Jurnal Polimesin
Department of Mechanical Engineering
State Polytechnic of Lhokseumawe
http://e-jurnal.pnl.ac.id/polimesin

e-ISSN	: 2549-1999	No.	: 3	Month	: June
p-ISSN	: 1693-5462	Volume	: 21	Year	: 2023

Article Processing Dates: Received on 2023-04-05, Reviewed on 2023-04-30, Revised on 2023-05-01, Accepted on 2023-05-05 and Available online on 2023-06-30

Effect of cooling media on hardness and microstructural changes in S45C carbon steel during heat treatment process

Bambang Hari Priyambodo[1], Reni Laili[2*], Rizqi Ilmal Yaqin[3], Suhartoyo[1]
[1]Mechanical Engineering Department, Sekolah Tinggi Teknologi Warga Surakarta, Sukoharjo 57552, Indonesia
[2]Industrial Engineering Department, Universitas Bina Darma Palembang, Palembang 30111, Indonesia
[3]Ship Machinery Department, Politeknik Kelautan dan Perikanan Dumai, Dumai 28826, Indonesia
*Corresponding author: lailireni20@gmail.com

Abstract

S45C Carbon steel is commonly used in the manufacturing of structural or machine components due to its numerous advantages. However, to fulfill its intended purpose, the mechanical properties of this material require improvement. One approach to achieve this is through heat treatment using different cooling fluids. Therefore, this study aimed to examine the effect of varying cooling fluids on heat treatment of S45C carbon steel, specifically its hardness and microstructure changes. The experimental method employed involves heating the specimens in a furnace at 850°C for 30 minutes, followed by cooling using different fluids, namely water, ice water, and oil. The results showed that faster cooling led to an increase in hardness. In particular, the specimens cooled using water, ice, and oil yielded hardness values of 697 HV, 481 HV, and 248 HV, respectively. The highest hardness value of 697 HV was achieved using ice water, indicating an increase of around 281%. The phase changes observed on the surface of the specimen showed the dominance of martensite.

Keywords: S45C, heat treatment, cooling fluids, hardness, microstructure.

1 Introduction

The advancement of the industry has led to the development of various materials science technologies, including metals. Consequently, numerous business entities have adopted metal processing and utilization as key components of their production. The study found that steel production keeps increasing every year due to its constant demand [1], [2]. Carbon steel, an alloy of steel and carbon, has been utilized since the inception of the industrial era. With the increasing demand for materials in the industrial sector, there is a growing need for materials with exceptional mechanical properties. Carbon steel is a wide material in the production of tools, agricultural equipment, automotive components, and household items [3], [4]. In the component manufacturing industry, different mechanical properties are required for various materials. Consequently, heat treatment process is often necessary to attain the desired mechanical properties for their intended use.

Heat treatment process involves heating a solid metal and then rapidly cooling it by using different coolant fluids, leading to increased mechanical properties. The purpose of this process is to improve certain mechanical properties based on the selected heating and cooling procedures [5]. Specifically, heat treatment of steel is a carefully regulated process that involves heating and cooling techniques [6]–[8].

In recent years, several studies have been conducted on steel treatment based on the rapid cooling process [9]–[11]. This process requires effective quenching, which is dependent on the cooling characteristics of the quenching medium and the metal's ability to reach a specific temperature. To achieve this, there are several types of quenching media available [12], namely gas (N_2, H_2, Ar, and He) and immersion liquids (water, oil, and so on) [8]. It is important to note that heat-treated materials undergo phase changes, microstructure modification, and crystallography transformations [13], [14]. Furthermore, heat treatment improves the mechanical properties of steel such as hardness, tensile strength, ductility, and shock load resistance [5]. Heat treatment is also a process used to optimize the mechanical properties of materials. Several studies have been conducted in this aspect in order to improve the mechanical properties of materials. For instance, Li et al [15] and Biswas [16] conducted a study on heat treatment that can improve microstructure, as well as material hardness. Similarly, Maurya et al [17] found that heat treatment could cause microstructural changes by altering heat distribution. Another research by Zheng et al [18] reported that heat treatment increased mechanical properties. It is crucial to acknowledge that the cooling media used during heat treatment can significantly impact the process's performance [19].

According to Abaas [20], differences in hardness were observed based on the volume of the cooling medium used for heat treatment of carbon steel. Similarly, Pita's study [21] examined the impact of different cooling media on the quenching heat treatment process of knives and found varying hardness values for each cooling medium used. The high viscosity of certain cooling media leads to a slower cooling rate, and eventually causes a lower hardness value than other cooling media.

Despite the numerous findings, the study on quenching heat treatment, particularly regarding medium carbon steel, which has desirable characteristics in manufacturing has not been extensively explored. Therefore, it is crucial to investigate the impact of different cooling media in heat treatment process. In this study, S45C carbon steel was used, and the treatment involved heating this material to the austenitic phase and subsequently quenching it in water, ice water, and oil. The objective was to analyze the effect of coolant variations on microstructure and hardness of the S45C carbon steel. The novelty of this study was in the impact of cooling media on heat treatment of medium carbon steel, which provided a wider range of choices for the process of fabrication and material engineering. The results offered significant benefits in the search for optimal cooling media information concerning heat treatment of medium carbon steel, which could be leveraged by the manufacturing industry to engineer fabricated materials more efficiently. Ultimately, this finding had the potential to improve the manufacturing process and enhance the quality of fabricated materials. This experiment evaluates the effect of three cooling media during heat treatment of S45C carbon steel on the hardness of metal alloys, as well as observing changes in microstructure.

2 Study Methods

2.1 Specimens

The specimens used in this study were JIS S45C carbon steel rods, which were cut into cylinders with a diameter and thickness of 20mm and 100mm, respectively. To prepare the specimen surface, an orbital sander with sandpaper of grit sizes 400, 600, 800, 1000, and 2000 was used successively. Furthermore, the specimen surface was smoothed using a metal polish called Autosol, which is designed to remove scratches and smoothen metal surfaces by eliminating dirt and scratches.

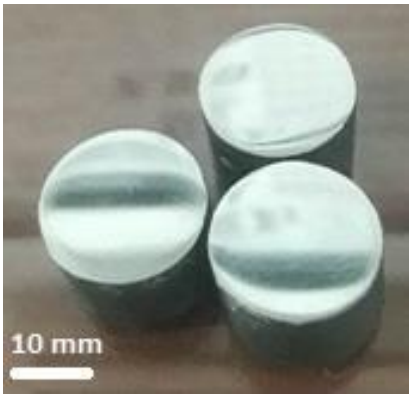

Fig. 1. S45C carbon steel specimens

2.2 Heat Treatment

Fig. 1 shows the S45C carbon steel specimen surface condition, which has been flattened to minimize inhomogeneous heating in the furnace. Meanwhile, Fig. 2 shows the heating process of the test object in a furnace at a temperature of 850°C (austenitic phase) for 30 minutes. The rapid cooling process was conducted by immersing the specimen in different cooling fluids, namely water, ice water, and oil.

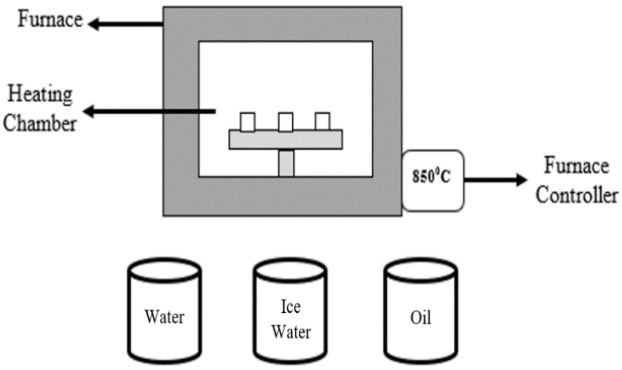

Fig. 2. Cooling fluids in heat treatment processes

2.3 Testing

Various methods were employed to determine the initial conditions of the tested specimens. Spectrometer testing was utilized to ascertain the chemical composition of the materials used in heat treatment. Additionally, the micro-Vickers hardness test method was employed to measure the hardness of the specimens. This method uses a pyramid-shaped diamond indenter with an angle of 136 degrees and a square base. The hardness testing was conducted following the ASTM E92 standard using a load of 0.49N and was held for 10 seconds [14]. Each specimen was tested for hardness 5 times, then the average was calculated.

To prepare the specimens for microstructure testing, the initial step involved cleaning any dirt on the surface, followed by smoothing using metal polish. The finely ground specimens were then watched with purified water and immersed in an etching solution composed of 1 ml of HNO_3 and 20 ml of alcohol. After waiting for 20 seconds, the etching solution is removed from the surface of the specimen. Subsequently, the surface was observed using a photo-optical microscope connected to a computer to determine the position and target image. A test was conducted to assess the changes in the condition of microstructure on the specimen surface during heat treatment process with various coolant fluids.

To ensure accurate and replicable results, it is crucial to thoroughly explain the method used. Specifically, the size, volume, replication, and workmanship techniques are described in detail in order to assist further studies. Established methods can be explained briefly by citing relevant references.

3 Results and Discussion.

The first test conducted in the study was to determine the chemical composition of the S45C specimen using a spectrometer. The results indicated that the main composition of the elements is 98.48% Fe and 0.481% C. These findings confirm that the specimens used meet the specifications of S45C carbon steel [22]. The results of the chemical composition tests are consistent with the investigation. The composition of the specimens used is summarized in Table 1.

Table 1**.** Chemical composition of S45C carbon steel

Element	**Specimen**	
	297/20-S682 (%)	**Deviation Standard**
C	0.481	0.0020
Si	0.223	0.0053
Mn	0.498	0.0057
P	<0.0100	0.0019
Si	<0.0100	0.0004
Cr	0.297	0.0024
Mo	0.020	0.0012
Ni	<0.0100	0.0015
Cu	0.010	0.0025
Al	0.008	0.0002
Co	<0.0050	0.0007
Mg	<0.0050	0.0001
Nb	0.021	0.0008
Ti	0.006	0.0003
V	<0.0050	0.0004
W	<0.100	0.0100
Fe	98.400	0.0130

Hardness testing was conducted on specimens that had been heat-treated at a temperature of 850°C and then cooled using water, ice water, and oil cooling fluids. The material's hardness was measured before and after treatment using a Vickers microhardness tester. The results of the steel hardness measurements are shown in Fig. 3. After examining the indentation traces, it was observed that S45C carbon steel treated with ice water cooling fluids had a higher hardness of 697 HV than other specimens, such as S45C non-treated, S45C water quenched, and S45C oil quenched, each having respective values of 206 HV, 481 HV, and 248 HV.

Heating the test specimen at 850°C for 30 minutes and rapidly cooling it using ice water led to the formation of a martensite structure in steel, as shown in Fig. 4. This formation led to an increase in the hardness of S45C carbon steel. Additionally, the rapid cooling process produced a smaller grain size on the specimen surface compared to the non-treated specimen. This phenomenon occurs because optimal grain growth was hindered due to the rapid cooling process. Consequently, an increase in grain boundaries occurred, which strengthened the resistance against plastic deformation on the specimen surface [23].

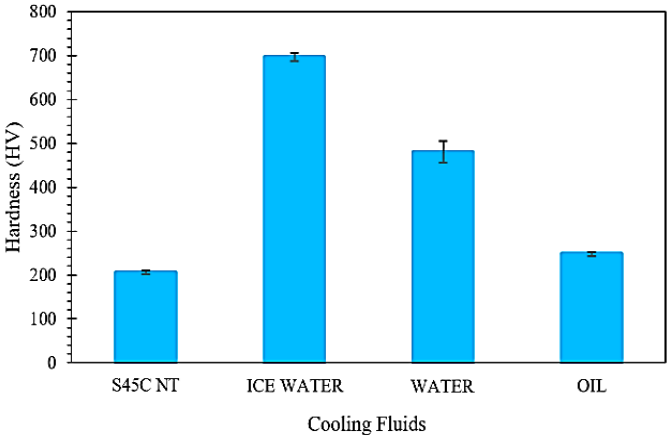

Fig. 3. Hardness values before and after heat treatment process with different cooling fluids at S45C

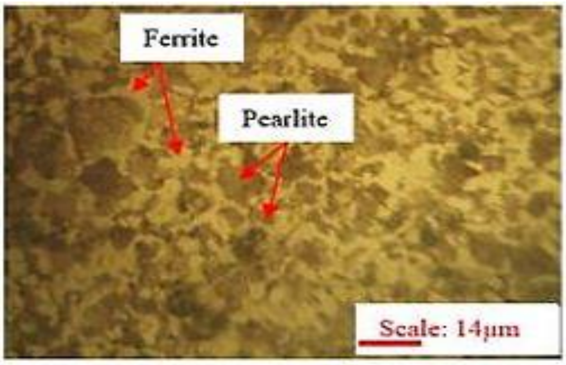

Fig. 4. Micro-structure of S45C non-treatment

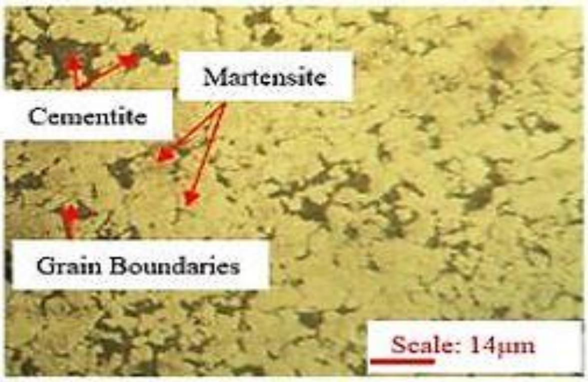

Fig. 5. Micro-structure of S45C quenched in ice-water

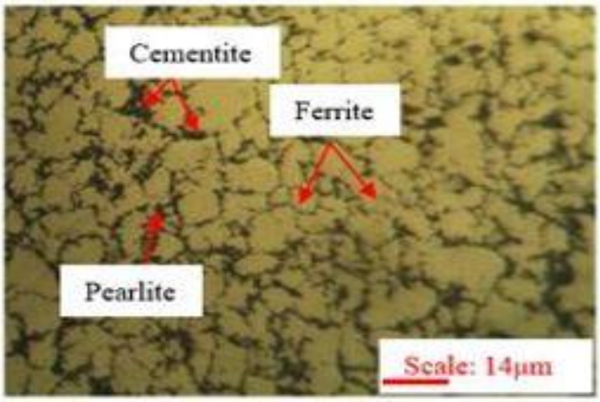

Fig. 6. Micro-structure of S45C quenched in water

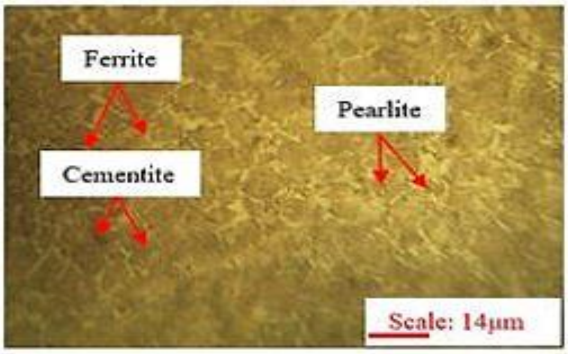

Fig. 7. Micro-structure of S45C quenched in oil

Ferrite, Pearlite, Martensite, and Cementite are all microstructures that can be found in steel and other alloys, and they have different effects on Vickers hardness. Ferrite is formed when steel is cooled slowly from high temperatures, and it has a body-centered cubic crystal structure. Pearlite is a mixture of ferrite and cementite, and it is formed when steel is cooled slowly from high temperatures. Pearlite has a layered structure, with alternating layers of ferrite and cementite. Pearlite has a higher Vickers hardness than ferrite but lower than martensite. Martensite is a very hard and brittle phase in steel, and it has a high Vickers hardness. Martensite is formed when steel is cooled rapidly, usually by quenching in water or oil. Martensite has a body-centered tetragonal crystal structure, and its high hardness is due to the distortion of the crystal lattice during quenching. Cementite is a hard and brittle phase in steel, and it has a high Vickers hardness. Cementite is a compound of iron and carbon with the chemical formula Fe3C, and it is often found in steel as small, dispersed particles. The hardness of cementite comes from its crystal structure, which is a type of iron carbide.

Microstructure observation results through a microscope reveal that the S45C Non-treatment (NT) specimen exhibits a large amount of ferrite (light color) and a small amount of pearlite (black color), as shown in Fig. 4. The presence of a ferrite structure in steel leads to low mechanical properties of steel, thereby making it mild steel. On the other hand, after being heat treated at a temperature of 850^{o}C for 30 minutes and cooled with different cooling fluids, various microstructure changes have been observed in S45C carbon steel. Microstructure of the specimens cooled in ice water revealed a higher proportion of martensite and cementite structures, as well as larger visible grain boundaries as shown in Fig. 5. The ice-water cooling method causes changes in the pearlite structure, increasing steel's hardness. Conversely, water cooling led to larger ferrite, pearlite, and cementite structures, as illustrated in Fig. 6. The hardness of the specimens cooled with water is lower than when cooled using ice because the process is faster. As shown in Fig. 7, microstructure of the specimens cooled with oil shows that the ferrite, pearlite, and cementite phases have larger sizes compared to microstructure of the specimens cooled with ice-water and water-cooling fluids.

However, the grain boundaries appear finer than those of the S45C Non-treated specimens. The microstructure of a material can have a significant impact on its mechanical properties, including its Vickers hardness. Vickers hardness is a measure of a material's resistance to indentation or penetration, and it is often used to assess the strength and durability of materials. In general, a material with a fine-grained microstructure will have a higher Vickers hardness than a material with a coarse-grained microstructure. This is because smaller grains in a material allow for a higher density of defects and dislocations, which impede the motion of dislocations under applied stress and make the material more resistant to deformation.

4 Conclusions.

This study aims to determine the effect of cooling media on the hardness and microstructure of S45C. The test results for S45C carbon steel showed that the S45C Non-treated specimens had a hardness of 206 HV, while ice water quenching produced a significantly higher hardness value of 697 HV. The water- and oil-quenched specimens had hardness values of 481 HV and 248 HV, respectively. These results indicate that ice water quenching leads to higher hardness compared to the other methods. Heat treatment of S45C carbon steel specimens at a temperature of 850°C for 30 minutes, using different quenching methods, causes changes in microstructure. Before heat treatment, microstructure consisted of ferrite and pearlite phase grains. After heat treatment with rapid cooling, martensite and cementite phase grains were produced, as evidenced by microstructure analysis.

References.

[1] J. Morfeldt, W. Nijs, and S. Silveira, "The impact of climate targets on future steel production - An analysis based on a global energy system model," *J Clean Prod*, vol. 103, pp. 469–482, 2015, doi: 10.1016/j.jclepro.2014.04.045.

[2] P. Wang *et al.*, "Efficiency stagnation in global steel production urges joint supply- and demand-side mitigation efforts," *Nat Commun*, vol. 12, no. 1, Dec. 2021, doi: 10.1038/s41467-021-22245-6.

[3] N. Haghdadi, M. Laleh, M. Moyle, and S. Primig, "Additive manufacturing of steels: a review of achievements and challenges," *Journal of Materials Science*, vol. 56, no. 1. Springer, pp. 64–107, Jan. 01, 2021. doi: 10.1007/s10853-020-05109-0.

[4] B. H. Priyambodo, R. I. Yaqin, Margono, K. C. Nugroho, "Pengaruh Perlakuan Annealing dan Shoot Peening terhadap Kekerasan dan Struktur Mikro Pada Baja Karbon JIS S45C," Jurnal Teknologi Terapan (JTT) 7 (2), 138-144, 2021, doi: 10.31884/jtt.v7i2.347.

[5] O. O. Agboola *et al.*, "Optimization of heat treatment parameters of medium carbon steel quenched in different media using Taguchi method and grey relational analysis," *Heliyon*, vol. 6, no. 7, Jul. 2020, doi: 10.1016/j.heliyon.2020.e04444.

[6] B. Nalcaci, O. C. Aydin, S. Yilmaz, and V. Kilicli, "Effect of Interrupted Quenching on the Microstructure, Mechanical Properties and Dislocation Density of Steel AISI 4340," *Metal Science and Heat Treatment*, 2023, doi: 10.1007/s11041-023-00843-z.

[7] Y. Cui, Y. F. Zhang, F. Yu, Y. Wang, Y. L. Zhao, and W. Q. Cao, "Influence of multiple quenching treatment on microstructure and tensile property of AISI M50 steel," *Mater Lett*, vol. 340, Jun. 2023, doi: 10.1016/j.matlet.2023.134175.

[8] A. A. Adeleke, P. P. Ikubanni, T. A. Orhadahwe, J. O. Aweda, J. K. Odusote, and O. O. Agboola, "Microstructural assessment of AISI 1021 steel under rapid cyclic heat treatment process," *Results in Engineering*, vol. 4, pp. 1–4, Dec. 2019, doi: 10.1016/j.rineng.2019.100044.

[9] P. P. Ikubanni, A. A. Adediran, A. A. Adeleke, K. R. Ajao, and O. O. Agboola, "Mechanical properties improvement evaluation of medium carbon steels quenched in different media," *International Journal of Engineering Research in Africa*, vol. 32, pp. 1–10, 2017, doi: 10.4028/www.scientific.net/JERA.32.1.

[10] J. O. Aweda, T. A. Orhadahwe, and I. O. Ohijeagbon, "Rapid Cyclic Heating of Mild Steel and its Effects on Microstructure and Mechanical properties," in *IOP Conference Series: Materials Science and Engineering*, Institute of Physics Publishing, Sep. 2018. doi: 10.1088/1757-899X/413/1/012016.

[11] T. O. Joshua, O. S. I. Fayomi, O. Seriki Ege, and N. E. Udoye, "Evaluation of microstructural and structural characterization of rolled medium carbon steel quenched in different media," *IOP Conf Ser Mater Sci Eng*, vol. 1107, no. 1, p. 012079, Apr. 2021, doi: 10.1088/1757-899x/1107/1/012079.

[12] A. Rafaaltaweel and M. Tolouei-Rad, "Effect Of Quenching Media, Specimen Size And Shape On The Hardenability Of Aisi 4140 Steel," *Emirates Journal for Engineering Research*, vol. 19, no. 2, pp. 33–39, 2014.

[13] V. Sreeja, P. Dinesh, and S. B. Patil, "Study of Mechanical Properties of Steel Quenched in a Blend of Biodegradable Oils with Quench Accelerators," *IJLTEMAS*, vol. 5, no. 5, pp. 20–24, 2016, [Online]. Available: www.ijltemas.in

[14] F. X. Ding, L. F. Lan, Y. J. Yu, and M. K. Man, "Experimental study of the effect of a slow-cooling heat treatment on the mechanical properties of high strength steels," *Constr Build Mater*, vol. 241, Apr. 2020, doi: 10.1016/j.conbuildmat.2020.118020.

[15] Z. Li, Z. Peng, Y. Qiu, K. Qi, Z. Chen, and X. Guo, "Study on heat treatment to improve the microstructure and corrosion behavior of ZK60 magnesium alloy," *Journal of Materials Research and Technology*, vol. 9, no. 5, pp. 11201–11219, 2020, doi: 10.1016/j.jmrt.2020.08.004.

[16] P. Biswas, A. Kundu, D. Mondal, and P. Kumar Bardhan, "Effect of heat treatment on microstructure behavior and hardness of en 8 steel," in *IOP Conference Series: Materials Science and Engineering*, Institute of Physics Publishing, Jul. 2018. doi: 10.1088/1757-899X/377/1/012065.

[17] R. Maurya, D. Mittal, and K. Balani, "Effect of heat-treatment on microstructure, mechanical and tribological properties of Mg-Li-Al based alloy," *Journal of Materials Research and Technology*, vol. 9, no. 3, pp. 4749–4762, 2020, doi: 10.1016/j.jmrt.2020.02.101.

[18] J. Zheng *et al.*, "Effect of heat treatment on mechanical properties and microstructure evolution of Mg-9.5Gd-4Y-2.2Zn-0.5Zr alloy," *Journal of Magnesium and Alloys*, vol. 10, no. 4, pp. 1124–1132, Apr. 2022, doi: 10.1016/j.jma.2021.05.018.

[19] L. Hou, H. Cheng, J. Li, Z. Li, B. Shao, and J. Hou, "Study on the cooling capacity of different quenchant," in *Procedia Engineering*, 2012, pp. 515–519. doi: 10.1016/j.proeng.2012.01.1061.

[20] A. M. Abaas, A. A. Ramadhan, and F. H. Hasan, "Study the effect of cooling medium on the torsion resistance and hardness of medium carbon steel," in *IOP Conference Series: Materials Science and Engineering*, Institute of Physics Publishing, 2018. doi: 10.1088/1757-899X/405/1/012005.

[21] M. Pita and L. Lebea, "Investigating the Effect of Cooling Media on Hardness, Toughness, Coefficient of Friction, and Wear Rate of Mild Steel Heat Treated at Different Temperatures," *Material Design and Processing Communications*, vol. 2022, 2022, doi: 10.1155/2022/3564875.

[22] B. H. Priyambodo, Margono, K. C. Nugroho, N. T. Atmoko, and R. I. Yaqin, "Effect of Oil Quenching and Shot Peening to Improve Hardness Behavior of S45C Carbon Steel," *Materials Science Forum*, vol. 1067, pp. 27–33, 2022, doi: 10.4028/p-dt2v5c.

[23] Akhyar *et al.*, "Evaluation of Welding Distortion and Hardness in the A36 Steel Plate Joints Using Different Cooling Media," *Sustainability (Switzerland)*, vol. 14, no. 3, Feb. 2022, doi: 10.3390/su14031405.