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Investigation of Annealing Temperatures/Soaking Time on The Impact and Hardness Properties of 0.17% C HSLA Steels

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Abstract
The structural makeup of steel has an impact on its physical characteristics. By changing the size, shape, and distribution of different elements, it is possible to get the necessary levels of mechanical characteristics. The impact of annealing temperature on the impact and hardness characteristics of 0.17% C of High Strength Low Alloy Steel is the subject of this investigation. By altering the annealing temperatures, steel sample samples were annealed to complete the investigation.The beginning temperature is determined by computing the carbon equivalent, which is 840. The following temperatures were obtained using a 30 oC interval: 840, 870, 900, 930, 960, and 990 oC. A 90-second soaking period was also employed. Their microstructures and values for hardness and impact strength were computed. The annealed sample at 840oC had the highest hardness value of 100.6 BHN and the highest impact values of 61.69 J and 63.76 J, respectively, according to the mechanical analysis results. The sample at 990oC had the lowest hardness value of 89.2 BHN and the highest impact value of 66.49 J. This study demonstrates that annealing improved the steel's fatigue property and tensile strength (wear strength). Finally, it was determined that annealing steel had a favorable effect on the mechanical characteristics of HSLA steels with 0.17% C.

Keywords: High Strength Low Alloy Steel, Microstructure, Hardness, impact properties, annealing temperature.

1. Introduction

Heat treatment is an operation, or set of operations, that involves heating at a predetermined temperature. To accomplish specific specified mechanical, physical, electrical, or magnetic qualities, a desirable microstructure is sought after. For regulating the characteristics of materials, two techniques that are often utilized are heat treatment and alloying. The microstructures of the materials are changed during heat treatment, which has an impact on mechanical qualities like strength, ductility, toughness, hardness, and wear (Sreeteja, 2017). According to Arasu et al. (2013), heat treatment is an industrial procedure used to soften steel that results in a change in grain size, an improvement in the material's structure, and a release of the stress that was previously applied to the material and may have caused fracture initiation and propagation.

One may describe it as a technique for both strengthening materials and changing some mechanical qualities, such as enhancing formability and machining. Heat treatment is a crucial manufacturing step that not only aids in the process but also has numerous benefits for the product's performance and other attributes. There are several different heat treatment procedures, including annealing, normalizing, hardening, tempering, and surface hardening. Annealing, normalizing, hardening, and tempering are among of the methods used to refine grains with the potential to produce ductility and weldability (Zhao et al., 2018).

In metallurgy and materials science, annealing is a heat treatment that modifies a material's physical, and occasionally chemical, properties to improve its ductility and decrease its hardness, making it more workable. (Seeteja et al., 2017) described the annealing process as a thermal system applied to a material to transform or modify its internal structure from cold worked propagation; (Hu et al., 2010) and (Zhao, 2017) described it as heating the material to above its recrystallization temperature, maintaining a suitable temperature, and then cooling; From metallurgical perspective, these variations in properties have an impact on the performance traits and the anticipated application. (Vervynckts et al., 2012) state that annealing is the heat treatment method most frequently used to soften iron or steel materials and refines its grain because of ferrite-pearlite microstructure; it is used in engineering materials where appreciable levels of tensile strength and elongations are required. This kind of process is usually carried out to relieve stresses and improve ductility by changing the annealing parameters, such as the annealing temperature and soaking time, it frequently makes it possible to build the required microstructure.

High strength low alloy steels (HSLA) as steels that are made up of microstructures formed by hard martensite particles distributed in the ductile ferrite matrix (Erdogan, 2003). They are compared to dual-phase steels due to their high hardening ability during deformation, high malleability and good surface quality (Dzupon et al, 2006). It also contributes to the stiffness and weight reduction being preferred in automobile industry. This is attributed to its good formability characteristics. These groups of steels play an effective role in the production of parts in vehicles such as suspension systems, support elements, longitudinal beams, transverse components and chassis (Kadkhodpour et al,. 2011). When these materials are exposed to high temperatures, there is a recrystallization of the microstructure in the heat affected zone which directly influences the resistance limit of the material (Costa, 2010) Utilization of HSLA steels are found in many engineering fields which include oil and gas pipelines, constructions and farm machinery, heavy- duty highway and off road vehicles, industrial equipment storage tanks, mine and rail road car, barges and dredges snow mobiles, power transmission towers light poles, lawn mowers, and passengers car components. Bridges, offshore structures, and building beams and panels are additional uses of these steels (ASM international, 2001). This special feature of HSLA steels has led to their being used increasingly in automobile components and structural engineering which are usually subjected to cyclic loading therefore, having a sound knowledge of their fatigue behavior cannot be over emphasized.

Several researchers (Zhuang, 2015); (Offor, et al 2010); (Sherman, 2016) have investigated on (dual phase) DP steels to find out the effect of heat treatment, soaking times on its properties. (Sharman, 2016) observed that they were able to exhibit fatigue resistance superior to that of HRLC (hot rolled low carbon) steels hence; it has a superior notch resistance, higher fatigue notch sensitivity than HRLC steels. (Zhuang Li, 2015) observed that long increasing holding times may not be needed because the major phase of microstructure does not change very significantly. From previous work, it has been discovered that fatigue is one of the major causes of failure in service which more often leads to loss of lives and properties (Gaurav, 2018) reported that to improve fatigue life, the effect of heat treatment on fatigue life and strength need to be studied for better designing and mechanical system; hence this work will help to investigate the effect of annealing temperatures on the impact and hardness properties of 0.17%C HSLA steels.

2. Materials and Methods

The steel used in the investigation was 25 mm diameter rod of high strength low alloy steel. Spark spectrometer analyzer (NCS Lab spark 750B) was used to determine its chemical composition. This was done at the quality control laboratory of universal steel Lagos state Nigeria. The result gotten is shown in table. The as- received steel material manufactured and supplied by Universal steel in Lagos state was subjected to preliminary machining to remove its ribs.

Table 1: Chemical composition of investigated steel.

Element	C	Si	Mn	S	P	Cr	Mo	Ni	Al
Weight (%)	0.1728	0.3016	1.2089	0.0352	0.0334	0.2559	<0.0100	0.1218	<0.0100
Element	Cu	Ti	V	Nb	W	Co	B		
Weight (%)	0.2560	<0.0100	<0.0100	<0.0150	<0.0500	<0.200	0.0047		

After machining, the samples were grouped for the different predetermined temperature and then Normalizing was firstly done so as to remove internal stress incurred during machining. Before the annealing was done the Carbon equivalent was calculated to tell the starting temperature from the Iron Carbon phase diagram.

$$CE= C+\frac{Cr+Mo+V}{5}+\frac{Mn+Si}{6}+\frac{Ni+Cu}{15} \quad \text{----------} \quad 1$$

From the chemical composition in table 1 above we have Cr =0.2559; Mo=0.0100; V= 0.0100; Mn=1.2089; Si=0.3016 Ni=0.1218 and Cu=0.2560 and C=0.17

Substituting these figures in equation 1 above, we have

$$CE= 0.17+\frac{0.2559+0.0100+0.0100}{5}+\frac{1.2089+0.3016}{6}+\frac{0.1218+0.2560}{15}$$

CE=0.17+0.05518+0.25175+0.02513=0.50206 hence CE is 0.5. Hence, from the Iron Carbon phase diagram, the ideal starting point for annealing is 840°C. After which annealing was carried out which involved the heating of the samples to various predetermined as discussed below.

This was then followed by annealing the samples into different annealing temperatures starting from 840°C to 990°C at 30°C interval and then soaked for 60 seconds to obtain the exact temperature to start off the annealing. Mechanical testing (hardness and impact) was carried out after which the microstructural analysis was then done to obtain the results shown below.

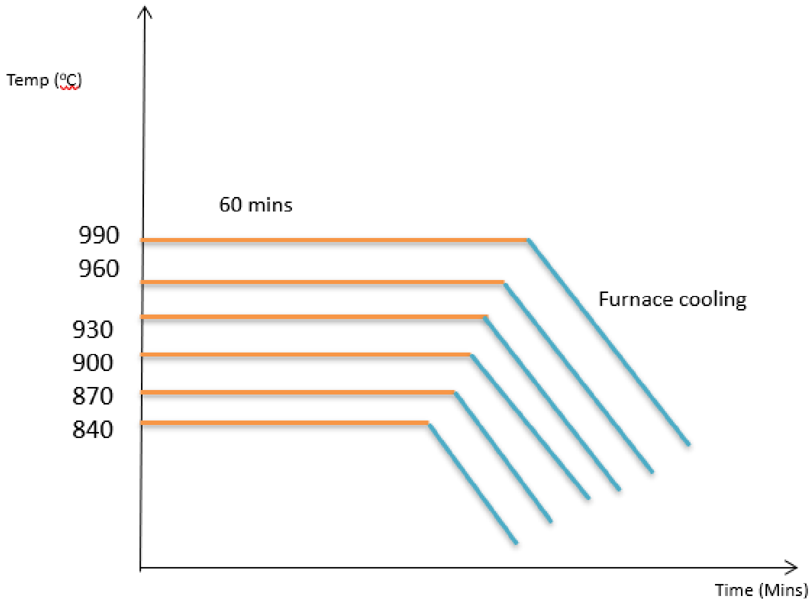
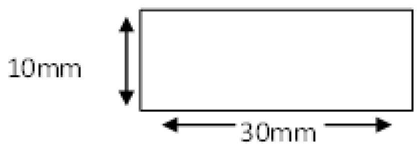


Fig 3.2 schematic Illustration of heat Treatment Schedule for HSLA at 90 mins soaking time.

Microstructure Characterization Techniques

Light Optical Microscope

Experiment was conducted in a metallographic laboratory (Obafemi Awolowo University) to reveal the microstructure of both the as-received and the heat-treated steel. Laboratory preparation of the samples included sectioning, mounting, grinding, polishing, etching and microstructure examination under a light optical microscope (LOM).



Hardness Testing

The Brinell hardness test was used to calculate for the hardness. The cut samples from different steel manufacturing company were subjected to the brinell hardness test according to ASTM/A29M-15 using Monsato Tensometer (model W). A 10 mm indenter made of hardened steel ball was mounted in a suitable holder and forced into a prepared surface of the specimen prior to the test; the surface would have been ground to 600 microns. A load of 750 kg was applied to the specimen on the machine and allowed for 15 minutes. The diameter of the impression left by the ball was measured using the Brinell Microscope and the corresponding Brinell hardness number was determined. The Brinell Hardness Number (BHN) was calculated according to equation.

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

Where F = Load applied
D= Diameter of the 10 mm indenter
d = Diameter of the impression

Impact Testing

Impact testing for all the specimens was done based on ASTM/A29M-15. These test specimens were tested for section thickness. The tests were carried out using Izod Impact Testing method on Hounsfield Impact Testing Machine. Specimen was notched at an angle of 45º from 28 mm end length of 75 mm. The amount of Impact energy absorbed by the specimen was read off on the calibrated scale attached to the machine as a measure of impact strength in Joules.

3. Results

Table 2: Results For Hardness and Impact Test.

TEMPERATURE(0c)	IMPACT(JOULES)	
840	61.69	100.6
870	62.76	97.4
900	63.63	94.6
930	64.57	93.2
960	65.57	92.1
990	66.49	89.2

Figure 1 Hardness Specimen

Figure 2 ***Impact Specimen***

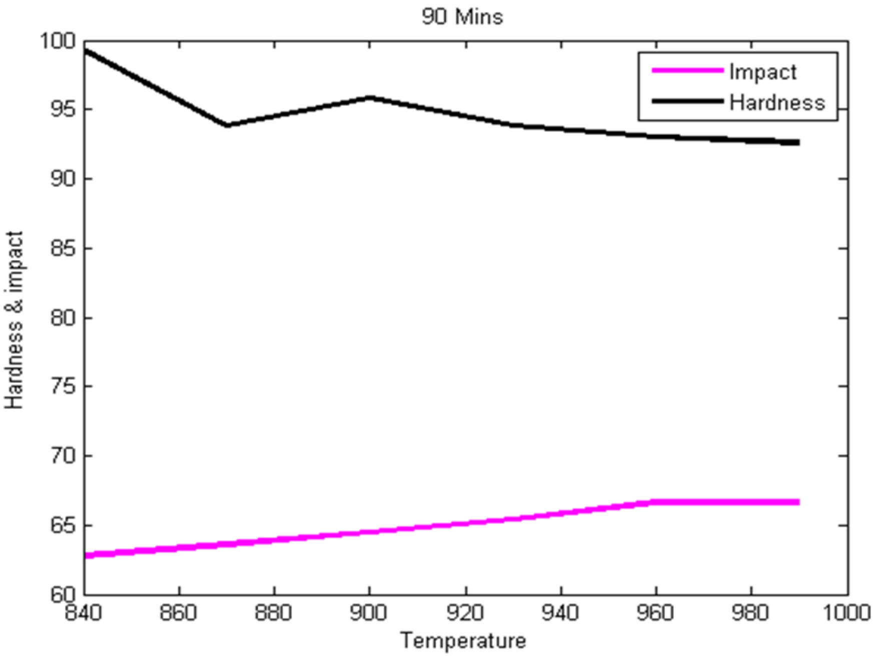


Figure 3: Effect of Annealing Temperatures on Hardness and Impact for 90 Mins Soaking Time.

Figure 3 depicts the impact and hardness effects of annealing temperature over a 90-minute soaking period. The graph shows that as the temperature rises, the impact increases from 62.79J at 840oC to 66.63J at 990°C, where the impact is highest, while the hardness steadily decreases from 99.8 (BHN) at 840oC to 92.6(BHN) at 990o C annealing temperature, where the hardness is lowest.

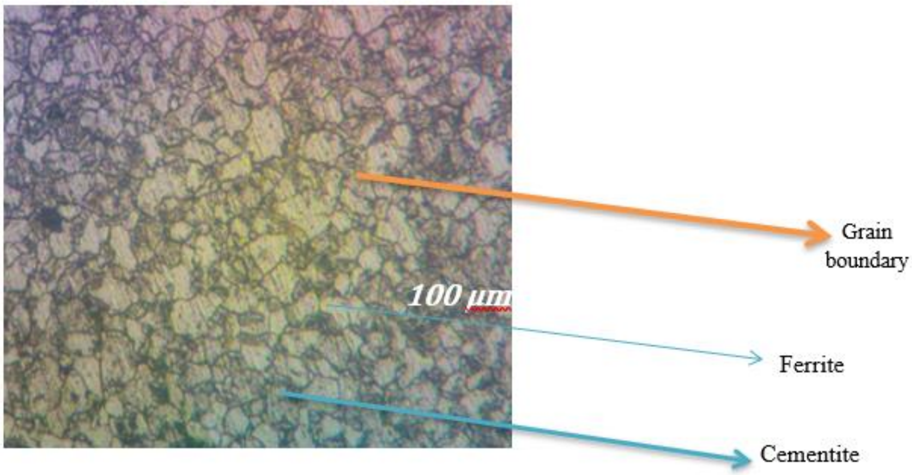


Plate 1: Microstructure Evolution at 840^{0}C for 90 Minutes Holding Time.

Plate 1 depicts the microstructure of a heat-treated (annealed) sample obtained at an annealing temperature of 990°C and a holding time of 90 minutes. It could be observed that as the temperature increases, the micrograph reveals coarse grains; pearlite is seen to be uniformly distributed and dominating in the microstructure while ferrite is seen to be non-uniformly distributed in the microstructure. It could be observed also that the grains boundaries are becoming visible. The point count calculation gave a percentage of 44:56 ratios of ferrite to pearlite.

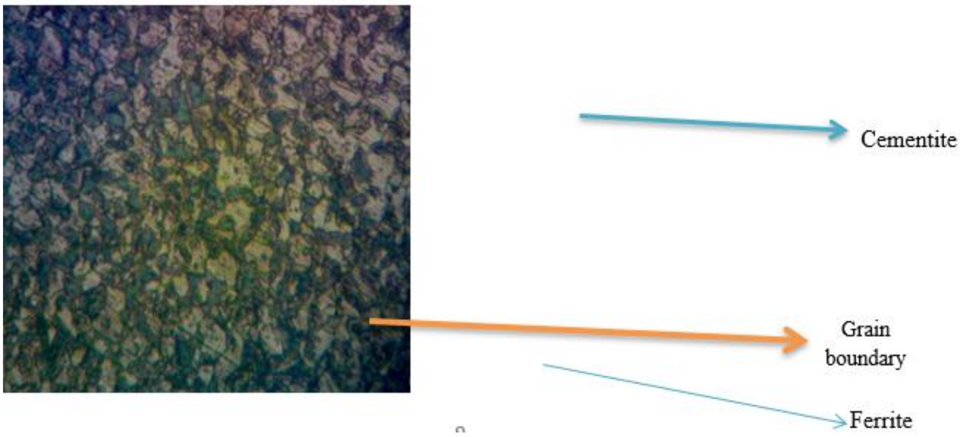


Plate 2: Microstructure Evolution at 870^0C for 90 Minutes Holding Time.

Plate 2 depicts the microstructure of a heat-treated (annealed) sample obtained at an annealing temperature of 870°C and a holding time of 90 minutes. As the temperature rises, the micrograph exposes coarse grains; pearlite and ferrite are seen to be evenly dispersed in the microstructure, and grain boundaries are visible. The point count calculation revealed an equal number of ferrite to pearlite ratio.

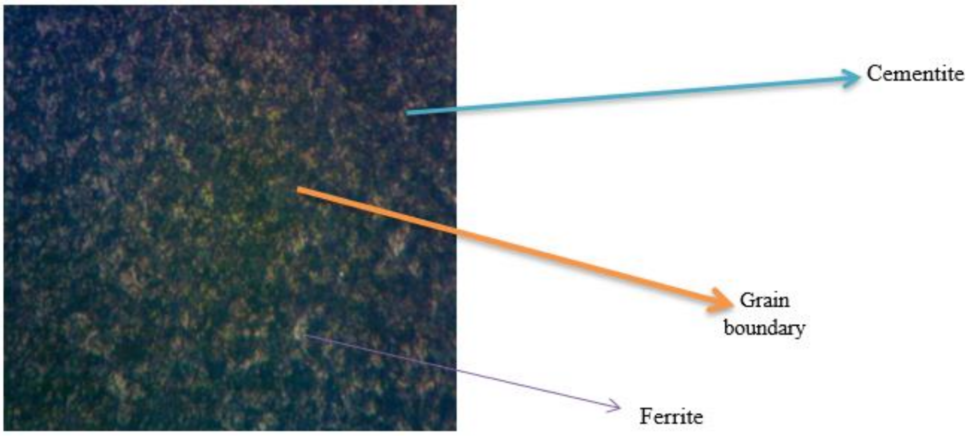


Plate 3: Microstructure Evolution at 900^0C for 90 Minutes Holding Time.

Plate 3 depicts the microstructure of a heat-treated (annealed) sample obtained at an annealing temperature of 900ºC and a holding time of 90 minutes. It could be observed that as the temperature increases, the micrograph reveals finer grains hence more grain boundaries; pearlite is seen to be uniformly distributed and dominating in the microstructure while ferrite is seen to be non-uniformly distributed in the microstructure. It could be observed also that the grains boundaries were invisible. Results from the point count shows that ferrite is 48% in the microstructure while pearlite is 52%.

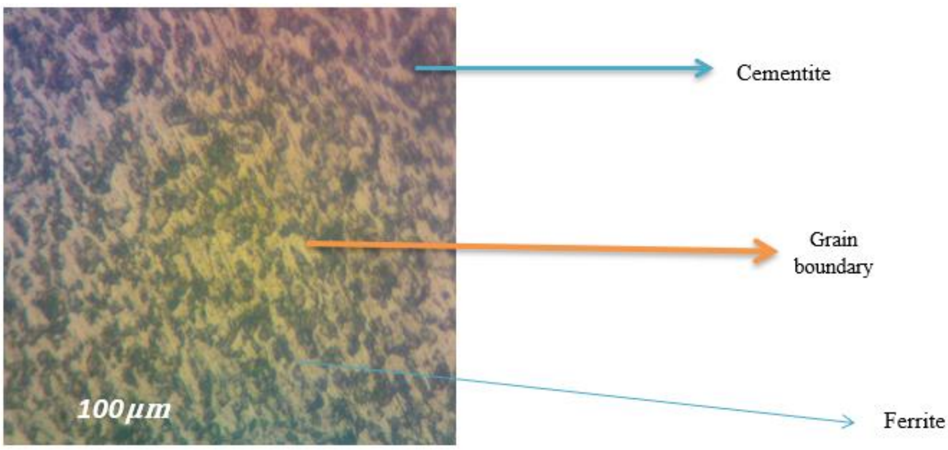


Plate 4: Microstructure Evolution at 930^0C for 90 Minutes Holding Time.

Plate 4 displays the microstructure of a heat-treated (annealed) sample obtained at a temperature of 930°C and a holding time of 90 minutes. It could be observed that as the temperature increases, the micrograph reveals finer grains hence more grain boundaries; pearlite is seen to be uniformly distributed and dominating in the microstructure while ferrite is seen to be non-uniformly distributed in the microstructure. It could be observed also that the grains boundaries were invisible. Results from the point count shows that ferrite is 42% in the microstructure while pearlite is 58%.

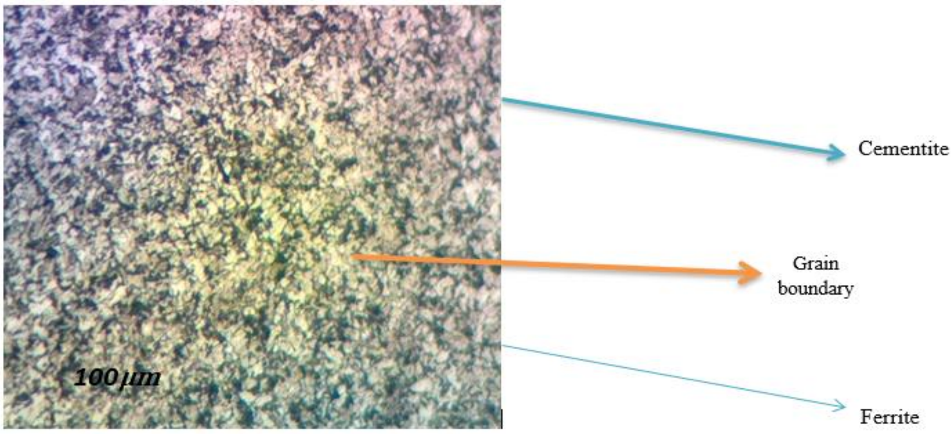


Plate 5 Microstructure Evolution at 960^{0}C for 90 Minutes Holding Time.

Plate 5 displays the microstructure of a heat-treated (annealed) sample obtained at a temperature of 960°C and a holding time of 90 minutes. It could be observed that as the temperature increases, the micrograph reveals finer grains hence more grain boundaries; pearlite is seen to be uniformly distributed and dominating in the microstructure while ferrite is seen to be uniformly distributed in the microstructure. It could be observed also that the grains boundaries were invisible. Results from the point count shows that ferrite is 49% in the microstructure while pearlite is 51%.

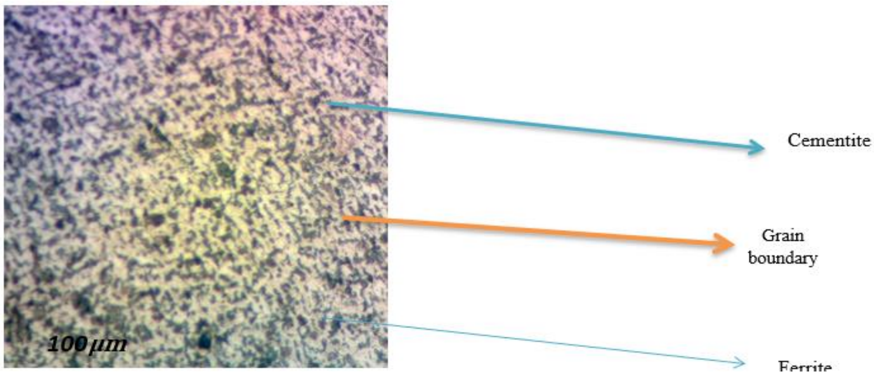


Plate 6: Microstructure Evolution at 990^{0}C for 90 Minutes Holding Time.

Plate 6 displays the microstructure of a heat-treated (annealed) sample obtained at a temperature of 990°C and a holding time of 90 minutes. It could be observed that as the temperature increases, the micrograph reveals finer grains hence more grain boundaries; pearlite is seen to be uniformly distributed and dominating in the microstructure while ferrite is seen to be uniformly distributed in the microstructure. It could be observed also that the grains boundaries were invisible. Results from the point count shows that ferrite is 46% in the microstructure while pearlite is 54%.

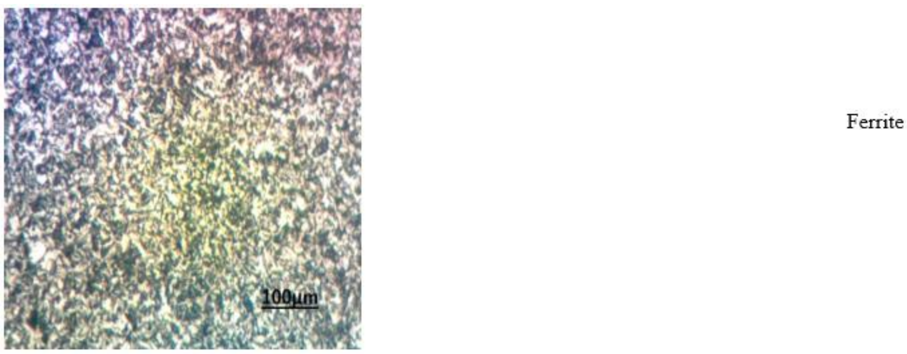


Plate 7: As Received.

Plate 7 depicts the microstructure ofthe as-received sample; pearlite increased and dominated the microstructure, while the grains were smaller, resulting in more grains and grain boundaries; ferrite was found to be distributed unevenly in the microstructure. In the micrograph, the grain boundaries are not clear. The calculation of point counts shows that the ferrite to pearlite ratio in the microstructure is equally distributed, suggesting a 50:50 ratio.

Table 3: Point Count Calculation for 90 Minutes Soaking Time.

Sample	Temperature (^OC)	$\sum P_T$	% $\sum P_F$	% $\sum P_P$	$\frac{\sum PF}{\sum PT}$	$\frac{\sum PP}{\sum PT}$
1	840	100	44	56	0.44	0.56
2	870	100	50	50	0.50	0.50
3	900	100	48	52	0.48	0.52
4	930	100	42	58	0.42	0.58
5	960	100	49	51	0.49	0.51
6	990	100	46	54	0.46	0.54

Table 4: Grain Size Calculation for 90 Minutes Soaking Time.

sample	TEMP(^OC)	No of grains intercepted	No of Lines	No of Lines Intercepted (mm)	Avera No of Grain Boundary (mm)	Average Grain Line (mm)	Average Grain Diameter(d)	Grain Size (G)
1	840	45	3	165	15.0	11.0	11.0×10^{-2}	4.49
2	870	38	3	165	12.7	13.0	13.0×10^{-2}	4.25
3	900	39	3	165	13.0	12.7	12.7×10^{-2}	4.29
4	930	40	3	165	13.3	12.4	12.4×10^{-2}	4.32
5	960	47	3	165	15.7	11.6	11.6×10^{-2}	4.55
6	990	35	3	165	11.7	14.1	14.1×10^{-2}	4.13

Table 4 displays the grain size measurements dependent on annealing temperature and soaking time at 90 minutes. According to the table, the number of grains intercepted at 840^o C was 45, which decreased to 38 at 870^o C, which had the fewest grains intercepted. The highest number of grains intercepted was 47 at 960^{o}C annealing temperature.

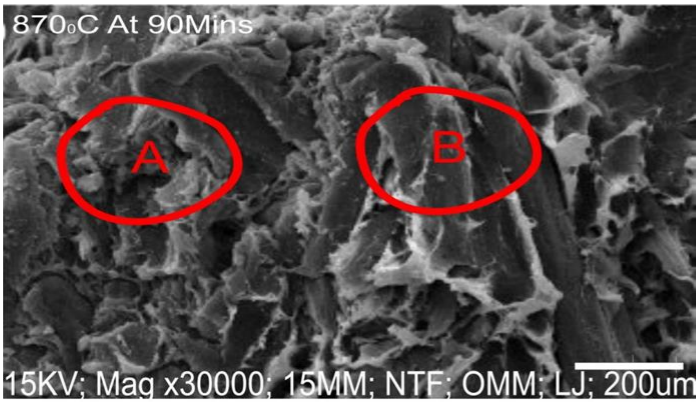


Plate 8:

Plate 8. reveals the SEM images of the fractured surfaces of broken fatigue samples at 870^O C annealing temperature and 90 minutes soaking time. The fractured surfaces show essentially some fibrous characterized by some cleavage facets can be seen on the surface.

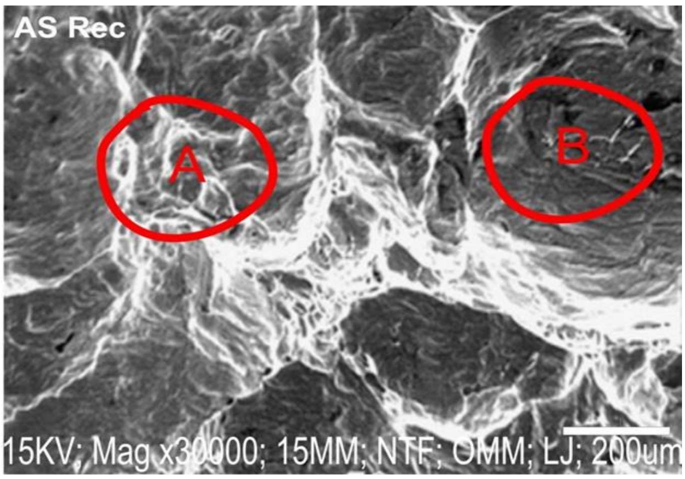


Plate 9 shows the fractured fatigue sample of the as-received, this sample was not subjected to any heat treatment procedures. The phase still retains the ferrite and pearlite phases, however since fatigue work was done on the sample and they were all fractured. There were wide distributions of micro voids resembling microstructure and crack facets at the fractured tips making it brittle compared with the ones that were subjected to heat treatment mechanism. They are not faceted like the annealed ones, and do not have sharp edges and corners. They are less ductile compared with the ones that were annealed.

4.Discussions

Effect of Annealing Temperatures on Impact Toughness and Hardness

A close analysis of Figure 3 shows that the yield strength, tensile strength, and impact strength of the steel increased in value with increasing annealing temperature. On the other hand, the value of hardness decreased over time. Mechanical properties of steels are measurably influenced by grain size; at room temperature, for instance, effects, yield strength, fatigue, tensile, and so on all increased as grain size decreases (Dieter et al, 1967). According to the findings, annealing substantially enhanced the hardness and impact properties of the steel. Zhoo et al., 2018; Seeteja et al, 2017, Fadara et al, 2011, Nurudeen et al, 2012; Jia et al.,; Al-Qaabah. et al, 2003; Yu, et al, 2005 discovered that annealing relieves internal tension and improves ductility. One can also infer that annealing enhanced the grain size of the steel and improved the hardness and impact properties of the steel, as Rajan et al,2012 observed that fine grained steels have higher fatigue strength than coarse grain steels because the finer the grain, the higher the yield strength and enhanced fatigue strength. It was discovered that when the annealing temperature increases, the impact increased while the hardness decreased.

Conclusions

Form figure 1, it will be said that the yield strength, tensile strength, and impact strength of the steel showed a continuous increase in value with increasing annealing temperature. On the other hand, there was a continuous drop in the value of hardness hence it could be said that annealing greatly improved the hardness and impact properties of the steel. This was observed by (Zhoo et al., 2018); (Seeteja et al., 2017) ; (Jia et al.,2003); (Al-Qaabah et al.,2003); (Yu, et al, 2005), that annealing helps to relieve internal stress and improve ductility.

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