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Influence of Heat-Treatment on Microstructural and Mechanical Characteristic of Steel

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Abstract

The AISI 1045 steel is one of the structural steels widely used in the automotive sector for several key components such as connecting shafts, axles etc. It is also used in petrochemicals and power generation units. In material science and engineering, four interdependent parameters are of paramount importance: process, structure, properties and performance. Among all factors, the microstructure is of utmost importance since it governs the properties at large. For instance, the shape, size and distribution of micro-constituents play a vital role therein. Therefore, the main objective is to investigate the influence of thermal correlation on the material, such as annealing, normalizing, tempering and hardening. This was followed by the characterization utilizing Optical Emission Spectroscopy, Impact Testing and Rockwell Hardness Tester. In addition, the microstructure was also studied using the Optical Microscope with up to 1000x optical zoom. Results suggested an improved toughness and hardness when tempering temperature was reduced. This is attributed to decreased grain sizes of micro-constituents upon such treatment.

Keywords: Medium Carbon Steel, Heat Treating, Toughness Hardness, Microstructure.

Introduction

In metallurgical engineering, attributes of alloys and metals depend absolutely upon their atomic and crystal structures together with the size and shapes of microconstituents. Altering the microstructure or phase of material is a voluminous study, subsequently posing several challenges in selecting the proper heat treatment process [2]. For example, in medium carbon steels, the heat treatment process governs the variation in ductility and hardness due to microstructural evolution upon such treatment. On the contrary, when dealing with pure iron instead of steel, the heat treatment does not affect its mechanical properties at large, but it does significantly when alloyed. Alloying elements such as carbon alter the mechanical properties and other properties. This is primarily due to micro-constituents and impurity levels. This behavior offers exciting opportunities to change the properties of steel based on different applications.

In particular, the structure affects mechanical characteristics, as various micro-constituents affect the appearance of microstructure hence mechanical properties [9]. Using various heat treatment processes in a solid-state, such properties could be altered or changed per desired specifications. [12]. However, many other methods are available to change the properties, such as surface engineering and metalworking operations. These techniques enhance the properties of metals and alloys and augment their life, consequently creating contrasting features[14].

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In this study, carbon-steel was selected to understand the recurring role of microconstituents (microstructure) on mechanical properties upon various heat-treatment methods, including annealing, normalizing, quenching and tempering. All these processes are distant from each other, depending upon the cooling rate and medium.

For example toughness of the material is enhanced and brittleness is reduced by the annealing process[3]. In contrast, internal stresses are generated by welding, forging and machining [4-6]. On the other hand, quenching hardens the material and provides strength to metals. This is because quenching produces different phases, such as martensite and bainite. In principle, treating steel in the range of austenitic temperature, the hardness and strength begin to reduce with an improvement in any factors (e.g., range of austenitic temperature, rate of cooling, holding time). This is the result of different grain sizes [10, 11]. The tempering process is widely associated with increasing the workability of steel and reducing the hardenability. The decrease in hardenability is dependent on the tempering temperature and chemical composition of the alloy/ steel.

Moreover, steel's strength and wear resistance is also increased[13]. Additionally, the workability of steel is also enhanced for working and forming operations [3]. It should be noted that mill test certificates (MTCs) provided the mechanical characteristics data of medium carbon-steel based on the applied heat treatment methods in hardened, tempered, normalized and annealed conditions[15, 16].

In brief, the medium carbon steel samples were heat-treated to evaluate their properties obtained upon microstructural evolutions [17].

Materials and Methods

The samples were purchased and chemical composition was analyzed using Optical Emission Spectrometry (O.E.S.)[1](**Table 1**).

The specimens were prepared as required by the standards, such as for Charpy impact testing, the V-notch of specific geometry was prepared. In total, seven sets of samples were prepared for heat treatment to form various microstructures.

After the quenching, heat treatment processes were carried out at variable temperatures ranging from 250ºC to 600ºC after the quenching. Such tempering temperatures are essential to understanding microstructure evolution and associated properties.

Table 1 Comparison of Medium Carbon and received samples chemical compositions[1].

Element	AISI 1045 [Wt. %]	Observed Composition
S	0.05	0.03
Si	≤0.22	0.23
P	≤0.04	0.02
Mn	0.75-0.1	0.77
C	0.45-0.50	0.47
Fe	Remaining	Remaining

It should be noted that in all given processes (except hardening), the holding time of the given samples is calculated at 24 minutes based on the dimension of the sample.

Annealing

In this process, the sample was heated to the Ac1 line and held for homogenizing, then cooling at natural temperature (furnace cooling). A typical annealing cycle adopted in this study is shown in (**Fig.1**).

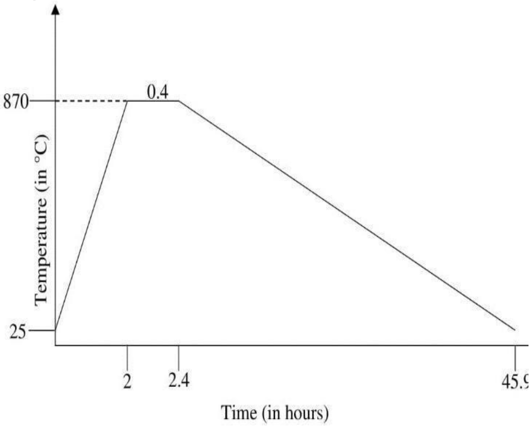

Fig. 1. The annealing cycle of the steel under consideration

Normalizing

In this process, the sample was heated to the Ac1 line. After that, it was maintained at such a temperature for homogenization and followed by air cooling (**Fig. 2**).

Quenching

The quenching process is triggered after heating samples up to the Ac1 line and holding for homogenization. This was followed by quenching in water. **(Fig. 3)** shows the quenching cycle of steel samples.

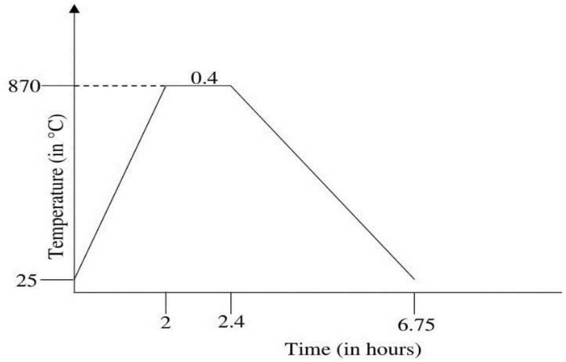

Fig. 2. The normalizing cycle for the steel samples.

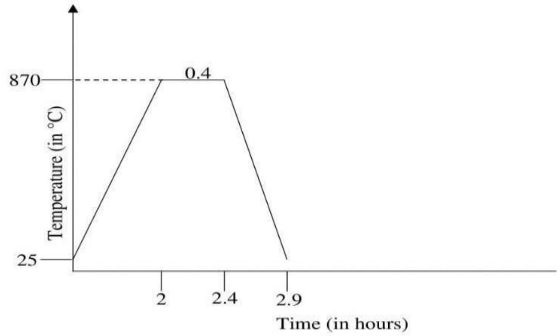

Fig. 3. The quenching process cycle.

Tempering

During this process, three samples were subjected to a quenching process followed by tempering. The samples were quenched and then tempered at 450ºC, 300ºC and 200ºC, respectively. After tempering, samples were air-cooled, as shown in **(Fig. 4).**

Hardening

During hardening, the sample was heated at a temperature below the Ac1 line followed by two-hour soaking time and then cooling under Ac line.

Metallography

Steel samples were subjected to metallographic operations such as grinding between 120 and 1200 SiC grit papers. This was followed by polishing using coarse to finer particles alumina paste to help in revealing the microstructure. It should be noted that before changing from one grit to another (grinding or polishing), the sample was washed and cleaned ultrasonically to avoid contamination of preceding papers or polishes. This was followed by etching of the samples before microscopy.

Characterization

Once the heat treatment process was completed, this was followed by the characterization. It includes hardness testing, impacts analysis and microstructural assessment. Microstructural analyses were carried out using optical microscopes[7, 8].

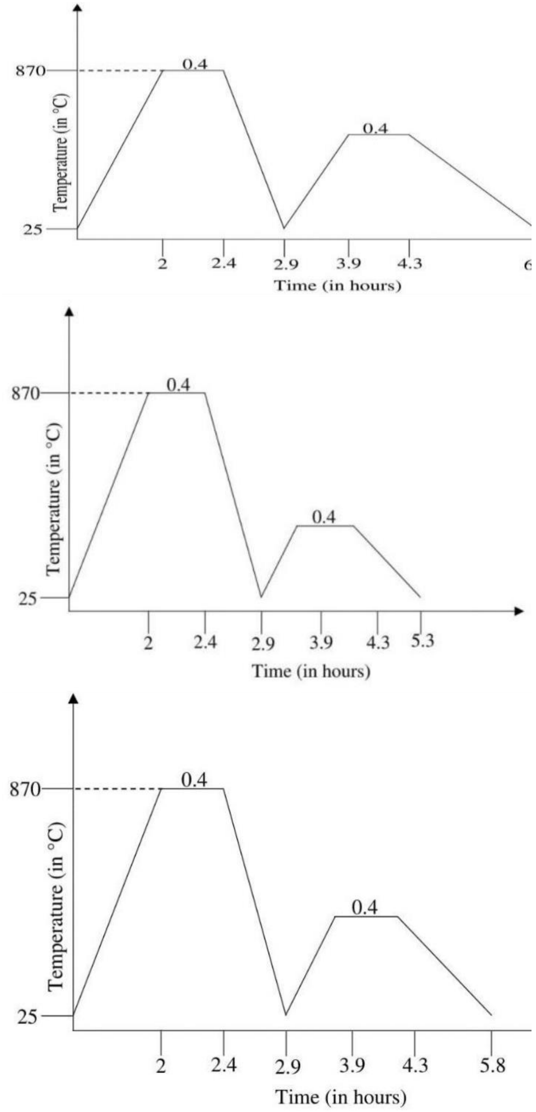

Fig 4. The Tempering process at (A) 450 °C (B) 300 °C and (C) 200 °C

Results and Discussion

Chemical Composition

Chemical analysis of samples was conducted after various heat treatment processes, as shown in **Table 2**. A slight change in the chemical composition was observed, which was under the

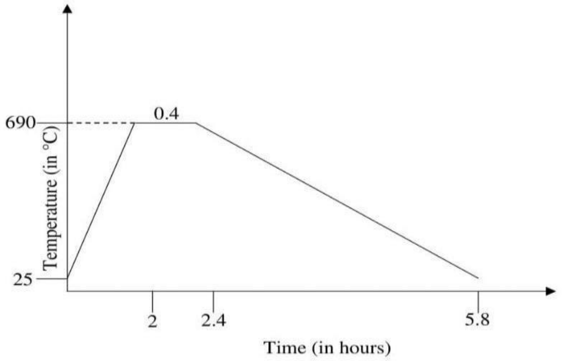

Fig 5. The hardening process cycle for the samples.

range of the standard AISI 1045 steel. This could be neglected. However, there will be minor variations in the mechanical properties too. In particular, the chemical composition of the hardened sample is changed significantly. This behavior is attributed to change in microstructure in terms of the formation of carbide globules.

Table 2. The composition/chemistry of steel samples at different conditions.

Elements	Heat Treatment Processes		
	Hardened	Quenched	Normalized
Mn	0.75	0.75	0.86
C	0.13	0.37	0.55
P	0.02	0.02	0.01
Si	0.24	0.24	0.29
S	0.03	0.03	0.04
Fe	Remaining	Remaining	Remaining

Microstructure

The microstructure was determined after necessary metallographic steps. Since it plays a fundamental role in determining the workability and mechanical properties of the material [5], all the specimens were etched using a Nital solution (2%). Multiple changes in microstructure were observed after the annealing process. **Fig 6** shows the comparison between as received and annealed samples. Presumably, pearlite was detected as the greyish region in the microstructure and the white region can be differentiated as α-ferrite. Carbides were only detected in the microstructure of the annealed sample as black regions.

In the microstructure of the normalized sample, two distinct regions were observed, namely α-ferrite and

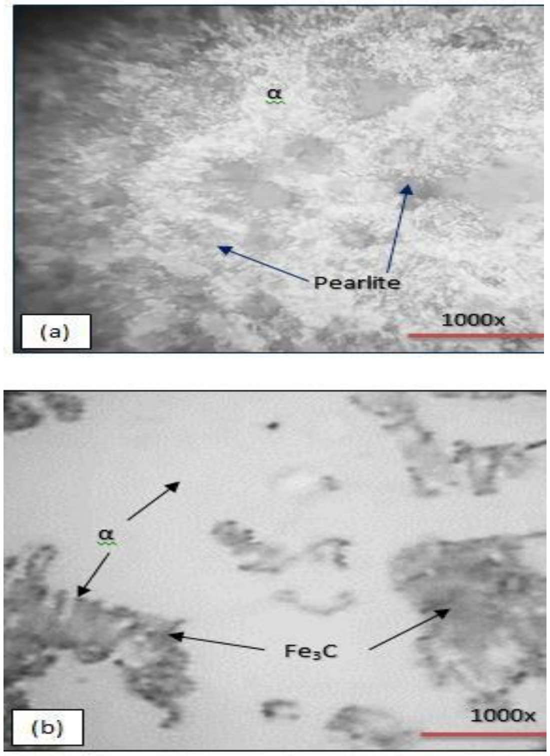

Fig. 6. The microstructural evolution of steel in (a) as-received condition and (b) exhibits after the annealing process.

The microstructure consisted of more refined grains as compared to the annealed specimen. In comparison, the microstructure of quenched sample consisted of multiple phases which were, α-ferrite as bright region, pearlite as the greyish region. While the martensite was detected in forms of colonies/lines alongside the retained austenite as shown in **(Fig. 7).**

The microstructure obtained during the tempering process is shown in **(Fig. 08).** There was a new phase identified after tempering of steel known as ‘Troostite.’ The formation of troostite is due to the tempering of the martensite and the austenite (retained austinite) due to tempering gathers martensite and retained austenite to combine and form troostite. Time plays a crucial role in the tempering process as increasing it changes the microstructure and affects the mechanical properties.

The microstructure obtained after hardening is shown in (**Fig.08**). Such microstructure consists of globular form carbide.

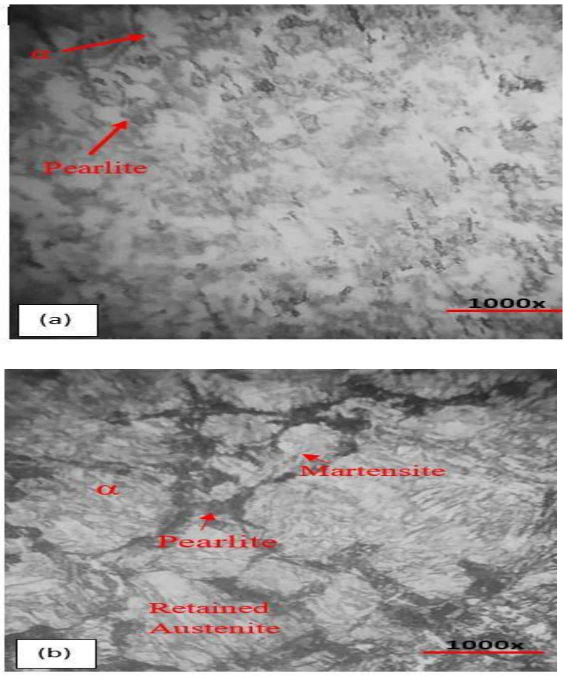

Fig. 7 (a) Microstructure of normalized sample and (b) Microstructure of quenched sample.

Such globules concentrate at various locations and could affect the mechanical properties. These findings are encouraging since AISI 1045 can replace other high alloy steels that are expensive.

Toughness

The Charpy impact testing machine tested all the Specimens. The toughness of the spheroidized sample could be visualized at its high level, as shown **(Fig.08).**

Hardness

The steel (1045), after a particular procedure of heat-treatment, exhibits distinct qualities. The carbon content breaks up in the grains themselves and makes novel highlights for having low hardness. The results of varying hardness are shown in **(Table 3).**

Table 3. The hardness data of the sample.

Sample	Hardness (HRC)
As-received	22.0
Annealing	20.0
Normalized	89.0 HRB
Quenched	21.5
Tempered @ 450 °C	43.0
Tempered @ 300 °C	49.0
Tempered @ 200 °C	48.0
Spheroidized	85.0 HRB

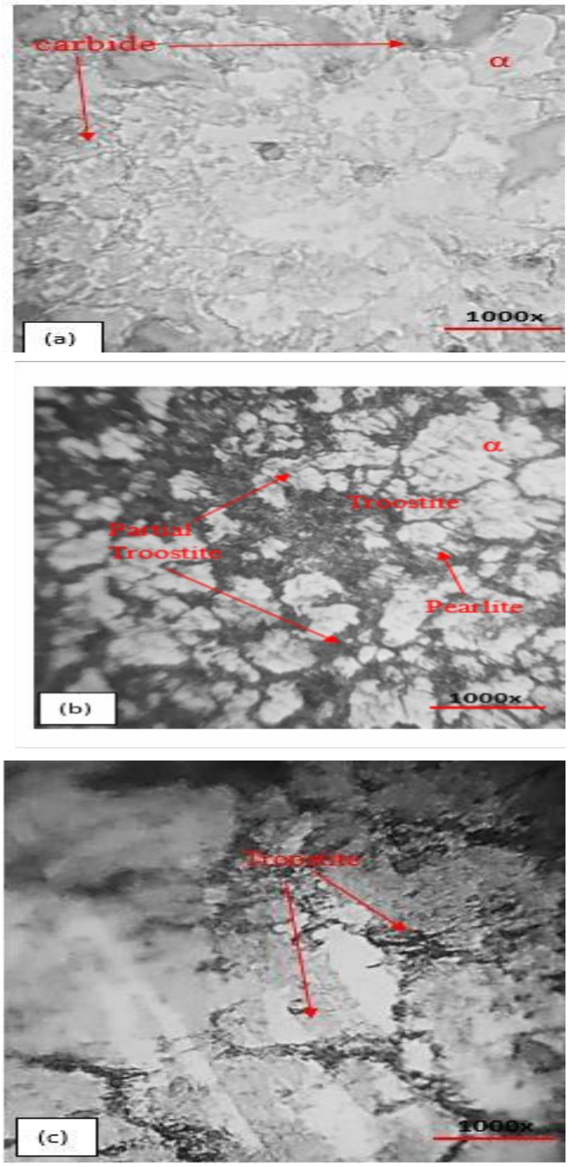

Fig. 8. Microstructure after tempering at (a) 450°C(b) 300°C and (c) 200°C.

CONCLUSIONS

The following are the concluding remarks of steel after heat-treatment. The chemical composition was affected slightly after normalizing, quenching and hardening.

However, somehow it falls in the tolerance level of MTC's. In addition, the microstructure (grain size, shapes and distribution) altered significantly consequently affecting mechanical properties at large.

More specifically, when spheroidized the hardness reduced, and a relative microstructure exhibited globules. In addition, tempering increased both hardness and toughness as the temperature was reduced. On the contrary, quenching has increased the hardness of the steel. While normalizing resulted in intermediate characteristics of annealed and quenched samples since its toughness was recorded to be 482.48 KJ /m^{2,} which is lower than that of annealed.

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