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Effect of Various Prestrain Levels on the Microstructure and Mechanical Properties of Heat Treated 0.14% Carbon Steel.

Obidimma D. Ikeh[1], Vandi Njelle[2], Efosa Osamudiamen[3], Stella I Monye[4]

[1,2,3,] Department of Mechanical Engineering, University of Benin, P.M.B 1154, Benin City, Nigeria.
[4]Department of Production Engineering, University of Benin, P.M.B 1154, Benin City, Nigeria.

Abstract.

The result of an investigation on the effect of various prestrain levels on the microstructure and mechanical properties of heat treated 0.14%C steel were analyzed. low carbon steel was heat treated by first austenitising at 910°C and then quenched in water. The specimens were then subjected to prestrain levels of 7%, 9%, 13%, and 20% in tension. Microstructural and mechanical analysis was carried out on specimens for the various prestrain values including the unstrained. The results showed that the microstructures and mechanical properties of the different specimens showed consistent changes with the increasing prestrain values. The increase in prestrain value also resulted in an increase of hardness but brought about a reduction in the ductility. Toughness increased at 7% prestrain but reduced for higher prestrain values. For optimum mechanical properties prestrain level of 7% produced a balance between the strength increase and reduction in ductility.

Keywords: *Prestrain, Microstructure, Mechanical properties, Heat treatment, Precipitate particles, Ferrite matrix*

1. Introduction

Heat treatment is a process in which materials are subjected to one or more temperature cycles to confer certain desired properties. Heat treatment of steel can also alter the size and shape of grains and micro constituents of the steel. The shape of the grains is altered by heating the steel to a temperature above that of recrystallization, the size of the grains is controlled by the temperature and duration of heating and the speed at which the steel is cooled after heating. Heat treatment is only effective with certain alloys because it depends upon one element being soluble in another in the solid state in different amounts under different circumstance [1].

The structure of a material usually relates to the arrangement of its internal components. In describing the structure of a material, it is important to make a clear distinction between its crystal structure and its microstructure. The term ‘crystal structure’ is used to describe the average positions of atoms within the unit cell, and is completely specified by the lattice type and the fractional coordinates of the atoms (as determined, for example, by X-ray diffraction). In other words, the crystal structure describes the appearance of the material on an atomic (or Å) length scale (Maj and Oliferuk, 2015). The term ‘microstructure’ is used to describe the appearance of the material on the nm-cm length scale (Kei et al, 2003). The microstructure can be briefly defined as the arrangement of phases and defects within a material. Microstructures form through a variety of different processes. Microstructures are almost always generated when a material undergoes a phase transformation brought about by changing temperature and/or pressure (e.g. a melt crystallizing to a solid on cooling). Microstructures can be created through deformation or processing of the material (e.g. rolling, pressing, welding etc.). Finally, microstructures can be created artificially by combining different materials to form a composite material such as carbon-fibre reinforced plastic. Microstructure can be observed using a range of microscopy techniques. The microstructural features of a given material may vary greatly when observed at different length scales. For this reason, it is crucial to consider the length scale of the observations you are making when describing the microstructure of a material (Kei et al, 2003).

The mechanical properties of a material are the intensive characteristics of a material that determines its response to a mechanical stimulus. Some of the important mechanical properties that are commonly analyzed by engineers are as follows: strength, hardness, ductility, and toughness. Strength is the capacity of a material to withstand or support an external force or load without rupture. It is expressed as force per unit area of cross-section. This is most important property of a metal, which plays a decisive role in designing various structures and components. A material has to withstand different types of load, e.g. tensile, compressive and shear load, therefore resulting in tensile strength, compressive strength and shear strength [2]. As stress is applied to a material, the material initially exhibits elastic deformation. The strain that develops is completely recovered when the applied stress is removed. With an increase in the applied stress, the material eventually "yields" to the applied stress and exhibits both elastic and plastic deformation [3]. The critical stress value needed to initiate plastic deformation is defined as the elastic limit of the material. In metallic materials, this is usually the stress required for dislocation motion, or slip, to be initiated. The maximum tensile stress that a material carries are called its tensile strength or ultimate tensile strength, which is the maximum stress on the engineering stress-strain curve [4]. The value is also commonly known as the ultimate tensile strength (UTS). In low carbon steel and other ductile materials, deformation does not remain uniform. The Ductility value of a material can be described as the ability of the material to suffer plastic deformation while still being able to resist applied loading. The more ductile a material is the more it is said to have the ability to deform under applied loading [5]. It is the deformation produced in a material at the breaking point and measured by the percentage of elongation and the percentage of reduction in area before rupture of test piece.

Low carbon steel contains between 0.002-0.25% carbon and accounts for a large proportion of the total output of steel. It finds applications in automobiles, tinplate, furniture, refrigerators and for structural purposes like beams, channels and angles for construction [1]. Its low carbon content makes it the most ductile category of steel. It combines moderate strength with excellent ductility and are used extensively for their fabrication properties in the annealed or normalized condition for metal forming, sheet metals applications and structural purposes such as bridges, buildings, cars and ships [6].

Prestrain is the prior plastic deformation of a material [7]. This can be done to improve the strength of the metal by work hardening. When a material does not return to its original dimension upon removal of the applied stress the material is said to have plastically deformed, and this only happens when the applied stress is greater than the yield strength of the material. The degree to which a material can be plastically deformed is dependent on the ductility of the material. Prestraining can also be found to occur during metal forming operations [8]. The prior deformation can occur during various metal working processes like rolling, forging, extrusion, spinning, pressing, drawing, stamping, etc. The dimensional changes that comes with plastic deformation also causes changes in mechanical properties. Prestrain can also occur unintentionally or accidentally like in machine malfunctions, earthquakes etc. [9].

Research has shown by Susilo et al, 2014 that prestraining alters the microstructure and mechanical properties of low carbon steel by increasing the strain level which results in the elongation and decrease in the sizes of grains. The elongation of the grain's point in the direction of the applied stress and produces a fiber texture in wire drawing and extrusion. Therefore, the aim of this study is to investigate the effect of heat treatment on the microstructural and mechanical properties on this steel subjected to various prestraining levels, so that adequate measures can be adopted to improve the micro-structural and mechanical properties when subjected in service; under load bearing capacity

2. MATERIALS AND METHODS

2.1 Materials

The material used in this study is low carbon steel rods of 0.14%C composition. The low carbon steel was obtained from the Universal Steel Company Plc. Ikeja Lagos State. Spectrometric analysis of the steel was carried out at the laboratory of the company and the chemical compositions is as shown in Table 1.

1.2. Methods.

2.2.1 Sample Preparation

The steel rods were machined to remove the ribs of the rod and other surface irregularities. This was done to ensure that there was no temperature differential across the axis of the rod during heat treatment. The rods were then cut to sample sizes of length 50mm for heat treatment.

2.2.2. Heat Treatment

The steel specimens were austenitised in a furnace at 920°C for one hour and then quenched in water. This was to ensure a diffusionless transformation of the microstructure for the purpose of obtaining a martensite microstructure.

The quenched specimens containing martensiteic microstructure were placed in the furnace and heated to a temperature of 700°C and held for 1hr.

2.2.3. Prestraining

Two specimens were tested to fracture, in order to get the tensile properties of the unstrained specimen and identify possible prestrain levels between the Yield Strength and the Ultimate Tensile Strength. This was found to be 7%, 9%, 13% and 20%, hence the other specimens were then separated into four batches of 10 specimens each and marked W, X, Y, Z. Batch W was strained to 7%, Batch X was strained to 9%, Batch Y was strained to 13% and Batch Z was strained to 20%.

2.2.4. Microstructural Analysis

Specimens of the unstrained and two specimens from each of the different prestrain levels were subjected to microstructural analysis by metallography technique and then examined by an optical microscope. These specimens analyzed were prepared by sectioning and mounting, grinding, polishing and etching of the surface.

a. Sectioning

The specimens examined were first sectioned at the midpoint and then mounted on a holder.

b. Grinding

This operation was done to produce a perfectly flat and smooth surface. Silicon carbide papers of different grades placed on the grinding machine was used in the order of 220,320,400 and 600, i.e. from coarse grade to fine grade. The grinding process was done under running water to wash away the grits and also to avoid overheating. The samples were rotated through 90^0 while changing from one grit size to another. This is to neutralize the scratching effect of the previous grinding of the former grit size.

c. Polishing

A universal polishing machine was employed. A polishing cloth (selvt cloth) was placed on the polisher for the initial polishing swamp with solution of one micron of silicon carbide solution, then, followed by the final polishing stage with selvt cloth swamped with solution of 0.5µm Silicon carbide until a mirror-like surface was attained. It was then washed with water and dried.

d. Etching

This was done to reveal the microstructure of the material by removing the layer of the polished surface. The mirror-like surface was etched in 2% nital. Again, it was washed with water, dried and later viewed under the metallurgical microscope.

e. Microscopic Examination

An optical metallurgical microscope with a 400-pixel magnification and fitted with a photographic device was used to view and record the etched surface. The etchant used ensured that the carbides appeared as darkened portions. The results can be seen in plates 1 – 5.

2.2.5 Mechanical Testing

Mechanical testing was conducted on the unstrained and the prestrained specimens. The mechanical properties including; yield strength, tensile strength, ductility and hardness according to the ASTN A370 specification were determined.

a. Tensile Test

Tensile testing of two specimens per batch (prestrain level) for a total of ten specimens were conducted according to ASTM standard E-8. The test was carried out at room temperature with a cross head speed of 1 mm per minute using a computerized Instron Electromagnetic Tensile testing Machine (Model 3369). The load and displacement values were recorded and ultimate tensile strength, yield strength and percentage elongation were calculated from the load and displacement values.

b. Hardness Test

Three specimens for each prestrain level and also the unstrained were subjected to Brinell Hardness test according to ASTM897M-90 using Monsato Tensometer (Model W) in compression mode. A 10mm indenter made of a hardened steel ball was mounted on a holder and forced into the prepared surface of the specimen polished to 600 microns using a dwell time of 15 seconds. The diameter of the impression left by the ball was measured using the Brinell calibrated hand lens and corresponding Brinell hardness number was determined. The hardness of each prestrain level was taken for three different specimens and the average was determined as the hardness value. The Brinell hardness number (BHN) was calculated with the Equation 2.1.

$$\text{BHN} = \frac{2F}{\pi D\left\{D-\sqrt{D^2-d^2}\right\}} \quad - \quad - \quad - \quad - \quad - \quad - \quad - \quad - \quad 1$$

Where

F = imposed load (kg), D = Diameter of the spherical indenter (mm)

d = Diameter of the resulting indentation (mm)

3. Results and Discussion

3.1 Results.

The chemical composition of the steel substrate as presented in the Table 1 reveals that the material is a low carbon steel as the carbon in this material is between 0.002-0.25%, while the others are alloying elements present in this material, as steel is basically an alloy of iron and carbon, and other alloying elements (Onyekpe, 2002).

Table. 1. Chemical composition of the steel.

Elements	C	Si	Mn	S	P	Cr	Cu	Ni	Ti	Fe
Composition	0.14	0.18	0.69	0.05	0.03	0.09	0.13	0.06	0.02	98.6

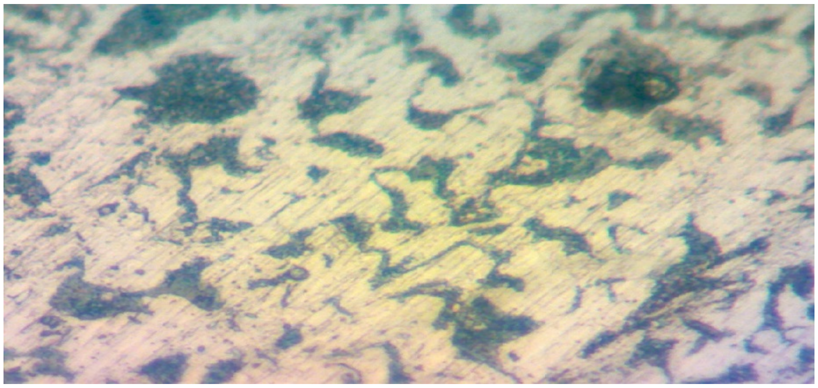

Plate 1: Micrograph of Low Carbon Steel Specimen (unstrained)

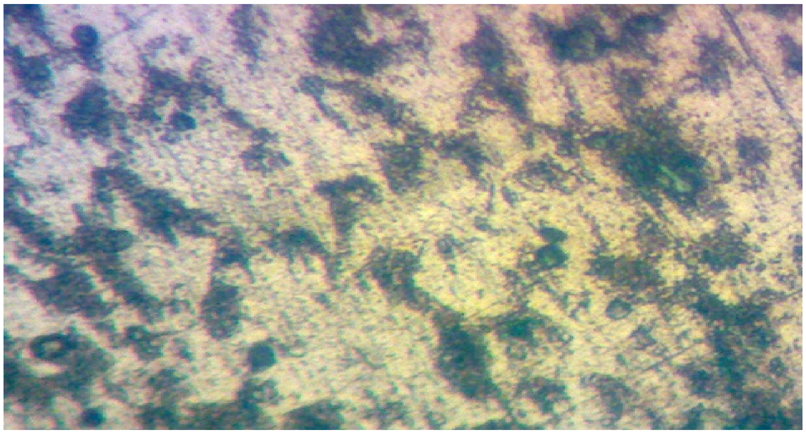

Plate: 2. Micrograph of Low Carbon Steel Specimen (7% prestrained)

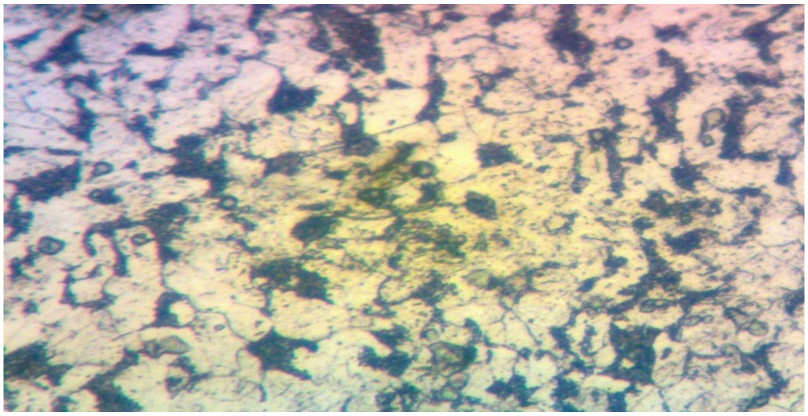

Plate 3.: Micrograph of Low Carbon Steel Specimen (9% Prestrained)

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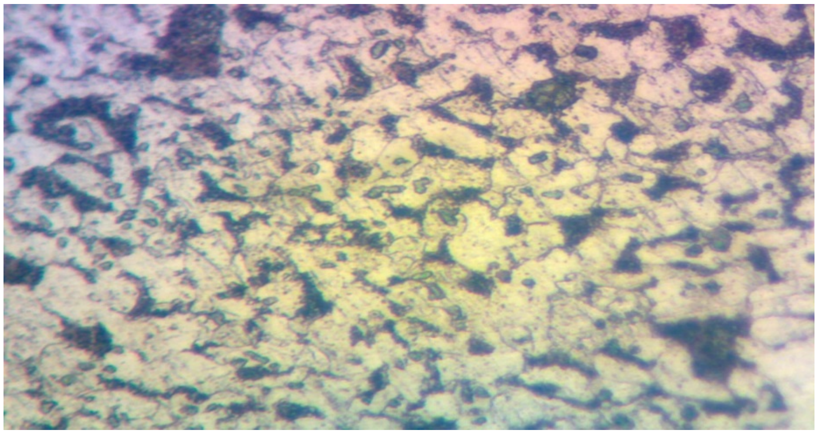

Plate 4: Micrograph of Low Carbon Steel Specimen (13% Prestrained)

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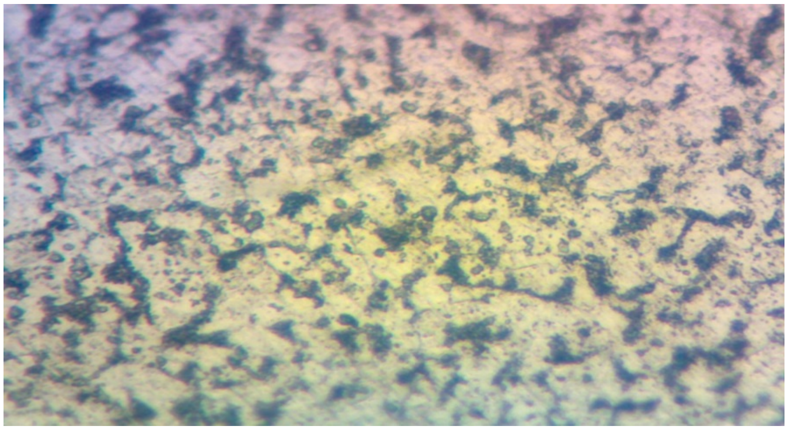

Plate 5: Micrograph of Low Carbon Steel Specimen (20% Prestraine)

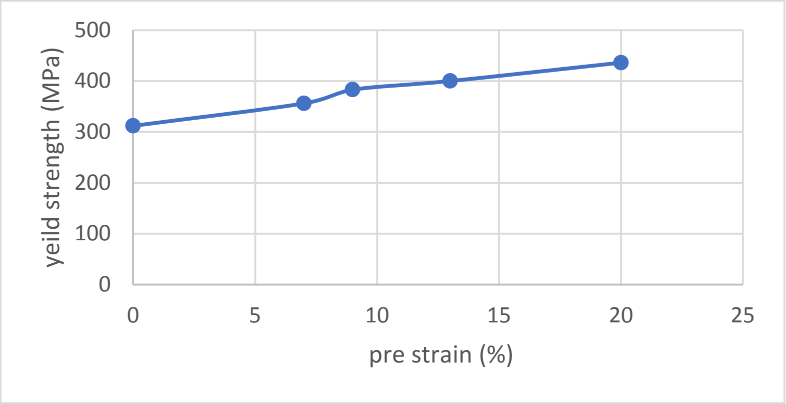

Fig 1. Graph of Yield Strength against Prestrain Levels.

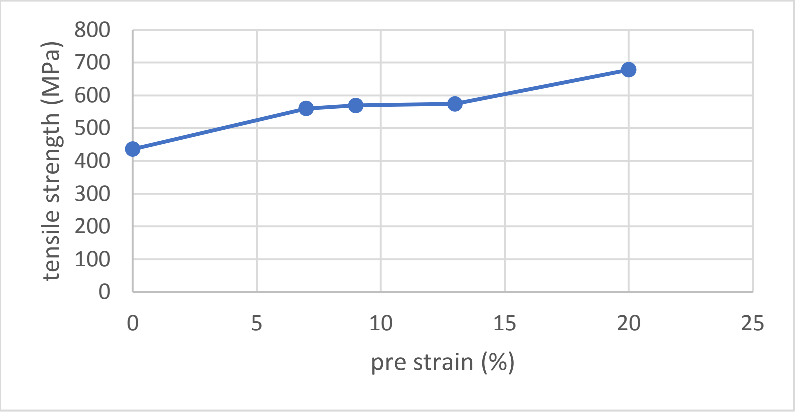

Fig 2. Graph of Tensile Strength against Prestrain Levels

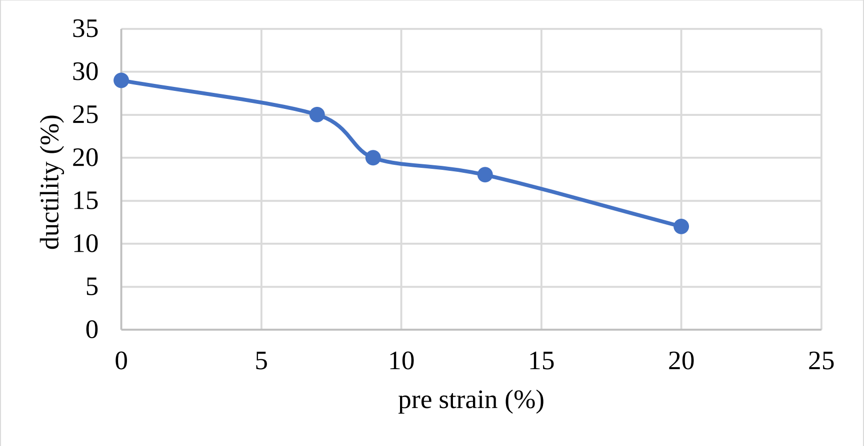

Fig 3. Graph of Ductility against Prestrain Levels

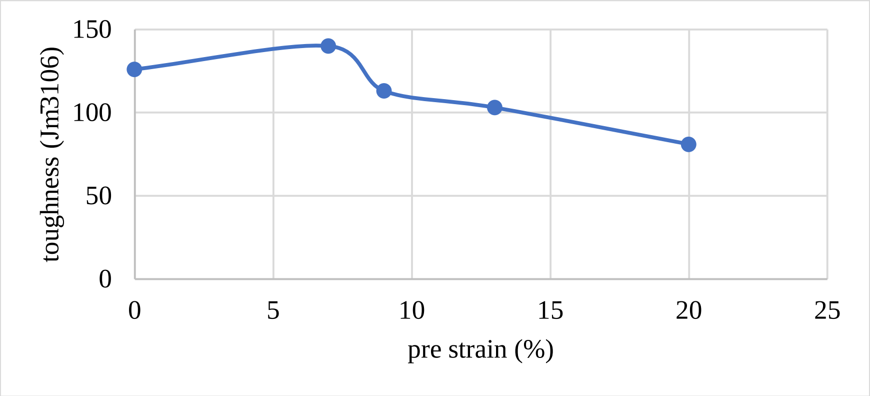

Fig 4. Graph of Toughness against Prestrain Levels

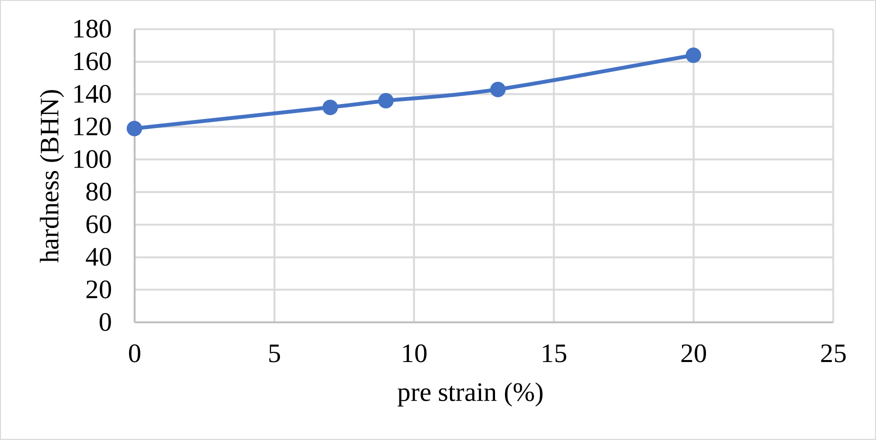

Fig 5. Graph of Hardness against Prestrain Levels.

3.2 Discussion.

The micrographs of the unstrained and pre-strained specimens are shown on Plates 1 – 5. The visible features are the parent ferrite and carbide (darkened). From Plate 1 which is the unstrained specimen shows dispersion of coarse precipitate particles within the ferrite matrix, this also reveals large inter particle distance between the particles. The agglomeration of the precipitate into coarse forms can be attributed to the sufficient thermal energy available when the specimen was reheated after quenching and held, this is supported by [1] which stated that high temperature transformations results in coarse microstructures. As the strain level increases the particles size tend to reduce and are more finely dispersed within the ferrite matrix and also results in a reduction in the inter particle distance. Plate 2 shows the distortion of precipitate particle shape and size resulting from the prestrain, Plate 3 shows a mix of coarse and fine precipitate particles dispersed within the ferrite matrix, it also shows a reduction in the inter particle distance, Plate 4 shows a fine dispersion of precipitate particles with very few coarse particles, the inter particle distance is small and Plate 5 which has the highest prestrain value also shows the finest dispersion of particles. Microstructural changes in prestrained low carbon steel can also be attributed to an increase in dislocation density and formation of sub cell structures in the ferrite, this is also supported by [2], who observed a formation of sub cells and increase in dislocation density due to prestrain. The finer carbide particles formed help to increase the strength of the steel by forming more obstacles to the movement of dislocations. The strengthening is due to the difficulty of the dislocations either shearing or bypassing the particles, this relationship was first showed by Orowon as stated by [1]. Also, the migration of solute atoms to dislocations results in the reduction of the strain energy associated with a give dislocation, therefore when dislocations slip the strain energy of the crystal increases because the solute atoms do not move with the dislocations. The energy comes from the forces acting on the dislocation resulting in an increase in the stress to be applied and the particle can be said to have had a dislocation pinning effect in agreement with [10], who stated that the migration of solute atoms to dislocation sites brings about a dislocation pining effect. With this increase in strength also comes a reduction in the ductility due to the decrease in the mean free path of dislocations.

The mechanical properties of the pre-strained specimens shown in Fig 1 – 5. Fig 1 and Fig 2 show the effect of prestrain on the yield strength and tensile strength respectively. The unstrained shows the lowest value for yield strength and tensile strength. The increase in strength with degree of prestrain is as a result of the work hardening of the material as also supported by [11] who observed that prestrain results in work hardening. The increase in strength with prestrain level can also be attributed to the reduction in the grain size on the ferrite due to the increase in the deformation of the material as also observed by [12] who observed a consistent increase in strength with a reduction in grain size. Also increased strength with increased prestrain level is due the increase in fine precipitate particles, which under stress induced ordering migrate to dislocation points and thus preventing the dislocations from further movement, this is supported by the findings of [7]. Fig 3 shows the effect of prestrain on ductility. It is measured by the percentage strain a material can undergo before it fails. From the graph it can be see that ductility reduces with increase in prestrain value. This can be attributed to the reduction in mean free path of dislocation movement which is also supported by [13] who stated that plastic deformation results in restriction in dislocation movement. Dislocations that have tangled as a result of prestrain and dislocations that have been pinned by particles within the matrix reduces the amount of dislocations available for deformation. Fig.4 shows the graph of toughness against prestrain level. From the graph it can be observed that the highest value of toughness is at prestrain level of 7%. This is due to a balance between the increase in stress and the reduction in ductility from the unstrained. At a strain of 7% the strength increased by 28% but ductility only dropped by 8%, while at 9% prestrain strength increased by 30% and ductility decreased by 13%, for 13% prestrain level strength increased by 31% and ductility dropped by 28%, for 20% prestrain strength increased by 55% and ductility dropped by 58%. Prestrain of 20% has the least toughness and therefore absorb the least energy before fracture. In Fig.4.5, from the graph it can be seen that hardness increases with increase in prestrain level. The increase is similar to that of tensile strength and is also as a result of the work hardening of the material which prevents deformation of the material. This is also supported by [11] who stated that prestrain results in work hardening

4. Conclusion

The results show that prestrain has an effect on the microstructure of low carbon steel. The coarse carbide particles become finer as the prestrain value increases and results in a reduction of the inter particle distance. The micrograph of the unstrained shows a dispersion of coarse precipitate particles within the ferrite matrix, this also reveals large inter particle distance between the particles. The micrograph of the 7% prestrain shows the distortion of precipitate particle shape and size resulting from the prestrain. The micrograph of the 9% prestrain shows a mix of coarse and fine precipitate particles dispersed within the ferrite matrix, it also shows a reduction in the inter particle distance. The micrograph of the 13% prestrain shows a fine dispersion of precipitate particles with very few coarse particles, the inter particle distance is small and the micrograph of the 20% prestrain shows very fine precipitate particles finely dispersed within the ferrite matrix. On the mechanical properties of low carbon steel, the results showed that yield strength and tensile strength of low carbon steel increases with corresponding decrease in ductility as the prestrain values increases. The optimum value for balance between increase in strength and decrease in ductility which resulted in the highest value of tensile and toughness was obtained at a prestrain level of 7%. At 7% prestrain yield strength and tensile strength increase by 14% and 28% respectively while ductility reduces by 13% and this resulted in a 10% increase in toughness. The effect of prestrain of low carbon also resulted in an increase in the hardness of the material. With an increase in prestrain value from 7% to 20% resulted in an increase in the Brinell hardness number from 132BHN to 164BNH.

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