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EXPERIMENTAL STUDY ON THE EFFECT OF SINGLE AND DOUBLE QUENCHING-TEMPERING ON THE MECHANICAL PROPERTIES OF AISI 1045 STEEL

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ABSTRACT

This study examined the effects of quenching, single quenching–tempering (SQT), and double quenching–tempering (DQT) on the microstructure and mechanical properties of AISI 1045 medium-carbon steel (0.54% C, 0.32% Si, 0.65% Mn, 0.015% P, 0.0112% S, balance Fe). All specimens were heated to 850°C for 25 minutes and quenched in coconut oil at 100°C. Tempering was subsequently performed at 650°C for the SQT and DQT treatments. Hardness testing revealed that quenching produced the highest hardness value of 242.38 kg/mm² due to the formation of martensite. The SQT treatment reduced hardness to 198.46 kg/mm², indicating improved toughness while maintaining relatively high hardness. Further reduction in hardness was observed in the DQT-treated specimens, reaching 158.13 kg/mm², reflecting a more ductile and tougher microstructure. Impact properties were evaluated using the Charpy method. Heat-treated specimens exhibited significantly higher impact strength than the untreated material. The SQT process increased impact strength to 1.5792 J/mm², demonstrating the beneficial effect of tempering on toughness. The highest impact strength was achieved through DQT, reaching 1.8542 J/mm², indicating superior energy absorption capability. The results show that repeated quenching and tempering cycles effectively enhance the toughness of AISI 1045 steel, although accompanied by a reduction in hardness. Overall, DQT provided the best improvement in impact resistance and toughness among the heat treatment conditions investigated.

Keywords*:* AISI 1045 Steel, Quenching, SQT, DQT, Coconut Oil

INTRODUCTION

Medium carbon steel (AISI 1045 steel) is one of the materials widely used in the automotive and machinery industries due to its good mechanical properties and ease of fabrication. A carbon content of 0.45% provides a balance between strength and toughness, making it ideal for applications that require wear resistance, such as gear components and shafts [1], [2]. One of the main challenges in using this steel is its resistance to wear that can occur due to repeated pressure and friction during operation. AISI 1045 steel can improve its performance by undergoing heat treatments such as quenching and tempering [3]. This process not only improves hardness but also affects the microstructure, which in turn impacts the mechanical properties and resistance of the steel to various types of use [4].

Quenching is a heat treatment technique that aims to increase the hardness of steel through rapid cooling from high temperatures. Research shows that temperature settings and cooling methods can significantly affect the mechanical properties of AISI 1045 steel. In one study, quenching at 850°C followed by cooling with water resulted in a significant increase in hardness [5]. However, the choice of cooling medium and cooling time are also important because they can affect the microstructure and corrosion resistance of the material [1], [5]. After quenching, tempering is performed to reduce internal stress and increase the steel's ductility. Variations in temperature and cooling time parameters can cause differences in the hardness and tensile strength of steel. [6].

Cooling and tempering can affect the manufacturing results of materials. Changes in processing methods can enable the production of more efficient and durable components. Improvements in heat treatment and mechanical properties will support innovation in component design [2], [7].

The quenching process begins by heating the specimen in a furnace to 850°C and holding for 25 minutes. The specimen is then rapidly cooled using coconut oil as a cooling medium. Next, tempering is performed at 650°C, held for 25 minutes, followed by slow cooling to room temperature to increase the material's ductility and strength. In this study, quenching, quenching-tempering, and double quenching-tempering heat treatments were performed using the same temperature and procedure.

The quenching and tempering heat treatment process on AISI 1045 steel was carried out by [1] in 2022, the steel was heated at a temperature of 850°C for 30 minutes then continued with rapid cooling or quenching using water. Furthermore, tempering was carried out by reheating the quenched sample at a temperature of 350°C with a holding time of 30 minutes and 60 minutes then continued with cooling in free air. The results obtained in this study show that steel quenched with water experienced a decrease after the tempering process, where the hardness value during tempering for 30 minutes decreased by 19.57% from 61.24 HRC to 49.57 HRC. Meanwhile, the 60-minute hold time decreased hardness by 22.83% to 47.26 HRC. The Quenching-Tempering heat treatment reduces the hardness value of AISI 1045 steel.

One important aspect in the study of AISI 1045 steel is the analysis of the microstructure after heat treatment. Research by Hariningsih et al. shows that the cooling rate affects microstructure development. The cooling rate, in turn, contributes to the final mechanical properties of steel [1]. This is in line with the theory that a homogeneous microstructure has good wear resistance and high strength.

Research by Li et al. shows that the strength of AISI 1045 steel can be improved through a warm rolling process. This increase in strength indicates that microstructure modification can be used to improve mechanical properties [8]. Other approaches, such as alloying, have been proven effective in improving the wear resistance of steel materials [4], [9]. With continuing technological advances, lasers and other modern processing methods have also been introduced to improve steel performance [7].

With the development of heat treatment technology and methods in the processing of AISI 1045 steel, further research is needed. The main objective of this research is to find the optimal combination of appropriate heat treatments. Appropriate heat treatment allows steel to be used in extreme environments while maintaining strength, wear resistance, and flexibility [10]. Therefore, an integrated approach that considers the influence of heat treatment methods and mechanical properties will help drive innovation in the modern automotive industry [11].

This study used the Vickers hardness test and the Charpy impact test. The Vickers test was conducted to determine the hardness of AISI 1045 steel using a pyramid indenter. The Vickers test has the advantages of being cost-effective and providing a continuous hardness scale over a wide range. Additionally, the Charpy impact test was conducted to determine the flexibility of AISI 1045 steel. The Charpy impact test used the ASTM E23 standard.

This research aims to explore various heat treatment techniques that can be used to improve the strength and durability of AISI 1045 steel. This comprehensive heat treatment approach is expected to produce a hard and ductile material. This comprehensive approach offers better solutions to wear and ductility issues. The relevance of this research is also reinforced by the automotive industry's need to produce stronger and more durable components.

Component replacement frequency and maintenance costs are minimized by improving material performance through optimized heat treatment. Understanding the interactions between these factors will enable greater efficiency in manufacturing and product development [12], [13], [14]. Improving the performance of AISI 1045 steel through heat treatment techniques is expected to contribute to the continued use of this material in industrial applications. This research is expected to drive the innovation needed in the automotive and machinery industries to meet the challenges of the modern era.

METHOD

This research was conducted at SMTI Bandar Lampung and the Engineering Materials Laboratory of the Mechanical Engineering Department at the University of Lampung, with the aim of analyzing the mechanical properties of AISI 1045 steel after heat treatment. AISI 1045 steel was used as the research specimen. A picture of AISI 1045 steel is shown in Figure 1.

Figure 1. AISI 1045 steel specimen

AISI 1045 steel is then processed using tools and materials, including a cutting grinder for cutting the specimens, a furnace for heating, sandpaper for smoothing the surface, and an impact testing machine and hardness tester for testing the impact and hardness of the material.

The first stage in this study was specimen preparation. Specimens for impact testing were cut into rectangular bars measuring 55 mm long, 10 mm wide, and 10 mm high. Next, a 2 mm notch was made using a cutting grinder. Impact testing specimens used ASTM E23. For hardness testing, the specimens were cut into rectangular plates measuring 10 mm x 20 mm x 10 mm. After specimen preparation was complete, the next stage was heat treatment. In this study, the quenching process began by heating the specimens in a furnace to a temperature of 850°C with a holding time of 25 minutes. The specimens were then rapidly cooled using coconut oil as a cooling medium. After that, a tempering process was carried out at a temperature of 650°C with a holding time of 25 minutes, followed by slow cooling at room temperature to increase the ductility and strength of the material. In this study, to obtain comparative data, quenching, quenching-tempering, and double quenching-tempering heat treatments were carried out with the same temperature and procedure.

Next, tests were conducted to analyze the mechanical properties of the material. Impact testing was performed using the Charpy method, in which the specimen was placed on a test table and a pendulum was released to strike the specimen. The impact energy absorbed by the specimen was calculated based on the test results. The impact test results were calculated using the following formula:

$$E = E1 - E2 \qquad (1)$$

Where :
E = Energy required to break the test piece (kg.m)
E1 = Energy expended (kg.m)
E2 = Remaining energy after breaking the test piece (kg.m)

The impact value (HI) of a material tested using the Charpy method is given by:

$$HI = EA \qquad (2)$$

Where : E = Energy, A = Cross-sectional area under the notch (mm^2)

In this study, hardness testing was also carried out using the Vickers method on a hardness tester machine, where the specimen was given a load of 50 kgf with a pyramid-shaped indenter. The hardness of the material was measured based on the depth of indentation and read on a major scale. All these steps were performed for each specimen tested in order to obtain valid data for further analysis. The formula used to calculate hardness is as follows:

$$HV = \frac{2F\sin(\frac{136}{2})}{d^2} \qquad (3)$$

Where :
HV = Vickers hardness (in kgf/mm^2)
F = Load applied to the indenter (in kgf)
θ = Angle between the two sides of the indenter pyramid (for Vickers indenters, θ = 136°)
d = Measured indentation diagonal length (in mm)

RESULT AND DISCUSSION

In this study, two mechanical tests were conducted, namely:

1. Vickers Hardness Testing

Vickers hardness testing was conducted at the Engineering Materials Laboratory and Industrial Metrology Laboratory of the University of Lampung. Hardness testing was performed to evaluate the effect of heat treatment, particularly quenching, quenching-tempering, and double quenching-tempering, on the hardness of AISI 1045 steel. Three specimens were used in this test, with each specimen tested at five test points. Vickers hardness was measured by determining two diagonals (d1 and d2) from the indentation mark made by a pyramid-shaped indenter, and the average value of these two diagonals was used to calculate the hardness value (HV). Figure 2 shows the results of the pyramid indentation mark in the hardness test.

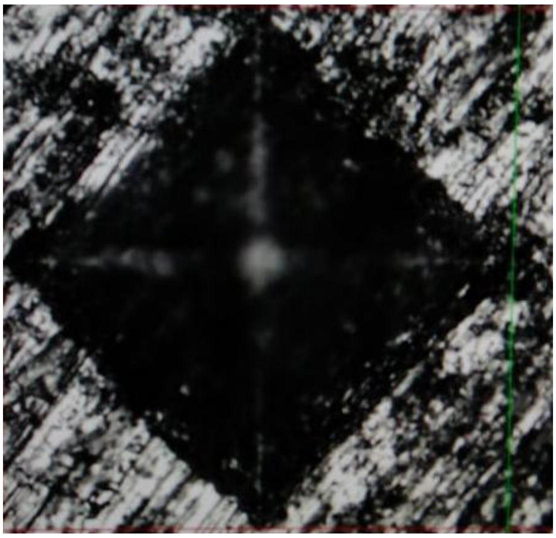

Figure 2. Vickers hardness test indentation results

The data obtained from the hardness test is shown in Table 1.

Table 1. Hardness Test Results

Materials	Heat Treatment	Specimen	Hardness Vickers (HV)	Average Hardness Vickers (HV)
AISI 1045 Steel	Raw Material	Raw Material 1	165.83	168.08
		Raw Material 2	172.06	
		Raw Material 3	166.35	
	Quenching	Specimen 1	233.68	242.3766667
		Specimen 2	243.37	
		Specimen 3	250.08	
	Quenching-Tempering	Specimen 1	198.52	198
		Specimen 2	198.52	
		Specimen 3	198.33	
	Q-T Ganda	Specimen 1	158.75	158
		Specimen 2	157.99	
		Specimen 3	157.64	

The results of raw material hardness testing on specimen 2 showed the highest hardness value of 172.06 Kg/mm². This was followed by specimen 3 with a value of 166.35 Kg/mm². Specimen 1 showed the lowest hardness value of 165.83 Kg/mm². This difference in hardness values was due to slight differences in the chemical composition and microstructure of the material, which could affect the distribution of hardness at different test points [15]. A standard deviation of 0.18 to 0.38 indicates that the material's hardness test results are accurate. The average hardness test result for raw AISI 1045 steel is 168.08 kg/mm².

Next, the Vickers hardness test results for AISI 1045 steel after heat treatment with coconut oil quenching. Coconut oil is used as a quenching medium because it helps maintain the metal's structure and reduces the potential for distortion. Hardness tests were conducted on three specimens with five test points each. The Vickers hardness test uses two diagonals (d1 and d2) to calculate the hardness value. Based on the data obtained, specimen 1 showed an average hardness value of 233.68 Kg/mm², specimen 2 had an average hardness of 243.37 Kg/mm², and specimen 3 recorded the highest hardness with an average of 250.08 Kg/mm². The average hardness value after quenching heat treatment was 242.377 kg/mm². The increase in hardness after quenching treatment was 44.02%.

From the test results, it can be seen that the hardness value tends to increase due to the quenching heat treatment. Quenching heat treatment on AISI 1045 steel significantly increases its hardness by changing the microstructure of austenite steel (Face-Centered Cubic structure) to martensite (Body-Centered Cubic structure), which has harder properties than the previous structure [16]. Hardness increases substantially after quenching heat treatment, but the side effect is a decrease in material toughness [17]. Therefore, further treatment such as tempering is often required to achieve a balance between hardness and toughness.

Vickers hardness (HV) test results for AISI 1045 steel after single quenching-tempering heat treatment. In this test, each specimen was tested at five points by measuring two diagonals (d1 and d2) of the indentation mark made by the indenter. The average Vickers hardness for specimen 1 was 198.52 Kg/mm². Meanwhile, specimen 2 had the same average of 198.52 Kg/mm². Specimen 3 showed a slightly lower hardness with an average value of 198.33 kg/mm². The average SQT hardness test result was 198 kg/mm². In the SQT hardness test, there was a 17.80% increase in hardness after the quenching-tempering heat treatment.

The results obtained show that the hardness of AISI 1045 steel after quenching-tempering heat treatment increased compared to the previous test results, which were only for raw materials. This can be seen from the average hardness value of 198 kg/mm². This average value is higher than the hardness value obtained for raw AISI 1045 steel. This shows that the quenching-tempering process provides a significant increase in hardness and because the tempering process after quenching helps reduce material brittleness [18]. The tempering process produces a more stable and homogeneous microstructure [19]. The tempering process contributes to increased steel toughness. Tempered steel produces a material that can be used in a wider range of applications due to its ductility.

Vickers hardness (HV) test results on AISI 1045 steel after double quenching-tempering heat treatment. Each specimen was tested at five points. Hardness testing was performed by measuring the two diagonals (d1 and d2) of the indentation mark produced by the indenter. The test results showed that specimen 1 had an average hardness of 158.75 kg/mm², specimen 2 had an average hardness of 157.99 kg/mm², and specimen 3 showed an average hardness of 157.64 kg/mm². Overall, the average Vickers hardness for the three specimens was 158 kg/mm². In the DQT hardness test, there was a 5.99% decrease in hardness after the quenching tempering heat treatment. Double quenching-tempering can cause smaller martensite grain sizes and reduced austenite formation. Reduced austenite formation allows carbide formation during the tempering process [20], [21]. Although the first quenching produces hard martensite, tempering accelerates the transformation of martensite into a more stable strengthening phase. The strengthening phase consists of a combination of martensite and carbide, thereby reducing the total hardness [22], [23].

Hardness test results show that quenching heat treatment is the optimal treatment for increasing the hardness of AISI 1045 steel. This is followed by single quenching tempering heat treatment and double quenching tempering heat treatment, as shown in Figure 3.

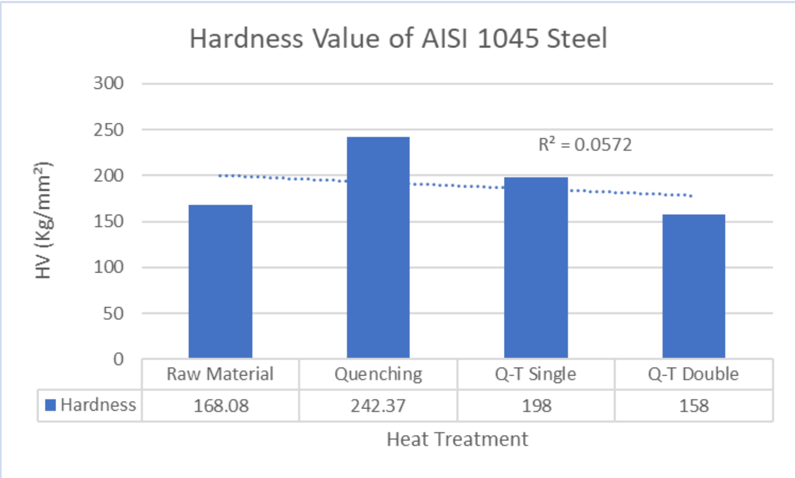

Figure 3. Graph of AISI 1045 Steel Hardness Values with Various Heat Treatments

2. Charpy Impact Testing

Impact testing was conducted to determine the mechanical properties of AISI 1045 medium carbon steel as the test material in this study. The test data covers raw steel material, steel after quenching heat treatment, quenching-tempering, and double quenching-tempering. Specimens were heat treated at a quenching temperature of 8500C and a tempering temperature of 6500C with a holding time of 25 minutes and coconut oil as the cooling medium. The results of the Charpy impact test are shown in Table 2.

Table 2. Results of AISI 1045 Steel Impact Testing

Materials	Heat Treatment	Specimen	Energy Impact (J)	Impact Value Impact (HI)	Average J/mm²
		Raw Material 1	36	0,45	
	Raw Material	Raw Material 2	34	0,425	0,4375
		Raw Material 3	35	0,4375	
		Specimen 1	25	0,3125	
	Quenching	Specimen 2	24	0,3	0,3125
		Specimen 3	26	0,325	
AISI 1045 Steel		Specimen 1	125	1,5625	
	Q-T Single	Specimen 2	128	1,6	1,57916667

	Specimen 3	126	1,575	
Q-T Ganda	Specimen 1	148	1,85	1,85416667
	Specimen 2	150	1,875	
	Specimen 3	147	1,8375	

Table 2 shows the final results of impact testing on AISI 1045 steel with various heat treatments. This test aims to measure the toughness of the material based on the impact energy absorbed and the ductility of the material as indicated by the impact value (HI) and the average J/mm² value.

In raw material (steel without heat treatment), the impact energy absorbed by specimens one to three was 36 J, 34 J, and 35 J. Meanwhile, the impact value (HI) on specimen one is 0.45 J/mm². The impact value (HI) on specimen two is 0.425 J/mm². The impact value (HI) on specimen three is 0.4375 J/mm². These results indicate good toughness in the base material of AISI 1045 steel that has not been given heat treatment. There is still room for improvement in AISI 1045 steel after heat treatment [24]. After double quenching and tempering heat treatment, the toughness and hardness of AISI 1045 steel can be increased, providing better performance in industrial applications.

After quenching heat treatment, the impact energy absorbed by specimens one to three was reduced to 25 J, 24 J, and 26 J, respectively. The measured impact values were 0.3125, 0.3, and 0.325 J/mm² for the same specimens. The average impact energy value for the quenched specimens was 25 J, while the average impact value was 0.3125 J/mm². There was a decrease in the toughness of the material compared to the raw material. This indicates that although hardening increases the hardness of the material, this process reduces the toughness of the material [25]. This decrease in toughness is in line with the finding that increasing hardness due to hardening can reduce the absorbed energy in AISI 1045 steel [26]. Therefore, it is important to consider the balance between hardness and toughness in material applications.

The quenching-tempering treatment showed a significant increase in material toughness. The impact energy absorbed by specimens one to three increased to 125 J; 128 J; and 126 J. The impact energy (HI) values were 1.5625; 1.6; and 1.575 J/mm², respectively. The average impact energy value for the quenching-tempering specimens was 126.33 J. While the average impact value was 1.57916667 J/mm². These results indicate an increase in toughness compared to the quenching heat treatment process. The tempering treatment after quenching helps to increase the material's ductility resulting in greater absorption of impact energy [27]. This increase is in line with previous findings showing that the tempering process at 650°C produces an impact energy of 136 Joules in AISI 1045 carbon steel [28]. The tempering process reduces the internal stresses in the martensite which makes it more stable and reduces its fragility [29].

In addition, the double quenching-tempering treatment causes an increase in the absorbed impact energy in specimens one to three, namely 148 J; 150 J; and 147 J. The measured impact values are 1.85; 1.875; and 1.8375 J/mm² for the same specimens. The average value of impact energy for specimens undergoing double quenching-tempering treatment is 148.33 J. While the average value of impact energy is 1.85 J/mm². These results indicate that the double quenching-tempering treatment provides a greater increase in resilience compared to the single quenching-tempering treatment. This double quenching-tempering process can improve the flexibility and resilience of the material better than other heat treatment processes. The double tempering process can increase the absorbed impact energy. The double quenching process in steel shows that the size of the martensite plate can be smaller compared to single quenching. In the study [30] it was stated that the size of martensite and carbide plates was reduced by applying the double quenching method. The reduction in the size of martensite and carbide plates contributed to the improvement of impact resistance and wear resistance. In addition, the double quenching process effectively refined the initial austenite (PAG) structure. The smaller diameter contributed to the improvement of overall mechanical properties [31].

The Charpy impact test results show that double quenching-tempering heat treatment is the optimal treatment to improve the malleability of AISI 1045 steel. The optimal treatment is then followed by single quenching-tempering heat treatment, and quenching as shown in Figure 4.

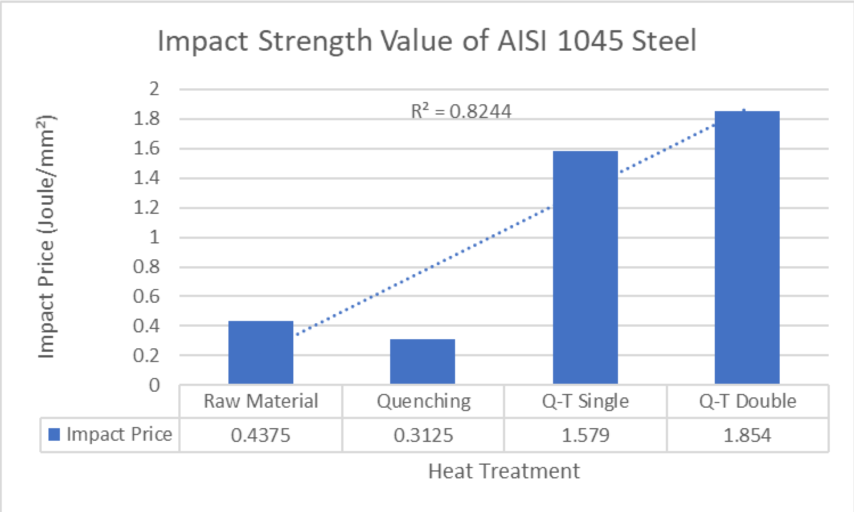

Figure 4. Impact values of AISI 1045 steel with various heat treatments

CONCLUSION

Based on the test results, it can be concluded that the double quenching-tempering treatment provides optimal results for applications requiring high toughness with an average impact energy value of 148.33 J and an average impact value of 1.854 J/mm². The double quenching-tempering process is proven to be more effective in increasing the toughness of AISI 1045 steel. This makes it the best choice for applications that require a balance between impact resistance and hardness. In applications that require high hardness, the quenching process provides the best results with a hardness of 242.38 Kg/mm² and a 44.02% increase in hardness, showing that quenching is more effective in increasing steel hardness.

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