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Original Article

Investigation of the mechanical properties of annealing heat treated low carbon steel

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ABSTRACT

The mechanical properties of steel materials usually vary under different conditions, thus choosing the suitable heat treatment is needed to obtain acceptable properties. In this research work, investigation of the mechanical properties of heat treated low carbon steel was determined using tensile tests, and hardness measurements. Also, the microstructure of the samples was characterized by means of optical microscopy. The samples of low carbon steels were sourced at local market in Nigeria. The collected samples were machined using lathe machine to a diameter of 10mm and gauge length of 30 mm. The chemical composition of the steel was determined using X-ray fluorescence spectroscopy. The mechanical properties of the heat treated and untreated samples were investigated at the temperatures of 900 °C, 950 °C, and 1000 °C. The results obtained show that the ultimate tensile strength and percentage elongation of samples increases after heat treatment. Also, yield strength and hardness tend to decrease for all annealed heat treated samples at different temperature as compared to as received samples. The results of the microstructural analyses of the as received samples showed fine dispersion of coalesced pearlite and ferrite grain. For the annealed samples, the steel microstructures compose of martensite distributed in the ferrite matrix. However, with increase in annealing temperature to 1000 °C and 1100 °C cementite and ferrite grain with partial grain boundary were observed.

1. Introduction

The demand for steel materials for industrial applications is high and this is due to their superior mechanical properties [1–3]. However, in the automobile industry, the use of steels includes the martensitic phase which is considered as the complex and hardest phase in steels [4-5]. On the contrary, the mechanical behaviour of stainless steel after heat treatment seems to be mainly controlled by microstructure features such as type, size, number of carbides and phases. Thus, heat treated is usually carried out on most steel parts before being put into service. More so, steel parts are heat treated mainly to enhance specific properties, such as hardness, strength, corrosion resistance, and also to improve uniformity of properties. However, the exact heat treatment applied depends on the type of alloy and the intended service conditions [6-8]. The main types of heat treatments frequently used to modify the mechanical properties of steel materials include annealing, tempering, quench hardening and normalizing [9-13].

Low carbon steel also called mild steel is the most common form of steel owing to the fact that its material properties are generally acceptable for many applications [14]. Low carbon steels with percentage carbon content of 0.002 %-0.25 % account for a large proportion of the total output of steel [15]. More so, the performance of mild steel in service depends on fundamental factors which include its

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grain size, presence of defects, its chemical composition, mechanical properties, etc. Besides, the mechanical properties of low carbon steel such as hardness, tensile strength, ultimate tensile strength, ductility, fatigue strength, amongst others enhances its performance in service. Several research works have shown that failure of carbon steels is as a result of poor design, use of inferior material, fabrication methods, manufacturing errors as a result of poor machining, and fatigue failure [16,17]. However, in order to overcome the aforementioned failures, the mechanical properties can be altered by heat treatment which fundamentally alters the microstructure of the steel [18].

Previous research work found in the literature also suggest that different secondary phase precipitating during heat treatment depends on the active chemical composition of the steel material. According to [19], the properties obtained in martensitic 12-18wt% chromium stainless steels are significantly influenced by matrix chemical composition after heat treatment. Also, [20] reported improvement in the strength and elongation of AISI 304 stainless steel after heat treatment. This research work, therefore, intends to investigate the mechanical properties of annealed heat treated low carbon steel.

2. Materials and Methods

The samples of low carbon steel were sourced at local market in Nigeria. The samples were machined using lathe machine to a diameter of 10mm and gauge length of 30 mm. The chemical composition of the low carbon steel used was determined using X-ray fluorescence spectroscopy at the laboratory of Petroleum Training Institute, Effurun, Delta State, Nigeria as shown in Table 1. In this research work, twenty (20) different samples were used for the experimental investigation of the mechanical properties of the low carbon. The samples were charged into an SXL muffle furnace and annealed at a temperature of 900 °C, 950 °C, 1000 °C, and 1100 °C. The annealed samples were then analyzed for hardness and tensile test.

2.1. Hardness Test

The hardness test was carried out using a Brinell Hardness Testing Machine. The samples were brought in contact with the indenter and allowed to rest for a dwell time. The hardness of the samples was indicated by the penetration of the indenter on the test samples, and displayed by the machine. Average values of different five samples tested were recorded after repeating the test for each of the test samples.

2.2. Tensile Test

The tensile test was carried out at ambient temperature on the Gunt Hamburg Universal Testing Machine following the ASTM E18 standard procedures. The test was carried out as follow;

i. The material was cut into dumbbell shape
ii. The sample was loaded into the tensile grips
iii. Extensometer was attached to the sample
iv. The test was initiated by separating the tensile grips at constant speed rate
v. The test is ended after sample rupture

The diameter at the point of fracture, the final gauge length, and the fracture load for each sample were recorded. Before the application of the uniaxial stress, the initial diameter and initial gauge length for each sample were noted as recommended by [21] and [22]. The percentage elongation and reduction of each sample were determined and the ultimate tensile strength and yield strength were obtained from the data generated.

3. Results and Discussion

The chemical composition of the low carbon steel samples used for this investigation is shown in Table 1. Also, the results of the effects of the heat treatment temperatures on the yield strength, percentage elongation, hardness, and ultimate tensile strength (UTS) test for the twenty samples comprising of five samples as received (control) and the other fifteen samples annealed at 900 °C, 950 °C and 1000 °C are shown in Table 2, Table 3, Table 4, and Table 5 respectively.

Table 1. Chemical Composition of the Low Carbon Steel Samples Used

Element Present	Percentage Composition (%)
Carbon (C)	0.170
Silicon (Si)	0.280
Phosphorous (P)	0.030
Niobium (Nb)	0.000
Nitrogen (N)	0.006
Manganese (Mn)	0.880
Tungsten (W)	0.005
Aluminium (Al)	0.024
Molybdenum (Mo)	0.005
Vanadium (V)	0.000
Chromium (Cr)	0.080
Nickel (Ni)	0.040
Copper (Cu)	0.330
Sulphur (S)	0.028
Titanium (Ti)	0.000

Table 2: Yield Strength of Heat Treated Low Carbon Steel

Temperature	Yield Strength (MPa)					
	1st	2nd	3rd	4th	5th	Average Value
As Received	768	775	755	770	725	758.60
900 °C	525	529	524	526	526	525.80
950 °C	546	548	542	543	542	544.20
1000 °C	575	577	576	579	575	576.40
1100 °C	276	279	275	280	274	276.80

Table 3. Percentage Elongation of Heat Treated Low Carbon Steel

Temperature	Percentage Elongation (%)					
	1st	2nd	3rd	4th	5th	Average Value
As Received	44	43	45	44	42	43.60
900°C	53	42	55	53	53	53.20
950°C	55	57	57	56	55	56.00
1000°C	59	58	60	59	60	59.20
1100°C	51	53	52	51	52	51.80

Table 4 Hardness Test of Heat Treated Low Carbon Steel

Temperature	Hardness Test					
	1st	2nd	3rd	4th	5th	Average Value
As Received	200	201	201	199	199	200.00
900°C	187	186	187	186	187	186.60
950°C	163	162	163	162	162	162.40
1000°C	146	146	147	148	145	146.40
1100°C	179	180	180	178	178	179.00

Table 5. Ultimate Tensile Strength of Heat Treated Low Carbon Steel

Temperature	Ultimate Tensile Strength (MPa)					
	1st	2nd	3rd	4th	5th	Average Value
As Received	830	775	755	770	725	771.00
900°C	845	847	849	847	850	847.60
950°C	880	882	881	882	884	881.80
1000°C	935	933	939	935	936	935.60
1100°C	427	430	429	435	432	430.60

As depicted in Fig. 1, yield strength tends to decrease for all the annealed heat treated samples of low carbon steel at different temperature as compared to as received samples. However, a sharp decrease in yield strength was observed at annealed samples from 1000 °C to 1100 °C. This could be attributed to the dissolution of carbide and chromium enriched region in the matrix, which subsequently results in decrease in strength of samples used as reported by [23] in his research work titled, "Effect of Heat Treatment Temperature on Mechanical Properties of the AISI 304 Stainless Steel". Besides, the observed decrease in strength at higher annealing temperatures of 1100 °C could also be associated to grain growth phenomena.

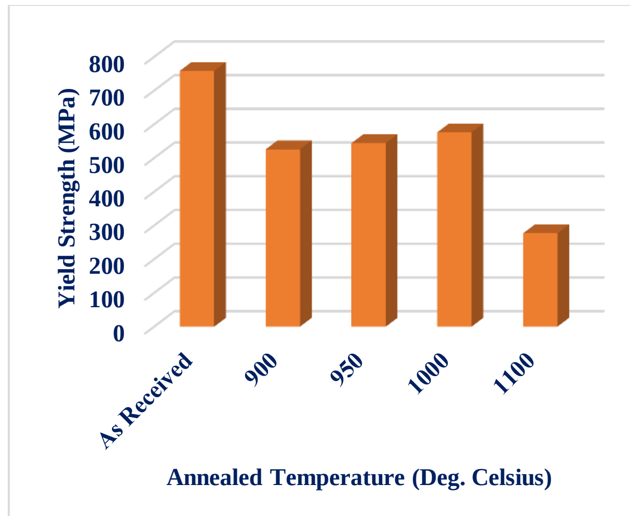

Fig. 1 Graph of Average Yield Strength of Low Carbon Steel at Different Annealed Temperature

As shown in Fig. 2, an increased in temperature from 900 °C to 1000 °C led to a corresponding increase in the ultimate tensile. Nevertheless, a decrease in ultimate tensile strength was recorded when the temperature was further increase to 1100 °C. This decrease was due to dissolution of carbide in chromium enriched region of the matrix and this finding agrees with the research work of [20, 23].

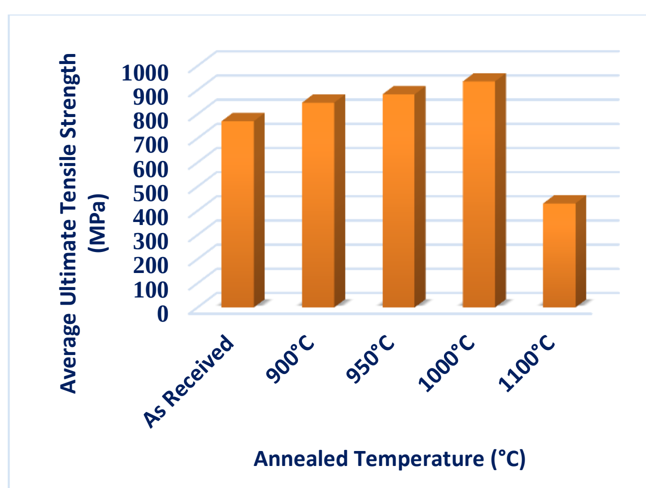

Fig. 2 Graph of Average Ultimate Tensile Strength of Low Carbon Steel at Different Annealed Temperature

Fig. 3 shows the comparative analysis of the variation of average yield strength and average ultimate tensile strength of samples at different annealed temperature. It was observed that different annealed temperature used in this research work increases ultimate tensile strength unlike yield strength that produces reduced values throughout. However, at annealed temperature of 1100 °C, reduction was observed in both yield strength and ultimate tensile strength of the samples with yield strength experiencing more reduction as compared to as received samples. According to Fig. 4, the hardness value of annealed samples significantly decreases from heat treated annealed temperature of 900 °C to 1000 °C but with a slight increase in hardness at 1100 °C. This decrease in hardness could be attributed to the dissolution of the carbide and chromium enrichment in the matrix at these temperatures. However, there was an increase in the hardness value of the low carbon steel from 146.40 BHN to 179.00 BHN at 1100 °C. This simply showed that more chromium carbides dissolve in the crystal's lattice at the annealed temperature of 1100 °C. Furthermore, this indicated that the samples matrix has been stressed, which resulted to an increase in sample strength. Thus, high annealed heat treatment on low carbon steels removed the formed alloy segregation and sigma phase after which resulted to an increased in ductility of the low carbon steel materials. This was attained due to the dissolution of the chromium carbides at the grain boundaries which in the process stalled dislocation movement as reported by [23]. Consequently, the matrix becomes less stretched, and dislocations were found to be relative to crystal movement, which give rise to a softer material. Besides, grain growth occurs during heat treatment when recovery and recrystallization stages are completed, and further reduction in the internal energy can only be achieved by reducing the total area of grain boundary [18].

Fig. 5 shows the results of percentage elongation of tested samples against heat treated temperatures. The percentage elongation of the samples increases as compared to as-received sample without heat treatment but with a slight decrease at sample annealed at 1100 °C. Lowest percentage elongation value of about 51.80 % was obtained at annealed temperature of 1100 °C. This phenomenon could be attributed to dislocations movement hindered by the chromium carbides precipitated at the grain boundaries. However, the highest value of percentage elongation of 59.20 % obtained at annealed temperature of 1000 °C is due to increase in the number of planes on treated sample for easy dislocation movement to occur. Fig. 7 shows the graph of comparative analysis of hardness and percentage elongation at different annealed temperature. As expected, at each evaluated annealed temperature, as the hardness of the low carbon steel is decreasing, the percentage elongation is increasing. However, at the annealed temperature of 1100 °C, there was a decrease in percentage elongation and corresponding increase in hardness of the samples.

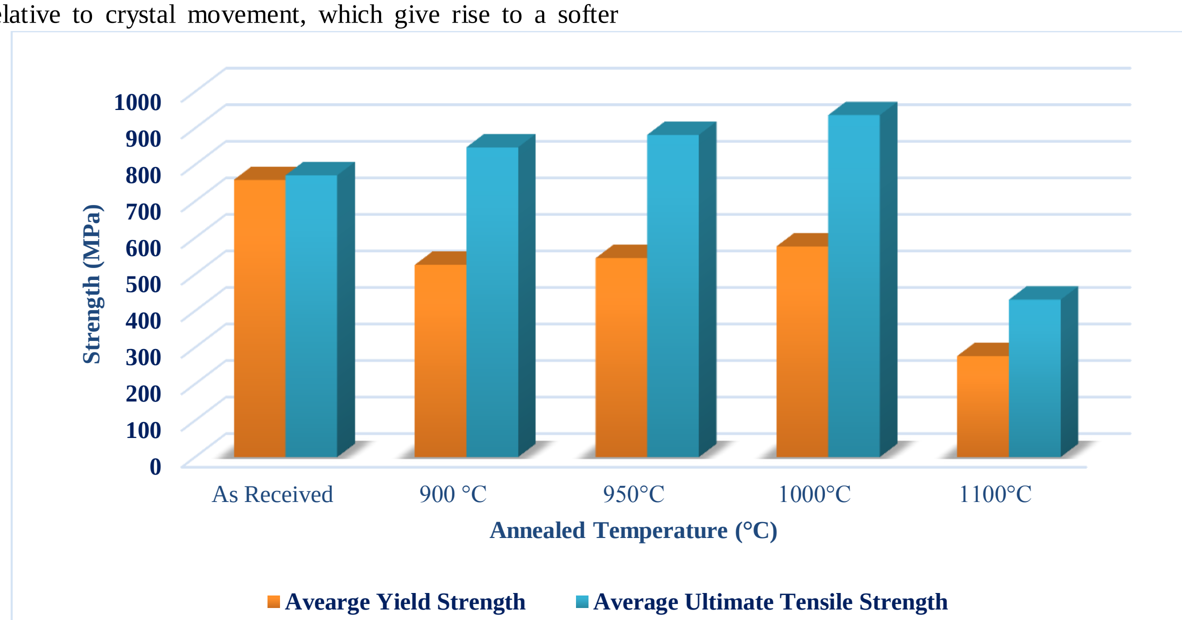

Fig. 3 Comparative Analysis of Average Ultimate Tensile Strength and Yield Strength of Low Carbon Steel at Different Annealed Temperature

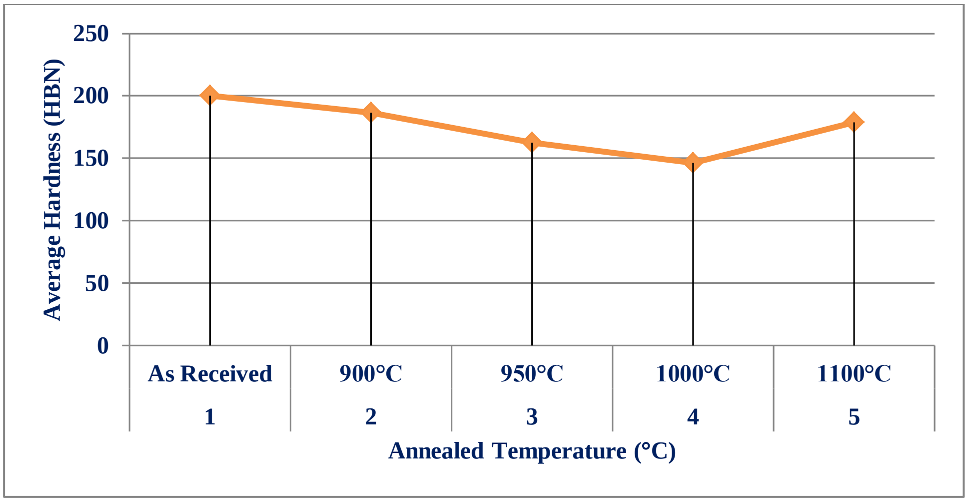

Fig.4 Average Hardness of Low Carbon Steel at Different Annealed Temperature

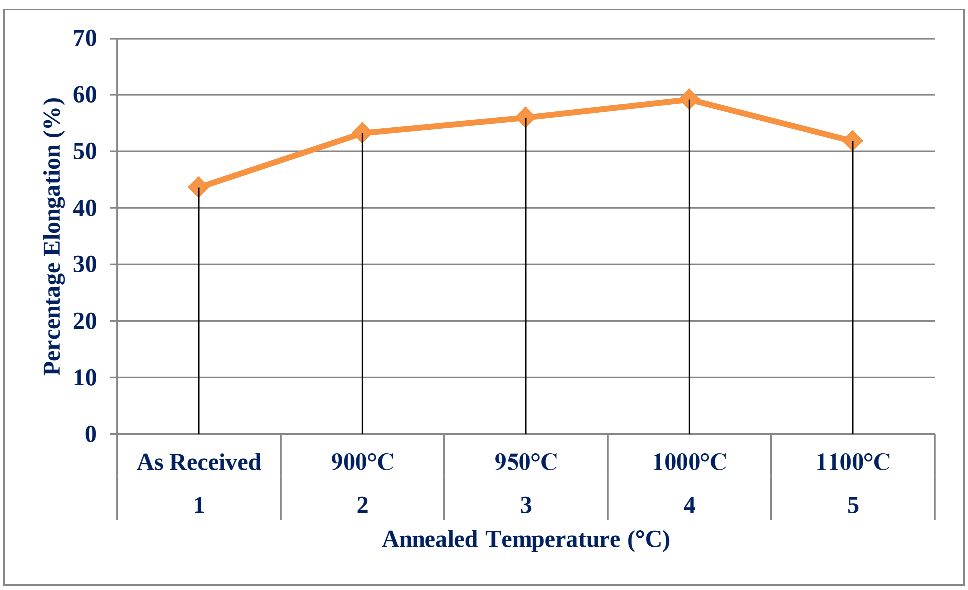

Fig. 5 Percentage Elongation of Low Carbon Steel at Different Annealed Temperature

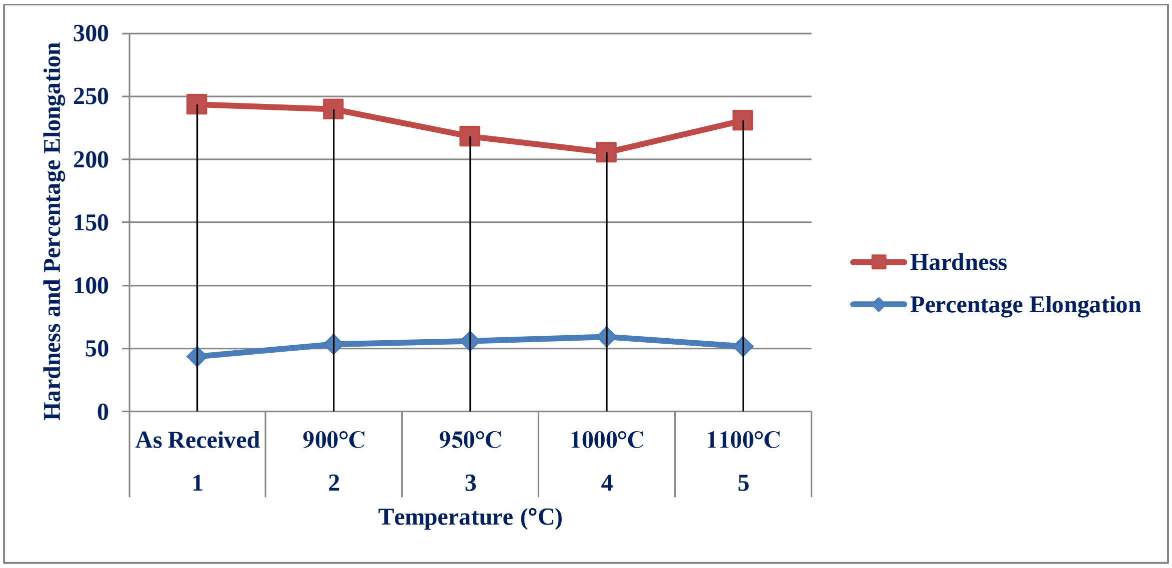

Fig. 6 Comparative Analysis of Hardness and Percentage Elongation of Low Carbon Steel at different Annealed Temperature

The results of the microstructural analyses of the as received samples showed fine dispersion of coalesced pearlite and ferrite grain (Fig. 7). For the annealed samples, the steel microstructures compose of martensite distributed in the ferrite matrix as shown in Fig. 8. Also, as received annealed low carbon steel at 900 °C showed a dispersion of coalescence cementite and ferrite grain. For the as received annealed low carbon steel at 950 °C, fine dispersion of cementite in matrix of ferrite grains was obtained. Nevertheless, with increase in annealing temperature to 1000 °C and 1100 °C, cementite and ferrite grain with partial grain boundary were observed. The low carbon steel takes the crystalline form of ferrite, and the iron carbide takes the crystalline form of cementite. The overall structure consists of bands of these two components and is known as pearlite.

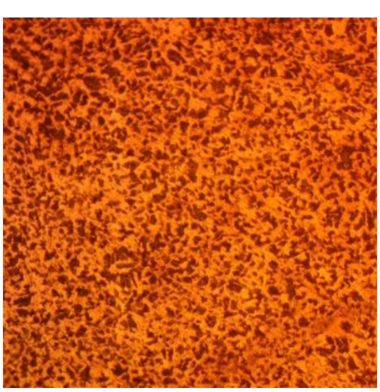

Fig. 7 As Received Sample

This transformation is as a result of grain growths that was favoured within the annealed temperature as reported in [24]. Also, as the annealing temperature increases, the cementite and ferrite grains are relatively isolated from each other. More so, the high annealed heat treatment on low carbon steels removed the formed alloy segregation and sigma phase [23].

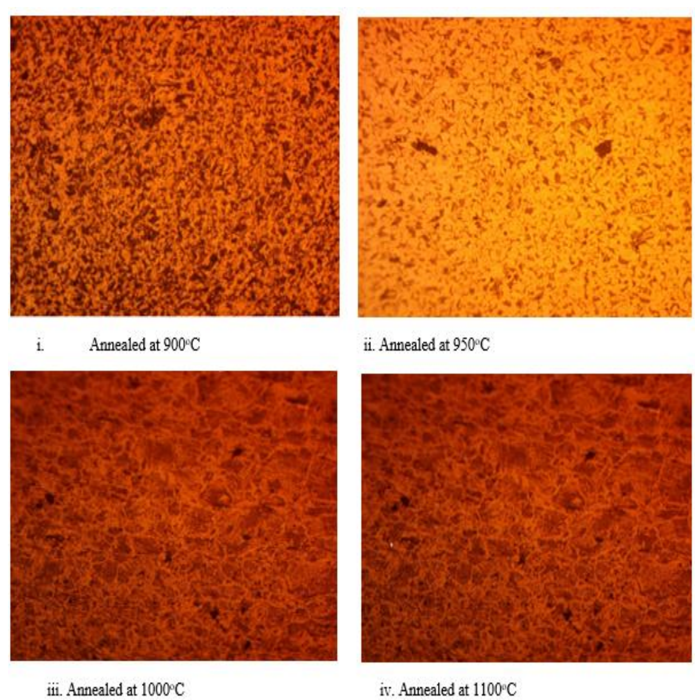

Fig. 8 Microstructure Analyses of Low Carbon Steel at different Annealing Temperature

4. Conclusion

From this this research work, the mechanical properties of annealed heat treated low carbon steel have been investigated. The findings revealed that the yield stress tends to decrease for all annealed heat treated samples as compared to as received samples. Also, for the ultimate tensile strength, there was an increase in strength with the exception of samples annealed at 1100^oC that showed decrease in strength. Besides, for the elongation, an improvement for all samples was recorded. The results of the microstructural analyses of the as received samples showed fine dispersion of coalesced pearlite and ferrite grain. For the annealed samples, the steel microstructures compose of martensite distributed in the ferrite matrix. However, with increase in annealing temperature to 1000^0C and 1100^0C, cementite and ferrite grain with partial grain boundary were observed. The low carbon steel takes the crystalline form of ferrite, and the iron carbide takes the crystalline form of cementite. The overall structure consists of bands of these two components and is known as pearlite.

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Conflict of Interest

The authors declare that they have no conflict of interest.

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