The effect of various heat treatment on mechanical properties of medium carbon steel (C45)

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Abstract

In this paper the influence of various heat treatments, such as hardening, tempering, normalizing and annealing, on the mechanical properties of the medium-carbon steel C45 was carried out by heating samples of the C45 alloy to the austenite phase field at 840˚C for 24 minutes. The socking time during the austenitizing treatment was calculated based on 1 hour per 1 inch section of the heat treated samples. In order to create different mechanical properties, the heated samples were directly cooled down from the austenitizing to room temperatures using three different cooling medium, which were; water quenching "hardening treatment", air cooling "normalizing treatment" and cooling in shutdown furnace "annealing treatment".

The mechanical properties of C45 alloy in the as-received condition, as well as, at the various heat treatment conditions were evaluated by conducting tensile, hardness and impact testes. The investigation results showed significant variation in the mechanical properties of C45 alloy with the cooling rate employed upon heat treatment

1. Introduction

Steels have a very long history. They are used nowadays in a wide field of applications. Their variability in properties make them versatile enough to fulfill various requirements of both structural and functional components. Their properties can be adjusted by mechanical deformation and heat treatments [1].

Today heat treatment process is widely used to achieve high mechanical properties. Major requirements of medium carbon steel are high yield strength, high proportional limit, and high fatigue strength. These desirable properties of medium carbon steel can be achieved by adding suitable alloying elements and secondly by heat treatment [2].

Heat treatment operation is a means of controlled heating and cooling of materials in order to effect changes in their mechanical properties. Heat

treatment is also used to increase the strength of materials by altering some certain manufacturability objectives especially after the materials might have undergo major stresses like forging and welding . It was however known that mechanical properties of steel were strongly connected to their microstructure obtained after heat treatments which are performed to achieve good hardened and tensile strength with sufficient ductility [3]. The material modification process, modify the behavior of the steels in a beneficial manner to maximize service life i.e stress relieving or strength properties e.g. cryogenic treatment or some other desirable properties . The Heat treatment generally is classified into thermal treatment which consists of softening process: annealing and normalizing, hardening and tempering process [4].

2. Experimental Procedure

The material investigated in this study was a medium carbon, steel C45 (AISI 1045) steel, supplied in the form of Ø 10 mm rolled rods of a nominal composition listed in Table 1.

Table 1:(chemical composition AISI 1045)[5]

Element	C	Si	Mn	Ni	P	S	Cr	Mo
Composition %	0,43-0.5	Max 0.4	0.5-0.8	Max 0.6	0.045	0.045	Max 0.4	Max 0.1

2.1- Heat Treatment

Samples of 1 cm length were cut from the C45, 10 mm Ø rods and subjected to the following heat treatments using a Gallen Kamp laboratory electrical furnace:

2.2 Quench Hardening –

Samples were loaded into a pre-heated furnace at 600˚C and then rapidly heated to the ferrite + pearlite → austenite transformation region at 840˚C. Samples were allowed to be soaked at this temperature for 24 minutes and then rapidly removed from the furnace and quenched in a water at room temperature (*quench delay less than 3 sec*).

2.3 Tempering –

Some of the water quenched samples were reheated to 600˚C for 24 minutes, then removed from the furnace and allowed to be air cooled to room temperature on a ceramic base.

2.4 Normalizing –

Samples were loaded into a pre-heated furnace at 600˚C, rapidly heated at 840˚C for 24 minutes and then rapidly removed from the furnace and allowed to be air cooled to room temperature on a ceramic base.

2.5 Annealing

Samples were loaded into a pre-heated furnace at 600˚C, rapidly heated at 840˚C for 24 minutes and then the furnace power was switched off allowing the samples to be slowly cooled into the furnace for 24 hours.

3. Results and Discussion

Here is the results and Discussion according to tests and analysis:

3.1 Effect of Heat Treatment on Mechanical Properties

The effect of heat treatment (annealing, normalizing, hardening, and tempering) on the mechanical properties (yield strength ,tensile strength, percentage elongation, impact energy, stress at break and hardness of the treated and untreated samples) is shown in Table (2).

Table (2) Mechanical properties of treated and untreated samples

Type treatment	Yield Strength N/mm2	Tensile strength N/mm2	Stress at break6 N/mm2	percentage elongation %	Hardnes s H.V	Impact energy J
As received	781	964.3	742.6	13.67%	285.3	7
Annealing	410.3	633.8	495.6	65%	180 3	8
Normalizing	536	711.3	522.2	54.3%	206.6	46.6
Hardening	**-**	677	677	3.6%	**607.3**	2.6
Tempering	846.8	880.3	565.3	29%	291.3	30

Comparing the mechanical properties of annealed sample with the as received sample, annealed sample showed lower tensile strength 34% , yield strength 47% , stress at break33% and hardness 33% and also increase in both elongation 78% and impact energy 81% , this can be associated with the very slow cooling rate employed during this annealing treatment and that caused a significant increase in the inter-lamellar spacing of pearlite phase **.**

Since the pearlite inter-lamellar spacing is known to be an important factor for controlling ductility and strain hardening, this identical Referenced [6] . We notes from the results that the lower value of the hardness and the increase of elongation comparing with the other heat treatments. The mechanical properties of the normalized specimen showed a lower tensile strength 26% , yield strength31%, stress at break29% and hardness 27% , where in the other hand it showed an increase in elongation74% and impact energy 85% , comparing with the As received sample, this due to the cooling rate employed during the normalizing treatment and that was slow enough to enhance diffusion-controlled transformations resulting in the formation of full ferrite-pearlite microstructure this identical Referenced[7] . It was obvious that the increase in the impact energy, comparing with the other heat treatments.

The mechanical properties of the hardened specimen were found to be lower in tensile strength 29% , yield strength100%, stress at break 9%, elongation 73% and impact energy62% and showed an increase in hardness 53% comparing with the As received sample and this can be associated with subsequent rapid quenching from the austenitizing region which was carried out in an ambient water.

The fast cooling which was enough for them to suppress the diffusion of iron and carbon atoms. Consequentially, diffusion controlled transformations of austenite to ferrite, pearlite, and bainite were highly suppressed in the matrix of the C45 alloy upon rapid quenching. On the other hand, transformation of austenite to martensite was enabled under such non-equilibrium conditions.

The austenite to martensite transformation during water quenching of the C45 alloy from the austenitizing region to room temperature was evident in the optical micrographs this identical Referenced [8] . further, it was obvious that the very lower in yield strength and increase in hardness comparing with all other heat treatments.

Comparing the mechanical properties of hardened and tempered sample with sample of the As received, it was found that there was decrease in tensile strength9%, yield strength8%, stress at break 24% and increase in elongation53% and impact energy 76% this is identical to Referenced [8] . further, it was obvious that the increase in yield strength comparing with all other heat treatments.

The variability in ultimate yield strength ,tensile strength, percentage elongation, impact energy, stress at break and hardness of treated and untreated medium carbon steel (C45). are shown in **Figures (1) to (6),** respectively.

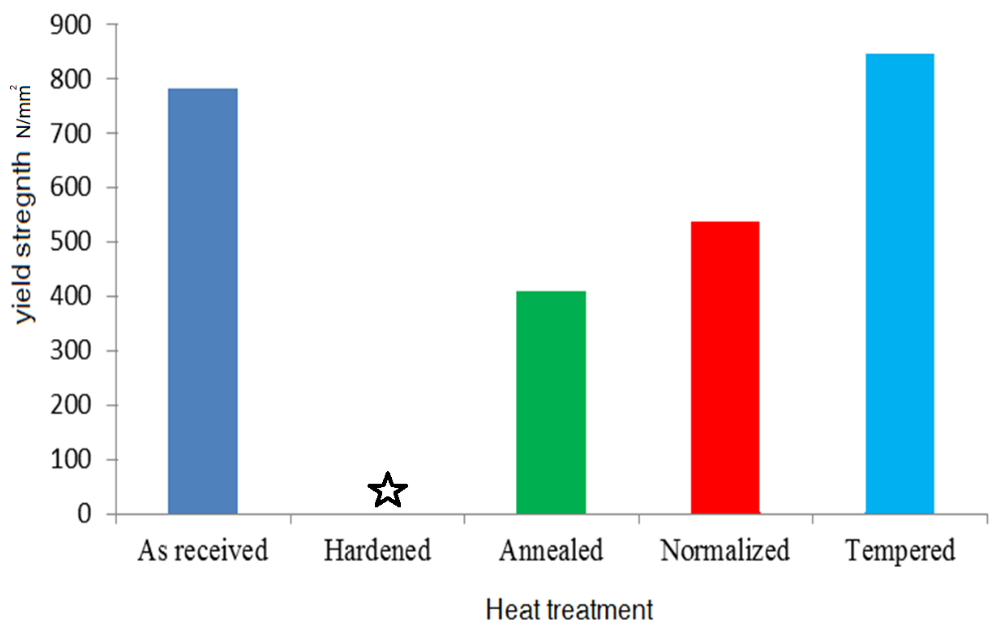

Figure 1 :Yield strength of treated and untreated samples of medium carbon steel (C45).

☆Note

Cause metal is very Brittle can be occurs the following points:

1- No appreciable plastic deformation.

2- Crack propagation is very fast.

3- Crack propagates nearly perpendicular to the direction of the applied stress.

4- This much lower fracture strength is explained by the effect of stress concentration at f microstructures flaws.

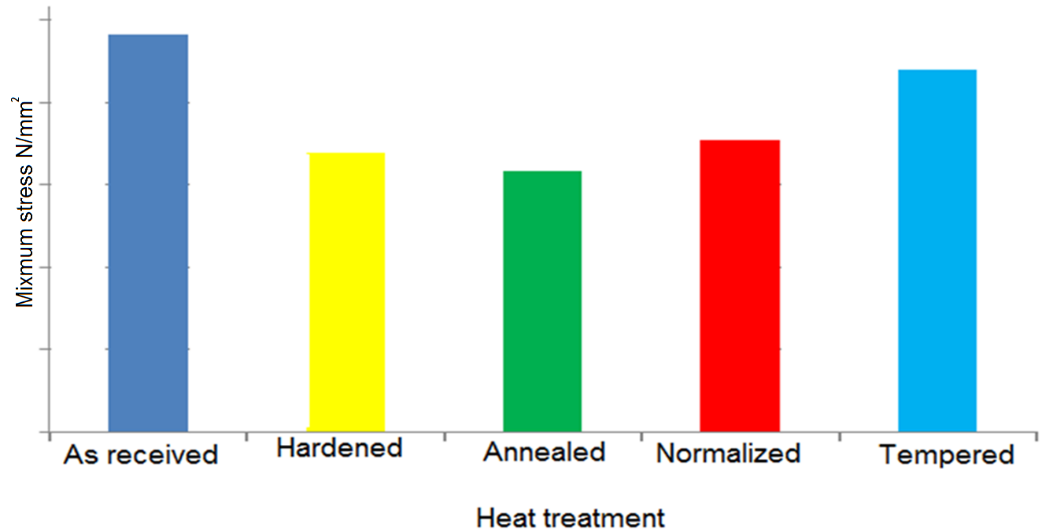

Figure 2: Tensile strength of treated and untreated samples of medium carbon steel (C45).

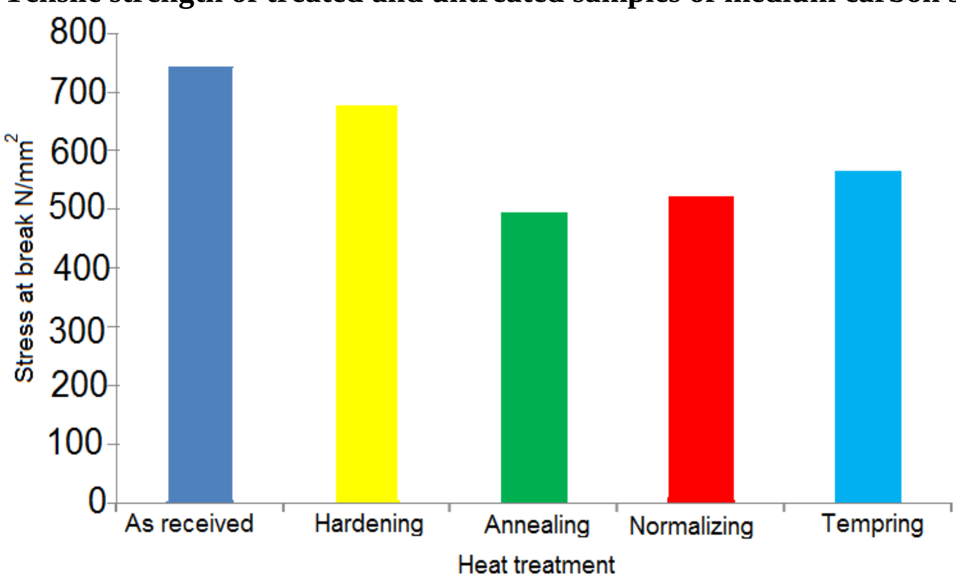

Figure 3 :Stress at break of treated and untreated samples of medium carbon steel (C45).

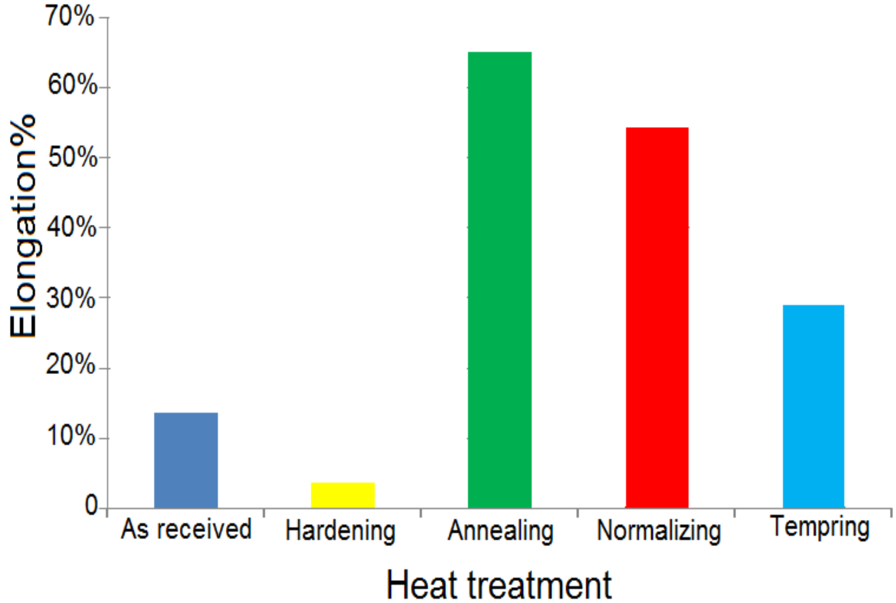

Figure 4: Percentage elongation of treated and untreated samples of medium carbon steel (C45).

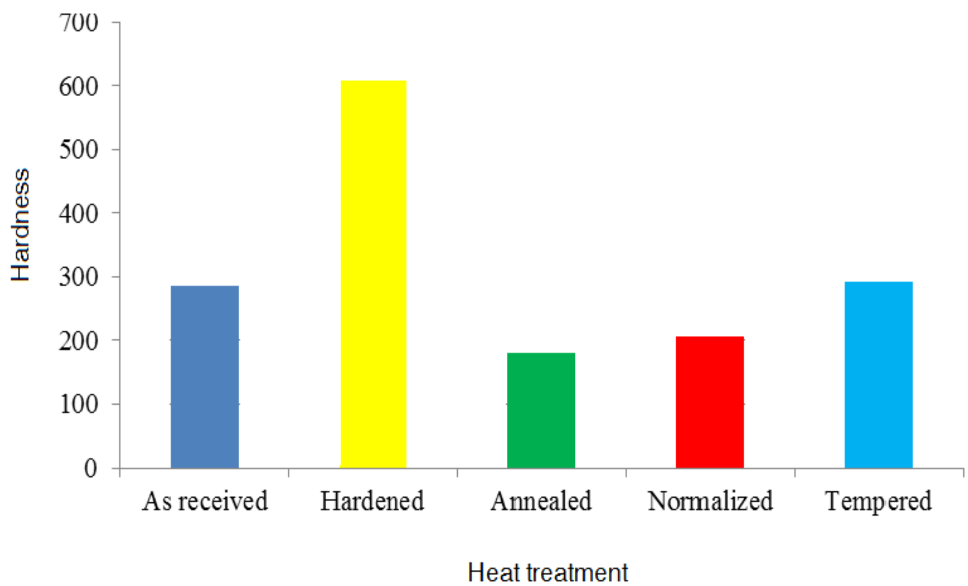

Figure 5: Hardness of treated and untreated samples of medium carbon steel (C45).

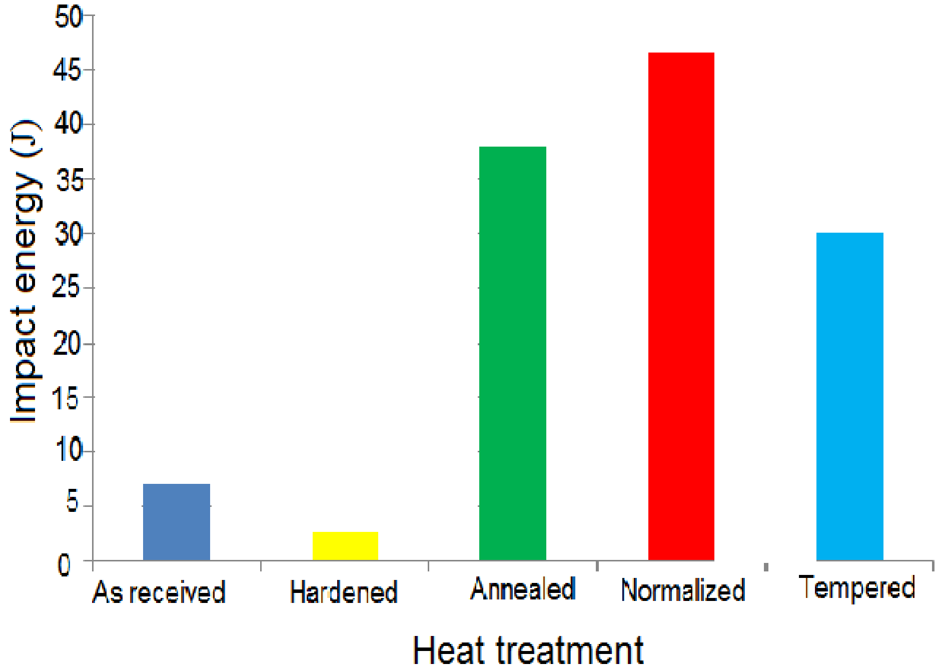

Figure 6: Impact energy of treated and untreated samples of medium carbon steel (C45).

3.2 Tensile Test Results and Analysis

Due to importance of this test the results have been taken in to consider with more details :

3.2.1 As received specimen

From the tensile strength specimen which have been taken in the untreated condition of medium carbon steel (C45), the maximum load which the specimen can with stand and gives uniform elongations was (964.3 N/mm^2). Medium carbon steel (C45), undergoes several stages of deformation during the tensile test. Referring to **figure (7)** the medium carbon steel (C45), surface deforms in an elastic manner. The slope of the line is start at load of (775 N/mm^2). At yield point strength of (781 N/mm^2) the medium carbon steel (C45), reaches its proportional limit and starts to deform plastically. During the uniform elongation portion of the tensile test, two variables have been changing. The metal has been work hardening with each increment of deformation. This means an increase in load is required to deform the specimen an additional increment of length each additional increment of length increase also causes the cross sectional area of the specimen to decrease.

The reduction in cross sectional area causes the applied load to be more effective in deforming the metal. As the tensile specimen is elongated, the amount of hardening increases and the amount of geometrical softening increases

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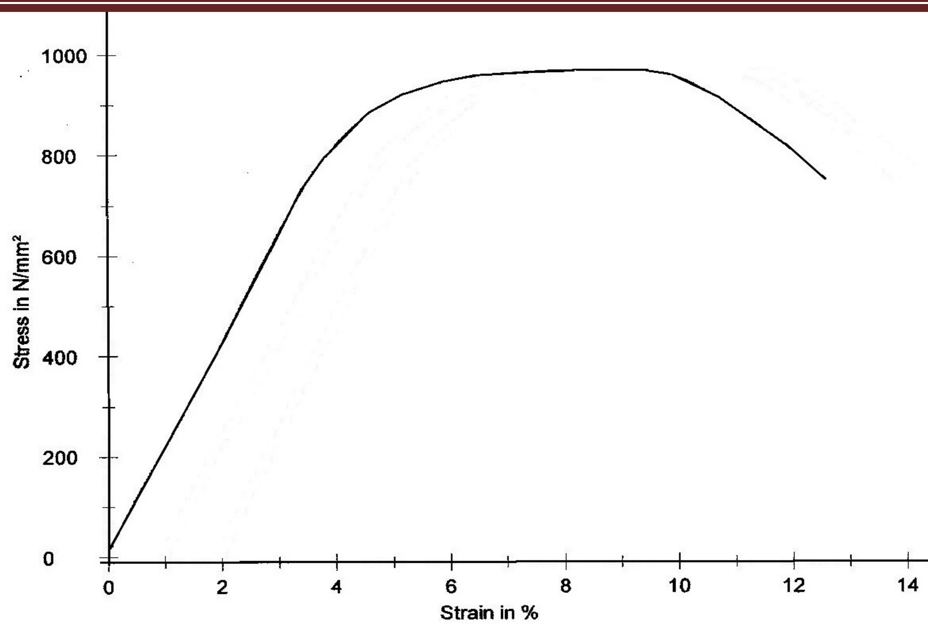

Figure 7: Tensile test curve for As received specimen.

As the specimen elongates, a reduction in width occurs, resulting in a diffuse neck. The onset of diffuse necking terminates uniform elongation because additional increments of deformation are not uniformly distributed throughout the entire length of the specimen. Continuing deformation causes another type of neck to form. This neck is a highly localized band across the specimen.

3.2.2 Annealing specimen

A full annealing was carried out on the specimen by heating the metal slowly at 840 ^{o} C. It is held at this temperature for sufficient time (about 24 minutes) for all the material to transform into austenite. It is then cooled slowly inside the furnace to room temperature. Then the tensile test was done to investigate the yield strength, ultimate strength and elongation of the sample before heat treatment. From the tensile strength specimen which have been taken in the annealing condition of medium carbon steel (C45), the maximum load which the specimen can with stand and gives uniform elongations was (610 N/mm^2 and 625 N/mm^2), therefore the specimen were subjected to load force average of (617.5 N/|mm^2). Medium carbon steel (C45), undergoes several stages of deformation during the tensile test. Referring to **figure (8)** the medium carbon steel (C45), surface deforms in an elastic manner. The slope of the line is start at load of (425 N/mm^2). At yield point strength of (625 N/mm^2) the medium carbon steel (C45), reaches its proportional limit and starts to deform plastically. During the uniform elongation portion of the tensile test, two variables have been changing. The metal has been work hardening with each increment of deformation. This means an increase in load is required to deform the specimen an additional increment of length each additional increment of length increase also causes the cross sectional area of the specimen to decrease.

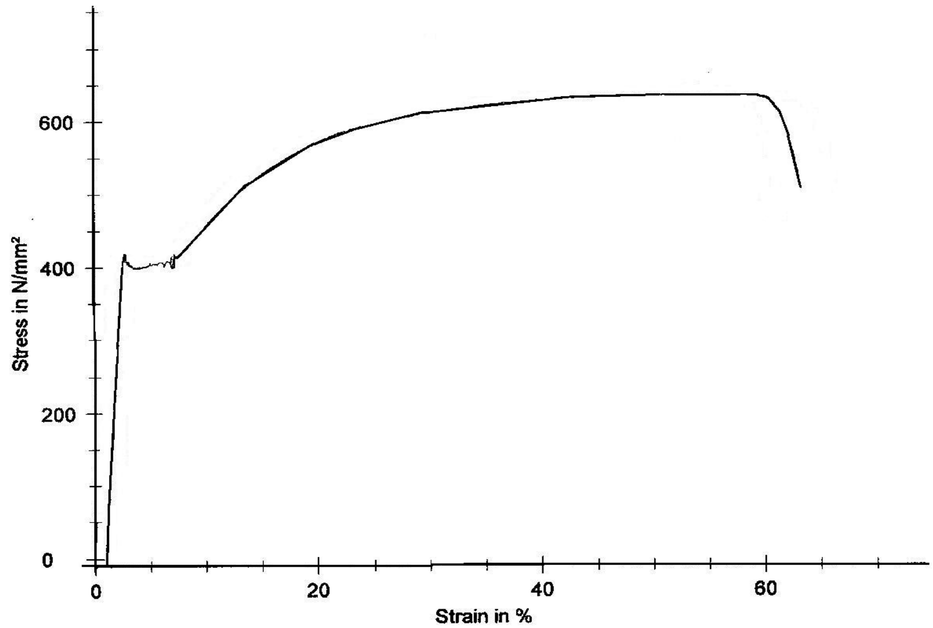

Figure 8: Tensile test curve for annealing specimen.

The reduction in cross sectional area causes the applied load to be more effective in deforming the metal. As the tensile specimen is elongated, the amount of hardening increases and the amount of geometrical softening increases. As the specimen elongates, a reduction in width occurs, resulting in a diffuse neck. The onset of diffuse necking terminates uniform elongation because additional increments of deformation are not uniformly distributed throughout the entire length of the specimen.

Continuing deformation causes another type of neck to form. This neck is a highly localized band across the specimen.

3.2.3 Normalizing specimen

A normalizing process was carried out on the specimen by heating the metal slowly at 840^0 C. It is held at this temperature for sufficient time (about 24 minutes) It is then the specimen taken out of the furnace to let cooled at room temperature.. From the tensile strength specimen which have been taken in the normalizing condition of medium carbon steel (C45), the maximum load which the specimen can with stand and gives uniform elongations was (711.3 N/mm^2). Medium carbon steel (C45), undergoes several stages of deformation during the tensile test. Referring to **figure (9)** the medium carbon steel (C45), surface deforms in an elastic manner. The slope of the line is start at load of (530 N/mm^2). At yield point strength of (536 N/mm^2). the medium carbon steel (C45), reaches its proportional limit and starts to deform plastically. As the tensile specimen is elongated, the amount of hardening increases and the amount of geometrical softening increases. As the specimen elongates, a reduction in width occurs, resulting in a diffuse neck. Continuing deformation causes another type of neck to form. This neck is a highly localized band across the specimen.

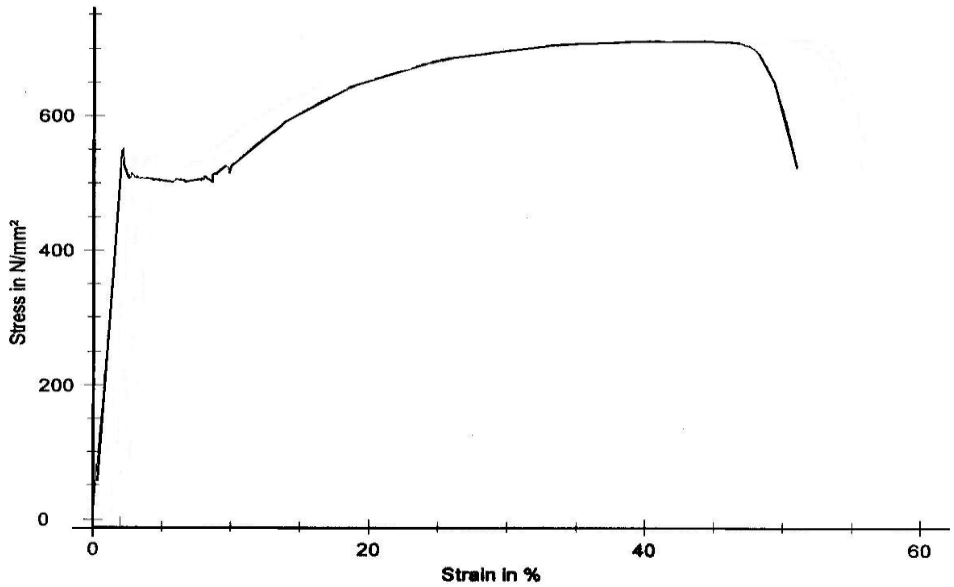

Figure 9Tensile test curve for normalizing specimen.

3.2.4 Hardening specimen

The specimens to be hardened were placed inside the furnace and heated to a temperature of 840^0C. The samples were retained at this temperature for a period of 24 minutes during which the transformation must have been completed, after which they were later removed from the furnace and dropped inside different containers of water for rapid cooling to room temperature. The hardening operation was carried out on three medium carbon steel samples having the same dimensions. From the tensile strength specimen which have been taken in the Harding condition of medium carbon steel (C45), the maximum load which the specimen can with stand and gives uniform elongations was (677 N/mm^2). Medium carbon steel (C45), does not deform during the tensile tes hardening specimen t. **(figure 10)**

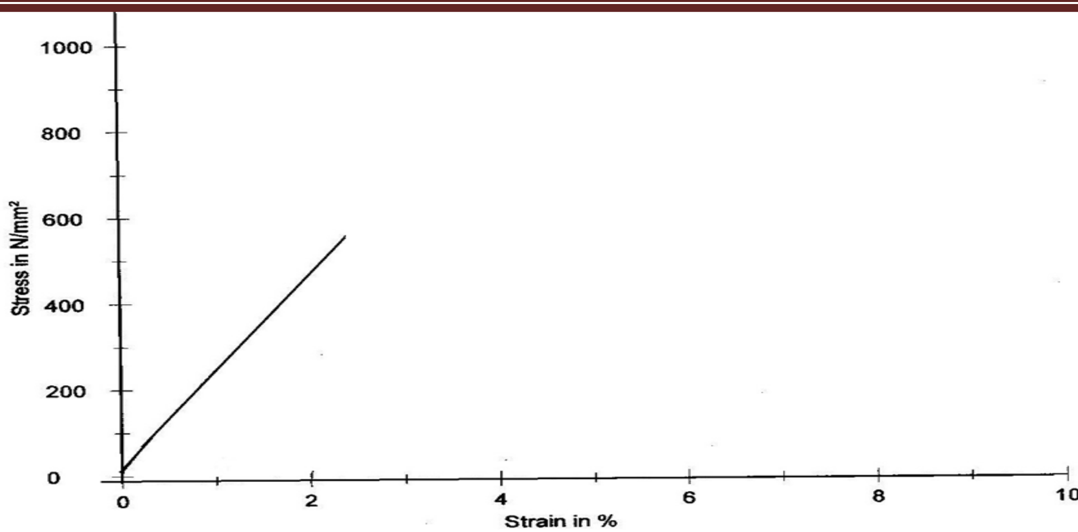

Figure: 10 Tensile test curve for hardening specimen.

3.2.5 Tempering

In the hardened carbon steel specimens, the as-quenched martensite is not only very hard but also brittle. The brittleness is caused by apredominance of martensite. This brittleness is therefore removed by tempering [9]. Tempering results in a desired combination of hardness, ductility, toughness, strength and structural stability. The process of tempering involves heating the hardened steel specimen to 600 ^{0}C. This process allows microstructure modifications to reduce the hardness to the desire level while increasing the ductility. From the tensile strength specimen which have been taken in the tempering condition of medium carbon steel (C45), the maximum load which the specimen can with stand and gives uniform elongations was (880 N/mm^2).

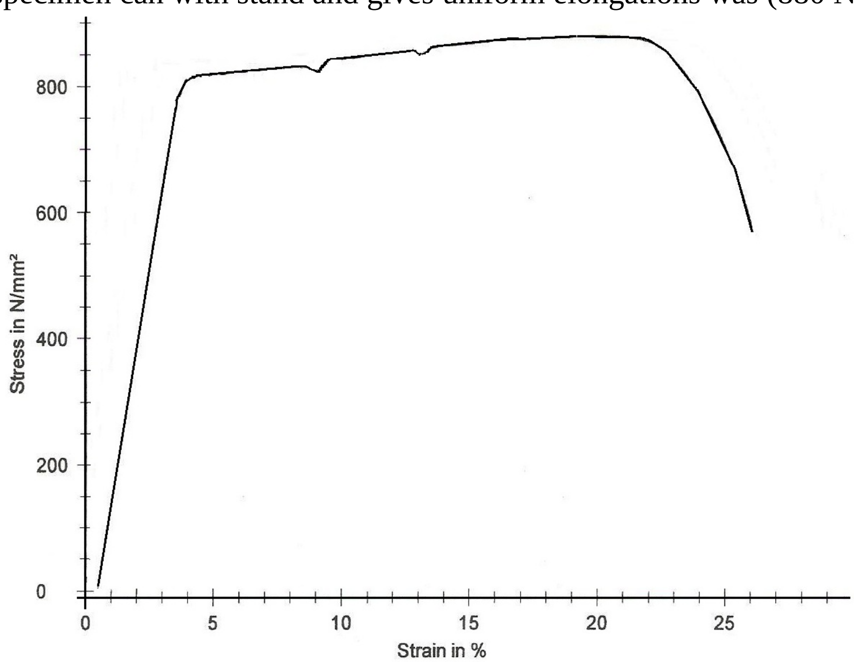

Figure: 11 Tensile test curve for tempering specimen.

Medium carbon steel (C45), undergoes several stages of deformation during the tensile test. Referring to **figure (11)** the medium carbon steel (C45), surface deforms in an elastic manner. The slope of the line is start at load of (840 N/mm^2). At yield point strength of (846 N/mm^2) the medium carbon steel (C45), reaches its proportional limit and starts to deform plastically. During the uniform elongation portion of the tensile test, two variables have been changing. The metal has been work hardening with each increment of deformation. This means an increase in load is required to deform the specimen an additional increment of length each additional increment of length increase also causes the cross sectional area of the specimen to decrease. The reduction in cross sectional area causes the applied load to be more effective in deforming the metal. As the tensile specimen is elongated, the amount of hardening increases and the amount of geometrical softening increases. As the specimen elongates, a reduction in width occurs, resulting in a diffuse neck. The onset of diffuse necking terminates uniform elongation because additional increments of deformation are not uniformly distributed throughout the entire length of the specimen.

Continuing deformation causes another type of neck to form. This neck is a highly localized band across the specimen.

4. Conclusion

The influence of heat treatment on the microstructure and mechanical properties of the medium carbon steel C45 was investigated.

The main conclusions of this investigation can be summarized in the following points:

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The microstructure of the as-received C45 alloy was quite similar to microstructure obtained by the laboratory normalizing treatment employed in the present study, suggesting that the C45 alloy was originally supplied in the normalized condition. The difference in the mechanical properties between the as-received and the re normalized C45 alloys can be related to the difference in the heat treatment conditions employed during the original normalizing treatment of the cold-rolled C45 with that employed in the present study.

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Heating the C45 alloy at 840°C for 24 minutes results in the transformation of the ferrite-pearlite microstructure into austenite during austenitizing treatment.

The fast cooling rate employed during water quenching from the of austenitizing temperature results in the transformation of austenite into martensite, which in turn, significantly increases the alloy hardness at the expense of severe reduction in the alloy tensile strength, stress at break and percentage of elongation.

During normalizing treatment, the cooling rate from the austenitizing temperature is slow enough to allow re-formation of the ferrite and pearlite phases, which enhances the percentage of elongation and impact energy of the C45 alloy.

The near equilibrium conditions employed during normalizing treatment, however, reduce the alloy tensile strength, stress at break and yield strength.

Upon annealing treatment, the very slow cooling rate from the austenite phase field allows a slow decomposition of the austenite into ferrite and perlite phases. Compared with the normalized condition, the ferritic-perlitic structure of the annealed C45 alloy is coarser and the spacing between the pearlite lamellae is larger.

Consequently, the annealed C45 alloy possess a slightly higher percentage of elongation and impact energy, but with lower hardness tensile strength, stress at break and yield strength relative to the normalized condition..

Tempering following hardening treatment does not induce a significant change in the lath-shaped martensitic structure of the as-quenched C45 alloy. This treatment, however, results in a significant improvement in the mechanical properties of hardened C45 alloy, such as yield strength percentage of elongation and impact energy.

The hardness and stress at break decrease, whereas, the percentage of elongation increases with increasing the cooling rate of the C45 alloy from the austenitizing temperature.

5. References

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