Analysis of the Impact of Cooling Medium Temperature on Heat Treatment Properties of AISI 1040 Steel

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Abstract. Materials play a crucial role in shaping human history and civilization, with metals, polymers, ceramics, and composites being fundamental to advancements in science and technology. Among metals, steel is favored in the manufacturing industry for its superior hardness and toughness. The heat treatment process significantly influences the material properties of steel. This study employs a PMI Master Smart Oxford OES (Optical Emission Spectrometry) device for composition analysis, an optical microscope for microstructural examination, and the Vickers method for hardness testing. AISI 1040 steel specimens were heated in a muffle furnace at 720°C for 60 minutes, followed by quenching in cold water (5°C), room temperature water (30°C), and hot water (70°C). The results showed that the specimen quenched in cold water exhibited the highest hardness value of 258.39 HV, with a microstructure comprising 45.45% pearlite and 54.55% ferrite. In contrast, the specimen quenched in hot water displayed the lowest hardness value of 215.09 HV, with a microstructure consisting of 29.20% pearlite and 70.80% ferrite. These findings highlight the significant impact of quenching medium temperature on the hardness and microstructural characteristics of AISI 1040 steel.

Keywords: Heat treatment, AISI 1040 steel, water quenching, water temperature.

1 Introduction

Materials are fundamental to technological advancements and the development of human civilization[1]. Their properties influence various applications across multiple fields, from construction to aerospace and automotive industries [2], [3]. Metals, in particular, have played a pivotal role due to their strength, ductility, and versatility [4]. Among these, steel stands out for its exceptional mechanical properties and widespread use [5].

Steel, an alloy primarily composed of iron and carbon, is renowned for its high strength-to-weight ratio, making it a preferred choice in various manufacturing processes [6], [7]. The selection of specific steel grades, such as AISI 1040, is critical based on their mechanical properties and suitability for specific applications [8], [9]. AISI 1040 steel, known for its medium carbon content, offers a good balance between strength and ductility, making it suitable for components requiring high wear resistance[10]

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The mechanical properties of steel can be significantly altered through heat treatment processes, which include annealing, quenching, and tempering [11]. Heat treatment modifies the microstructure of the material, resulting in changes in hardness, toughness, and ductility [12]. Quenching, a common heat treatment method, involves rapidly cooling the steel from a high temperature to trap a specific microstructure, typically martensite, which enhances hardness [13].

The choice of quenching medium—be it water, oil, or air—has a profound impact on the cooling rate and the resulting microstructure of the steel [14]. Water is a popular cooling medium due to its high heat transfer coefficient, although its effectiveness can vary significantly with temperature [15]. The cooling rate determines the phase transformation that occurs during quenching, ultimately influencing hardness and other mechanical properties [16].

For AISI 1040 steel, the balance between pearlite and ferrite phases plays a critical role in defining its hardness. The pearlite phase contributes significantly to hardness, while the ferrite phase provides ductility [17]. Understanding the relationship between cooling conditions and microstructural evolution is essential for optimizing the heat treatment processes to achieve desired material properties [18].

Despite the extensive research on heat treatment processes, there remains a need for more detailed studies focusing on the specific effects of varying cooling medium temperatures on AISI 1040 steel. This study aims to investigate how different quenching temperatures—cold water (5°C), room temperature water (30°C), and hot water (70°C)—affect the hardness and microstructure of AISI 1040 steel. The findings will contribute to a deeper understanding of how quenching conditions can be optimized for improved material performance in various applications.

This research is poised to fill existing gaps in the literature by systematically analyzing the impact of cooling media on the properties of AISI 1040 steel. By employing advanced analytical techniques, this study seeks to provide valuable insights that can inform both theoretical understanding and practical applications in metallurgy.

2 Methods

This research utilized a combination of literature review and experimental observation. The study focused on the testing of chemical composition for the test specimen, which is AISI 1040 steel (refer to Figure 1). The chemical composition of the specimen was determined using the PMI Master Smart Oxford OES (Optical Emission Spectrometry) machine (Table 1). Prior to testing, the specimen was polished to remove any corrosion. Once prepared, the specimen was placed in the OES machine for analysis, allowing for the observation of its chemical composition.

Fig. 1. Specimen AISI 1040 Steel (Medium Carbon Steel).

The heat treatment involved heating the specimen to 720°C with a holding time of 60 minutes. Three different quenching water temperatures were tested: cold water (5°C), room temperature water (30°C), and hot water (70°C). Microstructural testing aimed to examine the phase structure and characteristics of AISI 1040 steel before and after heat treatment. This analysis was conducted using metallographic techniques with an optical microscope. Proper surface preparation of the specimen was essential for accurate microstructural observation. Hardness was assessed using the Vickers method, which was performed on the specimens before and after the heat treatment process to evaluate the impact of quenching temperature on hardness values.

Table 1. Chemical Composition of the Specimen (Medium Carbon Steel).

Element	Fe	C	Si	Mn	P	S	Cr	Mo	Ni
Composition (%)	98.4	0.392	0.29	0.832	0.0092	0.0052	0.0084	0.005	0.0152

3 Results and Discussion

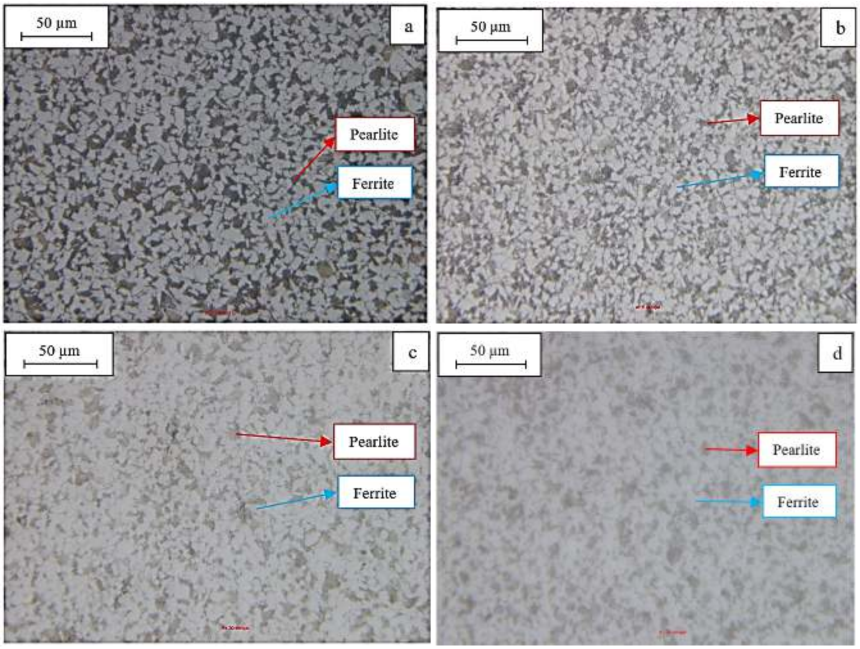

Fig. 2. Microstructure using an optical microscope after air quenching at temperatures (a) without heat treatment process; (b) 5°C; (c) 30°C; (d) 70°C.

(Fig. 2.)The calculations based on the ASTM E562 method and microstructural analysis revealed the percentage comparison of ferrite and pearlite phases at a magnification of

500x using an optical microscope. The results showed that the non-heat-treated specimen contained 68.36% ferrite and 31.64% pearlite. The cold water quenching (5°C) yielded 54.55% ferrite and 45.45% pearlite, while the room temperature water quenching (30°C) resulted in 66.08% ferrite and 33.92% pearlite. Lastly, the hot water quenching (70°C) exhibited 70.80% ferrite and 29.20% pearlite.

The reduction in ferrite content in the cold water quenched specimen indicates a transformation favoring the formation of pearlite, which is known for its strength and hardness. This suggests that quenching at lower temperatures can enhance the mechanical properties of AISI 1040 steel, making it more suitable for applications requiring higher strength.

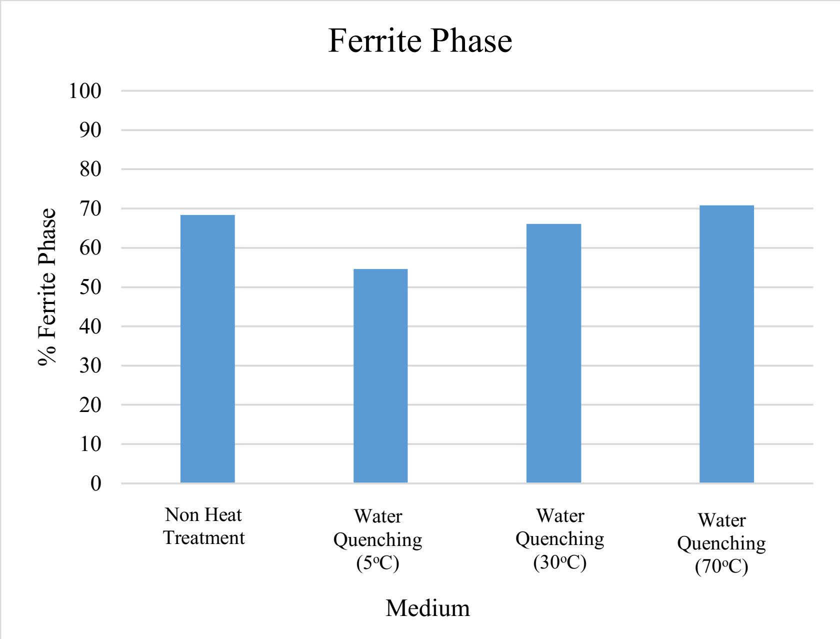

Fig. 3. Graph of Ferrite Phase Percentage.

Fig. 3. illustrates the percentage of ferrite phases in descending order: the specimen quenched in hot water (70°C) had the highest ferrite content at 70.80%, followed by the non-heat-treated specimen at 68.36%. The room temperature quenching (30°C) specimen had 66.08% ferrite, and the cold water quenched specimen (5°C) had the lowest ferrite percentage at 54.55%.

This trend highlights the impact of quenching temperature on phase distribution. The higher ferrite content in the hot water quenched specimen correlates with its softer properties, suggesting that this method may be less effective for applications requiring high strength. The microstructural transformations observed are essential for understanding how different quenching conditions affect material properties.

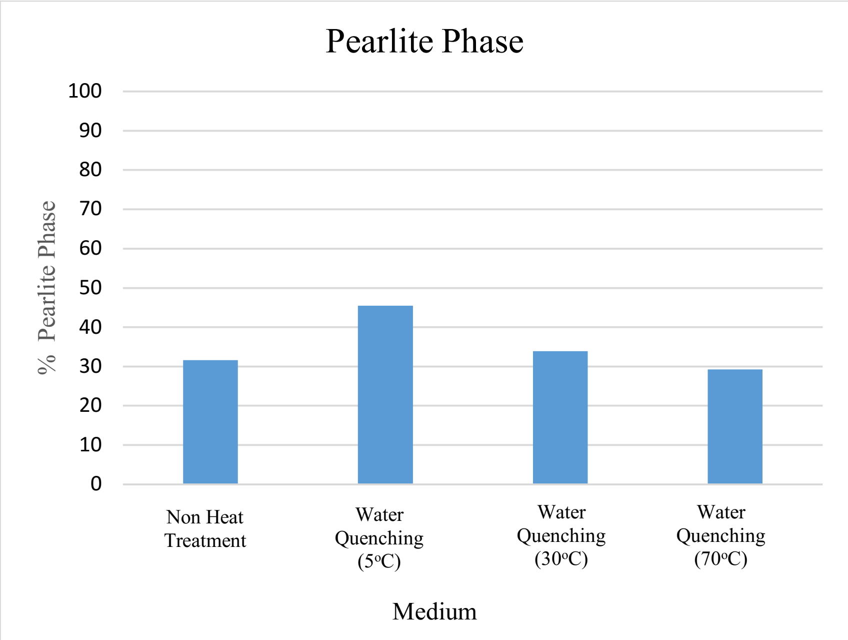

Fig. 4. Graph of Pearlite Phase Percentage.

Fig. 4. depicts the percentage of pearlite phases from highest to lowest: the cold water quenched specimen (5°C) showed the highest pearlite content at 45.45%, followed by the room temperature quenched specimen (30°C) at 33.92%. The non-heat-treated specimen had 31.64% pearlite, while the hot water quenched specimen (70°C) had the lowest pearlite percentage at 29.20%.

The increase in pearlite in the cold water quenched specimen illustrates the effectiveness of rapid cooling in promoting stronger phase formations. This suggests that controlling quenching parameters can optimize the desired balance of ferrite and pearlite, which is critical in tailoring the material's mechanical properties for specific engineering applications.

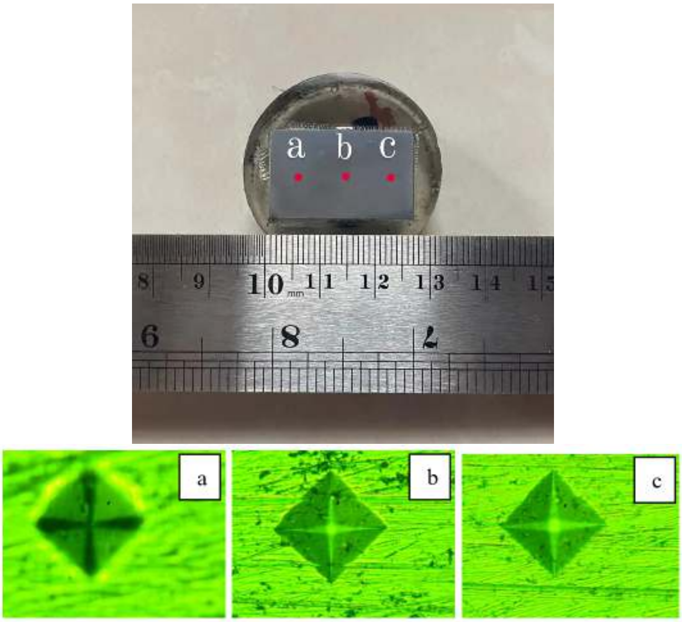

Fig. 5. Three Different Points during Vickers Hardness Testing on the Specimen: (a) Point One, (b) Point Two, and (c) Point Three.

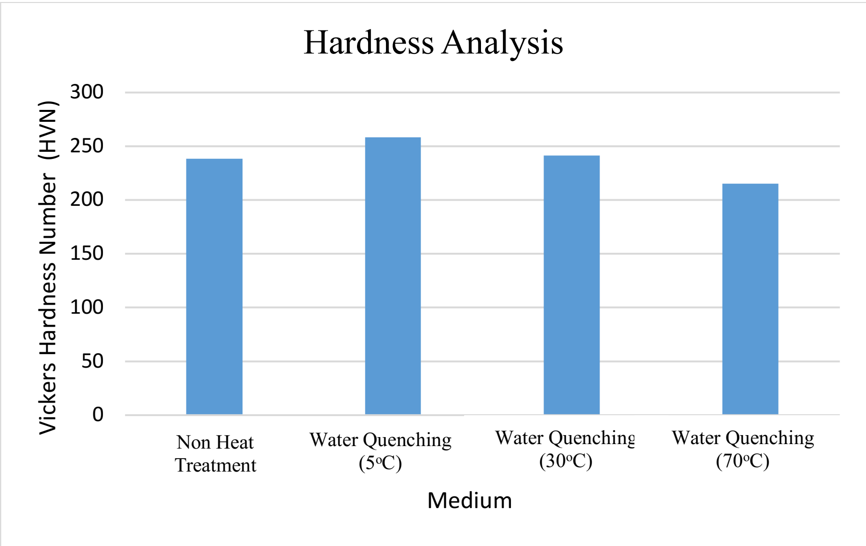

Fig. 6. Graph of Hardness Analysis.

Fig. 6. presents the average hardness values from highest to lowest: the cold water quenched specimen (5°C) had an average hardness of 258.39 HV, followed by the room temperature quenched specimen (30°C) with 241.59 HV. The non-heat-treated specimen showed an average hardness of 238.47 HV, while the hot water quenched specimen (70°C) had the lowest average hardness of 215.09 HV.

These hardness results reinforce the correlation between microstructural composition and mechanical properties. The increased hardness in the cold water quenched specimen is indicative of its higher pearlite content, which contributes to improved wear resistance and strength. This highlights the significance of heat treatment processes in enhancing the performance of medium carbon steels like AISI 1040.

4 Conclusion

1. The study demonstrated that the microstructural composition of AISI 1040 steel varied significantly with quenching temperature, with the non-heat-treated specimen containing 68.36% ferrite and 31.64% pearlite. Cold water quenching (5°C) resulted in 54.55% ferrite and 45.45% pearlite, while hot water quenching (70°C) yielded 70.80% ferrite and 29.20% pearlite.

2. The results indicate that lower quenching temperatures favor pearlite formation, enhancing the mechanical properties of the steel. The cold water quenched specimen exhibited the highest average hardness of 258.39 HV, underscoring the importance of controlling quenching parameters to optimize material properties.

3. The percentage of ferrite decreased with cold water quenching, highlighting the transformation favoring pearlite, which is known for its strength and hardness. This suggests that quenching at lower temperatures can improve the suitability of AISI 1040 steel for applications requiring higher strength.

4. The study also revealed that the hot water quenched specimen had the highest ferrite content but the lowest hardness (215.09 HV), indicating that higher ferrite content may lead to softer mechanical properties, making it less suitable for high-strength applications.

5. Overall, these findings emphasize the critical role of heat treatment processes in tailoring the microstructure and enhancing the performance of medium carbon steels like AISI 1040 for specific engineering applications, particularly those that require an optimal balance of strength and wear resistance.

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References

[1] D. Alemayehu Tegegn, “The role of science and technology in reconstructing human social history: effect of technology change on society,” *Cogent Soc Sci*, vol. 10, no. 1, Dec. 2024, doi: 10.1080/23311886.2024.2356916.

[2] S. Septianissa, B. Prawara, E. A. Basuki, E. Martides, and E. Riyanto, “Improving the hot corrosion resistance of γ/γ’ in Fe-Ni superalloy coated with Cr3C2-20NiCr and NiCrAlY using HVOF thermal spray coating,” *Int J Electrochem Sci*, vol. 17, no. 12, p. 221231, Dec. 2022, doi: 10.20964/2022.12.27.

[3] S. Septianissa, K. W. Widantha, and M. Waldi, “INVESTIGATION OF TEMPERATURES AND HOLDING TIMES ON HIGH-STRENGTH LOW-ALLOY STEEL FOR TANK TRACK LINKS,” *LOGIC : Jurnal Rancang Bangun dan Teknologi*, vol. 24, no. 2, pp. 87–92, Jul. 2024, doi: 10.31940/logic.v24i2.87-92.

[4] W. Ji, R. Zhou, P. Vivegananthan, M. See Wu, H. Gao, and K. Zhou, “Recent progress in gradient-structured metals and alloys,” *Prog Mater Sci*, vol. 140, p. 101194, Dec. 2023, doi: 10.1016/j.pmatsci.2023.101194.

[5] W. Jia *et al.*, “Transverse mechanical properties and microstructure of 1500 mm wide AZ31 magnesium alloy plate and its evolution during industrial rolling,” *Journal of Materials Research and Technology*, vol. 27, pp. 7271–7279, Nov. 2023, doi: 10.1016/j.jmrt.2023.11.033.

[6] G. R. Vadolia, K. P. Singh, M. K. Gupta, B. Doshi, and V. Rathore, “Introduction to Isostatic Pressing and Its Optimization,” in *Modeling and Optimization in Manufacturing*, Wiley, 2021, pp. 157–192. doi: 10.1002/9783527825233.ch6.

[7] H. Guo, X. Zhou, and Z. Liu, “Advanced Lightweight Structural Materials for Automobiles: Properties, Manipulation, and Perspective,” *Sci Adv Mater*, vol. 16, no. 5, pp. 563–580, May 2024, doi: 10.1166/sam.2024.4686.

[8] A. R. Machado, L. R. R. da Silva, D. Yu. Pimenov, F. C. R. de Souza, M. Kuntoğlu, and R. L. de Paiva, “Comprehensive review of advanced methods for improving the parameters of machining steels,” *J Manuf Process*, vol. 125, pp. 111–142, Sep. 2024, doi: 10.1016/j.jmapro.2024.07.044.

[9] D. Vukelic, K. Simunovic, Z. Kanovic, T. Saric, B. Tadic, and G. Simunovic, “Multi-objective optimization of steel AISI 1040 dry turning using genetic algorithm,” *Neural Comput Appl*, vol. 33, no. 19, pp. 12445–12475, Oct. 2021, doi: 10.1007/s00521-021-05877-z.

[10] H. V. Ozkavak, S. Sahin, M. F. Sarac, and Z. Alkan, “Wear properties of WC–Co and WC–CoCr coatings applied by HVOF technique on different steel substrates,” *Materials Testing*, vol. 62, no. 12, pp. 1235–1242, Dec. 2020, doi: 10.3139/120.111609.

[11] B. Chandra Kandpal *et al.*, “Effect of heat treatment on properties and microstructure of steels,” *Mater Today Proc*, vol. 44, pp. 199–205, 2021, doi: 10.1016/j.matpr.2020.08.556.

[12] Y. Chen, L. Wang, Z. Feng, and W. Zhang, “Effects of heat treatment on microstructure and mechanical properties of SLMed Sc-modified AlSi10Mg alloy,” *Progress in Natural Science: Materials International*, vol. 31, no. 5, pp. 714–721, Oct. 2021, doi: 10.1016/j.pnsc.2021.08.003.

[13] S. Kumar and S. B. Singh, “Evolution of microstructure during the ‘quenching and partitioning (Q&P)’ treatment,” *Materialia (Oxf)*, vol. 18, p. 101135, Aug. 2021, doi: 10.1016/j.mtla.2021.101135.

[14] P. Singh and S. Singh, “Effect of quenching media on microstructural evolution, mechanical and wear properties of AISI4135 steel,” *Proc Inst Mech Eng C J Mech Eng Sci*, vol. 235, no. 21, pp. 5616–5625, Nov. 2021, doi: 10.1177/0954406221990050.

[15] M. H. Mousa, C.-M. Yang, K. Nawaz, and N. Miljkovic, “Review of heat transfer enhancement techniques in two-phase flows for highly efficient and sustainable cooling,” *Renewable and Sustainable Energy Reviews*, vol. 155, p. 111896, Mar. 2022, doi: 10.1016/j.rser.2021.111896.

[16] G. Mandal, I. Dey, S. Mukherjee, and S. K. Ghosh, “Phase transformation and mechanical properties of ultrahigh strength steels under continuous cooling conditions,” *Journal of Materials Research and Technology*, vol. 19, pp. 628–642, Jul. 2022, doi: 10.1016/j.jmrt.2022.05.033.

[17] D. Prabhu, S. Sharma, P. R. Prabhu, J. Jomy, and R. V. Sadanand, “Analysis of the inhibiting action of pectin on corrosion of AISI1040 dual-phase steel with ferrite–martensite and ferrite–bainite structure: a comparison in 0.5 M sulphuric acid,” *Journal of the Iranian Chemical Society*, vol. 19, no. 4, pp. 1109–1128, Apr. 2022, doi: 10.1007/s13738-021-02368-9.

[18] X. Dong *et al.*, “Heterostructured Metallic Structural Materials: Research Methods, Properties, and Future Perspectives,” *Adv Funct Mater*, Aug. 2024, doi: 10.1002/adfm.202410521.