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MECHANICAL AND MICROSTRUCTURAL CHARACTERIZATION OF HEAT TREATED A-283C LOW CARBON STEEL

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ABSTRACT

The research is aimed at investigating the impact of heat treatment on the mechanical and microstructural characteristics of A-283C low carbon steel and its performance under different conditions of cooling. The combined effect of metallurgical microscopy for surface examination with mechanical testing such as Tensile Strength, Hardness, Yield Strength, Young Modulus, Percentage Elongation, and Percentage Reduction were analyzed. The findings posit that applying particular heat treatments for a given application in a given field greatly enhanced the mechanical properties of the mild steel. The outcomes of investigation showed that yield strength, tensile strength, and hardness of A-283C steel increased with plastic deformation while percentage reduction and elongation decreased due to strain hardening effect.

Keywords: Heat treatment, Mechanical properties, Microstructure characteristics, A-283C steel

INTRODUCTION

Mechanical testing of materials is an important aspect of engineering practice. In recent times, more attentions are being given to the interpretation of test results in terms of service performance, as well as giving reliable indications of the ability of the material to perform certain types of duty (Hassan, 2016). Mechanical tests are also employed in investigational work in order to obtain data for use in design to ascertain whether the material meets the specifications for its intended use. Heat treatment is defined as an operation or combination of operations involving heating and cooling of a metal or alloy in the solid state in such a way as to produce certain microstructure and desired mechanical properties (yield strength, toughness, hardness, ultimate tensile strength, Young's modulus, percentage elongation and percentage reduction). Normalizing, annealing, tempering and hardening are the most important heat treatments often used to modify the microstructure and mechanical properties of engineering materials particularly steels (Muhammad, 2024).

Steel is mainly an alloy of iron and carbon, where other elements are present in small quantities too minimal to affect the properties. Manganese and silicon are the other alloying elements present in simple carbon steel (Muhammad, 2024). Low carbon steel has the same soft, formable characteristics as iron. The metal becomes stronger and harder as the carbon content increases, but it also becomes less ductile and more challenging to weld. The increasing use of steel is due primarily to two factors: It exists in large quantities as Fe_2O_3 in the earth's crust, and processing it to Fe requires little energy; and It can be produced to have a wide range of mechanical properties and a huge variety of microstructures. Despite the thousands of different steel requirements, simple carbon steel makes up more than 90% of all steel production. Its relevance can be attributed to the fact that it is a tough, ductile, and affordable material with reasonable casting, working, and machining qualities, as well as being responsive to straight forward heat treatments to generate a variety of features.

Heat treating carbon steel is done to change the material's mechanical characteristics, which typically include hardness, yield strength, ductility, tensile strength, and impact resistance. The yield strength of the steels used in structural design is utilized to determine the standard strengths (Rao, 2011). The majority of structural engineering calculations are based on yield strength. The mechanical qualities (such as tensile strength, yield strength, ductility, corrosion resistance, and creep rupture) are enhanced by the heat treatment, which also generates hardness and softness. These procedures also increase the versatility of the machining process. They are used in a variety of applications, including train tracks, building support beams, concrete reinforcing rods, shipbuilding, boiler tubes for power plants, oil and gas pipelines, automobile radiators, and cutting tools. The main component that goes through the process of heat treatment and has numerous characteristics is mild steel, also known as low carbon steel. Mild steel typically falls within the range of 0.05% to 0.35% (Rao, 2011). Mild steel is an extremely useful and adaptable substance. It is less expensive, has good mechanical qualities, and can be fashioned into intricate designs. It makes up the vast majority of the steels used for sheet metal, general structural fabrication, and other applications.

A-283C low carbon steel is a widely used structural steel due to its good machinability, weldability, and cost-effectiveness. Its wide acceptability for construction and various applications of metal joining processes also make this steel material the preferable choice (Sonief et al., 2021). However, its mechanical properties can be significantly altered through heat treatment, thereby affecting its performance in various applications (Hassan, 2016)

Changes in the mechanical strength value of A-283C steel are strongly influenced by heat treatment process (Singh et al., 2024). Heat treatment process such as quenching prevents undesirable low-temperature process such as phase transformations from occurring. Heat treatment does this by reducing the window of time during which these undesirable reactions are both thermodynamically favorable and kinetically accessible (Yulianto et al., 2023). Other than that, quenching can also reduce the crystal grain size of both metallic and plastic materials, thereby increasing their hardness. In the work of Gong et al., 2010, A-36 mild steel was selected to analyze variations in tensile strength after heat treatment and it was observed that quenching improved the tensile strength to a great extent. Also Luqman (2024), analyzed different grades of mild for both their microstructure and mechanical properties. Results of his study demonstrated improvements in tensile strength, hardness, microstructure and corrosion resistance. The steels showed the highest hardness for salt water quenched product and the lowest for annealed samples. From available literatures and to the best knowledge of the authors, the microstructural and mechanical characterization of A-283C low carbon steel under varying heat and cooling media has not been reported elsewhere. Therefore this paper brings to the fore a worthwhile contribution to knowledge in the related literature.

MATERIALS AND METHODS

Materials

A-283C mild steel rectangular bar procured from Pan-taker, Market in Kaduna, was used as the base material for this research. The elemental composition of the steel as shown in Table 1 was determined using spark optical emission spectroscopy (OES). Emery cloth of different grit sizes were used for polishing of the mild steel surface prior to metallography.

Table 1: Chemical Composition of A-283C Steel

Element	Fe	Cu	C	Mn	P	S	Si
Composition (%)	98.0	0.20	0.25	1.03	0.040	0.280	0.050

Method

Heat treatment

The procured A-283C mild steel was cut into sizes with dimensions 15×10×30mm using a power hacksaw. Steel samples were heated in an electric furnace until the austenitizing temperature of 850- 900^oC was reached. Then the specific heat treatment operations; hardening, annealing, tempering and normalizing were carried out. For annealing, the specimen was put in the furnace at a temperature of 910^oC and was kept in that condition for approximately 70 minutes, after which it was removed and then cooled slowly in a heap of ashes. Hardening was carried out at a controlled temperature of the furnace at 910^oC and the temperature was maintained for approximately 30 minutes; it was then rapidly cooled in water. For normalizing, the specimen was put in the furnace at 910^oC and was kept in that condition for approximately 70 minutes, after which it was then cooled at room temperature (air). The specimen for tempering was put in the furnace and operated at a temperature of 450^oC. It was kept in that condition for approximately 70 minutes, after which it was similarly cooled at room temperature. Table 2 shows the heat treatment conditions as reported in the experimentation.

Table 2: Heat Treatment Process

Condition	Annealed	Normalized	Hardened	Tempered
Temperature, (^oC)	910	910	910	450
Heating time, (min)	70	70	30	70
Cooling medium	Ash	Air	Water	Air

Determination of Mechanical Properties

Test samples as per ASTM standards were machined using a lathe machine. Samples were subjected to different heat treatment: annealing, normalizing, hardening and tempering in accordance to ASTM E18 (2008). Heat treated specimens were tested for mechanical properties. Four specimens were prepared for each heat treatment type. The effects of heat treatment on the mechanical properties; tensile strength, hardness, yield strength, young modulus, percentage elongation and percentage reduction of the treated and untreated samples were determined using standard test methods as reported by Hassan, 2016. Before carrying out the mechanical examinations, oxide layers formed during heat treatment were removed by stage-wise grinding and then polished. Hardness test was conducted on a standard Rockwell hardness tester; the average Rockwell Hardness Number (BHN) readings were determined by taking two hardness readings at different positions on the samples. For tensile properties, tensile specimens were loaded on a 2000kg Mosanto Testometer hooked up to a data logger. Load-elongation data were recorded and converted into stress-strain graphs. Yield strength, ultimate (tensile) strength, Young's modulus and ductility (% elongation and reduction) were determined as reported elsewhere (Dewangan, 2021), and the results recorded in Table 3.

Microstructure Examination

Microstructure examinations of the treated and untreated samples were carried out with the aid of a metallurgical microscope. Each sample was carefully grounded progressively on emery paper of decreasing coarseness. The grinding surface of the samples were polished using Al_2O_3 carried on a micro clothe. The crystalline structure of the specimens were made visible by etching using solution containing 5% Cupric chloride, 8% HCl acid and 87% methylated spirit on the polished surfaces.

Microscopic examination of the etched surface of various specimens was then carried out by a technique which involves examining light absorption by a steel sample, with the absorption spectrum providing insights into the elements present in the steel. This process known as metallography, is a conventional method for analyzing the surface morphology of steel material (Gong et al., 2010).

RESULTS AND DISCUSSION

Effect of Heat Treatment on Mechanical Properties

The mechanical behavior of the untreated samples as shown in Table 3 indicates that tensile strength has a value of 400.42Mpa, hardness value of 68.9BHN, yield strength-218.03Mpa, Young modulus-208.26Gpa, percentage elongation-22.96%, and percentage reduction-55.54%. Comparing the mechanical properties of annealed samples with the untreated samples, the annealed samples showed lower tensile strength (389.84Mpa), hardness (64.45BHN), yield strength (211.74Mpa) and increase in young modulus (304.52Gpa), elongation (24.22%), reduction in area (62.71%),. The decrease in tensile strength and hardness can be associated with the formation of soft ferrite matrix in the microstructure of the annealed sample by cooling. The result is in agreement with the work of Hassan (2016).

Table 3: Mechanical Properties of Heat Treated and Untreated A-283C Steel

Heat Treatment	Tensile Strength (Mpa)	Hardness (BHN)	Yield Strength (Mpa)	Young Modulus (Gpa)	Percentage Elongation (%)	Percentage Reduction (%)
Untreated	400.42	68.9	218.03	208.26	22.96	55.54
Tempered	423.74	100.01	242.79	295.65	24.1	71.12
Annealed	389.84	64.45	211.74	304.52	24.22	62.71
Normalized	459.17	123.16	247.26	286.17	23.9	63.28
Hardened	724.3	283.7	277.18	638.07	8	39.36

As depicted in Table 3, the values of mechanical properties of tempered samples showed that the tensile strength, hardness, yield strength, young modulus, percentage elongation and percentage reduction were: 423.74Mpa, 100.01BHN, 242.79Mpa, 295.65Gpa, 71.12% and 24.1% respectively.. This showed that tempering temperature improved the degree of tempering of the martensite, softening the matrix and decreased its resistance to plastic deformation.

The mechanical properties of the normalized specimen were found to be 459.17Mpa, 123.16BHN, 247.26Mpa, 286.17Gpa, 23.9% and 63.28% for tensile strength, hardness, yield strength, young modulus, percentage elongation, and percentage reduction respectively. The increase in tensile strength and hardness as compared to annealed and untreated sample was due to proper austenising temperature at 910ºC and higher cooling rate, which resulted in decrease in elongation, which was lower than those obtained for untreated and annealed samples due to pearlite matrix structure obtained during the normalization of A-283C steel.

The mechanical properties of the hardened samples showed it had the highest value of tensile strength (724.3MPa), hardness (283.7BHN), yield strength (277.18MPa) and high young modulus (638.07Gpa). The specimen was austenite at 910°C for 30 minutes and then water quenched. This treatment increased the tensile strength and hardness but there was massive reduction in percentage elongation and reduction in area 8%, and 39.36%, respectively. The variability in ultimate tensile strength, percentage elongation, percentage reduction, hardness and toughness of treated and untreated A-283C steel are shown in Figures 1(a)-(f).

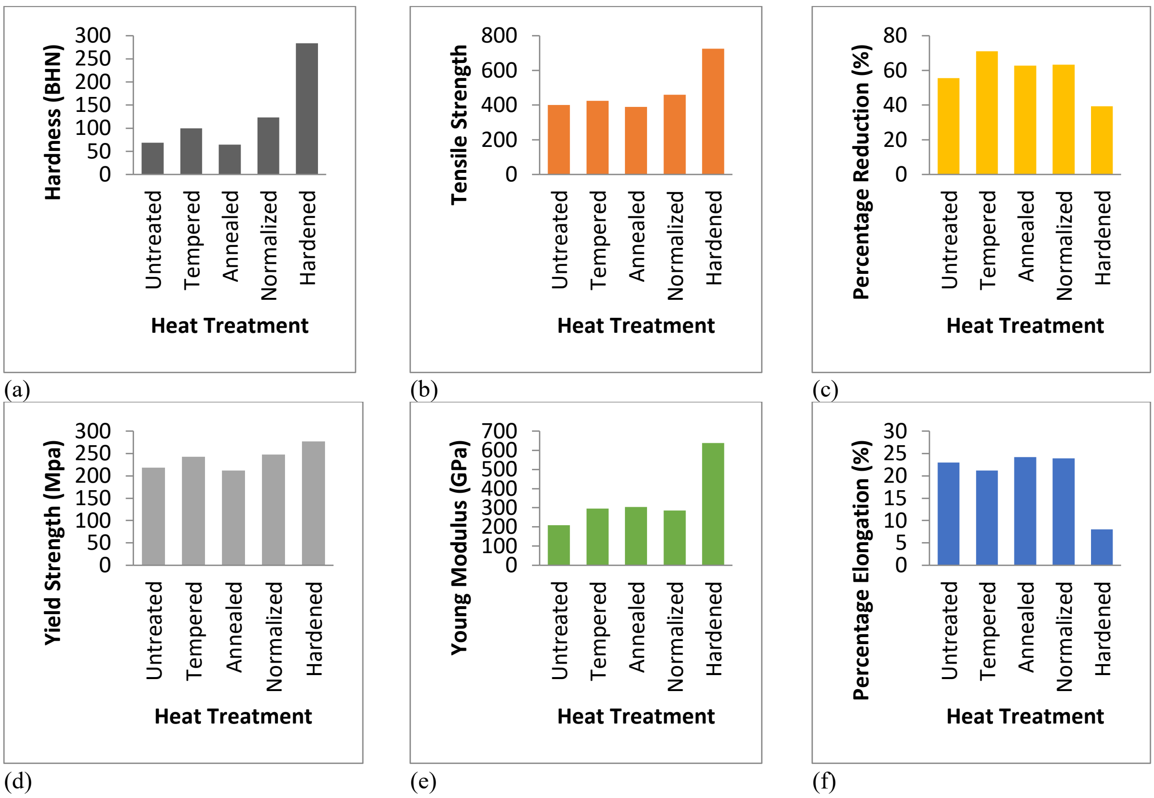


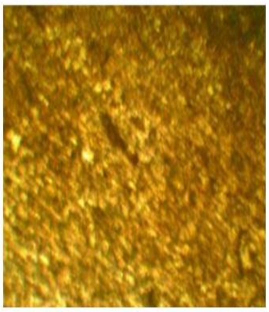
Figure: 1: Variation of untreated and treated samples of A-283C steel with; (a) Hardness (b) Tensile strength(c) Percentage reduction (d) Yield strength (e) Young modulus (f) Percentage elongation

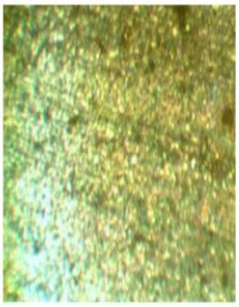
The values of tensile strength were observed to be in the order thus: hardened > normalized > tempered > untreated < annealed, this could be possibly as a result of the refinement of the primary phase after the subsequent cooling process. The value for hardness was observed to be higher for the hardened steel specimen. The hardness of the steel increases both with cooling rate and pearlite percentage. The reason being that martensite is one of the strengthening phases in steel. The increase in the hardness was due to the delay in the formation of pearlite and martensite at a higher cooling rate. The yield strength value for the hardened specimen was also observed to be higher than that of other specimens, while the normalized specimen also has a greater hardness value than that of tempered and annealed specimen.

Heat Treatment Effect on Microstructure

Prediction of microstructure transformations is prerequisite for successful estimation of mechanical properties after a heat

treatment and generation of stresses and strains during a heat treatment. Phase transformation modeling is one of the main challenges in modeling of heat treatment (Yulianto et al., 2023). During annealing, softening processes are under way in the microstructure and in some cases, recovery and recrystallization takes place as well. Naturally, the morphology of carbides changes as well (Hu et al., 2015).
The microstructure of untreated specimen in Figure 2a has two major constituents, which are ferrite (white) and pearlite (black). The light coloured region of the microstructure is the ferrite and the dark region is the pearlite. The microstructure of the annealed sample is as shown in Figure 2b. As it can be seen in the figure, the ferrite grains had undergone complete recrystallization and this constitutes the major portion of the microstructure of the annealed low carbon steel with stress-free matrix. At 910ºC, the deformed structure was fully homogenized and during the slow cooling from austenizing range to room temperature, the final microstructure consisted of fine ferrite grains in which the pearlite was more uniformly distributed.
Figure 2c shows the microstructure of the normalized A-283C steel. The normalized sample showed that the shape and size of the original austenite grains were influenced to a remarkable extent. The sample revealed a pearlite matrix in which shorter graphite flakes than in annealed sample existed. It was observed that there was many short graphite flakes surrounded with patches of uniformly distributed pearlite grains.


(a)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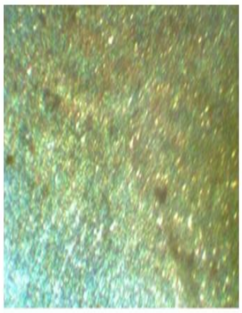
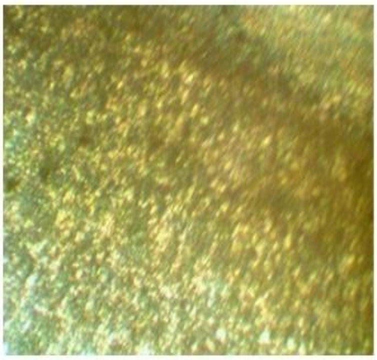

(c)


(d)

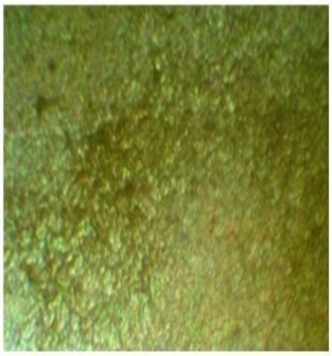

(e)

Figure 2: Microstructure of A-283C steel material: (a) Untreated (b) Hardened (c) Normalized (d) Annealed (e) Tempered

Figure 2d shows the massive martensite structure of hardened sample. When medium carbon steels are rapidly quenched from its austenite temperature to room temperature, the austenite will decompose into a mixture of some medium carbon martensite and fewer pearlite as a result of hard microstructure. Hence, there was an increase in tensile strength, hardness and reduction in ductility (Hu et al., 2015). The microstructure of hardened and tempered steel at 450ºC is as shown in Figure 2e. A highly recrystallized ferrite grains (white dotted areas) with some secondary graphite site was observed. This micrograph revealed that the microstructure of tempered specimen consisted of a number of appreciable carbide particles precipitated out from the matrix, which indicated that the precipitate carbide particles decomposed by a process of solution in ferrite matrix (Gong et al., 2010).
As slow cooling is done in annealing so it transforms austenite to soft pearlite and also mixed with ferrite or cementite and this cementite increases the brittleness of the steel. Normalizing converts soft steel to moderate hard steel. In this case, cooling rate is faster than annealing and for this reason, when the specimen is cooled in room temperature, ferrite and cementite are formed but their quantity is less. So the specimen is enhanced with considerable ductility by reducing its brittleness. In hardening process, austenite structure is directly formed into martensite structure for fast cooling. Although the rapid cooling converts most of the austenite into martensite which is a hard constituent and more stable than austenite at ordinary temperatures. In tempering process, austenite structure is directly formed into martensite structure matrix with recrystallized ferrite grains. Summary of the observed microstructure of the treated and untreated A-283C low carbon steel material is given in Table 4.

Table 4: Summary of Microstructure of Treated and Untreated A-283C Low Carbon Steel

Heat Treatments	Microstructure Developed
Untreated	Graphite flakes in ferrite and pearlite matrix
Hardened	Graphite flakes in martensite matrix
Normalized	Graphite flakes in pearlite matrix
Annealed	Graphite flakes in ferrite matrix
Tempered	Graphite flakes in martensite matrix with recrystallized ferrite grains

CONCLUSION

It can be deduced from the results obtained that mechanical properties are largely dependent on the different forms of heat treatment operations and cooling rate. Therefore, depending on the desired properties and applications for any design consideration, a suitable form of heat treatment can be adopted. If the required application is for high ductility and minimal toughness, annealed mild steel will give satisfactory results. The outcomes of investigation on the effect of heat treatment on mechanical properties and microstructure of A-283C mild steel showed that yield strength, tensile strength, and hardness of A-283C mild steel increased with plastic deformation while percentage reduction and elongation decreased due to strain hardening effect. Normalization treatment also resulted in improved hardness and tensile strength than annealed samples. Tempered samples gave higher hardness and tensile strength values than the untreated samples as a result of formation of tempered martensite and resultant ferrite structure that were formed. Hardened samples had the highest hardness and tensile strength with lowest ductility and impact strength when compared to other heat treated samples. Hardening is strongly recommended when the strength and hardness are the most desired properties in application. The mechanical properties of A-36 low carbon steel can be altered through various heat treatments. The results obtained confirmed the improvement in mechanical properties that can be obtained by subjecting A-283C steel to different heat treatments according to the study.

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