Step Cooling Influence on Microstructure & Mechanical Properties of Carbon Steel

Hemant Panchal[1], Devanshi Bhaliya[2], Moksha Patel[3]

[1]Assistant Professor, Department of Metallurgical and Materials Engineering, Faculty of Technology and Engineering, The Maharaja Sayajirao University of Baroda, Gujarat, India
[2,3]Graduate Student, Department of Metallurgical and Materials Engineering, Faculty of Technology and Engineering, The Maharaja Sayajirao University of Baroda, Gujarat, India

Abstract

This study delves into the impacts of step cooling on the microstructure and mechanical attributes of carbon steel. Step cooling, a methodical heat treatment process comprising sequential cooling phases, was administered to samples of carbon steel. Through optical microscopy, the evolution of microstructure, encompassing phase alterations and grain structure, was scrutinized. Mechanical traits, including hardness, tensile strength, were assessed via standardized tests, coupled with fractural structural analysis. The findings suggest that step cooling markedly affects microstructural refinement, modifying the distribution of present phases. Furthermore, discernible variations in mechanical properties were noted, revealing enhanced strength and toughness qualities in the step-cooled specimens when juxtaposed with those conventionally cooled. This investigation unveils valuable insights into the potential advantages of step cooling as a viable approach for augmenting the properties of carbon steel, thereby presenting avenues for optimizing its utilization in industrial settings.

Keywords: Plain carbon steel, step cooling, microstructural analysis, mechanical testing

1. Introduction

Steel is a quintessential material in modern engineering, renowned for its versatility and strength across a wide range of applications. One critical aspect that engineers continuously explore is the optimization of steel's microstructure to enhance its mechanical properties. The microstructure of steel plays a pivotal role in determining its strength, toughness, hardness, and other mechanical characteristics. [1]

One approach that has gained significant attention in recent years is step cooling, a heat treatment technique that involves controlled cooling at different stages of the process. Step cooling offers engineers a nuanced method to tailor the microstructure of steel, thereby influencing its mechanical properties. By strategically adjusting the cooling rates at specific temperatures, step cooling can refine grain structure, precipitate desired phases, and alleviate residual stresses, all of which profoundly impact the material's performance. [2, 3]

The influence of step cooling on the microstructure and mechanical properties of steel has been the subject of extensive research. Various parameters, including cooling rates, holding times, and alloy compositions, have been investigated to elucidate their effects on the final properties of the material. Understanding these relationships is crucial for optimizing the manufacturing processes and designing steel components with enhanced performance characteristics. [1-3]

While substantial progress has been made in this field, there remain gaps in our knowledge regarding the precise mechanisms by which step cooling influences the microstructure and mechanical properties of steel. Furthermore, the practical implications of these findings for real world applications necessitate thorough examination and validation.

In this study, we aim to contribute to the existing body of knowledge by investigating the influence of step cooling on the microstructure and mechanical properties of steel. Through comprehensive experimentation and analysis, we seek to uncover valuable insights that can inform the development of advanced steel manufacturing techniques and facilitate the design of high-performance steel components for various industrial applications. [4] Plain carbon steel is widely used in various industrial applications due to its desirable combination of strength, ductility, and affordability. The microstructure and mechanical properties of plain carbon steel can be significantly influenced by heat treatment processes. Among these processes, step cooling heat treatment has gained attention for its potential to enhance the properties of steel. [5-8]

In this research paper, we investigate the effect of step cooling heat treatment on three different grades of plain carbon steel with varying carbon content (0.2%, 0.3%, and 2.0%). [9,10] The steel samples were subjected to heat treatment cycles involving different holding temperatures (800 °C, 600 °C, and 400 °C) followed by air cooling. Microstructural analysis, tensile testing, and hardness testing were conducted on both the as-received samples and the heat-treated samples to evaluate the changes in microstructure and mechanical properties. [5,8,10]

By comparing the results obtained from the as-received samples with those from the heat-treated samples, we aim to elucidate the impact of step cooling heat treatment on the microstructure and mechanical properties of plain carbon steel. This research provides valuable insights into optimizing the heat treatment processes for enhancing the performance of plain carbon steel in industrial applications. [12,13]

2. Methodology

2.1 Material selection

We have selected three grades of plain carbon steel, distinguished as low, medium, and high, with carbon contents of 0.2%, 0.36%, and 0.88% respectively. This choice allows us to examine how the same heat treatment process affects different types of plain carbon steel.

2.2 Heat treatment of Steel Samples

In the initial phase of the experiment, we subjected each grade of steel to a common treatment process. The steel samples were heated to a temperature of 800 °C, representing a critical point where significant structural changes can occur within the material. Once the samples reached this temperature, they were held there for duration of 45 minutes to ensure thorough thermal exposure. Subsequently, the samples were allowed to cool naturally in ambient air conditions.

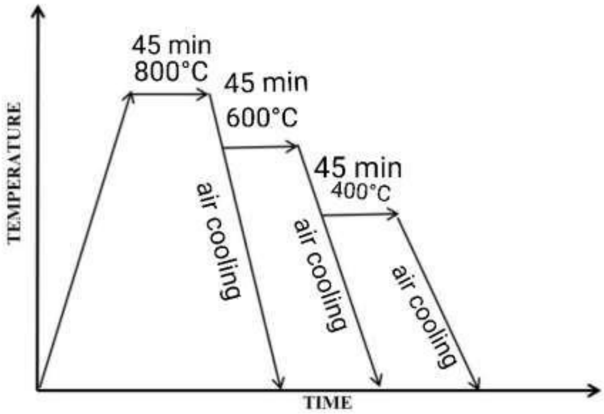
For the second phase of the experiment, we introduced a variation to the cooling process. After the initial heating and holding period at 800 °C, similar to the first phase, we implemented a step-cooling procedure. This involved reducing the temperature of the samples to 600 °C, a temperature below the critical range but still significant enough to induce structural changes. The samples were then maintained at this temperature for 45 minute duration before being air-cooled.

Figure 1: Heat treatment of 0.23% C, 0.36% C and 0.88% C steel samples holding at (a) 800 °C, (c) 600 °C and (c) 400 °C temperature.

(a) (b) (c)

In the final phase of the experiment, we further extended the step-cooling process. Following the initial heating and holding at 800 °C and the subsequent step-cooling to 600 °C, we introduced an additional step-cooling stage to 400 °C. This multi-step cooling process allowed us to explore the effects of a more gradual temperature reduction on the properties of the steel. Each intermediate holding period at 600 °C and 400 °C lasted for 45 minutes before the samples were finally air-cooled.

Figure 2: Heat treatment cycles for 0.23% C, 0.36% C and 0.88% C steel samples



2.3 Specimen preparation for tensile test and hardness test

To conduct hardness tests, a small section was cut from each of the twelve rods across all specimens. These cut samples were then utilized for hardness testing on one side and microstructural analysis on the other side. Metallographic specimens were prepared from the as-received samples by standard metallographic techniques. Optical microscopy was used to examine the microstructure of the samples.

To prepare the tensile test specimens, straight rods were used and shaped into a dumbbell configuration following ASTM standards, utilizing a lathe machine.

The prepared tensile test specimens were then subjected to testing using a Universal Testing Machine (UTM).

3. Testing and Analysis

3.1 Spectroscopy analysis

Spectroscopy analysis of plain carbon steel offers a means to discern its elemental constitution and structural attributes by assessing the emitted or absorbed electromagnetic radiation. This method facilitates the characterization of the material's chemical makeup and the detection of any impurities or alloying components.

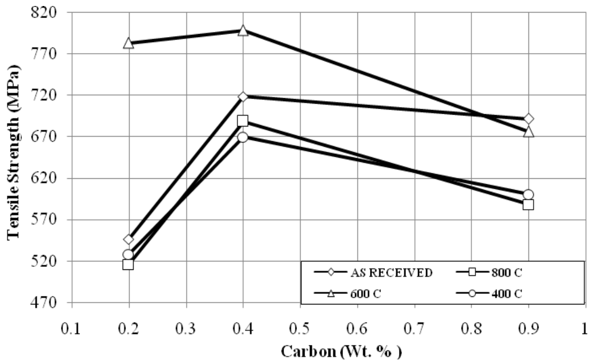
Table:1 Spectroscopy analysis of various ferrous samples

Element	C	Si	Mn	Cr	Mo	Ni	Fe
Cycle 1	0.2368	0.189	0.668	0.250	-	0.109	98.5472
Cycle 2	0.3680	0.236	0.836	0.902	0.1528	-	97.5052
Cycle 3	0.8887	0.2038	0.3590	1.3979	-	-	97.1506

3.2 Tensile Testing

Tensile testing of plain carbon steel involves subjecting the material to controlled stretching until it fractures, allowing for the measurement of its mechanical properties such as yield strength, ultimate tensile strength, and elongation. This method provides crucial insights into the material's structural integrity and performance under tensile forces.

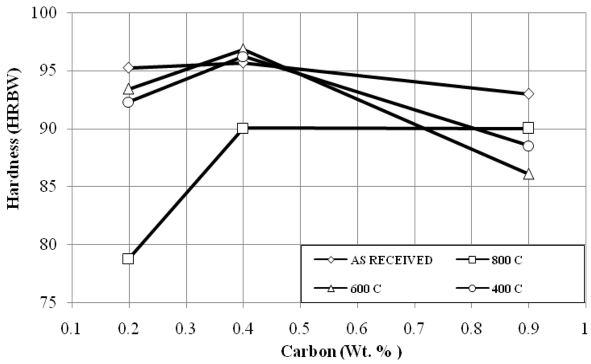
Figure 3: Tensile Test Results



3.3 Hardness Testing

Rockwell hardness testing on the B scale is conducted on plain carbon steel to determine its hardness level by measuring the depth of penetration of a specified indenter under a predetermined load. This method offers a reliable assessment of the material's resistance to indentation and serves as a key indicator of its mechanical strength.

Figure 4: Hardness Test Results



3.4 Microstructure Analysis

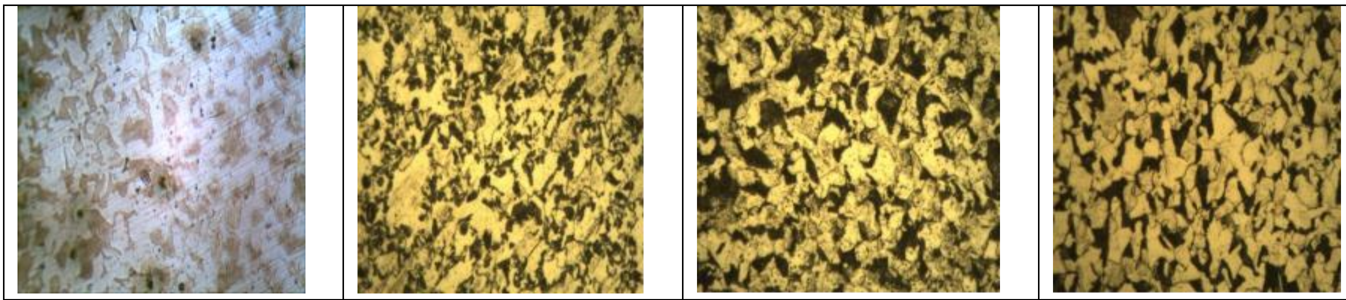
Microstructure analysis of plain carbon steel involves examining its internal structure at a microscopic level to identify various phases, grain boundaries, and defects, providing crucial insights into its mechanical and thermal properties. This analysis aids in understanding the material's behavior under different processing conditions and optimizing its performance for specific industrial applications.

In the received sample of 0.23% carbon steel, the microstructure exhibited a relatively coarse arrangement of ferrite and pearlite grains. Following the normalizing process, the grain size became noticeably finer compared to the as-received state. After undergoing a step cooling process, the grain size became coarser relative to the normalized condition, though it remained finer than the as-received sample. Upon completing a second step cooling stage, the steel displayed a uniform dispersion of ferrite and pearlite with a relatively fine grain structure. An approximate composition of 75% ferrite and 25% pearlite is desired.

In the as-received 0.36% carbon steel sample, the microstructure presents an irregular dispersion of ferrite and pearlite. Post-normalization, the grain size diminishes, promoting a more homogeneously distributed structure. Conversely, the subsequent step cooling process yields a uniform phase distribution, albeit with coarse grains. Upon completion of the final step cooling phase, the grains grow further in size while ensuring an equitable distribution of ferrite and pearlite at an approximate ratio of 50% each.

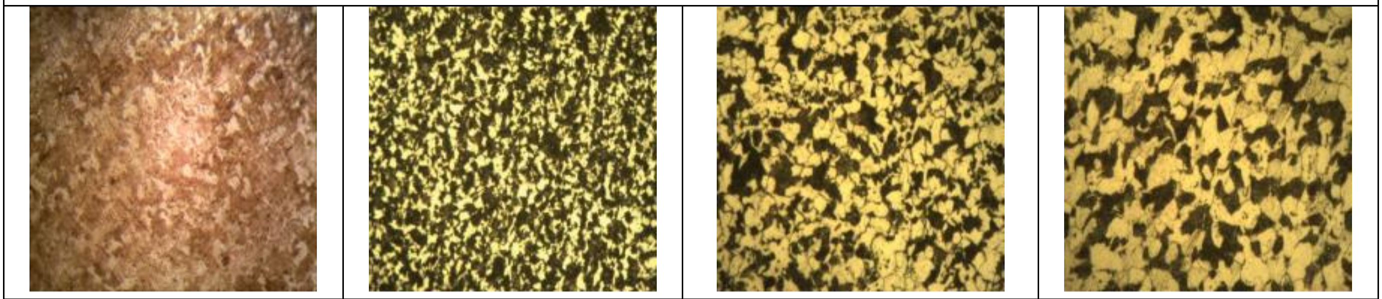
In the as-received 0.88% carbon steel sample, the microstructure is characterized by an absence of clearly defined grain boundaries and an inconsistent allocation of pearlite and cementite. Normalizing fosters a marginally more uniform distribution of pearlite and cementite, albeit with a coarse grain size relative to the as-received state. Subsequent step cooling induces grain enlargement. The concluding phase of the step cooling process results in a microstructure distinguished by finely distributed pearlite and cementite, comprising roughly 2% cementite and 98% fine pearlite.

Figure 5: Microstructure of (a) as received, (b) 800 °C step cooled, (c) 600 °C step cooled and (d) 400 °C step cooled 0.23% C steel at 400X magnification.



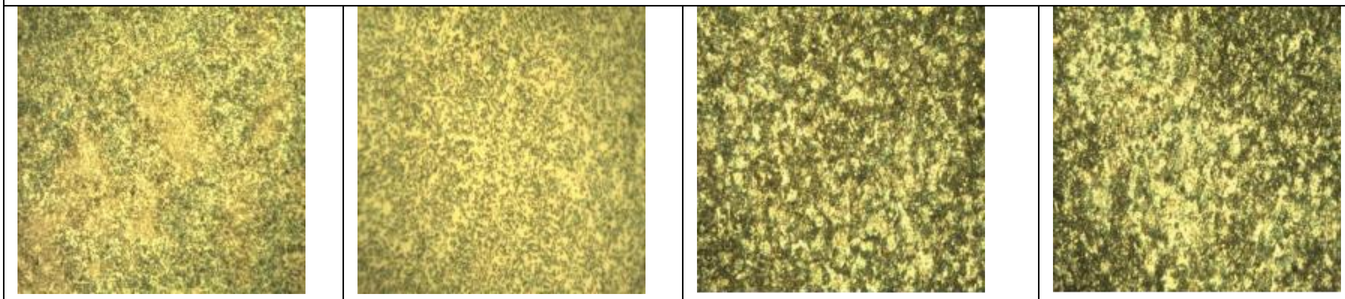
(a) (b) (c) (d)

Figure 6: Microstructure of (a) as received, (b) 800 °C step cooled, (c) 600 °C step cooled and (d) 400 °C step cooled 0.36% C steel at 400X magnification.



(a) (b) (c) (d)

Figure 7: Microstructure of (a) as received, (b) 800 °C step cooled, (c) 600 °C step cooled and (d) 400 °C step cooled 0.88% C steel at 400X magnification.



(a) (b) (c) (d)

4. Conclusion

From the above experimental study, we can draw the following concluding remarks:

1. Hardness of all steel samples increased to the maximum values for 0.36% C at 400 °C, 600 °C and 800 °C step cooling treatment. But, step cooling treatment of 0.4% C at 600 °C, hardness was found highest as compared to 400 °C and 800 °C step cooling.
2. Similar to the hardness of all steel samples, the tensile strength is increased to the maximum values for 0.36% C at 400 °C, 600 °C and 800 °C step cooled steel samples. But, step cooling treatment of 0.4% C at 600 °C, tensile property was found highest as compared to 400 °C and 800 °C.
3. The Sound and more homogeneous distributed microstructure of 0.36% C at 600 °C step cooled sample was found. It is more refined and favorable as far as the mechanical properties are concerned.
2. Hence it is clear from above experimental study that the step cooling treatment of 0.36% C at 600 °C is more advantageous and it is giving improved results of micro-mechanical properties.

5. References

1. Yassin Mustafa Ahmed, “The influence of annealing and normalizing processes on the mechanical properties and chemical composition of carbon steel”, International Journal of Recent Technology and Engineering (IJRTE), Volume-8, Issue-5, 2020, pp: 4928-4933
2. Bhaskar Chandra Kandpal, D.K. Gupta, Ashok Kumar, Ashish Kumar Jaisal, Atul Kumar Ranjan, Ankit Srivastava, Prashant Chaudhary, “Effect of heat treatment on properties and microstructure of steels”, pp 1-7.
3. Saurabh Dewangan, Neha Mainwal, Manwi Khandelwal and Prateek Sunil Jadhav, “Performance analysis of heat treated AISI 1020 steel samples on the basis of various destructive mechanical testing and microstructural behavior”, Australian Journal of Mechanical Engineering, 2019, pp 1-16.
4. Hasan MF, “Analysis of Mechanical Behavior and Microstructural Characteristics Change of ASTM A-36 Steel Applying Various Heat Treatment”, Journal of Material Science & Engineering, Volume 5, Issue 2, 2016, pp 1-6.
5. Akhyar Ibrahim and Sayuti, “Effect of Heat Treatment on Hardness and Microstructures of AISI 1045”, Advanced Materials Research, April 2015, pp 575-579.
6. S. Jyothirmai, I. Aparna Devi, I. Sudhakar and R. Ramesh, “Hardness Prediction Model for En Grade Steels Subjected to Different Heat Treatment Processes Advanced Materials Manufacturing & Characterization”, Vol 4, Issue 2 (2014), pp 106-110.

7. Z. Lu a, R.G. Faulkner, N. Riddle, F.D. Martino, K. Yang, “Effect of heat treatment on microstructure and hardness of Eurofer 97, Eurofer ODS and T92 steels”, Journal of Nuclear Materials, (2009), pp 445–448.
8. Hemant Panchal, Moksha Patel, Devanshi Bhaliya, “Effect of heat dissipation on the final properties of steel upon quenching: A Review”, International Journal of Creative Research Thougth [IJCRT], Volume 11, Issue 9 (2023), pp 60-65.
9. Kunda Du, Zhifeng Lv , Weichao Fan , Ruikong Zhang , Xuexian Li and Lipeng Xu, “Effect of Heat Treatment Process on Microstructure and Mechanical Properties of High-Carbon H13m Steel Processes”, (2023), 11, pp 1-19.
10. Saurabh Dewangan, et. al., “Analyzing strength, hardness and grain-structure of 0.2%-C steel specimens processed through an identical heating period with different continuous transformation rates”, Mater. Res. Express 9 (2022), pp 1-15.
11. Rahul George, Manoj Samson R, Keshav Ottoor, Geethapriyan T, “The Effects of Heat Treatment on The Microstructure and Mechanical Properties of EN19 Steel Alloy”, International Journal of Materials Science and Engineering, (2018) pp 56-66.
12. Mohamed H. Frihat, “Effect of Heat Treatment Parameters on the Mechanical and Microstructure Properties of Low-Alloy Steel”, Journal of Surface Engineered Materials and Advanced Technology, 2015, 5, 214-227.
13. Ashish Bhateja, Aditya Varma, Ashish Kashyap and Bhupinder Singh, “Study the Effect on the Hardness of three Sample Grades of Tool Steel i.e. EN-31, EN-8, and D3 after Heat Treatment Processes Such As Annealing, Normalizing, and Hardening & Tempering”, The International Journal of Engineering And Science (IJES) (2012), Volume 1, Issue 2, pp 253-259.