



Effects of Quenching Media and Heat Transfer Rate on the Hardness and Microstructure of Low-Carbon Steel

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Abstract

This paper examines the impact of heat transfer during quenching on the hardness and mechanical properties of low carbon steel, specifically evaluating how various cooling media affect the microstructure and mechanical behavior of the material. Steel samples underwent heat treatment involving austenitizing at about 800 °C for 30 minutes, followed by quenching in water, engine oil, and air cooling (normalizing) to achieve uniform temperature and complete phase transformation. Mechanical characterization of impact, tensile and microstructural examination using optical microscopy test were carried out. The energy absorption values for the samples increased with different quenching methods with control (18.15 Joules), air-cooled (21.22 Joules), water-quenched (23.82 Joules), and highest for engine oil quenched (25.19 Joules). Hardness also improved, with air-cooled at 243.2 HV, water-quenched at 278.4 HV, and engine oil at 258.9 HV, all exceeding the control's 230.0 HV. Tensile strengths were 583.87 MPa for control, 589.03 MPa for air-cooled, 530.3 MPa for water-quenched, and 525.1 MPa for engine oil-quenched. The study reveals that cooling rates in quenching media affect microstructure and hardness, with water-quenching leading to the highest hardness due to increased martensite. Oil-quenching results in lower hardness but better impact energy, while air-cooled samples show a ferrite-pearlite structure. The findings highlight the trade-offs between hardness, tensile strength, and ductility, emphasizing the need to choose appropriate quenching media for optimal performance in engineering applications.

Keywords: Martensite formation, cooling rate, characterization, optimizing heat treatment, quenching media.

1.0 Introduction

Steel, an alloy of iron and carbon, is vital in engineering due to its modifiable mechanical properties enhanced by heat treatment. This process improves hardness by controlling heating and cooling, particularly through rapid cooling (quenching) to form martensite. Optimizing heat treatment seeks to balance hardness, toughness, and ductility, while minimizing defects such as cracking. The key steps involved are austenitizing, quenching, and tempering [1]. The consistent hardness in steel components offers substantial economic benefits, including enhanced durability and reduced maintenance costs in automotive applications, resilient infrastructure in construction, and cost savings in manufacturing by optimizing processes and using less energy-intensive quenchants, such as polymers [2].

The quenching heat transfer process is pivotal as it impacts cooling rates and phase transformations, which affect hardness. Poor heat transfer can result in uneven cooling and softer structures, such as bainite or pearlite, instead of martensite. Optimizing parameters for uniform heat extraction is crucial to achieve targeted hardness levels, measured on Rockwell, Vickers, or Brinell scales [3]. Hardness, linked to microstructure, is essential for material resistance to deformation, especially in high-stress applications in automotive, aerospace, and energy sectors [4].

Heat treatment is essential for modifying the mechanical properties of steel, particularly hardness, which impacts wear resistance, strength, and service life. The process entails heat transfer during heating, soaking, and cooling stages. Steel, mainly an iron-carbon alloy, is classified based on carbon content into low-carbon ($\leq 0.25\%$ C), medium-carbon (0.30–0.60% C), and high-carbon ($> 0.60\%$ C) steels, which are appropriate for diverse applications [5].

Medium carbon steels are essential in mechanical engineering due to their ability to respond to heat treatment, enhancing hardness and strength by altering their microstructure. These steels are used in components like crankshafts, connecting rods, and gears, but typically need heat treatment to improve performance as their hardness in the as-rolled or normalized state is often inadequate [6]. AISI 1030 steel is a medium carbon steel with 0.28–0.34% carbon and 0.60–0.90% manganese, which enhances hardenability and strength. Its untreated state has a ferrite-pearlite microstructure and moderate mechanical properties. Heat treatment followed by rapid cooling transforms the microstructure into martensite, significantly increasing hardness [7].

Controlled heat treatment modifies the microstructure and properties of medium carbon steel through processes such as annealing, normalizing, hardening, and tempering [8]. Hardening is essential for enhancing hardness, requiring heating the steel above its critical temperature to form austenite, holding that temperature for uniform transformation, and then rapidly cooling with a quenching medium. The success of hardening is contingent on the efficiency of heat transfer during both heating and cooling [9]. Furnace heat treatment with electric muffle furnaces ensures precise temperature control and even heat distribution, critical for achieving consistent material hardness. Uniform heating promotes complete austenitization, whereas uneven heating can lead to non-uniform microstructures and varied mechanical properties. Studies show that furnace temperature stability notably affects the hardness of medium carbon steels [10].

Heat transfer during furnace heating involves conduction, convection, and radiation. At high temperatures, radiation from furnace walls predominates, supported by convection from hot gases and conduction within the steel sample. Effective heat transfer is crucial for uniform temperature distribution, particularly in cylindrical samples like 16 mm diameter rods, as poor transfer can create temperature gradients, causing incomplete austenitization at the core [11].

Heating steel above its critical temperature (A_{c3}) transforms it from ferrite and pearlite to austenite. The subsequent cooling rate influences the resulting phase: slow cooling yields pearlite or bainite, while rapid cooling leads to martensite, a hard and brittle variant. The formation of martensite is influenced by the steel's chemical composition and quenching heat transfer rate [12].

Time Temperature Transformation (TTT) diagrams illustrate the relationships between time, temperature, and phase transformations in medium carbon steel during isothermal cooling. They are crucial in avoiding pearlite and bainite formation, facilitating martensitic transformation [13]. Continuous Cooling Transformation (CCT) diagrams reflect industrial cooling processes more accurately, demonstrating that increased cooling rates result in higher martensite content and hardness, guiding effective cooling strategies in heat treatments and controlled quenching [14]. The selection of quenching medium significantly affects the cooling rates and heat transfer properties. Water offers the fastest cooling but risks cracking, while oil provides a balance between hardness and toughness. Air cooling is slower and yields lower hardness. Research supports oil quenching as the optimal choice for medium carbon steels, and optimized conditions can enhance microstructure and hardness by over 30%, while reducing defects. This underscores the advantages of systematic optimization rather than relying on trial-and-error methods [15].

Mechanical testing is essential for assessing the effectiveness of heat treatment in medium carbon steels. Important tests include hardness, tensile strength, and impact toughness. Studies show enhanced hardness achieved through techniques such as furnace hardening and oil quenching. There is a gap in research focusing on the combined effects of hardness, tensile, and impact testing in plain carbon steels under controlled conditions [16]. Advancements in heat treatment technologies face challenges in achieving uniform hardness, acceptable toughness, and minimal distortion in medium- to high-carbon and low-alloy steels, especially for complex geometries. Limitations in conventional quenching and control over localized heat transfer during cooling contribute to these issues. The optimization of heat treatment processes is crucial for enhancing hardness and reducing thermal stress. This involves correlating cooling rates with microstructure, identifying hardness distribution, and addressing residual stresses to develop a digital process window for precision quenching. Such advancements will facilitate the adoption of high-performance steel components with reduced alloy content and a lower carbon footprint [17].

This paper explores the optimization of heat treatment for low carbon steel like AISI 1020, addressing process parameters, heat transfer conditions for various steel-quenchant combinations, and aims to maximize surface and core hardness while minimizing distortion and quench cracking. It also investigates the use of eco-friendly quenchants as substitutes for mineral oil without compromising hardness, and develops predictive models linking process parameters to cooling curves, microstructure, and hardness.

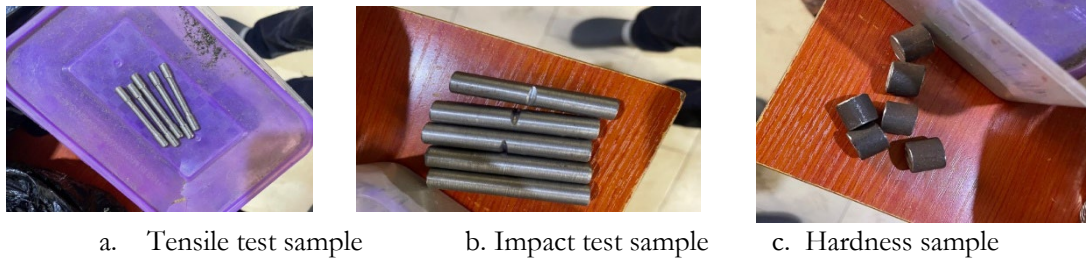
2.0 Materials and Methods

AISI 1020 steel is a low carbon steel featuring high manganese, silicon, phosphorus, and sulfur content, recognized for its machinability and weldability. The steel underwent spark testing, machining, furnace heating, and quenching in various media. The heat treatment process includes austenitizing, quenching, and tempering, with samples normalized and austenitized at 800°C. Cooling rates were monitored to estimate heat transfer coefficients, with data logging and Jominy end-quench tests supporting findings on the impact of cooling rates on microstructure and hardness. Chemical analysis revealed 0.235 wt.% carbon and other trace elements. Post-quenching, samples were subject to hardness testing and microscopic examination to establish correlations between cooling rates, heat transfer, and hardness of the steel.

The cooling rate was calculated as contained in equation 1.

$$C_R = \frac{T_1 - T_2}{t_2 - t_1} \quad (1)$$

Where C_R is cooling rate, T_1 and T_2 are temperatures at times t_1 and t_2



a. Tensile test sample b. Impact test sample c. Hardness sample

Figure 1(a-c): Tested samples

2.1 Characterization of the Heat-Treated Mild Steel

Characterization of heat-treated mild steel samples was performed through carburization and several analytical methods. Optical and SEM microscopy, along with XRD, were utilized to evaluate microstructures, ensuring structural properties met acceptable limits. Mechanical properties were assessed using Rockwell and Vickers hardness testers, following ASTM E92-17 for Vickers testing. The Charpy Impact Machine conducted toughness tests with 55mm by 10mm by 10mm specimens, measuring fracture energy through the potential energy difference of the hammer before and after rupture. Tensile and compressive strengths were determined via a Universal Testing Machine (UTM). Corrosion behavior was analyzed focusing on failure analysis through weight loss in saline water (3.5% NaCl), employing the Weight Loss Method (WLM) according to ASTM G31 to establish effective corrosion resistance.

3.0 Results and Discussion

3.1 Impact Test

Each heat treatment operation has a notable effect on the energy absorption of AISI 1020 steel samples. According to the data presented, control samples recorded the lowest impact energy at 18.15 Joules. Comparatively, air-cooled samples show an increase to 21.22 Joules, while water-quenched samples further increase to 23.82 Joules (Table 2). Engine oil quenched samples achieved the highest energy absorption at 25.19 Joules, attributed to their slower and more uniform cooling process. This method reduces internal stress and enhances the formation of a more favorable martensitic structure, as discussed by [12].

Table 1: Impact of the heat-treated samples in cooled air, water and engine oil

Samples (one each)	Impact (Joules)
Control	18.15
Air cooled	21.22
Water quenched	23.82
Engine oil quenched	25.19

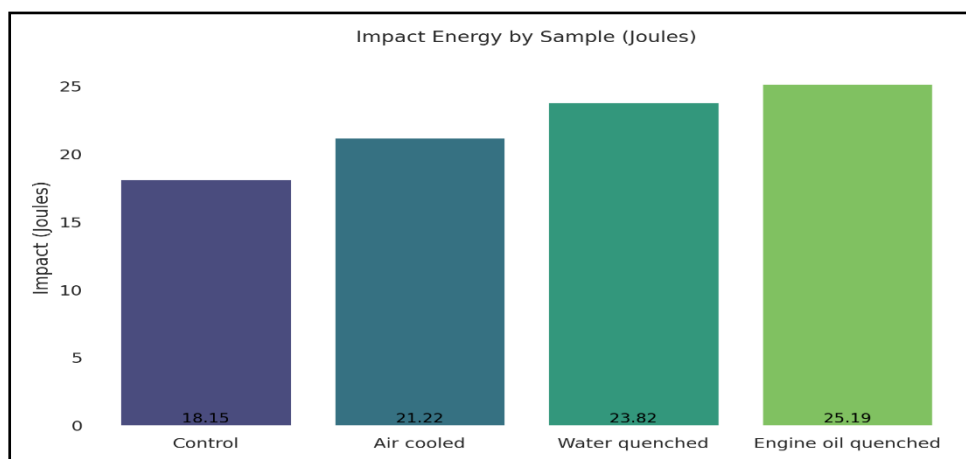


Figure 2: Impact of heat treatment on different quenching medium on AISI 1020 steel

3.2 Hardness Test Result

The heat treatment operation (Table 2) enhanced the energy absorption of samples, with hardness values increasing significantly compared to the control sample: Air cooled (243.2 HV), Water quenched (278.4 HV), and Engine oil quenched (258.9 HV) compared to the control's 230.0 HV.

Figure 3 shows that heat-treated samples experience varying hardness values depending on quenching media, with faster cooling rates (tracking temperature drop over time during quenching using a K-type thermocouple) increasing martensite formation and hardness. Water quenched samples had the highest hardness, followed by engine oil quenched samples, while the control sample had the lowest. This is due to water's rapid cooling promoting maximum martensite formation, whereas oil cooling, while forming martensite, reduces cracking and results in slightly lower hardness but better properties [17].

Table 2: Hardness value of the samples cooled in air, water and engine oil

Samples	Hardness (HV)
Control	230.0
Air cooled	243.2
Water quenched	278.4
Engine oil quenched	258.9

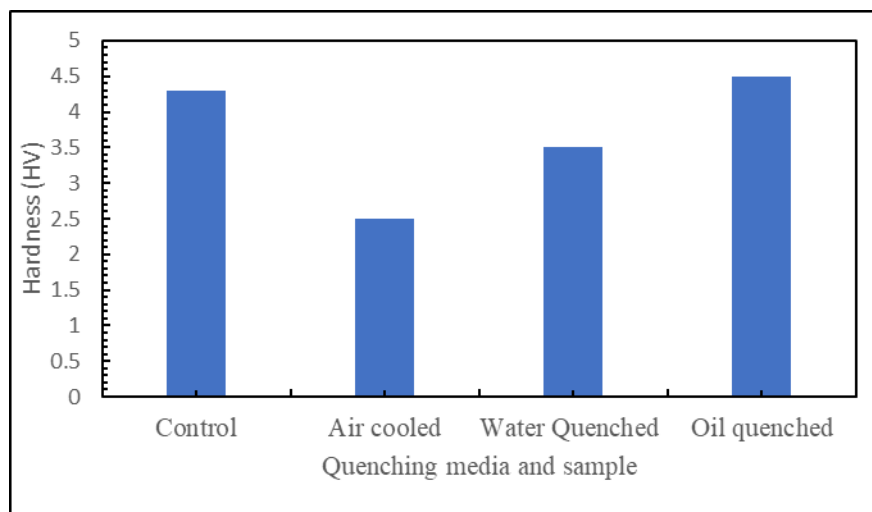


Figure 3: Hardness value of the heat-treated samples

3.3 Tensile Test Result

Table 3 shows the tensile strength results for different quenching media applied to heat-treated steel samples, with the control sample showing a tensile value of 583.87 MPa, air-cooled samples at 589.03 MPa, water-quenched samples at 530.3 MPa, and engine oil-quenched samples at 525.1 MPa.

Air cooling yields the best tensile properties (out of four samples), surpassing the control sample, which has the lowest properties (Figure 4). This enhancement is attributed to the air-cooled state being closer to the normalized condition, facilitating a fine ferrite-pearlite structure that offers a favorable balance of strength, ductility, and toughness, alongside a slight increase in hardness [8].

Table 3: Tensile results of the samples

Sample	Tensile (MPa)
Control	583.87
Air cooled	589.03
Water quenched	530.30
Engine oil quenched	525.10

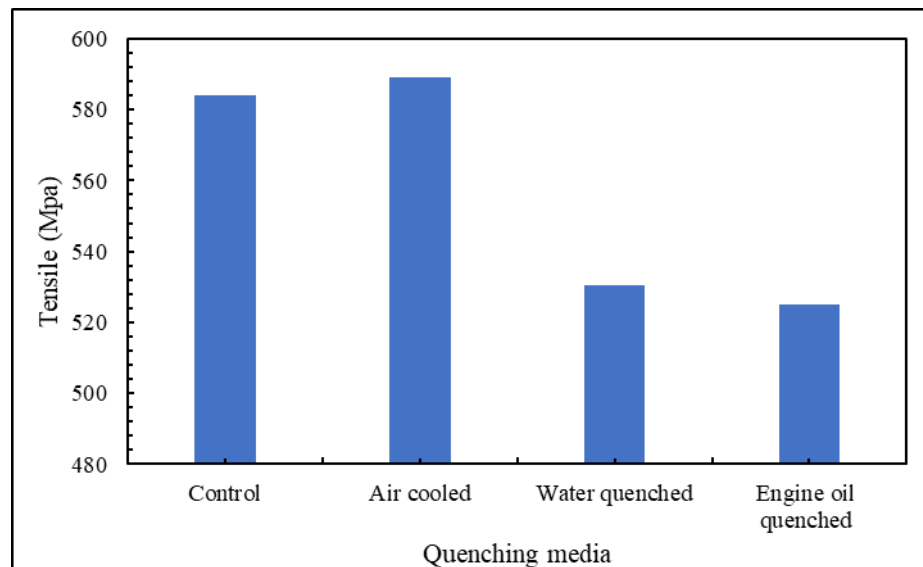


Figure 4: Tensile value of the heat-treated samples

3.4 Cooling Rate

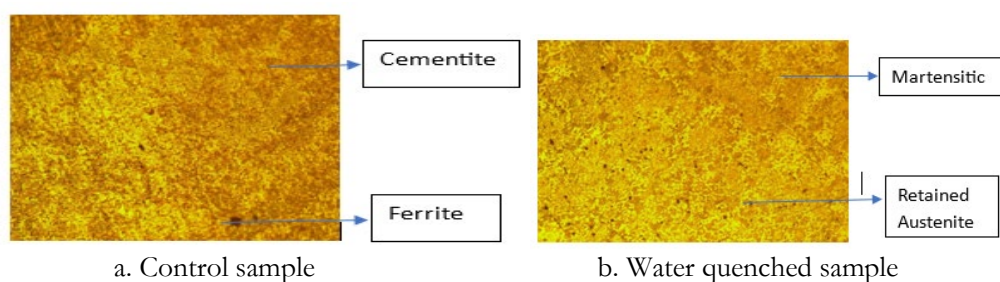
Furnace cooling (0.1 °C/s) yields pearlite and ferrite, while air cooling (3 °C/s) could produce fine pearlite or bainite. Water quenching (500 °C/s) produces martensite, and engine oil quenching (200 °C/s) may lead to bainite or martensite. Cooling rates for low-carbon steel notably increase from furnace cooling to water quenching. Water quenching led to the fastest cooling, while air produced the slowest rate among forced media. This higher heat transfer in water and oil inhibits diffusion-controlled transformations, resulting in harder martensitic and bainitic structures. Conversely, the slower cooling rates from air and furnace cooling allowed for pearlite and ferrite formation. The choice of quenching medium thus directly influences the final hardness of low-carbon steel, allowing for customized mechanical properties tailored to specific engineering needs without altering the alloy composition.

Table 4: Results of cooling rates in different media

Quenching medium	Cooling rate (°C/s)	Remarks
Control (furnace cooled)	0.1	Slow cooling, and produced pearlite and ferrite
Air cooled	3	Moderate cooling, and formed either fine pearlite or bainite
Water quenched	500	Fast cooling, and favoured martensite formation
Engine oil quenched	200	Fast cooling, and promotes either bainite or martensite

3.5 Microstructural Examination

Figure 5 presents micrograph images showing the results of micro examination on medium-carbon steel samples quenched in different media, highlighting the effects of various heat treatments. The control sample contains a coarse ferrite matrix with pearlite. The water quenched sample exhibits a martensitic microstructure characterized by fine needle martensite without pearlite. The oil quenched sample displays lath martensite, which is finer and predominantly martensitic, resulting in the highest hardness. In contrast, the air-cooled sample shows a fine ferrite-pearlite microstructure with refined grains and a more uniform pearlite distribution, as indicated by [11].



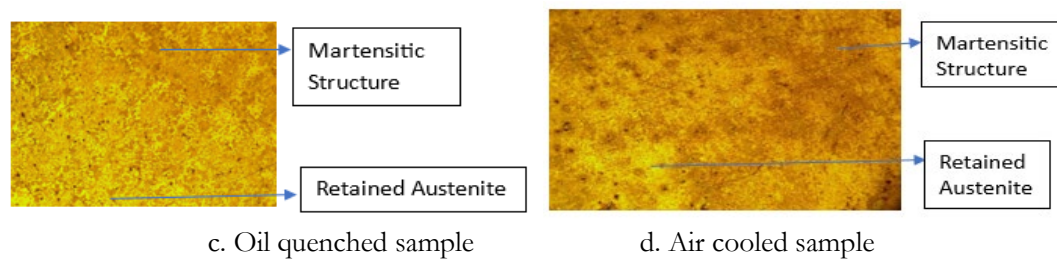


Figure 5 (a-d): Microstructural images

4.0 Conclusion

The examination of heat treatment on low-carbon steel revealed that the cooling rate significantly affects hardness, microstructure, and tensile strength. The control sample exhibited the softest condition with a coarse ferrite-pearlite structure. Hardness is closely linked to the martensite volume fraction, but untampered martensite's brittleness can result in lower tensile strengths for quenched samples (530.3 MPa for water quenching, 525.1 MPa for oil). While rapid quenching increases hardness, it decreases tensile ductility. The results indicate that hardness improvements in AISI 1020 steel are notable compared to its as-received condition, though limited relative to higher carbon steels. Tempering is advised to reduce brittleness and enhance tensile strength in quenched samples.

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