Microstructure and Mechanical Properties of Low Carbon Steel Alloy During Normalizing, Annealing & Tempering Heat Treatment Processes

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Abstract: ***The main objective of this project is to study and analyze the microstructures and mechanical properties of low carbon steel alloy during normalizing, annealing & tempering heat treatment processes. Generally for low carbon steels Normalizing is preferred heat treatment process to obtain desired properties even though there are plethora of other heat treatment processes, we were curious to find out its reason in that process we had referred through many sources i.e.,(internet & books). We haven't found any proper reason for it so we decided to complete the project. This project describes about the change in microstructure of low carbon steel alloy with respect to time during various heat treatment processes, it also illustrates the change in mechanical properties during different heat treatment processes through stress strain curves.***

Keywords: Microstructures, low carbon steel, alloy, mechanical properties, heat treatment, normalizing, annealing, tempering

1. Introduction

Low carbon steel (iron containing a small percentage of carbon, strong and tough but not readily tempered), also known as plain-carbon steel and mild steel, is now the most common form of steel because its price is relatively low while it provides material properties that are acceptable for many applications. Mild steel contains approximately 0.05–0.25% carbonmaking it malleable and ductile. Mild steel has a relatively low tensile strength, but it is cheap and easy to form; surface hardness can be increased through carburizing [7].

In applications where large cross-sections are used to minimize deflection, failure by yield is not a risk so low-carbon steels are the best choice, for example as structural steel. The density of mild steel is approximately 7.85 g/cm^3 (7850 kg/m^3 or 0.284 lb/in^3) and the Young's modulus is 200 GPa (29,000 ksi).

Generally for low carbon steels Normalizing is preferred heat treatment process to obtain desired properties even though there are plethora of other heat treatment processes.

2. Heat Treatment Processes

2.1 Normalizing

Normalizing is a technique used to provide uniformity in grain size and composition throughout an alloy. The term is often used for ferrous alloys that have been heat treated and then cooled in open air. Normalizing not only produces pearlite, but also martensite and sometimes benite, which gives harder and stronger steel, but with less ductility for the same composition than full annealing [3].

2.2 Annealing

Annealing consists of heating a metal to a specific temperature and then cooling at a rate that will produce a refined microstructure, either fully or partially separating the constituents. The rate of cooling is generally slow. It is most often used to soften a metal for cold working, to improve machinability, or to enhance properties like electrical conductivity.

It is usually accomplished by heating the metal beyond the upper critical temperature and then cooling very slowly, resulting in the formation of pearlite. In both pure metals and many alloys that cannot be heat treated, annealing is used to remove the hardness caused by cold working. The metal is heated to a temperature where recrystallization can occur, thereby repairing the defects caused by plastic deformation. In these metals, the rate of cooling will usually have little effect. Most non-ferrous alloys that are heat-treatable are also annealed to relieve the hardness of cold working [2].

2.3 Quenching

Quenching is the rapid cooling of a workpiece in water, oil or air to obtain certain material properties. A type of heat treating, quenching prevents undesired low-temperature processes, such as phase transformations, from occurring. It does this by reducing the window of time during which these undesired reactions are both thermodynamically favorable, and kinetically accessible; for instance, quenching can reduce the crystal grain size of both metallic and plastic materials, increasing their hardness.

In metallurgy, quenching is most commonly used to harden steel by introducing martensite, in which case the steel must be rapidly cooled through its eutectoid point, the temperature at which austenite becomes unstable[3].

2.4 Tempering

Tempering is a process of heat treating, which is used to increase the toughness of iron-based alloys. Tempering is usually performed after hardening, to reduce some of the excess hardness, and is done by heating the metal to some temperature below the critical point for a certain period of time, then allowing it to cool in still air. The exact temperature determines the amount of hardness removed, and depends on both the specific composition of the alloy and on the desired properties in the finished product. For instance, very hard tools are often tempered at low temperatures, while springs are tempered to much higher temperatures [2].

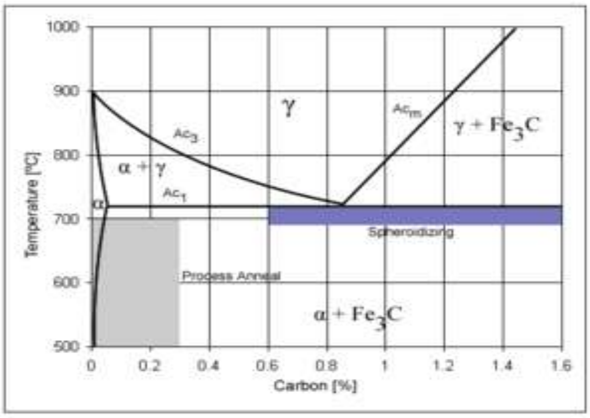


Figure 2.1: Temperature vs Carbon percentage graph

Heat Treatment Processes	Material						Optimum temperature of material	Soaking Time	Type of Cooling
	LCS	MC	HCS			Mn Steel, LAS			
Normalizing	*	*	*	*	-	-	890-930°C	1"/25mm-1Hr Soaking	A/c
Annealing	-	-	*	-	-	-	890-930°C		F/c
Tempering	-	-		*	*	-	600-720°C		A/c, F/c
Water quenching	-	-	-	-	-	*	1050-1080°C		S/c
Oil quenching	-	-	-	-	*	-	890-920°C		S/c

- A/c-Air cooled
- S/c-Sudden cooled
- F/c-Furnace cooled

Table 2.1: The above table illustrates the suitable heat treatment process for different types of steels

3. Compositions and Methodology

3.1 Compositions as per AISI standards

Main elements	**Residual elements**
Carbon - 0.3%	Copper – 0.3%
Manganese - 1%	Nickel – 0.5%
Silicon – 0.6%	Chromium – 0.5%
Sulphur – 0.045%	Molybdenum – 0.2%
Phosphorous – 0.04%	Vanadium – 0.3%

The obtained chemical compositions of test specimen after spectrometry test are as follows

Main elements	**Residual elements**
Carbon - 0.24%	Copper – 0.3%
Manganese – 0.93%	Nickel – 0.53%
Silicon – 0.48%	Chromium – 0.45%
Sulphur – 0.035%	Molybdenum – 0.12%
Phosphorous – 0.034%	Vanadium – 0.32%

3.2 Methodology

3.2.1 Microstructural Analysis

4 Specimens of mild carbon steel of dimension 8×8×3 mm was cut using power hacksaw. Then they are grinded & polished. Specimens were subjected to various heat treatment process and each sample is observer under microscope (50μm) for a time variation of 10 minutes**.**

3.2.2 Analysis of Mechanical Properties:

The Test specimens are cut as per AISI standards. They are tested in UTM(universal testing machine) & BHM(brinell's hardness testing machine) before and after heat treatment process in order to obtain brinell's hardness number, ultimate load, yield load& fracture load of each individual specimen.

Later on the data is plotted in the form of graph.

UTM: A universal testing machine (UTM), also known as a universal tester, materials testing machine or materials test frame, is used to test the tensile strength and compressive strength of materials [6].

Brinell Hardness Test

The Brinell hardness test method as used to determine Brinell hardness, is defined inASTME10.Most commonly it is used to test materials that have a structure that is too coarse or that have a surface that is too rough to be tested using another testing method.

4. Experimentation

4.1Analysis of Microstructure during various heat treatment processes:

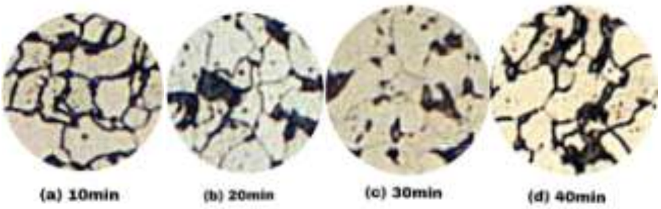
4.1.1Normalizing

4 Specimens of mild carbon steel of dimension 8×8×3 mm was cut using power hacksaw. Then they are grinded & polished. Specimens were subjected to normalizing and each

Paper ID: ART20183852 DOI: 10.21275/ART20183852

sample is observer under microscope (50µm) for a time variation of 10 minutes.

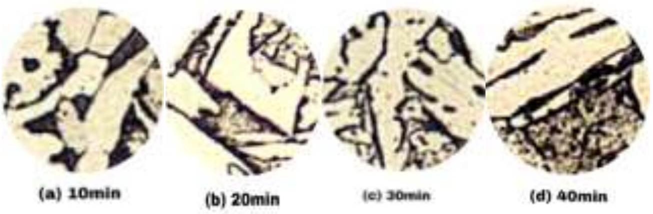
AT(50µm)



However we can observe the formation of pearlite in the step by step procedure, pearlite is formed because of slow cooling of austenite.

4.1.2 Annealing:
4 Specimens of mild carbon steel of dimension 8×8×3 mm was cut using power hacksaw. Then they are grinded & polished. Specimens were subjected to annealing and each sample is observer under microscope (50µm) for a time variation of 10 minutes.

AT(50µm)

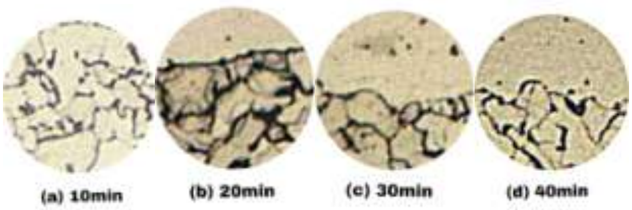


The above microstructures illustrates the formation of partial bainite we can't observe clearly because of insufficient amount of carbon atoms present in the composition of low carbon steel alloy. Generally the test specimens which undergoes through annealing produces bainite because of its moderate cooling rate.

4.1.3 Tempering:
Before the test specimen's undergoes through tempering it was subjected to oil quenching in order to obtain better results.

4 Specimens of mild carbon steel of dimension 8×8×3 mm was cut using power hacksaw. Then they are grinded & polished. Specimens were subjected to tempering and each sample is observer under microscope (50µm) for a time variation of 10 minutes.

AT(50µm)



The above microstructures recapitulates the formation of partial martensite we can't observe clearly because of insufficient amount of carbon atoms present in the composition of low carbon steel alloy. Generally the test specimens which undergoes through oil quenching followed by tempering produces martensite due to its fast cooling rate.

4.2 Analysis of Mechanical Properties

Mechanical properties like tensile strength, brinell's hardness number, ultimate load, yield load & fracture load are been determined by conducting tests as per AISI standards in UTM and brinell hardness test before and after heat treatment processes.

<u>Before Heat Treatment</u>
UTM RESULTS
<u>BEFORE FRACTURE:</u>
Nominal Diameter as per AISI standard's
Diameter(D_1) = 12.6 mm
Length (L_1) = 50 mm
<u>AFTER FRATURE:</u>
Diameter = 9.70 mm
Length (L_2) = 60 mm
Yield load = 39 KN
Ultimate load = 55 KN
Fracture load = 52 KN
Yield strength = 312.80N/mm^2
Tensile strength = 441.12N/mm^2
Fracture strength = 416.13 N/mm^2
% of elongation = 20%
% of reduction = 40.72%

BHN RESULTS
Total load =3000KGF
Stage load =250KGF
Diameter of indenter = 10mm
Diameter of indentation = 6.78mm
Brinells hardness number = 72.04kgf/mm^2

<u>After Normalizing</u>
UTM RESULTS
<u>BEFORE FRACTURE:</u>
Nominal Diameter as per AISI standard's
Diameter(D_1) = 12.6 mm
Length (L_1) = 50 mm
<u>AFTER FRATURE:</u>
Diameter = 9.40 mm
Length (L_2) = 63.20 mm
Yield load = 44 KN
Ultimate load = 70 KN
Fracture load = 66 KN
Yield strength = 352.90N/mm^2
Tensile strength = 561.43N/mm^2
Fracture strength = 528.16N/mm^2
% of elongation = 26.40%
% of reduction = 44.34%
BHN RESULTS
Total load = 3000KGF
Stage load = 250KGF
Diameter of indenter = 10mm
Diameter of indentation = 4.68 mm
Brinells hardness number = 165.33kgf/mm^2

After Annealing

UTM RESULTS

BEFORE FRACTURE:

Nominal Diameter as per AISI standard's

Diameter(D_1) = 12.6 mm

Length (L_1) = 50 mm

AFTER FRATURE:

Diameter = 7.6 mm

Length (L_2) = 62.6 mm

Yield load = 27 KN

Ultimate load = 49 KN

Fracture load = 45 KN

Yield strength = 216.55N/mm^2

Tensile strength = 393N/mm^2

Fracture strength = 360.11N/mm^2

% of elongation = 25.2%

% of reduction = 63.61%

BHN RESULTS

Total load = 3000KGF

Stage load = 250KGF

Diameter of indenter = 10mm

Diameter of indentation = 7.23 mm

Brinells hardness number = 61.71kgf/mm^2

After Tempering

UTM RESULTS

BEFORE FRACTURE:

Nominal Diameter as per AISI standard's

Diameter(D_1) = 12.6 mm

Length (L_1) = 50 mm

AFTER FRATURE:

Diameter = 7.1 mm

Length (L_2) = 61.6 mm

Yield load = 29 KN

Ultimate load = 53 KN

Fracture load = 50 KN

Yield strength = 232.59N/mm^2

Tensile strength = 425.08N/mm^2

Fracture strength = 400.12N/mm^2

% of elongation = 23.2%

% of reduction = 68.24%

BHN RESULTS

Total load = 3000KGF

Stage load = 250KGF

Diameter of indenter = 10mm

Diameter of indentation = 5.83 mm

Brinells hardness number = 101.75kgf/mm^2

5. Formulas

1. Brinell's Hardness Number = $\frac{P}{A}$

$$BHN=\frac{2P}{\pi D\left(D-\sqrt{D^2-d^2}\right)}$$

where [1]

BHN= Brinell Hardness Number (kgf/mm^2)

P=applied load in kilogram-force (kgf)

D=diameter of indenter (mm)

d = diameter of indentation (mm)

2. Yield strength $= \frac{yield\ \ load}{area}$ [1]

3. Tensile Strength = $\frac{Ultimate\ \ load}{area}$ [1]

4. Fracture Strength = Fracture load/area

5. % of elongation $= \frac{(L2-L1)}{L1}*100$ [4]

6. % of reduction $= \frac{(A1-A2)}{A1}*100$ [4]

6. Results and Discussion

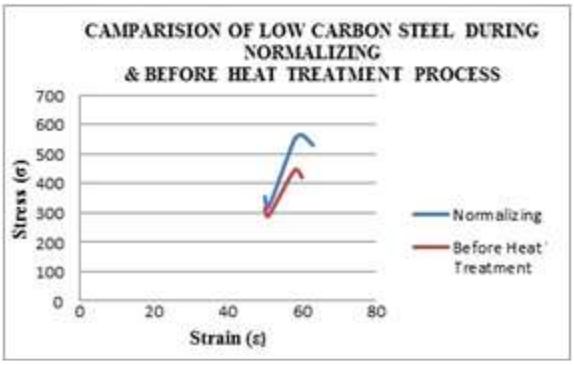


Figure 6.1: Illustrates the stress – strain relation between the specimen before heat treatment process and the specimen after Normalizing heat treatment process.

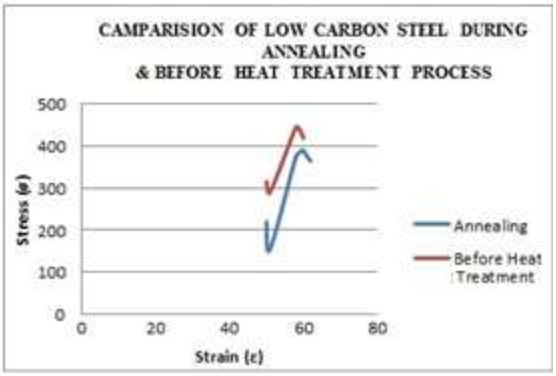


Figure 6.2: Illustrates the stress – strain relation between the specimen before heat treatment process and the specimen after Annealing heat treatment process.

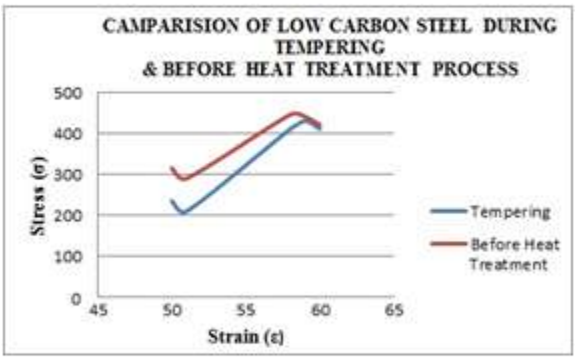


Figure 6.3: Illustrates the stress – strain relation between the specimen before heat treatment process and the specimen after Tempering heat treatment process.

Paper ID: ART20183852 DOI: 10.21275/ART20183852

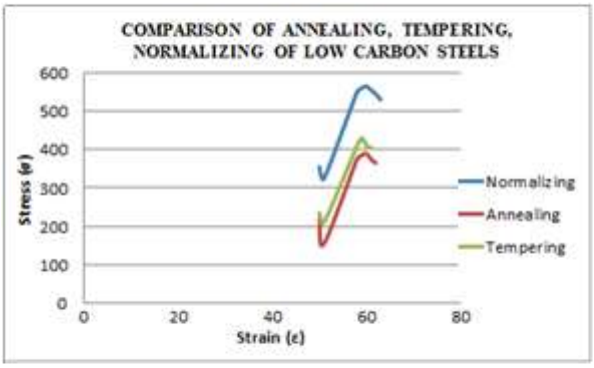


Figure 6.4: illustrates the stress – strain relation between the specimen Normalizing, Annealing, Tempering heat treatment processes

7. Conclusion

From the above graphs & microstructures we can decide that Normalizing as the best process among other heat treatment processes in order obtain desired properties for low carbon (or) Mild steels on the basis of strength and the proper formation of pearlite structure. In case of the other two the conditions for formation of microstructures aren't suitable for the formation of Bainite & Martensite due to insufficient carbon deposits in the composition. Even if we consider in terms of strength, the specimen which had subjected to Normalizing heat treatment process possess greater strength when compared to other heat treatment processes.

We can conclude that Normalizing processes is effective heat treatment process for low carbon (or) Mild steels on the basis of strength, optimum economy, time consumption, as well as defects occur during heat treatment are comparatively low.

8. Acknowledgement

We take this opportunity to thank all those magnanimous persons who rendered their full co- operation for completion of this project.

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