

EFFECT OF VARIOUS HEAT TREATMENT METHODS ON MECHANICAL PROPERTIES OF LOW CARBON STEEL

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ABSTRACT

Heat treatment of metals under a controlled sequence of heating and cooling in order to alter their physical and mechanical properties to meet the desired engineering application is an alternative commonly practice on steel. This study reports the effect of heat treatment methods (annealing, normalizing, hardening and tempering) on the microstructure and some properties (toughness, tensile strength, hardness, yield strength, young modulus elongation and reduction) of both the treated and untreated low carbon steel samples. The purchased samples were analyzed spectrometrically and heat treated in an electric furnace at different temperature levels, holding times and then cooled in different media. Standard engineering methods and practices were used in determining the mechanical properties and metallographic microscope with inbuilt camera was used to examine the microstructure of the samples. Result showed that the mechanical properties of low carbon steel can be altered so as to be improved by various heat treatment methods for particular application. It was therefore found out that the annealed sample with largely ferrite structure possesses the lowest tensile strength and highest value of deformation and toughness value while the hardness sample which is made up of large pearlite and martensite gave the highest tensile strength and hardness value with lowest deformation and toughness values.

KEYWORDS: Cooling; Heating; Heat treatment; Low carbon steel; Mechanical properties

INTRODUCTION

Adequate knowledge about material properties of metals for engineering component is important to forestall failure of structure since mis-fit of component will be averted starting from the design stage of production. In order to do this, the mechanical properties of metals to be used can be changed as desired by heat treatment which fundamentally alters the microstructure of the metal “low carbon steel” in this context (Raji & Oluwole, 2012). Low carbon steel also called mild steel have 0.2% carbon content and manganese content below 0.7% with maximum value for silicon at 0.6% and it is the most common form of steel due to the fact that its

material properties are acceptable for many applications (Joseph & Alo, 2014).

To increase the material properties of low carbon steel, heat treatment which is a required method of modifying mechanical properties of metals is unavoidable. It is therefore very important to note that, all the different heat treatment processes consist of three stages, which are; heating of the material, holding the temperature for a stipulated period and cooling, usually to room temperature. But, due to amenability of low carbon steel to heat treatment process, steel finds its wide application in both structural and domestic uses (Momoh et al., 2013). Some of the heat treatment process that can be used include:

annealing, normalizing, hardening and tempering (Fadare et al., 2011).

Munigan and Matthew (2013) investigated the effect of heat treatment on the mechanical properties of medium carbon steel by heat treating samples of medium carbon steel to 900°C and soaking it for 60 minutes in a muffle furnace and quenching in oil. It was gathered that the hardness values and tensile strength of the quenched sample were relatively higher than those of the as-received samples, suggesting an improved mechanical property. Miernik et al., (2010) also presented the results of the impact of incomplete quenching technique on the mechanical properties of low carbon structural steel. Here, the significant influence of heating method to $\alpha + \gamma$ field was observed on the strength and plasticity after hardening process and the best combination of mechanical properties were obtained for the 3th technique consisting of pre-heating the material to the austenite field, next cooling to the appropriate temperature in the $\alpha + \gamma$ and hardening from that dual phase region. The high levels of toughness with relatively high strength were observed compared to the properties obtained for the two other ways to quench- annealing.

Offor et al., (2010) studied the effect of various quenching media on the mechanical properties of intercritically annealed 0.15 Wt%C- 0.43 Wt%Mn steel. Prequenching of hot rolled low carbon steel was done from 900°C (within the full austenitic range) using SAE 40 engine oil as quench medium. Hence, sets of steel samples made from the previously quenched steel sample were intercritically heat treated from 750°C to 810°C at intervals of 10°C for 1 hour in a laboratory muffle furnace and quenched in SAE 40 engine oil, water and brine as quench media respectively. It was discussed that the quench

media increase the strength and hardness properties but decrease the ductility and notch impact properties of the original hot-rolled steel. Brine having the highest strength (708.02 N/mm² at 810°C) and hardness value (233 BHN at 810°C) followed by water, and oil respectively. This implies that the steel quenched in oil had the highest ductility value and notch impact toughness values (24.7% at 750°C and 22.8J/cm² at 750°C respectively) followed by those quenched in water and brine respectively.

Mechanical properties of low carbon TRIP steel for heat treatment process were studied by (Joshi et al., 2010), using XRD impact test and tensile test and the result showed that trip steel could obtain three-phase organization of ferrite, bainite and retain austenite after heating at 790°C, holding insulation for 50 minutes and their being isothermally quenched at 380°C for 20 minutes. Joshi et al., (2014), studied the effect of heat treatment process on micro - grain structure of steel in different electrical furnace at different temperature levels varying the holding temperature and heat treatment medium. The study showed that by heat treating the steel, the material properties like ductility, toughness, hardness, tensile strength can easily be changed to suit our design.

Fadare et al., (2011) studied the effect of heat treatment methods on the microstructure and some selected properties of NST 37-2 steel where sample were purchased from local market and the spectrometry analysis was carried out. The steel sample was heat treated in an electric furnace at different temperature levels and holding times and then cooled in different media. The mechanical properties of the treated and the untreated samples were determined using standard methods and microstructures of the samples were examined using metallographic

microscope equipped with camera. The results showed that the mechanical properties of NST 37-2 steel can be changed and improved by various heat treatment methods for a particular application.

MATERIALS AND METHOD

Sample of low carbon steel bar with 10mm diameter and 5m long was purchased from local steel traders in Ado-Ekiti, south western, Nigeria. Chemical composition of the steel was determined using optical emission spectrometer and the result is shown in Table 1. Standard hardness, tensile and impact specimens were produced from the low carbon steel with the aid of the lathe machine. The specimens were subjected to different heat treatment methods; annealing, normalizing, hardening and tempering in accordance to ASM international standards. The heat treatment conditions are stated in Table 2. Four specimens were prepared for each heat treatment method.

Determination of mechanical properties

Standard methods were used to determine the mechanical properties of the treated and the as-received (untreated) samples. Stage-grinding and polishing machine were used to remove the oxide layers formed during heat treatment method on the specimen to be used for hardness test. Average brinell hardness readings were determined by taking two different readings at two different points on the specimen using hardness tester. Impact energy was recorded using izod impact tester. Load elongation data were recorded and converted into stress-strain graph. Yield strength, ultimate (tensile) strength, Young's modulus and ductility (elongation and reduction) were determined based on these graph in accordance to ASTM standard test procedures (ASTM E18, ASTM E23, ASTM E8).

Microstructural examination

In carrying out the microstructural examination of the heat treated and the untreated samples, each sample was carefully grinded with emery cloth. The grinded surfaces were cleaned using Aluminum Oxide Al_2O_3 . Etching was done using a solution containing 2% Nitric acid to make the crystalline structure of the specimen visible and methylated spirit was used to polish the surfaces. The microscopic examination of the etched surface of the sample was undertaken using metallographic microscope with inbuilt camera through which resulting microstructure of the samples were magnified and are photographically recorded.

RESULTS AND DISCUSSION

Effect of heat treatment on mechanical properties

Various heat treatment methods (normalizing, annealing, tempering and hardening) has various effects on the mechanical properties (tensile strength, hardness, deformation, elongation and toughness) of the treated and the as-received (untreated) samples as shown in Table 3 The tensile strength of the as-received specimen was 680.50MPa and the hardness value of 111.00BHN, Elongation of 2.24mm, deformation of 0.074mm, Young modulus of 22944.81MPa and toughness of 64.2J were obtained.

Comparing the mechanical properties of the Normalized sample with the as-received sample, the normalized sample had mechanical properties as follow; 720.38MPa, 8601.80N, 23954.58MPa, 0.045, 1.64, 113.00BHN and 65.71J for maximum tensile strength, load at yield, Young modulus, deformation, elongation, hardness and toughness respectively. The increase in tensile strength and hardness as compared to the as-received sample was due to proper austenising temperature at 900°C and higher cooling rate,

which resulted in elongation and deformation that was lower than those obtained for the as-received sample and this is as a result of the pearlitic matrix structure obtained during the normalization process of the low carbon steel.

Mechanical properties of the annealed sample as compared with the as-received sample showed that the annealed sample had a lower tensile strength (446.67MPa), yield load (5613.12N) and hardness (95.00BHN) and an increase in deformation (0.21mm), elongation (6.34mm) and toughness (65.35J). The decrease in tensile strength and hardness can be related to the formation of soft ferrite matrix in the microstructure of the annealed sample during cooling.

The mechanical properties of the hardened sample revealed the highest values for tensile strength, yield load and hardness for the experiment in the following order; 776.68MPa, 9228.45N and 156.00BHN respectively. The specimen was austenised at 900°C for 60minutes and then water quenched. This treatment increased the tensile strength and hardness but a massive decrease in elongation and toughness were equally recorded.

Mechanical properties of tempered sample showed that the tensile strength, yield load, toughness, deformation, elongation and hardness were 576.83MPa, 7248.73N, 65.14J, 0.18mm, 5.43mm and 130.00BHN respectively. On comparing the mechanical properties of the tempered sample with the hardened sample, it was found that there was a decrease in tensile strength and hardness at tempering temperature 350°C while there is an increase in deformation, elongation and toughness which can be attributed to graphitization of the precipitated carbides that resulted in the formation of ferrite at tempering temperature of 350°C. These showed that the

tempering temperature improved the degree of tempering of the martensite, softening the matrix and decrease its resistance to plastic deformation. The test results however, showed that the annealed treatment gave an elongation higher than other heat treatment studied. Variability in maximum tensile strength, toughness, modulus of elasticity, hardness and elongation of as-received and treated samples of the low carbon steel are as shown in Figure 1-5 respectively.

Effect of heat treatment on microstructure

The microstructure of the as-received specimen in Figure 6 showed a mixture of ferrite, cementite and little martensite which is responsible for its tensile strength, while the microstructure of the normalized sample in Figure 7 revealed a fine grain of pearlite and ferrite with a uniformly distributed pearlite grain due to moderate transformation caused by slow cooling. Figure 8, revealed a large ferrite structure with pearlite boundary around it. It shows that the ferrite grain had undergone complete recrystallization and thus constitutes the major portion of the microstructure of the annealed low carbon steel with stress free matrix, hence responsible for softness of the sample thereby making it ductile. The micrograph of the tempered sample shown in Figure 9 reveals a distribution of pearlite and martensite which is responsible for its high toughness and hardness (Daramola et al., 2010).

The microstructure of the hardened sample as shown in Figure 10 revealed a large pearlite grain which is responsible for high hardness value and low impact resistance which makes the sample brittle in nature and it was due to the presence of the martensite structure (Fadare et al., 2011). The summary of the observed microstructure of the treated and untreated low carbon steel is given in Table 4.

CONCLUSIONS AND RECOMMENDATIONS

The following conclusion was made from the results of investigating the effect of heat treatment on mechanical properties of low carbon steel:

Tensile strength of hardened samples and normalized samples were greater than that of the as-received sample followed by that of the tempered and the annealed sample in that order. Likewise, the yield strength, followed the trend of an increase in plastic deformation while impact strength increases with elongation.

Hardness treatment had also resulted in higher tensile strength and hardness than any other heat treatment method. This treatment is recommended when strength and hardness are the prime properties desired in a design.

The tempered sample gave an increase in hardness and impact strength than the as-received sample which is as a result of formation of tempered martensite and the resultant pearlite structure that were obtained.

Therefore, mechanical properties of low carbon steel can be altered by various heat treatment methods because the result obtained confirmed that an improvement can be obtained by subjecting it to various heat treatment methods as shown in this study.

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Table 1. Chemical composition of low carbon steel.

C(%)	Ni(%)	Fe(%)	Mo(%)	Si(%)	Cu(%)	Mn(%)	Al(%)
0.0486	0.1827	98.75	0.1106	0.0202	0.046	0.3654	0.000
P(%)	V(%)	S(%)	Co(%)	Cr(%)	Nb(%)	W(%)	Sn(%)
0.026	0.000	0.0406	0.0119	0.005	0.000	0.2958	0.0000

Table 2: Heat treatment conditions

Condition	Annealed	Normalized	Hardened	tempered
Temperature (°C)	900	900	900	450
Soaking time (min)	60	60	60	90
Cooling medium	furnace	air	water	air

Table 3: Mechanical properties of heat treated and untreated low carbon steel

specimen	Maximum tensile (MPa)	Yield load (N)	Elastic modulus (MPa)	Deformation (mm)	Elongation (mm)	Hardness (BHN)	Toughness (joule)
As-received	680.50	8551.41	22944.81	0.074	2.24	111.00	64.21
Normalized	720.38	8601.80	23954.58	0.045	1.64	113.00	65.21
Annealed	446.67	5613.12	28556.15	0.21	6.34	95.00	65.35
Tempered	576.83	7248.73	32561.39	0.18	5.43	130.00	65.14
Hardened	776.68	9228.45	22479.31	0.02	1.05	156.00	23.12

Table 4: Summary of microstructure of treated and untreated low carbon steel.

Heat treatment	Microstructure development
As-received	Ferrite, cementite, and martensite
Normalized	Pearlite and ferrite
Annealed	Ferrite surrounded by pearlite
Tempered	Pearlite and martensite
Hardened	Large pearlite and martensite

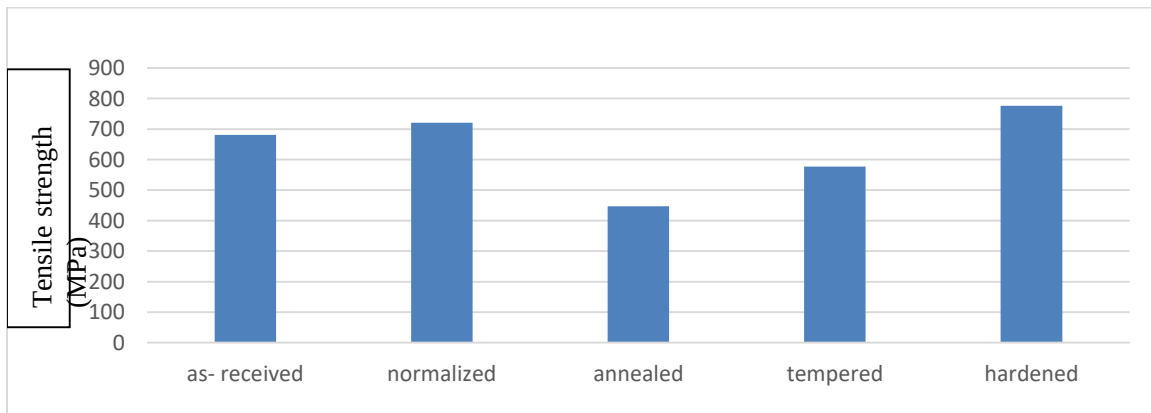


Figure 1: Ultimate tensile strength of treated and untreated samples

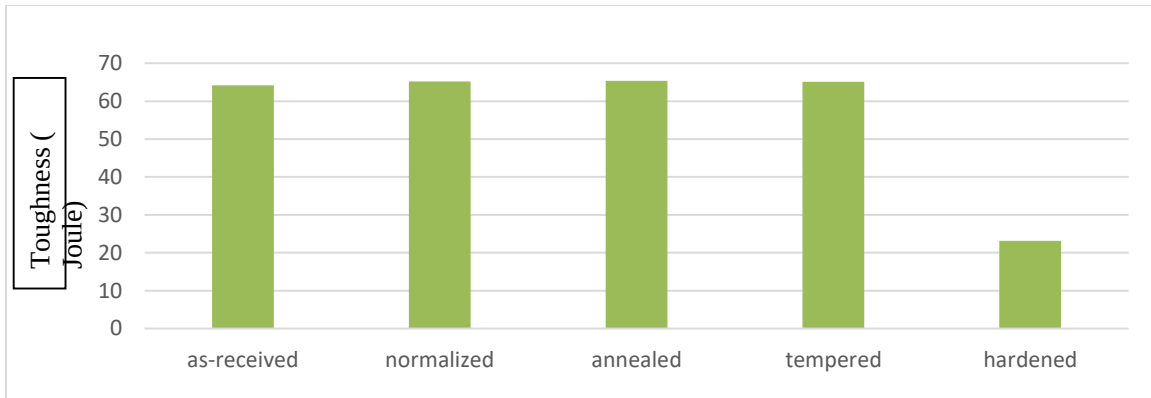


Figure 2: Toughness of as-received and heat treated samples.

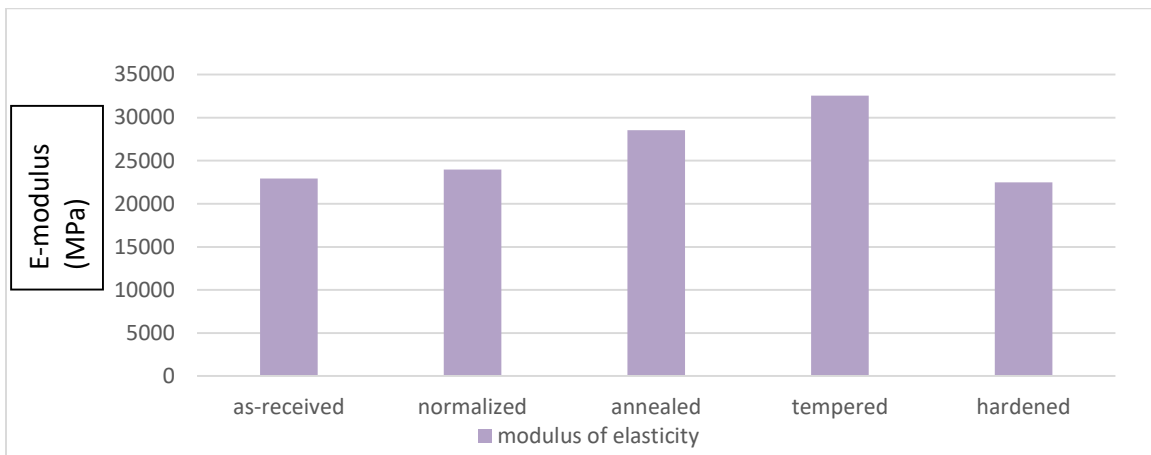


Figure 3: Modulus of Elasticity of as-received and heat treated samples.

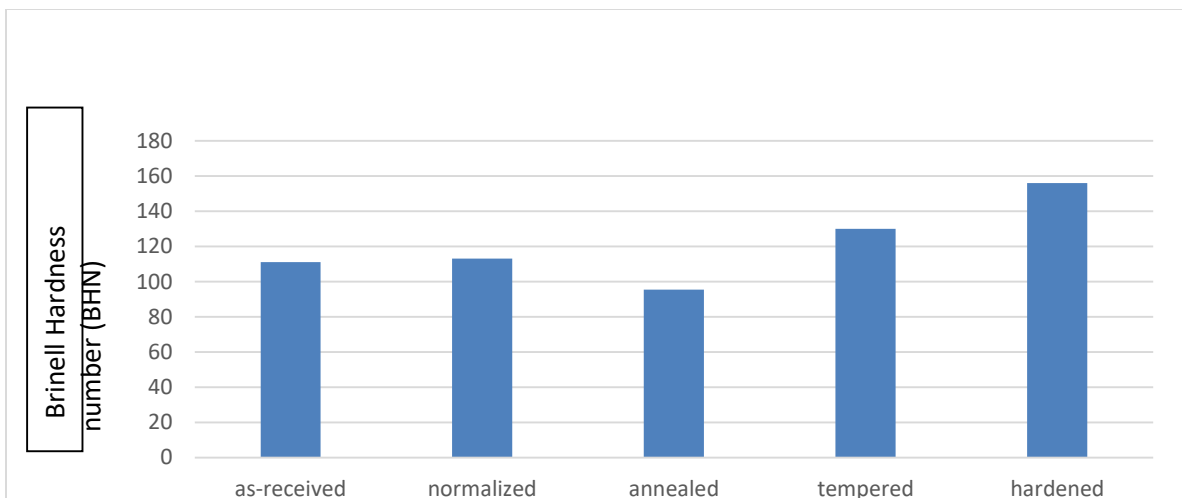


Figure 4: Hardness of as-received and heat treated samples.

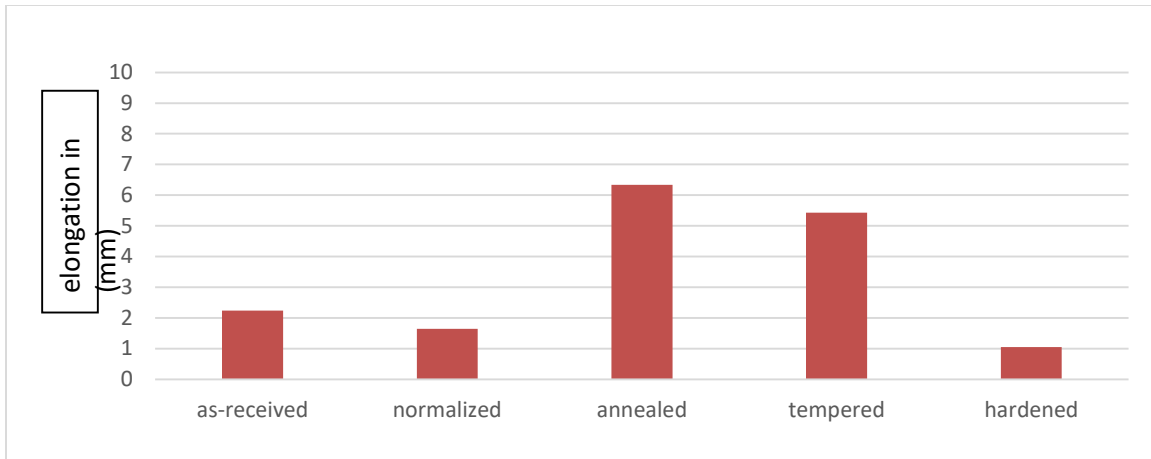


Figure 5: Elongation of as-received and heat treated samples.

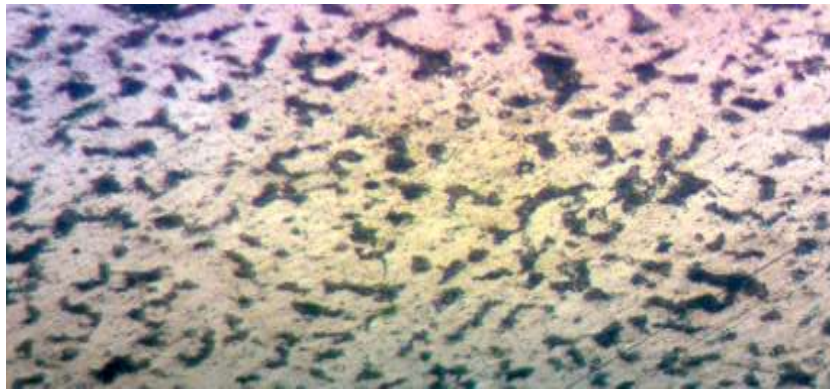


Figure 6: Micrograph of as-received low carbon steel sample.

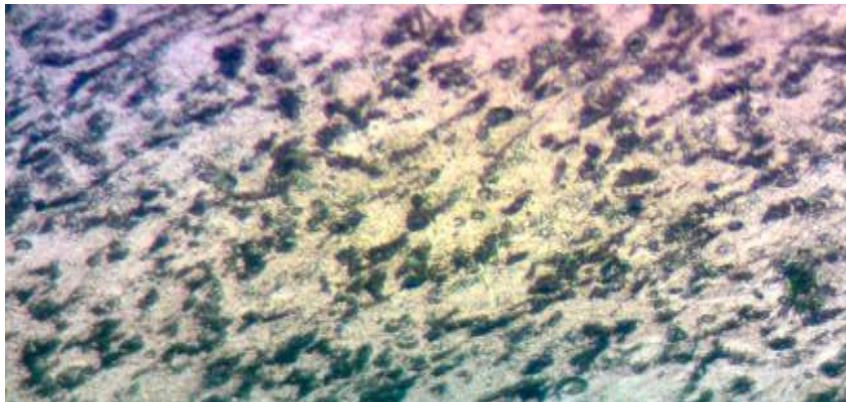


Figure 7: Micrograph of normalized sample

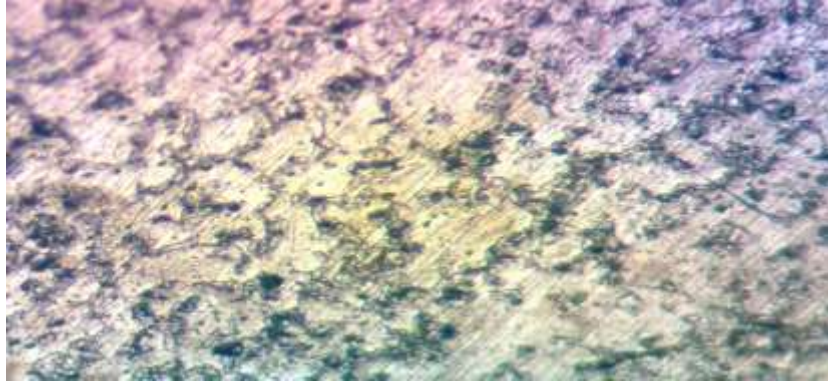


Figure 8: Micrograph of annealed sample

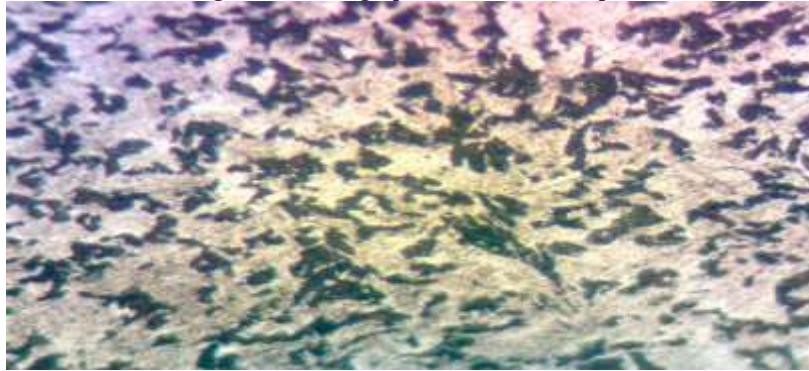


Figure 9: Micrograph of tempered sample

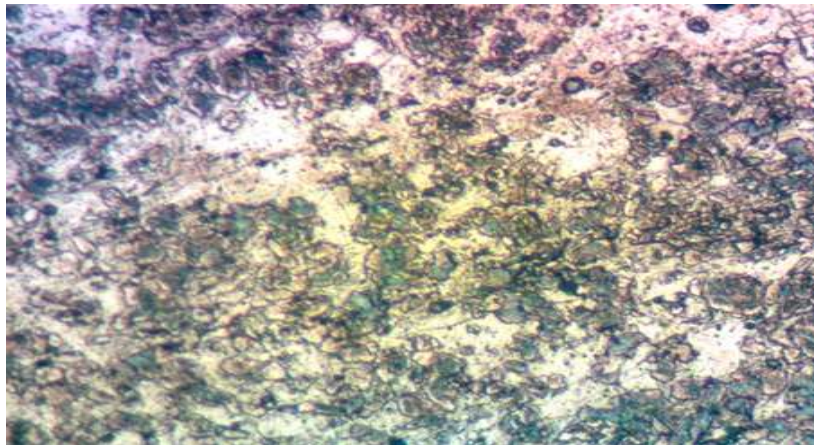


Figure 10: Micrograph of hardened sample