

EFFECT OF HEAT TREATMENT ON THE MECHANICAL AND MICROSTRUCTURAL PROPERTIES OF A LOW CARBON STEEL

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Abstract: *Low carbon steels have wide applications in oil and gas pipelines, power plant components and armour structures due to their good mechanical properties. However, the presence of ferrite and pearlite phases in the microstructures of steels can sometimes be detrimental to their structure-mechanical property relationship. In this work, the effect of heat treatment on the mechanical and microstructural properties of low carbon steel is examined. Eight Samples of the low carbon steel were heat treated to an austenising temperature of 850°C using an electric furnace. Two samples each were subjected to annealing, hardening, normalizing and tempering heat treatments. Microstructural characterization and selected mechanical properties tests of heat-treated and untreated samples were carried out. The optical microscopy analysis revealed that heat-treated samples are characterized with ferrite and pearlite in varying proportions. The most refined microstructure is found to be from the annealed sample. Sample subjected to hardening shows the highest Brinell's Hardness number of 434 BHN while annealed sample was the toughest and thus most ductile with an impact energy value of 65.43 J. The microstructure of the heat-treated samples showed a more refined grain structures when compared with that of the control untreated sample. Therefore, cautious selection of heat treatment types provides useful approach for modifying the microstructure of low carbon steels towards the attainment of outstanding mechanical properties. .*

Keywords: *Heat treatment, Characterisation, Mechanical Properties, Microstructure, low Carbon steel*

1. INTRODUCTION

Steel is a ferrous metal classified based on their percentage of carbon. The Carbon content ranges from 0.15-1.5%. Although the number of steel specifications runs into thousands, plain carbon steel accounts for more than 90% of the total steel output. Fracturing of materials and effort to prevent it, cost the US industry about \$119 billion a year, 90% of the failure of components in a material is caused by stress application. This poses a great threat to the people, environment and economy at large.

Paris and Erdogan (1963) in their effort to monitor crack growth proposed a relationship between crack growth with stress intensity factor "K" at the crack tip. The relationship is given as:

$$m \frac{da}{dn} = C(K) \quad \text{Where C and m are material properties.}$$

The needs for new designs and Materials with properties that can better withstand fracturing are two paramount reasons why heat treatment is done. The most important and commonly utilised heat treatment method include: Annealing, Normalizing, Hardening and Tempering. Heat treatment alters the Mechanical and Microstructural properties of the Material and makes it amenable for the particular purpose for which it is intended. (Dell 1989). Nam and Bae (1999) proposed that during Annealing, softening of Microstructure take place and sometimes recrystallization and recovery occur. They postulated also that the morphology of carbides is naturally expected to change as well. Heat treating the Steel improves its machinability, ductility, Hardness, Tensile strength, Impact and corrosion resistance. The low Carbon Steel investigated was procured from Universal Steels Rolling Mill in Lagos, Nigeria and has wide applications in oil and gas pipelines, power plant components, armour structures and Building Construction. To the best of the Author's finding, no characterization of the Steel when subjected to heat treatment has been done. This research is geared towards the evaluation of selected Mechanical properties and the examination of the Microstructure of that low Carbon when subjected Annealing, Normalising, Hardening and Tempering. The study also seeks to make comparison of such properties and postulate the Heat treatment method to be used when a certain mechanical property is prioritised.

2. MATERIALS AND METHODOLOGY

Sample of Carbon Steel bar were obtained from the Universal Steels Rolling Mill, Ogba, Ikeja, Lagos, Nigeria. The Spectrometric analysis of the Steel was done in order to determine the Chemical composition. This is presented in Table 1.

Table 1: Chemical Composition of the low Carbon Steel

C (%)	Si (%)	Mn (%)	S (%)	P (%)	Cr (%)	Ni (%)	Cu (%)
0.2560	0.2220	0.7370	0.0470	0.1300	0.1300	0.0920	0.2740
Nb (%)	Al (%)	B (%)	W (%)	Mo (%)	V (%)	Ti (%)	Fe (%)
0.0001	0.0200	0.0001	0.0001	0.0001	0.0001	0.0001	98.1700

Standards Sample, 2 each for Annealing, Hardening, Normalizing and Tempering were cut using a Lathe Machine and prepared to specification. The Samples were placed into an electric Furnace which was regulated to 850° C. For the various Heat Treatments, the procedure followed is elucidated:

- i. Hardening: The temperature of the Specimen was quenched suddenly from 850°C to room temperature using water.
- ii. Tempering: The temperature of the Specimen was quenched suddenly from 850°C to room temperature using water. This was later placed in the electric furnace and gradually reheated to 250°C. It was thereafter brought out to be air cooled.
- iii. Annealing: The temperature of the Specimen was cooled under a controlled condition from 850° C to room temperature. This was achieved by leaving the specimen in the Oven while it was switched off.
- iv. Normalising: The temperature of the Specimen was gradually cooled from 850°C to room temperature by air cooling.

2.1. Mechanical Testing of the Low Carbon Steel

Standard samples of the untreated Steel which served as the control and the heat treated steel were subjected to various testing in order to determine some specific mechanical properties. The toughness test was carried out using an Impact tester machine, the Brinell Hardness test (BHN) was done using a Tensiometer, the tensile tests were carried out using a computerized Instron Testing Machine (model 3369). This Toughness test, Brinell's Hardness test and Tensile test all followed the ASTM E23, ASTM E18 and ASTM E8M test specification respectively. It should be noted that the oxide layer formed during the heat treatment was removed by stage grinding before subjecting it to heat treatment. The ASTM E606 Test specification was followed in order to generate the S-N curve behavior of the specimen.

2.2. Metallographic Examination

The Metallographic examination of the control and heat treated specimen were performed. The Metallographic examination processes include: grinding, polishing, etching before final examination under the metallurgical microscope. Each sample was grinded using Silicon carbide papers of different grades. The grading of the Silicon Carbide is in the order of 220,320,400 and 600. That is, from coarse to fine grade. A universal polishing machine was employed. The initial polishing was done using Selyt cloth alone. Selyt Cloth swamped with one micron and 0.5µm of Silicon Carbide solution respectively were utilized for polishing until a mirror-like surface is attained. This was then washed and dried. After this, etching was done to reveal the microstructure of the polished surface. The mirror-like surface was etched in 2% Natal etchant (2% NITRIC ACID and 98% of Ethyl Alcohol). The surface of the specimen was thereafter observed using a computer aided optical Accuscope Microscope.

3. RESULTS AND DISCUSSION

3.1. Effect of Heat Treatment on Mechanical Properties

The selected Mechanical properties of the Controlled, Annealed, Hardened, Normalized and Tempered specimen evaluated are presented in the Table 2a and 2b.

Table 2a: Effect of Heat Treatment on the Low Carbon Steel

	Impact Energy (J)	Brinell Hardness Number(BHN)	Tensile Strength (MPa)
CONTROL	40.13	178.0	832.616
ANNEALING	65.12	121.5	695.828
HARDENING	10.90	434.0	195.131
NORMALISING	64.87	156.5	711.402
TEMPERING	21.01	277.5	474.806

Table 2b: Continuation on the effect of Heat Treatment on the Low Carbon Steel.

	Yield Strength (MPa)	Young Modulus (MPa)	Percentage Elongation (%)
CONTROL	595.00	18112.329	18.695
ANNEALING	460.00	19315.320	20.595
HARDENING	75.00	21396.045	1.986
NORMALISING	450.00	16750.049	16.378
TEMPERING	120.00	20966.185	3.739

Comparing the Impact Energy of the untreated and Heat treated Specimens, the highest value of toughness was obtained for Annealing (65.43J), followed closely by Normalizing (64.87J) and the Least is Hardening (10.90J). This result agrees with Fadare et al (2011) in which Annealing gave the highest value of toughness evaluated as 64.10J of the NST 37-2 Steel considered. The Micrographs of Normalised and Annealed Sample also revealed a more refined structure when compared with the untreated Sample. The more refined grain structure of Normalised and Annealed Sample establishes also the reason for the higher value of toughness.

For the Brinell's Hardness Test Result. The Hardened sample gave the highest value of hardness of 434BHN and the Least was the annealed sample (195.13BHN). It is also noted that Tempering and Hardening increases the Hardness of the low Carbon Steel, while Normalising and Annealing reduces the hardness of the material. This is in resonance with Oluwole et al (2011) work on "Tempering Heat Treatment effects on steel weld" in which it was discovered that Hardness increased with tempering. Normalising and Annealing reduces the hardness. The microstructure of Hardened Sample revealed a coarse Martensitic structure, Tempering has more refined Martensite due to recrystallization by reheating while the microstructure of Normalised and annealed Steel show a soft ferrite structure. The Martensitic structure in Hardened and Tempered sample is the reason for the higher Brinell Hardness Number.

For the Tensile Strength, the Hardened sample gave the lowest value of (195.13MPa). This shows that the hardened Sample trades its ductility and tensile strength for Hardness. There exists a negative result of untreated steel sample having the highest value of Tensile strength.

The highest Modulus of Elasticity obtained was for the Hardened sample (21.396GPa) and the Least is the Normalised sample (16.75GPa). By comparing the result of Hardness test and that of Modulus of Elasticity, we can deduce that hardness and Modulus of Elasticity are directly related. The relationship between the Percentage Elongation of the low carbon alloy Steel of the various Heat treatment Sample is showed that the highest Percentage Elongation was

obtained for the annealed sample (20.59%). This can be traced to the fact that its internal stress is not highly built when the steel is slowly cooled.

The S-N graph depicting the Fatigue behavioural characteristic of the low Carbon steel subjected to various heat treatment processes if extrapolated reveals that all Heat treatment processes would improve the fatigue life of the Specimen with Annealing and Normalising give the best possibility respectively.

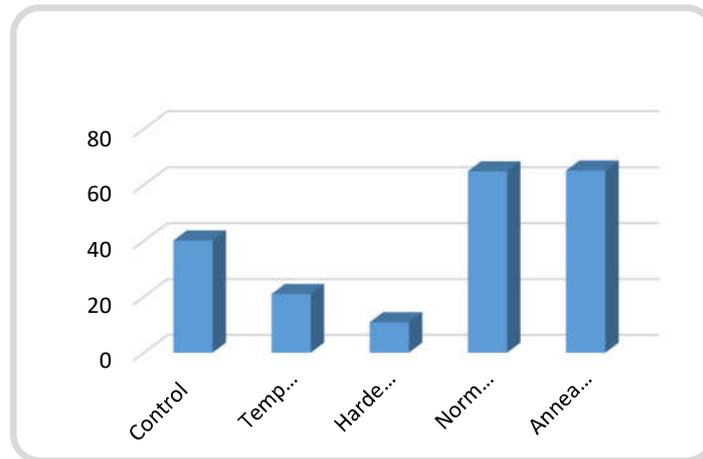


Fig1: Effect of various Heat Treatment process on the Toughness (Impact Energy) of the 0.26% Low Carbon Steel Sample.

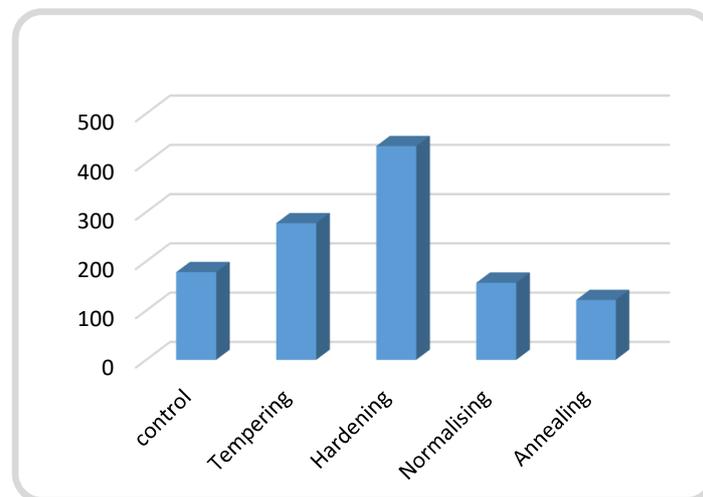


Fig 2: Effect of various Heat Treatment process on the Brinell's Hardness Number of the 0.26% Low Carbon Steel

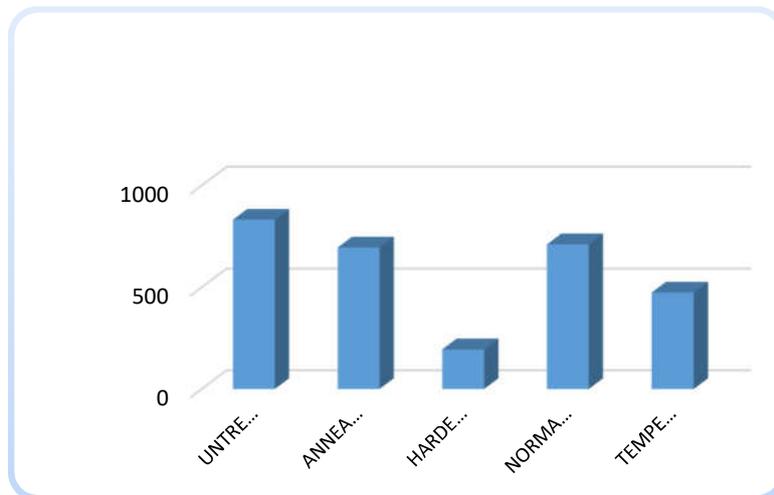


Fig 3: Effect of various Heat Treatment process on the Tensile Strength of the 0.26% Low Carbon Steel

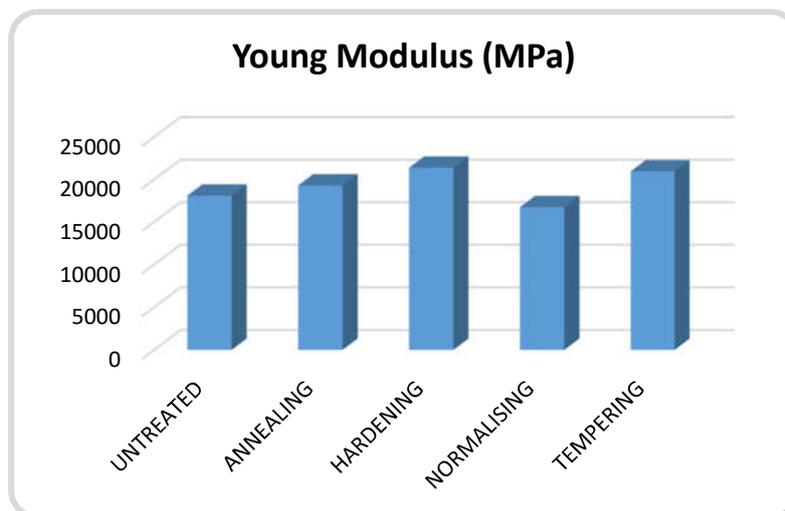


Fig 4 :Effect of various Heat Treatment process on the Modulus of Elasticity (E) of the 0.26% Low Carbon Steel

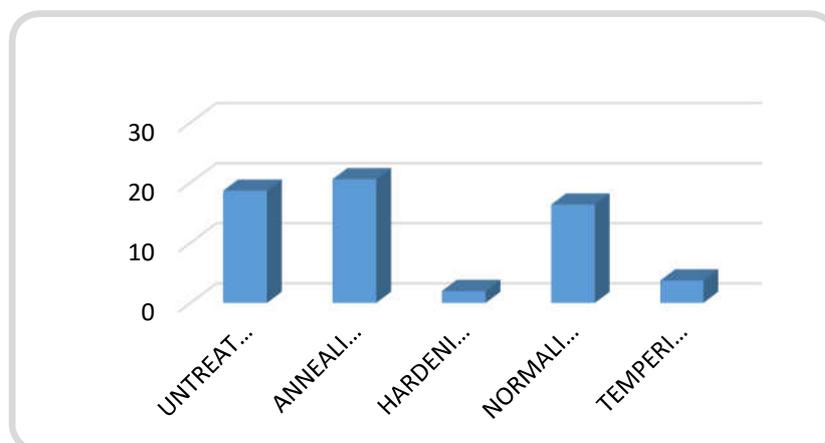


Fig 5: Effect of various Heat Treatment process on the Percentage Elongation of the 0.26% Low Carbon Steel

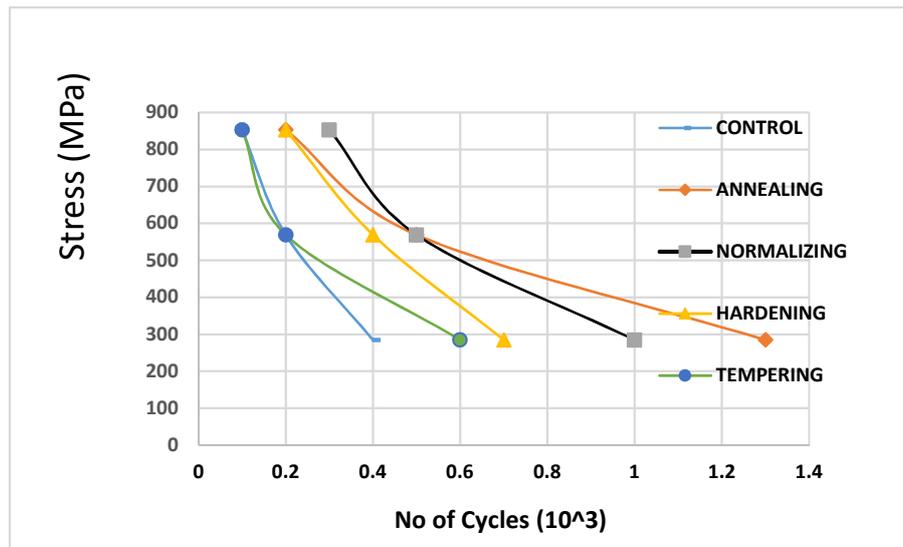


Fig 6: S-N behavior of the controlled and Heat treated specimen.

3.2. Effect of Heat Treatment on the Microstructural Properties

All Iron-carbon alloys contains some amount of ferrite if it is allowed to reach equilibrium at room temperature. The exact amount of ferrite so contained will depend on the cooling process that the Iron-carbon alloy undergoes as it cools. (Peter, 2009).

The Micrograph of the Untreated Low Carbon Steel Sample showed a combination of ferrite and Pearlite phase. The Ferrite being the white region and the pearlite the dark region. This is as expected, for a Fe-C Phase diagram reveals that a steel with composition of 0-0.8% carbon should have a α -ferrite and Pearlite phase. It is worthy of note that Ferrite is a Body Centered Cubic (BCC, alpha iron) form of iron with Crystalline structure which gives steel its magnetic properties. (Davis, 1997). The Microstructure of the control untreated grain Sample is large when compared with all the Heat treated Sample Micrograph for the grains of the control Sample is unrefined

The Micrograph of the Annealed 0.26% Low carbon Steel Sample shows a Microstructure, which has a thick band of Pearlite. This is due to the fact that Annealing, which is a controlled slow cooling of Steel heated above the Austenising temperature. Austenising Temperature is the temperature at which the Austenite Phase is formed. For steel, the Austenising temperature is between 727⁰C to 1500⁰C (Davis, 1997). The Austenite phase when slowly cooled, allows the formation of the Pearlite Structure. The Pearlite Phase contains both the Ferrite and Cementite phase, both phases alternates themselves in layers. Annealing, or heating the steel at moderate temperatures for an extended period of time, causes the cementite to form spherical regions inside the ferrite matrix. This new microstructure is called Spheroidite. The reduction of the cementite results in a lower strength but restores much of the ductility. This is confirmed by the Impact Energy test which is a measure of ductility in which the Annealed Sample had the highest value of 65.43J. The grain structure of the annealed structure is the most refined, when compared to the untreated controlled samples and the other Heat treatment. The dark patches are the pores in the steel.

The Micrograph of the Hardened 0.26% Low carbon Steel Sample shows primarily a Martensite structure. Hardening results by cooling the steel so rapidly that pearlite or primary ferrite cannot form, but, instead, an entirely new phase, Martensite. Martensite is formed in steels when the cooling rate from austenite is sufficiently fast. It is a very hard constituent, due to the carbon which is trapped in solid solution. Unlike decomposition to ferrite and pearlite, the transformation to Martensite does not involve atom diffusion, but rather occurs by a sudden diffusionless shear process called Displacive Mechanism. (Callister, 2001). Martensite is essentially a supersaturated solid solution of carbon in Iron. The amount of carbon in Martensite far exceeds that found in solid solution in ferrite. Because of this, the normal Body Centered Cubic (BCC) lattice is distorted in order to accommodate the carbon atoms. The Martensite

will have the same carbon content as the austenite from which it is formed. (Davis 1997). The grain structure of the hardened sample is the most coarsened when compared to the other Heat treatment.

The Micrograph of the Normalized 0.26% Low carbon Steel Sample shows a microstructure that has fine bands of Pearlite, that is, the interlayer of Cementite and the ferrite. Since the austenite is air cooled, this allows enough time for pearlite to form resulting in very fine bands of ferrite and cementite. Thinner bands of the Pearlite is formed of the normalized sample as when compared to that of the Annealed. The dark patches are the pores in the steel. The microstructure of the normalized sample is fine, but less refined when compared to that of the annealed Sample.

The Micrograph of the Tempered 0.26% Low carbon Steel Sample reveals primarily a Martensite matrix with Ferrite structure. Austenite phase will change to the Martensite phase during rapid quenching. When the temperature is raised after the rapid cooling, there occur a recrystallization of some of the Martensite structure to yield the ferrite phase.

The Martensite Structure is very hard due to the coarse nature of the grain. Tempering is done in order to trade off some of its hardness and thus brittleness in order to make the Steel sample tougher and more ductile. This makes the Steel Tempered Steel sample more amenable to engineering application when compared to the Hardened Sample. This is confirmed by the Hardness and Impact energy test also. This confirms Callister (2001), which postulated that the Martensite when tempered, the metastable supersaturated solid solution decomposes to form tiny spheres of iron carbide in a matrix of ferrite. The tempering reaction forms a new constituent, tempered Martensite. Tempered Martensite is composed of two phases, ferrite and cementite.

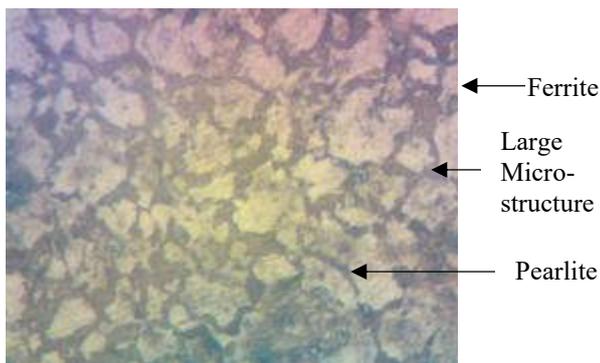


Fig 7: Micrograph of the Untreated 0.26% Low carbon Steel Sample

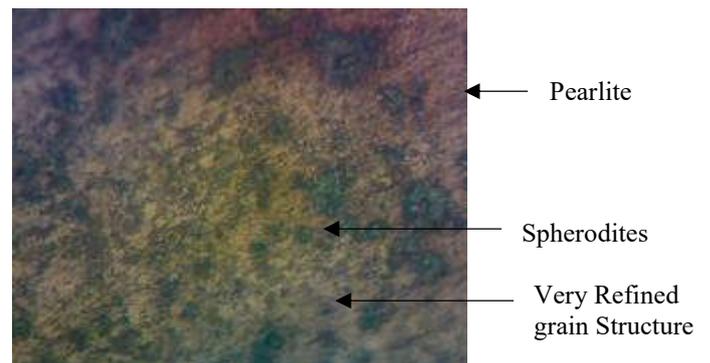


Fig.8: Micrograph of the Annealed 0.26% Low carbon Steel Sample

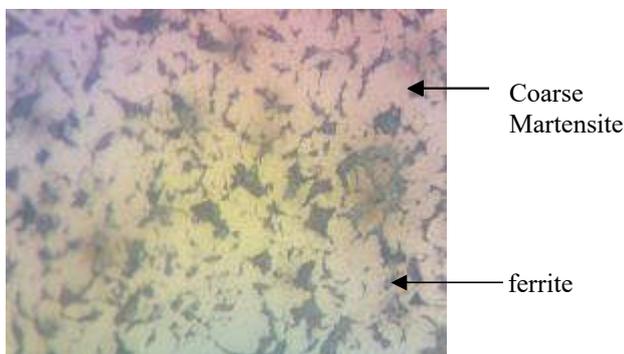


Fig.9: Micrograph of the Hardened 0.26% Low carbon Steel Sample

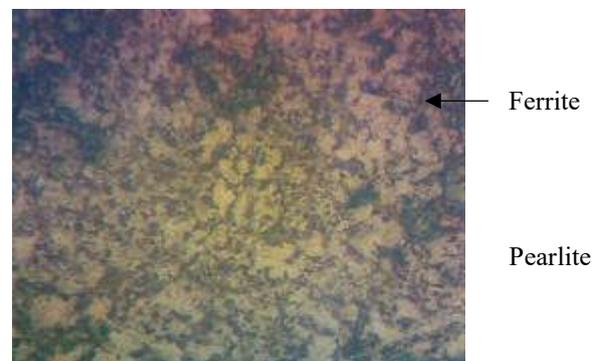


Fig.10: Micrograph of the Normalised 0.26% Low carbon Steel Sample

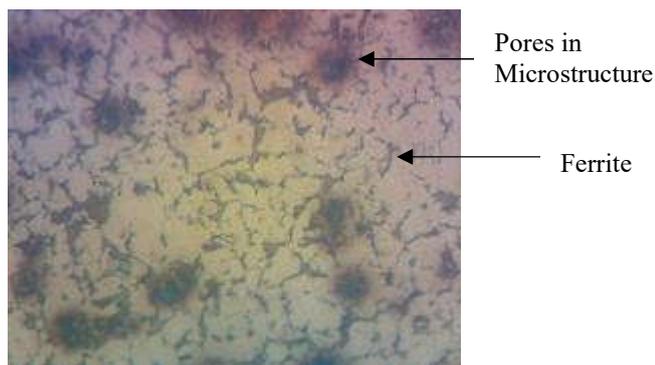


Fig.11: Micrograph of the tempered 0.26% Low carbon Steel Sample

4. CONCLUSION

The study of the effect of heat treatment on the steel sample shows that there is always a tradeoff of a property for another. Hardening for example trades off its ductility (i.e. toughness, tensile strength, Percentage elongation) for Hardness. Annealing the steel increases its toughness and thus its ductility, while its hardness is greatly lowered. Normalising result into higher strength and hardness, but lower toughness (ductility). Tempering reduced the toughness (ductility) and tensile strength of the steel but increases its hardness moderately. The Brinell's Hardness Number of Tempering is close to that of Hardening. From the fatigue experiment carried out on the test samples, the SN graph generated for the Annealed, Normalized, Tempered and the Hardened Sample reveals all the heat treatment processes would improve the fatigue life of the Steel

The Metallographic examination revealed the accurate characteristic of the steel Sample. The Microstructure of the control untreated phases reveals Ferrite and Pearlite, Hardened micrograph shows primarily a Coarse Martensite, Tempered Sample Microstructure revealed a Martensite Phase with a recrystallization of ferrite Phase. The Annealed and the Normalised Microstructure revealed primarily a pearlite Structure. From the work done, it can be deduced that the low Carbon Steel properties can be improved upon by subjecting it to various Heat treatment. Also through specific heat treatment, the properties of the low Carbon Steel can be manipulated to the properties needed for a desired design by subjecting it to a particular heat treatment that would make it amenable for the purpose.

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