NILEST JOURNAL OF SCIENCE, TECHNOLOGY, AND MANAGEMENT (NIJOSTAM) VOLUME 4, ISSUE 1, JANUARY, 2025, pp. 11-19
eISSN: 3027-2580 www.nijostam.org

HEAT TREATMENT OF HIGH CARBON STEEL FOR ENGINEERING AND INDUSTRIAL APPLICATION

[1]Aminu O. Yusuf, [2]Aishat O. Salawu and [1]Bucham J. Osang

1. Department of Mechanical Engineering, College of Engineering, Kaduna Polytechnic, Kaduna, Nigeria
2. Department of Metallurgical Engineering, College of Engineering, Kaduna Polytechnic, Kaduna, Nigeria

Correspondence: aminuomeiza40@gmail.com

ABSTRACT

High-carbon steel is widely used in engineering and industrial applications due to its enhanced strength and hardness. Enhancing the mechanical properties of high-carbon steel is a process that will modify its microstructure and display its toughness, hardness, and wear resistance. The focus of this study was the analysis of heat treatment of high-carbon steel that can be used for engineering, structural, or industrial applications. The study commenced with procuring and preparing specimen material for the research. The specimen was subjected to various heat treatment processes, including annealing, normalising, and hardening. The experimental results showed that the annealed specimen recorded a high tensile strength of 1968 Mpa, followed by the normalised samples having 1033 Mpa, implying improved mechanical properties, while the hardened (quenched) specimen recorded 608 Mpa, indicating high wear resistance. The annealed specimen was observed to have a large grain size of pearlite, which was distributed across the entire microstructure surface, indicating a refined grain size and structure. The heat-treated and the received (untreated samples) microstructure were examined. The results also showed that the annealed specimen had a large grain size of pearlite, which was distributed across the entire microstructure surface, implying a refined grain size and structure. In contrast, the hardened samples showed relieved internal stress and were tough enough to resist shock load. The hardness of the specimen was found to have increased by 25%, 50 HRC after the Silica was quenched, compared to the received results obtained from the Rockwell Hardness tester. There was an increase of 15% in hardness when quenched in water compared to as received.

KEYWORDS
Annealing; Specimen; Pearlite; Microstructure; grain-size

ARTICLE HISTORY:
Received: December 2024
Received: in revised: March 2025
Accepted: March 2025
Published online: April 2025

INTRODUCTION

Heat treatment is a controlled process of heating and cooling metals or alloys to alter their microstructure, properties, and performance. This process involves the control of temperature, time, and cooling rates to induce phase transformations, which can significantly impact the material's mechanical, thermal, and electrical properties. The phase transformation will initiate a change in the crystal structure or arrangement of atoms within a material, forming new phases or microstructures suitable for industrial and engineering applications. Since quite a number of engineering, structural, and industrial components/parts carry loads in one form or the other, it follows that analysis of the heat treatment option of such part is essential to determine the mechanical property of the material such component is likely to be subjected to minimise the effects of individual component failure in service. Heat treatment can impart the required or desirable mechanical properties to such components (steel or alloys) for normal operations. Several heat treatment processes involve micro-structural alteration and property changes in the bulk of the material or component.

The research is focused on optimising heat treatment processes, controlling microstructure evolution, reducing energy consumption, and enhancing the performance of high-carbon steel in more demanding applications through various heat treatment processes such as annealing and quenching (Peh, 2019). One of the key challenges in heat treatment, particularly in the quenching process, is controlling the cooling rate. Rapid cooling leads to martensite formation, a hard but brittle phase desirable in some applications. However, if the cooling rate is too fast, it can induce thermal stresses, cracking, and distortion in the material. This research primarily focuses on controlling the cooling rate using quenching media such as water, oil, and air; heat treatment is the controlled heating and cooling of metals to alter their physical and mechanical properties (Rajan *et al.,* 1989). Heat treatment is also an energy-intensive process carried out in different furnaces. Generally, all the heat treatment processes consist of three stages: heating the material, holding the temperature for a time and then cooling, usually to room temperature. During the heat treatment, the material usually undergoes micro-structural and crystallographic changes (Honeycombe & Bhadeshia, (2000).

REVIEW OF RELATED LITERATURE

Wang *et al*. (2023a) explained that the heat treatment process would change the quantity and formation of backward austenite in low-carbon steel. Quenching temperatures up to 950 ℃ can increase the impact toughness of steel and the effectiveness of forming the pearlite and martensite phases. He explained that parts of machines affected by external environmental factors can be heat treated through controlling and quenching to obtain good wear resistance and impact toughness. Hu *et al.* (2023), in their experiment on the texture and mechanical properties of quenching and partitioning of steel, discussed quenching steel using water media. Quenching in water media helps form martensite and ferrite structures, which is desirable for obtaining good mechanical features. The results of his work show an improvement in the hardness values of martensite and ferrite.

Heat treatment of 1030 steel and then quenching by water compared with oil and polyvinyl chloride can improve yield, ultimate strength, hardness, and microstructure, especially when quenching is followed by tempering, which decreases the refinement of pearlite and ferrite phases (Huang, Lei, & Fang, 2023). Jayvardhan *et al.* (2023) emphasise that when using different types of cooling media during heat treatment of steel, oils, water and air were used for quenching, and a comparison of their impact on mechanical properties and microstructure of medium carbon steel was observed. The specimen quenched in air and soaked up more energy before breaking. In contrast, the specimens quenching in water soaked up less and had a martensite structure with good hardness, strength, and microstructure. The same result was obtained when quenched in oils media in case of hardness, and the microstructure has martensite with little ferrite and pearlite.

Different media types (brine, oil, and water) were investigated to study their effectiveness on microstructure and mechanical properties like hardness, tensile strength, ductility, and toughness of alloy steel to produce elevated-strength ingredients. The water media significantly improved strength and hardness, while the toughness was observed in oil media quenching (Agunsoye *et al*., 2019). In their work, Tkachev et al. (2023) improved the strength, fracture toughness, and microstructural design of 0.25C steel with Si, Mn, and Cr. Water was used as a quenching liquid while tempering at different temperatures. An increment of temperature ranging from 200 to 400 ˚ C produced a decrease in strength and higher toughness, but at a temperature of 500 ˚ C, the tensile and yield strength decreased.

A cyclic oil quenching (COQ) method was achieved for medium carbon steel to prevent the intense residual strain and get refined grains that offered eminent tensile strength above 1690 MPa with modest ductility (Wang *et al*., 2023b). Wang et al. (2023b) confirmed that the deposit of CuNiAl-rich particles of ultra-high low carbon steel was obtained by direct quenching and tempering (DQ-T) process; the aim was to analyse the effect it has on fine grains with high dislocation density.

The quenching samples were investigated to study the effectiveness of various tempering times and temperatures of AISI 1040 steel and subsequent mechanical properties. The results proved a reverse relation between the hardness and ultimate tensile strength with tempering time and temperature, where increasing tempering time and temperature decreases the hardness and ultimate tensile strength while increasing elongation. However, at constant temperature and an increase in time, maximum ductility due to reordering of grain structure is indicated (Mandal & Yada, 2023).

Results from related literature have shown that water-cooled high-carbon steel, after heating to austenite temperature, helps form martensite and pearlite, which improves mechanical properties, such as the hardness value. The highest effect on improving the strength and hardness of high-carbon steel was observed in water as a quenching medium, while the toughness was observed in oil media quenching (Huang, Lei, & Fang, 2023; Agunsoye *et al*., 2019 and Tkachev *et al*., 2023)

Alfatlawi (2019) examined the impact of heating and cooling on the cutting force of steel and its surface machining under various cutting conditions. In the first group of samples, the steel was heated to an austenitic temperature and then cooled using polyethylene glycol. The second group underwent the same heating treatment but was cooled in still air. The results indicated that the heat treatment significantly influenced cutting and machinability, with cooling in polyethylene glycol providing superior machinability.

Traditionally, quenched and tempered steel sheets are employed in the automotive industry for structural members, power transmission, and impact resistance systems. Certain engineering components require high hardness values to be used successfully for heavy-duty processes. Hardening as a heat treatment has been used to achieve these requirements in metal or alloy components. The effects of heat treatment are well identified by the variations in mechanical properties and microstructure variations.

(a)

(b)

Figure 1(a): Microstructure of AISI 52100 steel (Etching: Nital 0.3%: 50µm)
Figure 1(b): Microstructure of the AISI 1020 steel heat-treated at 75^{0}0c for 150 min (Etching: Nital 0.3%; 50µm) (Rajan *et al.,* 1989)

For instance, the hardness of AISI 5150 steel can vary from -20 to 60 HRC, depending on its heat treatment (Rajan et al., 1989). In many situations, however, alterations of only the surface properties of a part are necessary. The term case hardening is desirable. This method improves resistance to surface indentation, fatigue and wear. Typical applications for case hardening (heat treatment) are gear teeth, cams, shafts, bearings, fasteners, pins, automotive clutch plates, tools and dies (Kalpakjian,1997). Because of the increasing demands imposed on high-performance materials and component parts, as well as to minimise the disastrous and costly results of component failures, the need for heat treatment and fracture research has gained significant importance (Honeycombe & Bhadeshia, 2000). Therefore, this work aims to analyse the various heat treatment options of high carbon engineering, structural, and industrial applications at different temperatures according to the heat treatment process and methodology (Lakhtin*,* 1977*;* Akay *et al.,*2009).

EXPERIMENTAL PROCEDURES

Materials and Equipment

The A1S1 high-carbon steel experimental material used in this study, shown in Fig.2, was obtained from a steel trader in Lagos, Nigeria. It is an ASTM A682 Standard specification for steel, strip, high carbon cold–roll, with a composition of 0.-0.7 carbon, 0.6-0.9 Mn, and 0.2 Si. It has high hardness, high strength, and good wear resistance. This research uses an electrical resistance furnace, a Grinding and Polishing Machine, and an Optical microscope.

Sample Preparation.

The test piece sample was selected from a building rod of 10 mm diameter. A sample was taken for a composition test to know the percentage of carbon in the sample. The composition test was done using a spectrometer. The test result shows a high carbon steel with a carbon content of 0.75%. The test pieces were produced from the same material and machined for a tensile through grinding, cutting and polishing.

Silica Quenched Sample

One of the produced test samples of A1S1 1065 high carbon was cleaned and degreased on the surface to prevent contamination and ensure effective quenching. It was then austenite by heating it to 1,600°C, then removed, and submerged in the silica quenchant for about 30 minutes.

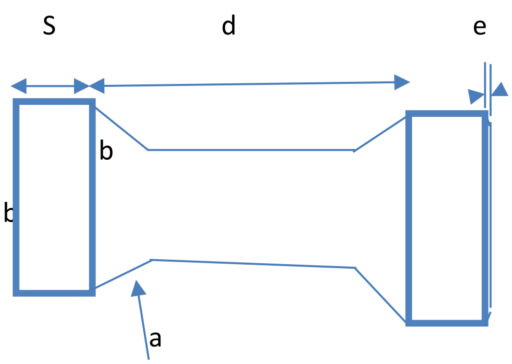

Figure 2: Schematic view of the specimen used for the heat treatment

a = 30 mm radius
b= 12 mm
c= 15 mm
d= 40 mm
e= $1x45^0$

The sample specimen was high-carbon steel AISI1065 or Ck65. The chemical composition of the workpiece is given in Table 1.

Table. 1: Chemical composition of the as-received workpiece

C	Si	Mn	P	Ni	Cr	Cu	Mo	Fe
0.61	1.44	0.68	0.02	0.01	0.26	0.07	0.02	Balance

(Akay *et al.,* 2009)

Most carbon steels are primarily heat-treated to create matrix microstructures and associated mechanical properties that are not readily obtained in as-cast conditions (Akay *et al.,* 2009). Depending on substance size and alloy composition, as-cast grounded substance microstructures usually consist of ferrite, pearlite, or combinations of both. The aim of this research is to carry out heat treatment options on high-carbon steel at different temperatures according to the heat treatment process and methodology (Lakhtin, 1977; Akay *et al*., 2009)

Effect of heat treatment on mechanical properties

The effect of the heat treatment on the mechanical properties of heat-treated workpiece studies is shown in Table 2. The annealed workpiece recorded the highest tensile strength of 1968 Mpa, followed by the normalised workpiece having 1033 Mpa. The hardened workpiece recorded tensile strength values of 608 Mpa. Furthermore, Vickers' hardness values of 390 were recorded for the normalised workpiece. This is followed by hardened and annealed workpieces having Hv 357 and Hv 295, respectively.

Table 2: Mechanical properties of the workpiece after the heat treatments

Heat treatment	Tensile strength (Mpa)	Hardness Vickers 300g
Control	867	210
Annealed	1968	295
Normalised	1033	390
Silica Sand and Hardened	608	357

Microstructural Analysis

After testing, the workpiece was subjected to a microstructural study by Optical Microscopy (Fig 3). For the microstructure study, the workpiece was cut to 10 mm and polished using different grades of emery cloth.

RESULTS AND DISCUSSION

Three samples were prepared for the controlled, annealed, normalised, and silica-quenched samples. The details of the result of mechanical properties investigated under various heat treatments of all the samples tested were recorded and tabulated from Table 2 and discussed as follows:

Figure 3: Optical Microscope used for the study

Samples of A1S1 1065 High carbon steel were investigated after heat treatment for hardness test. Hardness test using Vickers hardness tester was recorded as follows:

1. The test specimen A1S1 1065 high carbon steel was cleaned and dry-free from surface imperfection.
2. A load of 200kgf was loaded to the specimen using a Vickers tester.
3. It was held for 13 seconds to allow indenter penetration into the specimen.
4. The diagonal length of the indentation was measured using a Vickers hardness microscope.
5. Vickers hardness number was calculated using the relation $HV = 1.84P/d^2$ where P is load and d is the diagonal length.

Sample A was placed as a control Experiment. Sample B was annealed after heating to an austenite temperature of 7500C for 25 minutes and tested to have attained a tensile strength of 198 Mpa and a 215/300kg hardness test. Sample C was normalised after heating, and the tensile strength was found to be 1033Mpa, 340/300kg hardness test. Sample D was hardened after heating and quenched in silica sand. It has a tensile strength of 357Mpa and a 608/300kg hardness.

The results before optical microscopy show that a normalised sample has the highest tensile strength, followed by the annealed sample. The monograph of all samples after optical microscopy is shown in Figures 3 –7. The cooling rate for the specimen quenched in Air was 98°C/min, and the cooling rate for the specimen quenched in silica was 120°C/min.

Cooling in quenching media such as water will form martensite with good hardness, strength and microstructure. The same result was obtained when quenched in oils media in case of hardness and microstructure with martensite with little ferrite and pearlite. It is observed that the specimen quenched in air soaked up more energy before breaking (Jaardhan *et al*., 2023). However, if a high-carbon steel is not heat treated, it will exhibit reduced hardness and strength, increased ductility, poor machinability and an increased risk of cracking.

Microstructures of the workpiece for the various heat treatments

Figure 4 shows the micrograph of the as-received (control) workpiece. It can be observed (Fig. 5) that a uniform distribution of ferrite and pearlite (a mixture of ferrite and cementite), which are congested along the grain boundaries, is also slightly dispersed over the ferrite. The grain sizes are moderate, and the boundaries appear smooth, apart from the pearlitic presence.

The micrograph of the annealed specimen (Fig. 5) shows a large grain size of pearlite distributed across the microstructure. Unlike the untreated specimen, the pearlite phases, which were congested along the grain boundaries, are now distributed across the entire surface of the microstructure. Annealed materials are usually ductile and stress-free due to these stated characteristics. In addition, when a crack or void forms in a pearlitic matrix, it will tend to run along the length of a pearlite lamella. Examining this type of fracture under the SEM reveals that the base of the samples contains fractured pearlite lamella (Avner, 2008).

Sample A
Figure 4: Micrograph of control (as-received) workpiece (x600)

Sample B
Figure 5: Micrograph of the annealed workpiece (x600)

As compared to the annealed workpiece (Fig. 5), the micrograph of the normalised workpiece (Fig. 6.) shows a relatively similar grain size and a balanced distribution of ferrite and pearlite with uniform fine grain and quite similar to that of the control workpiece (Fig. 4.). Still, it appears relatively brighter than annealed and the control workpiece (Figs. 4 and 5).

In addition, the silica quenched workpiece (Fig. 7) shows a fine and relatively smaller ferrite and pearlite distribution and a relatively lower amount of pearlite concentration than the control workpiece (Fig. 4) and annealed workpiece (Fig. 5).

Sample C
Figure 6: Micrograph of the normalised workpiece (x600)

Sample D
Figure 7: Micrograph of silica quenched specimen (x600)

CONCLUSIONS

The Phase transformation during this heat treatment process has initiated a change in the arrangement of atoms within the sample A1S1 1065 high-carbon steel, resulting in the formation of new microstructures that will make it suitable for Industrial and Engineering applications.

Based on the result of the analysis of heat treatment carried out on high-carbon steel to evaluate its effect on components/parts for engineering, structural and industrial applications, The following conclusions are drawn:

1. The experimental analysis revealed significant variations in the mechanical properties of heat-treated specimens. The annealed sample exhibited a tensile strength of 1968 MPa, outperforming the normalised samples, demonstrating a tensile strength of 1033 MPa. In contrast, the quenched specimen recorded a tensile strength of 608 MPa, suggesting enhanced wear resistance. Additionally, the hardness of the specimens increased by 25%, with a further comparative analysis using the Rockwell Hardness tester indicating a 15% increase in hardness when quenched in water relative to the as-received condition. Microstructural examination disclosed that the annealed specimen possessed a predominance of large pearlite grains uniformly distributed across the microstructure, indicative of refined grain size and overall structural integrity. These findings underline the impact of different heat treatment processes on the mechanical and microstructural characteristics of the material.
2. The annealed specimen gave the largest and coarse grain size and structure, while the smallest was given by normalising, which is the fastest. In other words, it is established that the slow cooling rate is proportional to grain and structures.
3. The microstructure of the specimens corroborates with the obtained mechanical properties, as the hardened specimen showed relieved internal stress and was tough enough to resist shock load.

Recommendations

Hardened specimens, such as cams, shafts, gear teeth, automotive clutch plates, tools and dies, showed better resistance to surface indentation in applications where surface indentation is important. Heat treatment plays a crucial role in enhancing the mechanical properties of high-carbon steel, making it suitable for demanding applications. By selecting the appropriate treatment processes – annealing, quenching, tempering, or case hardening – steel manufacturers can tailor the material's properties to meet specific performance requirements. Therefore, future developments in heat treatment technologies should include advanced monitoring systems, controlled atmosphere treatments, and more energy-efficient processes to enhance further optimisation of the properties of high-carbon steel while reducing environmental impacts.

REFERENCES

Agunsoye, J. O., Fakolujo, O. A., & Oladele, I. O. (2019). Influence of quenching media on the microstructure and mechanical properties of heat-treated medium carbon steel. *Materials Science Forum*.

Akay, S. K., Yazici, M., & Bayaram, A. (2009). Effect of quenching on mechanical properties. *Journal of Materials Processing Technology, 209*, 3358-3365. https://doi.org/10.1016/j.jmatprotec.2008.07.038.

Alfatlawi, S. H. A. (2018). The effect of heat treatment on the machinability, tensile strength, hardness, ductility, and microstructure of carbon steel (GOST 50). *Journal of University of Babylon, Engineering Sciences, 26*(4).

Avner, S. H. (2008). *Physical metallurgy* (2nd ed.). McGraw-Hill.

Honeycombe, R. W. K., & Bhadeshia, H. K. D. H. (2000). *Steels* (2nd ed.). Butterworth-Heinemann Publishing Ltd.

Hu, P., Su, Y., Li, J., & Zuo, Z. (2023). Texture and mechanical properties of quenching and partitioning steel. *Materials Research Express.* https://doi.org/10.1088/2053-1591/acd1d2.

Huang, W., Lei, L., & Fang, G. (2023). Optimizing heat treatment to improve the microstructure and mechanical properties of 5CeNiMoV steel. *Metals.* https://doi.org/10.3390/met13071263.

Jayvardhan, P. P., Chaugule, Y. G., Shinde, S. N., Panade, R. J., Atigre, P. S., & Kamble, S. B. (2023). A review on the effect of different quenching media on properties of steel. *International Research Journal of Modernization in Engineering Technology and Science, 05*(05).

Kalpakjian, S. (1997). *Manufacturing process for engineering materials* (3rd ed.). Addison-Wesley Loryman, Inc.

Lakhtin, Y. M. (1977). *Engineering physical metallurgy and heat treatment.* Mir Publication.

Mandal, N. K., & Yada, Y. K. (2023). Experimental analysis of tempering temperature and time on mechanical properties of AISI 1040 steel. *IJARIIE, 9*(1).

Peh, L. S. (2019). Effect of annealing on the microstructure and properties of high carbon steel. *Materials Science and Engineering Journal, 30*(4), 550-556.

Rajan, T. V., Sharma, C. P., & Sharma, A. (1989). *Heat treatment: Principles and techniques.* Prentice Hall of India Private Limited.

Tkachev, P. E., Borisov, S., Belyakov, A., Kniaziuk, T., Vagina, O., Gaidar, S., & Kaibyshev, R. (2023). Effect of quenching and tempering on structure and mechanical properties of a low-alloy 0.25C steel. *Materials Science and Engineering, 868*, 144757. https://doi.org/10.1016/j.msea.2023.144757.

Wang, X., Shi, X., Hui, Y., Chen, B., Gan, B., & Shen, J. (2023b). Mechanical behavior and strengthening mechanism of a fine-grained medium carbon steel produced via cycle oil quenching. *Materials Science and Engineering: A, 866*, 144669. https://doi.org/10.1016/j.msea.2023.144669.

Wang, Y., Wang, R., Yu, W., & Gao, Y. (2023a). Effect of heat treatment parameters on the modification of nano residual austenite of low-carbon medium-chromium steel. *Nanomaterials MDPI, 13*, 2829. https://doi.org/10.3390/nano13212829.