

The Effect of Quenching and Tempering on the Hardness of Medium Carbon Steel: AISI 1045

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Abstract. Technological advancements have improved steel production through enhanced raw material quality and processing techniques. AISI 1045 steel is widely used in machine components. However, its mechanical properties, particularly hardness and ductility, often require modification to suit specific applications. This study investigated the effects of different quenching media and a subsequent tempering process on the hardness of AISI 1045 steel. The specimens were austenitized at 850°C and quenched using water, oil, and air, followed by tempering at 600°C for 30 minutes. An experimental research method was employed, and hardness values were evaluated using the Vickers hardness test with descriptive statistical analysis. The results indicated that water quenching produced the highest hardness, reaching 421.0 VHN in the as-quenched condition. After tempering, the highest hardness was still obtained from water-quenched specimens, with a value of 312.5 VHN. These findings indicate that quenching media significantly influence the hardness of AISI 1045 steel, both before and after tempering.

Keywords: heat treatment, quenching, tempering, AISI 1045, hardness

1. Introduction

In Indonesia, the manufacturing sector primarily employs metal applications as the primary raw material for engineering materials in product design, especially machinery [1]. AISI 1045 steel is commonly utilized in machine tools because of its ease of processing and ability to deform to meet specifications, attributed to its 0.3 to 0.6% carbon content. This steel is often utilized for manufacturing essential structural components that require superior strength due to its remarkable properties [2]. Although it possesses considerable raw material potential, AISI 1045 lacks sufficient hardness because it still has a carbon content of under 0.6%. Heat treatment is required to attain the desired qualities, varying from soft to hard. Quenching and Tempering (Q-T) heat treatment significantly improves the mechanical properties of steel by promoting the formation of a microstructure characterized by a fine grain size [3]. The quenching process, part of heat treatment, entails heating steel to 850 °C to reach the austenization phase, followed

by rapid cooling. This procedure alters the microstructure of the steel based on the cooling medium used, thereby influencing its mechanical properties [4]. Quenching typically achieves success through tempering, which reduces the brittleness induced by quenching while maintaining high strength levels [5]. Quenching followed by tempering is an effective method for obtaining steel that exhibits an optimal balance of hardness, toughness, and mechanical reliability. This straightforward process adds to its widespread use in industrial applications.

The formation of martensite during the transition from austenite plays a crucial role in enhancing the mechanical properties of steel. During the formation of the martensite phase, it is essential to eliminate residual stresses and brittleness in the steel through a tempering procedure [6]. Tempering reduces the hardness and strength of steel, while enhancing its ductility and diminishing brittleness [7]. The hardenability, thickness, component form, and cooling rate required to attain the desired microstructure all influence the choice of quenching media [8]. Maintaining consistent cooling conditions is essential to reduce the likelihood of cracking, distortion, and uneven hardening [9]. Tempering involves heating hardened steel to a designated temperature and maintaining that temperature for a specified duration [10]. The tempering process is designed to decrease or remove internal stresses in steel while partially reinstating its ductility and hardness [11]. The stable martensite formed after quenching remains at room temperature, while new martensite develops when the austenite undergoes quenching [12]. Tempering involves reheating hardened steel to a temperature below its critical threshold and gradually cooling [13].

An isothermal transition (IT) or time-temperature transformation (TTT) diagram, as depicted in Figure 1, illustrates the influence of time and temperature on the transformation of austenite into various phases in steel [14]. The TTT diagram assesses the behavior of steel throughout multiple stages of heat treatment, as well as its microstructure and mechanical properties during the cooling process [15]. To create a TTT diagram, carbon steel is heated until it reaches an austenitic temperature, followed by a controlled cooling process within the austenitic phase zone [16]. An iron-carbon equilibrium diagram demonstrates the relationship between the temperature at which phase transitions occur during cooling and the incremental heating of carbon content [17]. The iron-carbon equilibrium diagram is a valuable tool for determining the optimal heating temperature for various heat treatment processes, such as annealing, normalizing, and hardening [18]. This study examines the hardening processes, specifically emphasizing quenching and tempering. The investigation presents the methodology and results illustrated through hardness value data.

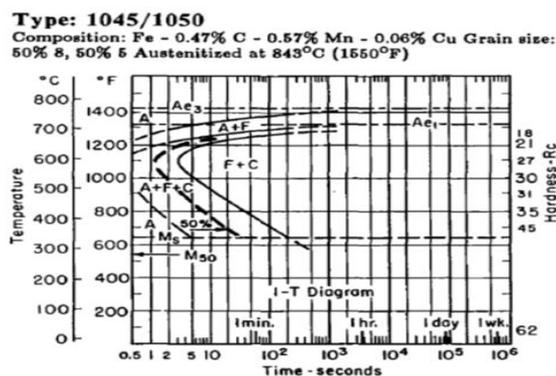


Fig. 1. TTT diagram of AISI 1045 steel [19]

2. Research Methods

This study collected data from quenched and tempered specimens to investigate the influence of heat treatment on material hardness.

2.1. Tools and Materials

The testing equipment included a milling machine equipped with coolant to prevent overheating of the specimen during cutting, a scraping machine for specimen preparation, an aluminum container for the quenching media, furnace accessories (including clamping pliers), a heat-treatment furnace, and a Vickers Hardness Testing Device.

The materials utilized in this study were as follows:

1) The material utilized was AISI 1045 medium-carbon steel, fabricated into cylindrical specimens measuring 25 mm in diameter and 20 mm in height, as seen in Figure 2, which illustrates the geometry and dimensions of the test specimen used in the experiments.

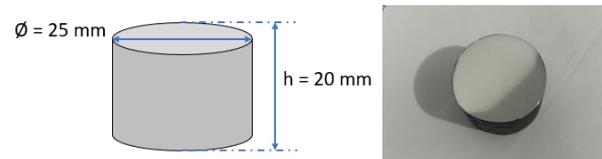


Fig. 2. Dimensions of the specimen and the prepared specimen

2) The quenching media comprised 1 liter of each liquid medium, specifically water and lubricating oil. Furthermore, ambient air served as the cooling medium throughout the experimental procedure.

2.2. Heat Treatment Process

The experimental approach comprised multiple stages, including heat treatment, mechanical testing, and data collection. The heat treatment procedure for specimens, as illustrated in Figure 3, is described as follows:

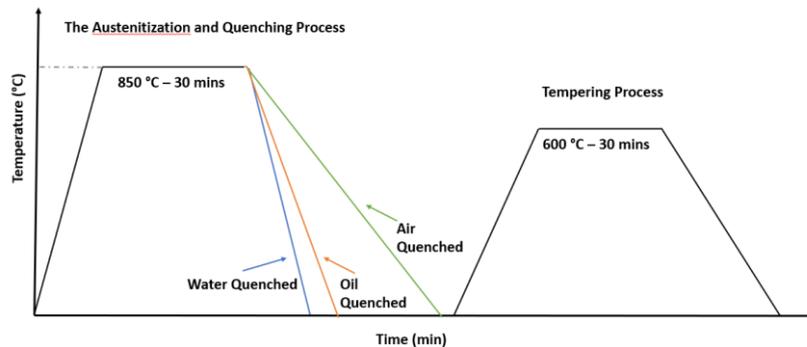


Fig. 3. The Heat Treatment Process Diagram

a. The Austenitization and Quenching Process

The furnace was initially activated and calibrated with a thermocouple to ensure accurate temperature control. The specimens were subsequently heated in the furnace to an austenitization temperature of 850 °C and maintained at this temperature for 30 minutes to attain a homogenous austenitic structure. After the holding period, the specimens were promptly quenched utilizing several cooling media, specifically water, lubricating oil, and ambient air.

b. Tempering Process.

Following the quenching process, all specimens underwent tempering at a temperature of 600 °C for 30 minutes to alleviate internal stresses and enhance the equilibrium between hardness and toughness.

2.3. Evaluation of AISI 1045 Steel Specimens

The hardness of specimens was evaluated utilizing the Vickers Hardness Testing Method, conforming to ASTM E92: Standard Test Methods for Vickers Hardness of Metallic Materials. The principal test load (P) was established at 25 kgf, and a diamond pyramid indenter was affixed to the testing device. The specimen was positioned on the testing table, and the anvil handle was adjusted until the indenter contacted the specimen surface. Before loading, the testing equipment was calibrated to a zero reference point. Thereafter, the load was imposed by activating the load lever and sustained for a duration of 15 seconds. The hardness value displayed by the instrument was recorded post-unloading. The anvil handle was subsequently lowered to detach the indenter from the specimen. The test was conducted at different locations on the specimen surface to ensure measurement accuracy and consistency.

3. Results and Discussion

3.1. Research Results

The purpose of this study is to compare the hardness before and after quenching and tempering with various cooling media, using AISI 1045 steel as the object. The AISI

numbering system is used to classify alloy and carbon steels based on their chemical composition. AISI 1045's coding scheme uses a particular code, such as 10xx. 10 is carbon steel, and xx is the carbon percentage at 100%. The number 45 in carbon steel in the AISI standard indicates that the carbon content is around 0.45%. Table 1 shows the chemical composition of AISI 1045.

Table 1. Chemical Composition of AISI 1045

Element	C	Si	Mn	P	S
%	0,4278	0,2119	0,6354	0,0170	0,0084

This study compared the quenched and tempered sample results with data from the original sample material (raw material). The raw sample was examined for hardness. Hardness was determined using the Vickers test method, often known as the Diamond Pyramid Hardness (DPH) test. A primary load (P) of 25 kgf was used for testing at three different locations. The original sample's hardness measurement results are provided below:

Table 2. Raw Material Hardness Test Results

No.	Sample	Area	Hardness (VHN)	Average (HVN)
1.	Raw Material	1	189.6	224.1
		2	235.7	
		3	246.9	

Table 2 displays the results of the steel specimens before quenching and tempering. The highest hardness value at point 3 (edge) is 246.9 VHN, whereas the average is 224.1.9 VHN. The Vickers test method was used to determine hardness, employing a diamond pyramid-shaped indenter with an angle of 136° between its faces. In this hardness study, testing was done at three different places, as shown in Figure 4.

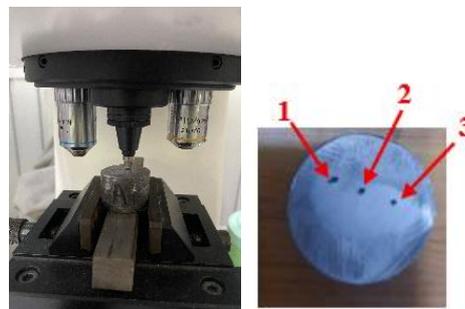


Fig. 4. Hardness Testing Point for Specimen

Macroscopic inspection was used to perform the Vickers test. The hardness test was carried out using a load of 25 kgf. The decision to apply a 25 kgf load was influenced by the probability of deformation, the test specimen's 20 mm thickness, and previous research findings. The hardness test results are provided in the following table:

Table 2. Vickers' Hardness Test Results

No.	SampeI	Area	Hardness (HVN)	Average (HVN)
1	Q 850 °C,	1	437.0	421.0
	Media Water	2	404.2	

		3	421.7	
2	Q 850 °C, Media Oil	1	372.2	367.7
		2	362.1	
		3	368.9	
3	Q 850 °C, Media Air	1	349.9	342.5
		2	336.1	
		3	341.4	
4	Q 850 °C, Media Water + T 600 °C, 30 minutes	1	313.1	312.5
		2	317.7	
		3	306.7	
5	Q 850 °C, Media Oil + T 600 °C, 30 minutes	1	251.8	241.4
		2	235.9	
		3	236.5	
6	Q 850 °C, Media Air + T 600 °C, 30 minutes	1	217.5	217.5
		2	217.2	
		3	217.8	

Table 2 displays the Vickers hardness values and average hardness across all specimens. The specimens were tested at three different places, resulting in differing degrees of hardness, although the discrepancies were not significant. Figure 5 displays hardness values visually.

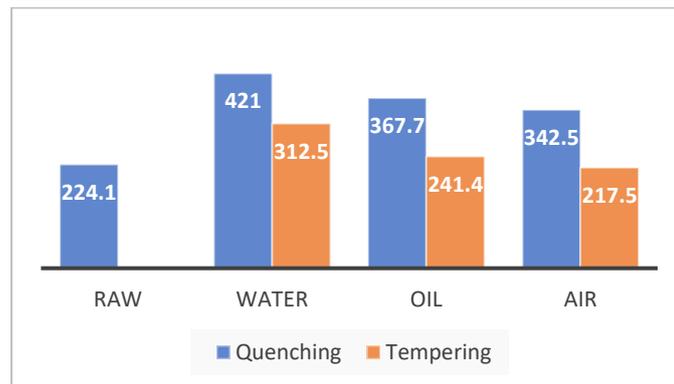


Fig. 5. Hardness Value Graph

Figure 4 and Table 3 demonstrate that quenched specimens have greater hardness ratings than raw material specimens. These values change based on the cooling media employed. Specimens heated to 850 °C and quenched with water have the most significant average hardness values, reaching 421 VHN. Meanwhile, the use of oil media resulted in a rise in hardness under water media, 357.7 VHN, and the use of air media resulted in the smallest increase in hardness compared to other media, 342.5 VHN. The specimens were then heated to 600 °C for 30 minutes after being cooled in several quenching media. The tempering process resulted in a decrease in hardness across the entire specimen. However, specimens quenched with water initially still had the highest hardness compared to specimens quenched with other media.

3.2. Discussion

In the quenching stage, the mechanical characteristics typically exhibit increased hardness, signifying that the steel becomes hard and brittle relative to the raw material. The hardness ratings of quenching media, including water, lubricating oil, and air, vary due to the differing cooling rates of each medium. The hardness value diminishes upon tempering, which involves warming the steel below the austenitization temperature. The study was performed at 600°C for 30 minutes.

The TTT diagram of AISI 1045 steel indicates that quick cooling yields martensite, medium cooling results in bainite, while slow cooling generates ferrite and pearlite [20]. This aligns with prior findings suggesting that a rapid cooling rate produces a martensite microstructure [6][19]. The martensite structure is a metastable phase of carbon dissolved in iron, formed during heat treatment that reaches the austenite limit and is rapidly cooled, trapping carbon and inducing internal stress, which increases the steel's hardness due to the efficacy of interstitial carbon in obstructing dislocation movement. Following tempering, a diminished martensite quantity is produced relative to post-quenching steel. Still, an increased formation of ferrite occurs, enhancing the ductility of this steel and consequently leading to a lower hardness level. At the austenite temperature, the objective is to dissolve the carbides; however, during the reheat treatment (tempering), these carbides reappear alongside ferrite, enhancing the ductility of AISI 1045 steel. Tempering results in a tempered martensite structure, indicating a rapid cooling rate followed by reheating. This aligns with earlier data suggesting that hardness diminishes post-tempering [5][7][10]. This aligns with the hypothesis that the microstructure or phase present significantly affects alterations in the mechanical properties of steel.

4. Conclusion

The specimen heated to 850 °C and cooled with water has the maximum hardness, 421,0 HVN. In comparison, the specimen treated with a heating temperature of 850 °C and oil cooling medium produces a hardness of 367.7 VHN. After tempering, the hardness begins to decrease, with the lowest hardness value obtained at 600 °C with a holding time of 30 minutes and previously quenched with air media, and the highest hardness value, 312.5 VHN, was obtained at 600 °C and had a holding time of 30 minutes. This depicts how the quick cooling process alters the microstructure of the water-quenched specimen, producing martensite while retaining austenite phases. Because of the slower cooling rate, oil-quenched specimens retain less austenite and produce martensite and bainite phases than water-quenched specimens.

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