness was achieved for samples quenched in water at 850 °C, whereas the minimum hardness occurred for furnace-cooled samples at 750 °C. This behavior is attributed to the faster cooling rate in water, which promotes the formation of harder microstructures.

Sharan Mudda et al [4] studied the effect of various heat treatment methods and the optimization of their parameters on the mechanical properties of AISI 4140 steel. The heat treatment processes considered in this study were annealing, normalizing, and oil quenching. Key process parameters, namely temperature and holding time, were varied at three levels: 900 °C, 925 °C, and 950 °C, and 1, 1.5, and 2 hours, respectively. Results showed that an increase in temperature and holding time led to a reduction in hardness of the material.

Nehal Ahmad et al [5] investigated the effect of different quenching media on the mechanical properties of low carbon steel (E250). The steel samples were heated to 900°C and soaked for three hours in a furnace, followed by quenching in

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brine, water, and oil separately. The results indicated that the hardness of the quenched samples was significantly higher than that of the as-cast samples.

III. MATERIALS AND METHODS

Material used

The material selected for this investigation is low carbon steel (E250). Table-1 shows the chemical composition of E250 steel. The chemical composition affects weldability, formability, and mechanical properties. The heat treatment conditions are listed in Table 2.

Table 1: Chemical composition of E250

Chemical composition of E250 steel	
Element	**Content (%)**
Carbon	0.23 max
Manganese	1.5 max
Silicon	0.4 max
Phosphorous	0.045 max
Sulfur	0.045 max
Iron	Balance

The tensile strength, percentage elongation, and hardness of low carbon steel are strongly influenced by its chemical composition, particularly the carbon, silicon, and manganese contents. Carbon is the principal strengthening element in low carbon steel and significantly enhances tensile strength and hardness. An increase in carbon content generally leads to higher tensile strength and hardness, while reducing percentage elongation due to decreased ductility. Silicon improves the strength and hardness of steel. Moderate additions increase tensile strength without much loss of ductility. Higher silicon content reduces percentage elongation. Manganese plays a vital role in enhancing the strength and hardness of low carbon steel. An increase in manganese content generally improves tensile strength and wear resistance; however, excessive manganese may lead to a reduction in ductility.

Table 2: Heat treatment conditions

Condition	Annealed	Normalized	Hardened
Temperature, °C	900	900	900
Holding time, min	60	60	60
Cooling medium	Furnace	Air	Water

Advantages of E250

- Good weldability
- Excellent formability
- Good ductility
- Cost-effective
- Easy availability
- Good machinability

Applications of E250

- E250 steel plates are widely used across multiple industries due to their excellent mechanical properties, weldability, and formability.

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- In the construction industry, they are extensively utilized in the fabrication of buildings, bridges, industrial structures, and large-scale infrastructure projects.
- In the fabrication sector, these plates are preferred for manufacturing machinery, equipment, storage tanks, and various structural components because they can be easily shaped and welded without compromising strength.
- In automotive manufacturing, they are commonly used for producing truck bodies, trailers, and agricultural equipment, where durability and the ability to withstand heavy loads are essential.
- In the railway industry, these plates are utilized in wagon construction and infrastructure development due to their high load-bearing capacity and excellent structural integrity.
- Additionally, in general engineering applications, they are used for constructing platforms, supports, frames, and other components that require strength, stability, and reliability.

Heat Treatment

Steel specimens are prepared for mechanical testing. Standard specimens are used for the tensile test, while cylindrical specimens are prepared for hardness testing. Out of four sets of specimens, three sets are subjected to different heat treatment processes, namely annealing, normalizing, and hardening, while one set is kept untreated for comparison. All the three sets to be subjected to heat treatment are first heated to 900^0C for 60minutes. One set to be hardened is quenched in water, second set to be normalised is cooled in air, while the set to be annealing is cooled in the furnace slowly after switching off the furnace.

Mechanical Testing of Specimen

Mechanical properties (tensile strength, percentage elongation and hardness) of the treated and untreated samples are determined using standard methods.

IV.RESULTS AND DISCUSSIONS

The effect of heat treatment (annealing, normalizing and hardening) on the mechanical properties (tensile strength, percentage elongation, and hardness) of the treated and untreated samples is shown in Table 3.

Table 3: Mechanical test results

Heat Treatment	Tensile Strength (MPa)	Percentage Elongation (%)	Hardness (HV)
Untreated	397.2	23.1	118
Annealed	373.7	25.3	112
Normalized	436.3	22.6	133
Hardened	672.1	14.8	202

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Tensile strength

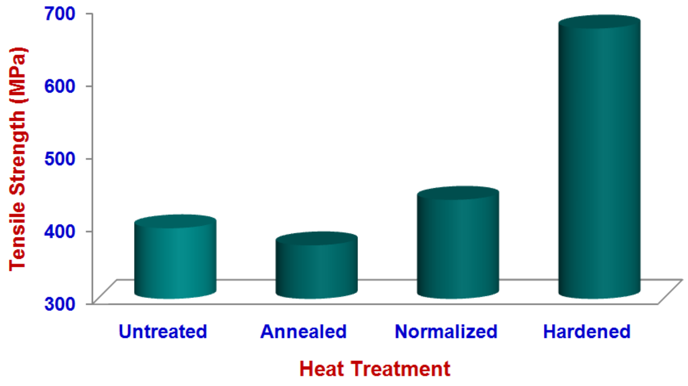

Figure 2: Tensile strength of treated and untreated samples

Figure 2 shows the effect of heat treatment on the tensile strength of low carbon steel. The results indicate that the hardened specimen exhibits the highest tensile strength compared to normalized, annealed, and untreated specimens. The normalized specimen shows higher tensile strength than both untreated and annealed specimens, while the annealed specimen possesses the lowest strength. The increase in tensile strength in the hardened specimen is attributed to the rapid cooling rate employed during the hardening process. In hardening, the material is quenched in water, which provides a significantly faster cooling rate compared to air cooling used in the normalizing process. Water, being an efficient quenching medium, facilitates the formation of a harder microstructure, thereby resulting in maximum tensile strength. The mechanical properties of mild steel (ASTM A-283C) subjected to different heat treatment processes were investigated by Muhammad Nasir Uddin [6]. In this study, the specimens were heated to 910°C and held at this temperature for 70 minutes to achieve proper soaking. After soaking, the samples were cooled using three different media: furnace cooling, air cooling, and water quenching. The results indicated that the tensile strength of the hardened specimen is higher as compared to normalized, untreated and annealed specimens, while the untreated specimen also has a greater value than that of annealed specimen, which has the least value. Khaled Saleh Mohammed Alwaer et al [7] investigated the effect of different cooling media on the mechanical properties of low carbon steel (C17). The specimens were heated in a heat treatment furnace to approximately 980 °C and held for about 1 hour, followed by cooling using various quenching media such as water, air, and oil. The results revealed that the highest tensile strength was achieved in the water-quenched samples, indicating that rapid cooling significantly enhances the strength of low carbon steel compared to slower cooling methods.

Percentage elongation

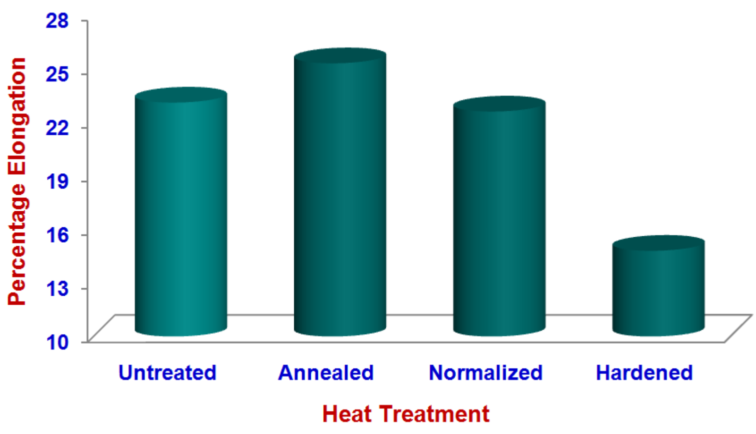

Figure 3: Percentage elongation of treated and untreated samples

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Figure 3 presents the percentage elongation of the as-received and heat-treated low carbon steel specimens. It is observed that the annealed specimens exhibit the highest percentage elongation, followed by the untreated specimens, indicating improved ductility. The hardened specimens show the lowest percentage elongation due to the formation of a hard and brittle microstructure. This trend highlights the inverse relationship between strength and ductility resulting from different heat treatment processes. D. A. Fadare et al [8] investigated the effect of heat treatment processes on the mechanical properties of NST 37-2 steel. In this investigation, the influence of annealing, normalizing, and hardening on the microstructure and selected mechanical properties was examined. The steel samples were heat treated in an electric furnace at various temperature levels and holding times, followed by cooling in different media. The mechanical properties of both treated and untreated samples were evaluated using standard testing methods. The results indicated that the annealed specimens exhibited the highest percentage elongation, followed by the untreated specimens, while the hardened specimens showed the lowest percentage elongation. Devendra Yadav et al [9] conducted an investigation to examine the effect of heat treatment on the mechanical properties of low carbon steel. In this study, low carbon steel containing 0.26% carbon was heated in a furnace and then rapidly cooled in water. The results revealed that the percentage elongation of the specimen decreased after heat treatment, indicating a reduction in ductility due to the formation of a harder microstructure.

Hardness

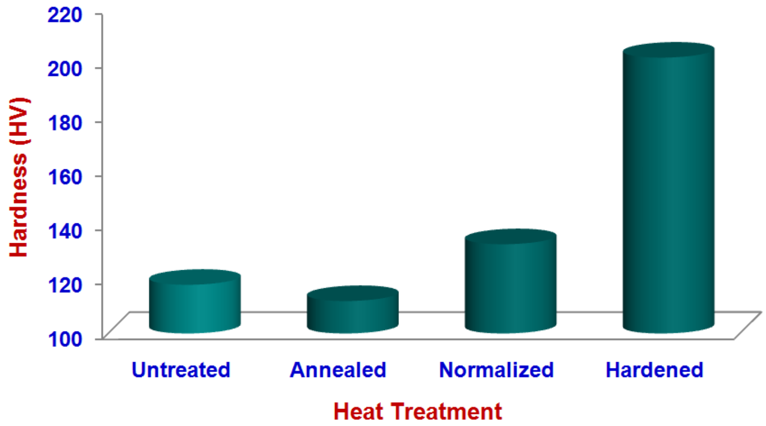

Figure 4: Hardness of treated and untreated samples

Figure 4 shows the hardness of the untreated and heat-treated specimens. The hardness is observed to be highest for the hardened specimens, followed by the normalized and annealed specimens. A comparison between the annealed and untreated samples indicates that the annealed specimen exhibits lower hardness. This reduction in hardness is attributed to the formation of a soft ferritic matrix during the annealing process, resulting from slow cooling. Mst. Nazma Sultana et al [10] investigated the effect of heat treatment processes on the mechanical properties of mild steel (ASTM A36). In this study, mild steel was selected as the specimen to evaluate various mechanical properties. The samples were heated to 900°C and subsequently cooled in different media. The influence of heat treatment processes, namely annealing, normalizing, and hardening, on the mechanical properties of the selected specimens was analyzed. The results revealed that the hardness of the hardened specimens was higher compared to the normalized, untreated, and annealed specimens. Furthermore, the untreated specimens exhibited higher hardness than the annealed specimens, which showed the lowest hardness values. Ashish Thakur et al [11] investigated the effect of heat treatment on the mechanical properties and microstructure of ST 37-2 steel used in rear trailing arms. The tensile properties, bending strength, impact strength, and hardness of both treated and untreated samples were evaluated using standard testing methods. The results showed that the mechanical properties of ST 37-2 steel can be significantly improved through various heat treatment processes. It was also observed that the annealed samples exhibited the lowest hardness values, whereas the hardened samples showed the highest hardness values.

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V. CONCLUSIONS

From the results of investigation on the effect of heat treatment on mechanical properties of low carbon steel, the following conclusions were made:

❖ The annealed sample exhibited the lowest tensile strength and hardness, but the highest percentage elongation, when compared to both heat-treated and untreated samples.

❖ The normalized samples exhibited moderate tensile strength and hardness, higher than the untreated samples but lower than the hardened samples, along with improved percentage elongation compared to the hardened samples.

❖ The hardened sample exhibited the highest tensile strength and hardness, but the lowest percentage elongation, when compared to other heat-treated and untreated samples.

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