The Effect of Annealing on the Microstructure of Mechanical Properties of a Rolled Steel Product.

Patrick Adebisi Olusegun Adegbuyi, M.Eng. and Andrew Atiri, B.Sc.

Faculty of Engineering, Technology, and Environmental Science,
Lagos State University, Ojo, PMB 1087, Apapa, Lagos, Nigeria.

*E-mail: paorene2001@gmail.com

ABSTRACT

Annealing describes a number of different heat treatments, which can be applied to metals and alloys. This process includes recovery, recrystallization, and grain growth. The essence of this study is to determine the effect of annealing at the recovery, recrystallization, and grain growth stage on rolled steel product. Steel bars of known chemical composition were used as experimental samples and subjected to different conditions of heat treatment. The results show that the microstructure and mechanical properties of the rolled steel were considerably affected.

(Keywords: effect of annealing, microstructure, mechanical properties, rolled steel product)

INTRODUCTION

Annealing describes a number of different heat treatments, which can be applied to metals and alloys. The cold-worked state is a condition of higher internal energy than the undeformed metal. Although the cold worked dislocated cell structure is mechanically stable, it is not thermodynamically stable (4). With increasing temperature, the cold worked state becomes more and more unstable. Eventually the metal becomes soft and returns to a strain-free condition.

Annealing is very important commercially because it restores the ductility to a metal which has been severely strain-hardened. Therefore, by interposing annealing operations after several deformations on a metal, it is possible to regain its metallic structure to a great extent (4). The process of annealing is usually divided into three fairly distinct processes: recovery, recrystallization, and grain-growth.

Recovery, is usually defined as the restoration of physical properties of the cold-worked metal without any observable change in the microstructure. Electrical conductivity increases rapidly towards the annealed value during recovery and lattice strain is appreciably reduced. The properties that are mostly affected by recovery are those which are sensitive to point defects (1)(5).

The strength properties, which are controlled by dislocation, are not affected at recovery temperature, giving the clue that it is possible to recover completely the yield stress of a strain-hardened crystal without producing recrystallization.

Recrystallization, is the replacement of the cold-worked structure by a new set of strain-free grain. Recrystallization is readily detected by the metallographic method and it is evident by a decrease in the hardness or strength of the metal and an increase in ductility.

The density of dislocations decreases considerably on recrystallization and all effect of strain hardening are eliminated. The stored energy of the cold work is the driving force for both recovery and recrystallization (9). If the new strain-free grains are heated at a temperature greater than that required to course recrystallization, there will be a progressive increase in grain size. The driving force for grain growth is the decreases in free energy resulting from a decrease in grain-boundary which is due to an increase in grain size.

The recrystallization process consists of the nucleation of a strain-free region whose boundary can transform the strained matrix into strain-free material as it moves. In the growth of the boundary out from the nucleus, the dislocations are annihilated in the region swept through. This requires that the moving boundaries be in a high angled boundary so that there is a high degree of misfit to accommodate the dislocation.

At least two distinct nucleation mechanisms have been identified for recrystallization. The first is called induced boundary migration (3)(5) where a strain free nucleus is formed when one of the existing grain boundaries moves into its neighborhood leaving a strain-free recrystallized region behind. The boundary moves into the grain which contains the high dislocation density in the local region in the second nucleation mechanism, new grain boundaries are formed in region of sharp lattice curvature through sub-grain growth (1). The mechanism seems to predominate at high strains with nuclei appearing at grain boundaries, twin boundaries, or at inclusion or second phase particles. The nuclei form only in regions, which through homogeneous deformation have been rotated, into an orientation appreciably different from that of the matrix.

The six-matrix variable that influences recrystallization behavior is:

1. Amount of prior deformation
2. Treatment temperature
3. Holding time
4. Initial grain size
5. Composition and
6. Amount of recovery prior to the start of recrystallization.

Because the temperature at which recrystallization occurs depends on the above variation, it is not a fixed temperature in the sense of a melting temperature.

For a more pragmatic consideration, a recrystallization temperature can be defined as the temperature at which a given alloy in a highly cold worked state completely recrystallizes in the hour (11).

Annealing can be seen as any heat treatment intended to reduce or eliminate deformation-induced damage. It is usually carried out to soften steel, improve machinability to relieve internal stresses caused by previous treatment (cold rolled or uneven cooling after hot rolling, forging) and to remove coarseness of grain.

The first distinction to be made during the annealing process is between recovery and recrystallization. The term recovery covers all changes which do not involve the sweeping of the deformed structure by migrating high angle grain boundaries. The deformed crystal (or poly-crystalline structure) retains its identity which the density of the crystals detects and their distribution changes. A special form of recovery occurs, residual stresses resulting from metal working processes are removed by heat treatment, where such stresses are long-range (i.e., approximately uniform over a long distance compared with the grain size) then the removal is termed stress relief.

In recrystallization (5), the crystal orientation of any region in the deformed material is altered, maybe more than once. This results from the passage through the material of high angled grain boundaries.

A population of a new grain is nucleated often at the boundaries of a deformed material, and these then grow at the expense of the deformed structure until it is all consumed (2). Therefore, grain boundaries continue to move or migrate, but more slowly at this stage of cannibalism among the new population of grains is term “grain growth”. Usually, all boundaries move to a uniform size area, however movement is restricted to a minority of boundaries only so that a few grain grows very large at the expense of the rest (5).

EXPERIMENTAL SPECIMEN COMPOSITION

The steer bar used for this study was deformed or ribbed bar. The specimen with billet number 123744. (Heat Number) was obtained from Quality Assurance

Mechanical Laboratory of Delta Steel Company, Alakija, Nigeria.

COMPOSITION OF RIBBED OR DEFORMED BAR NO. 123744

C	Si	Mn	P	S	Cu	Cr
0.45	0.23	1.01	0.03	0.006	0.02	---

The specimen is a ribbed bar of diameter 20mm and was cut into four different samples of length 520 mm.; a suitable length for tensile testing of such diameter (Sample A, Sample B, Sample C, and Sample D, respectively).

ANNEALING

Annealing was carried out at temperature for recrystallization, grain-growth, and stress relief. The three samples were subjected to heat treatment of 650ºC, 700ºC, and 850ºC, respectively.

- Sample A, was annealed to temperature 650ºC,
- Sample B, annealed to temperature 700ºC,
- Sample C, annealed to a temperature of 850ºC,
- Sample D, served as the control experiment or specimen "as received".

Each sample underwent annealing at the different temperatures as stated above and were left to cool in the furnace which took approximately 72 hours each. Samples of about 35mm were cut of from each of the annealed samples including the control (sample D) for hardness tests and metallographic structure all to identify what happens to steel product after undergoing heat-treatment at different temperatures (9)(10).

For the stress-relief stage, the specimens were heated at relatively low temperature of 650ºC for a period of one hour then cooled in air and tested.

For recrystallization, the specimen were heated to a temperature of 750ºC for about 1 hour and tested. The specimen for grain-growth annealing was heated to a temperature of 850ºC for same 1 hour. Cooled in air and tested.

Precaution was taken to improve accuracy during this process includes. The annealing temperature at any of the stages was maintained (though by the furnace pneumatically) to avoid annealing at very low temperatures to prevent remnants of the as-cast structure, and avoiding rapid cooling in other to prevent stress from setting in.

METALLOGRAPHY

Metallographic testing was carried out on the specimens for studying the changes in their microstructure at the various stages of annealing (8). The specimen was ground to produce a flat surface and polished to remove marks made during grinding. The polishing process continued till the surface became mirror like though hiding the crystal structure.

In other to reveal the crystal structure, the samples were 'etched' in 4% Nitral (i.e., a 4% Nitral acid in alcohol solution). The etching reagent dissolves the amorphous layer of the metal. The samples were inspected under the microscope, magnified to x 100, and photographed (7).

Precautions were taken during the metallographic process to avoid overheating of the specimen during grinding because this may cause a tempering effect. Absolute cleanliness was ensured at every stage and light pressure was applied at all time during grinding and polishing.

TENSILE TEST

The steel sample was cut to length using a specially designed press cutter. The universal tensile testing machine in the quality controlled laboratory was used for the tensile strength of the samples. Loading was applied in a progressive increasing tensile pull until it fractured (4).

Before testing, the gauge lengths were marked out on the specimens and measured, and the length and weight were taken using vernier calipers and a precision balance scale. The specimens were griped and loaded till yield point was reached.

The stress and corresponding strain at this point was recorded. The loading (tensile pull) continued till the maximum loading point was reached, again the stress and the corresponding strain at this point recorded, and finally, with continued application of load, the material got to its break point. At this point, the stress and the corresponding strain was recorded including the gauge length (i.e., after the fracture). Results obtained for this testing are recorded as shown in Table 1.

During the testing, the following mechanical properties were examined. The yield stress, tensile stress, fracture stress, elastic limit stress, ductility, young modulus, and elastic stain energy.

YIELD STRESS: The yield stress of a material is the point where there is appreciable elongation or yielding of the material without any corresponding increasing in load. Although very few materials show yield point or stress but it is of great importance because it occurs in mild steel which is an important engineering material. The yield stress is commonly used as a measure of the "strength of a material" (6).

PROPORTIONAL LIMIT STRESS: The proportional limit stress is the point at which the stress of a material is proportional to strain. It is from proportional manner of material that hooks law came to be.

RESULTS

METALLOGRAPHY/ PHOTOMICROGRAPHY RESULTS: The photomicrographs of the crystal structure of the steel bar before and after various annealing stages are being displayed. The photographs below show the microstructure of the various stages of the effect of annealing on the specimen No. 123744 as shown in Figure 1.

TENSILE TEST RESULT: Samples A-D show specimens before and after various annealing treatments that were later subjected to tensile testing.

Table 1 shows the weights, cross sectional area, and gauge length of the specimen at various temperatures.

Table 2 shows the yield load and maximum load at various temperatures.

Table 3 shows the yield stress, tensile stress and fracture at various temperatures.

Table 4 shows the Brinell hardness test.

Table 1: Tensile Test Results for Ribbed Bar of 20mm.

Sample	Dimensions		X-Sectional Area, Ao	Gauge Length (mm)		Yield Load	Maximum Load (KN)	Fracture Load (KN)	Yield Stress N/mm²	Tensile Stress N/mm²	Fracture Stress	% Elongation	Remark
	Wt (g)	L (mm)		Lo	Li								
A (650)	1350	524	328.2	200	226.10	135	223	212	411.33	679.46	645.95	13.05	
B (700)	1320	520	323.4	200	231.60	122	209	203	377.24	646.26		15.8	
C (850)	1320	520	323.4	200	236.40	112	199	194	346.32	615.34		18.2	
D Control	1320	520	323.4	200	225.60	147	240	230	476.32	751.84		17.08	Fracture outside marked gauge length

Table 2: Yield and Max Load at Various Temperature.

Sample at various temp	Yield load	Max Load	Fracture Load
A 650ºC	135	223	212
B 700ºC	122	209	203
C 850ºC	112	199	194
D Control	147	240	230

Table 3: Yield Stress, Tensile Stress and Fracture at Various Temperatures.

Sample at various temp	Yield stress (N/mm²)	Tensile stress (N/mm²)	Fracture stress (N/mm²)
A 650ºC	411.33	679.46	645.95
B 700ºC	377.24	646.26	627.71
C 850ºC	346.32	615.34	599.88
D Control	454.55	742.12	711.19

Table 4: Brinell Hardness Test

Sample at various temp	Indent diameter	Ball diameter in mm.	HB
Control.	2.4	10	219
650ºC	2.5	10	200.38
700ºC	2.7	10	172.08
850ºC	2.85	10	155.29

BRINEL HARDNES TEST
Ball diameter = D = 10mm

DISCUSSION

Discussion on Metallography and Photomicrography Results: Figures 1-4 shows the microstructure of the various stages of annealing treatment carried out on the specimens, stage of annealing shows the microstructure of the cold-work crystal at the physical stage. At this stage the metal is in considerable mechanical stress, resulting from elastic strain internally balanced, this elastic strain added to the jamming of the dislocation which occurred during cold information.

At the stress-relief stage, there is visible alternation in the distorted shape of the cold-work crystal. Stage B shows an observable alteration, new crystal begin to grow from nuclei produced in the deformed crystal.

Stage C show the small crystals so formed at stage B has gradually grown to bigger crystal by absorbing each other in a cannibal-fashion, thus the structure is relatively coarse grained.

In order words:

a. Between 0ºC - 650ºC there is a great transformation as the structure or micrograph revealed different picture. Again there is increase in grain size, the normal has fine grain size but at 650ºC the grain is coarse (compare control and 650ºC).

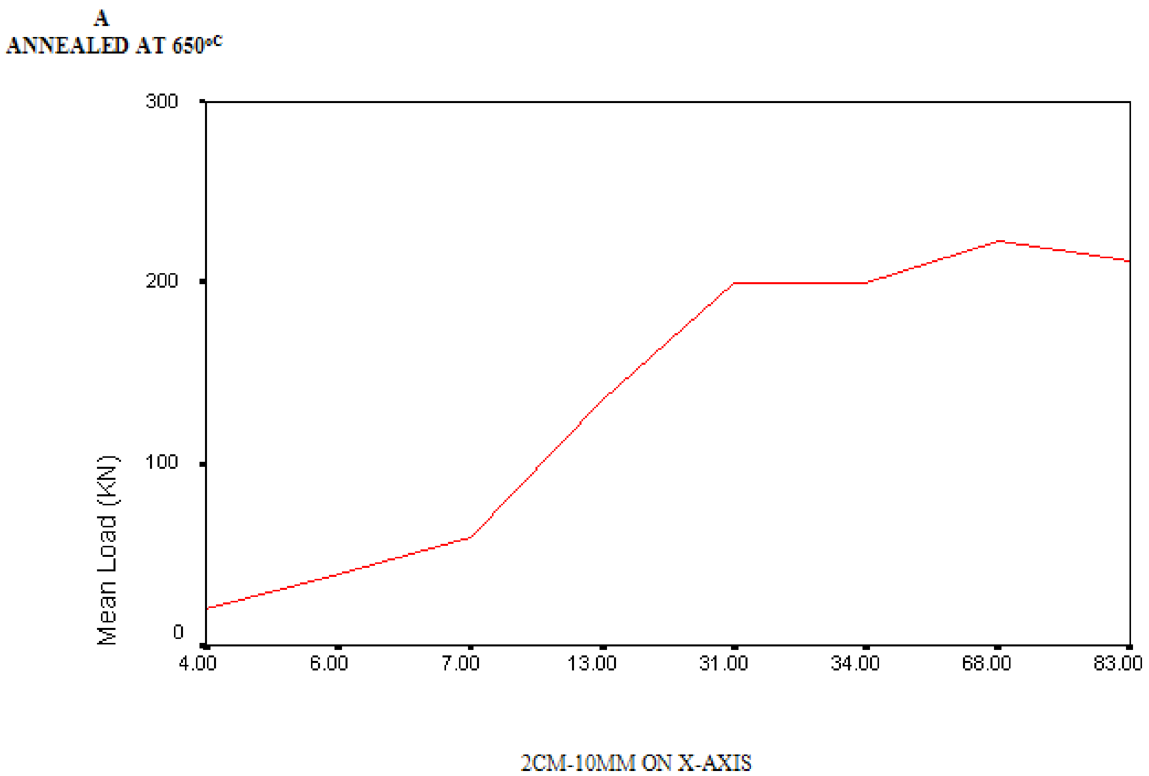

Figure 1 A: Load vs. Extension Graph for Sample A.

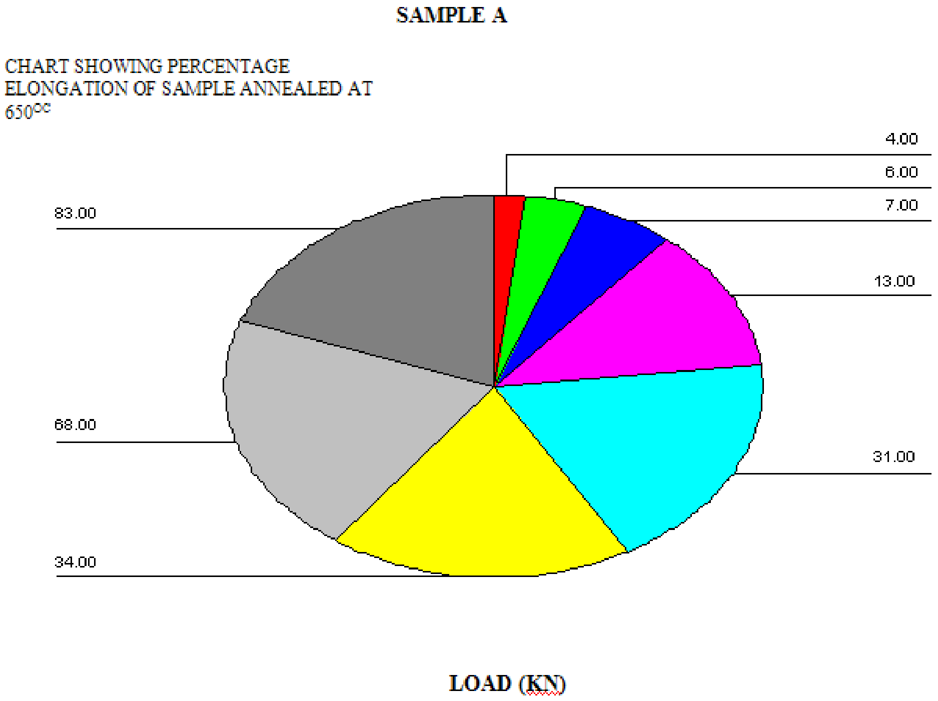

Figure 1 B: Percentage Elongation of Sample A Annealed at 650°C.

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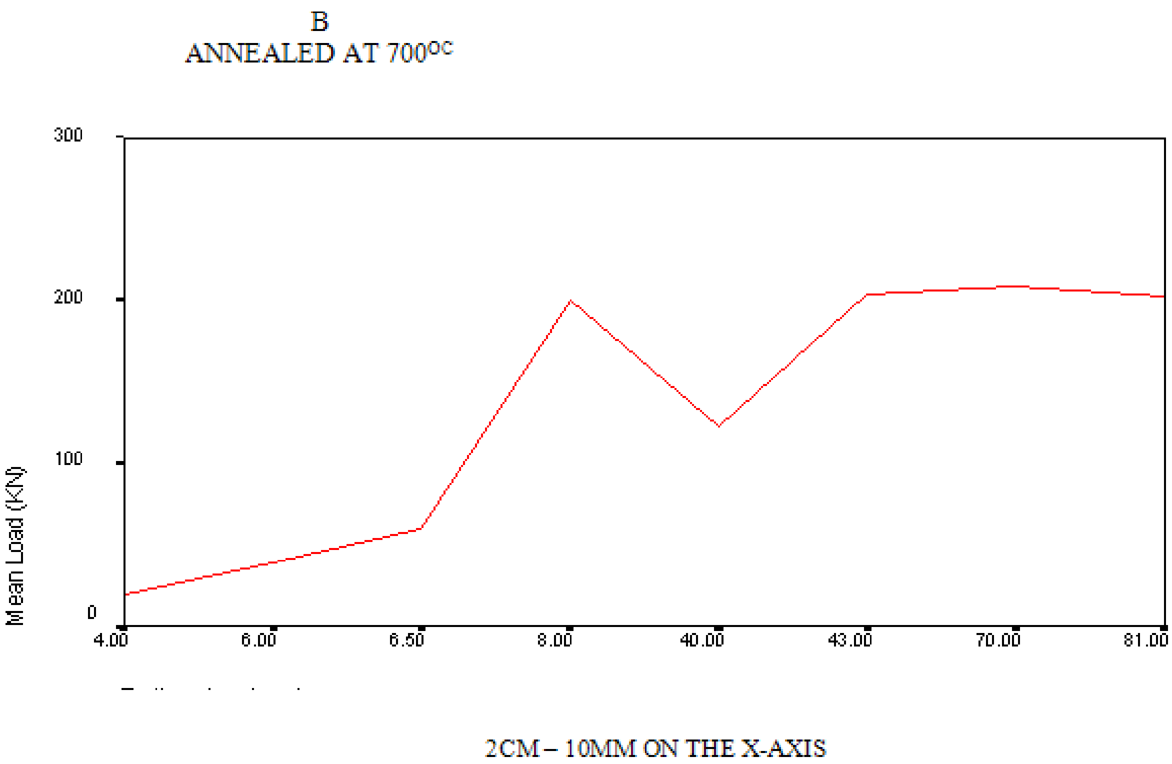

Figure 2 A: Load vs. Extension Graph for Sample B.

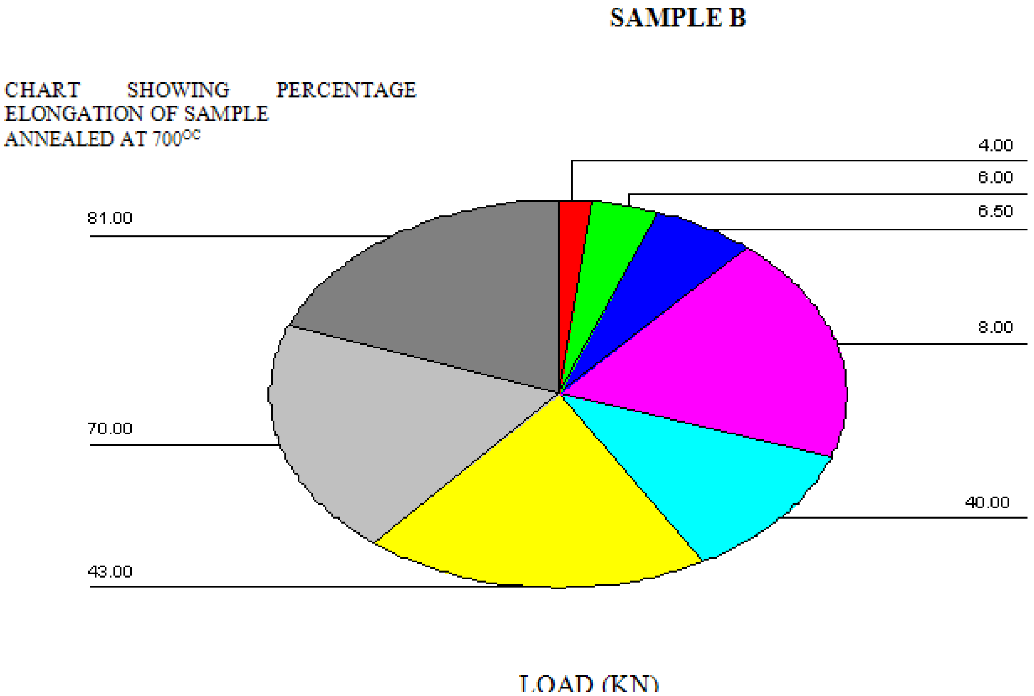

Figure 2 B: Percentage Elongation of Sample B Annealed at 650°C.

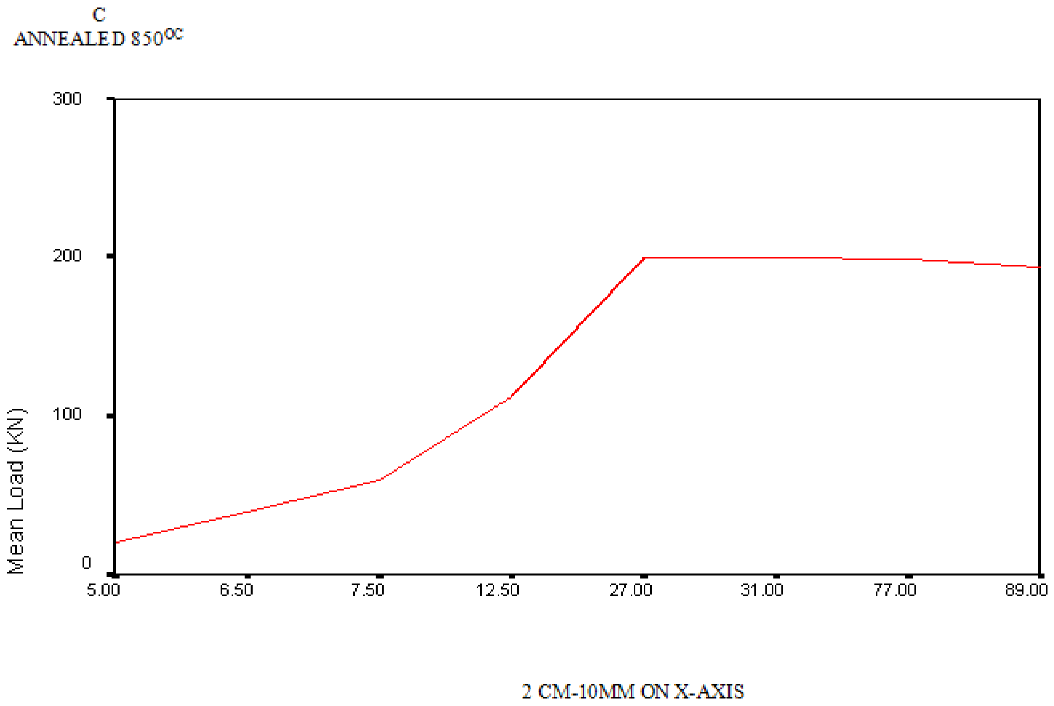

Figure 3 A: Load vs. Extension Graph for Sample C.

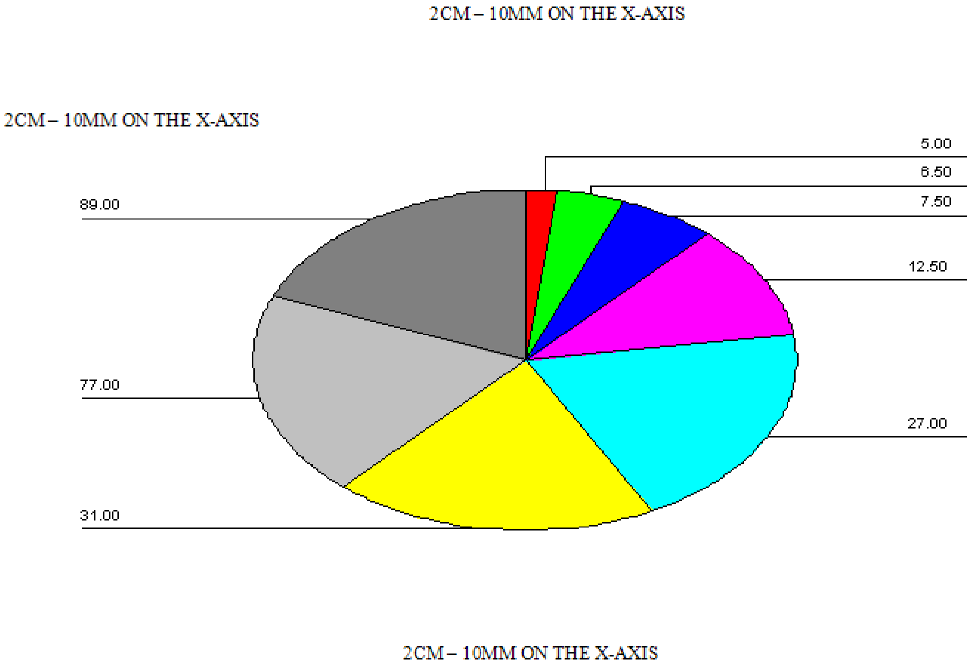

Figure 3 B: Percentage Elongation of Sample C Annealed at 650°C.

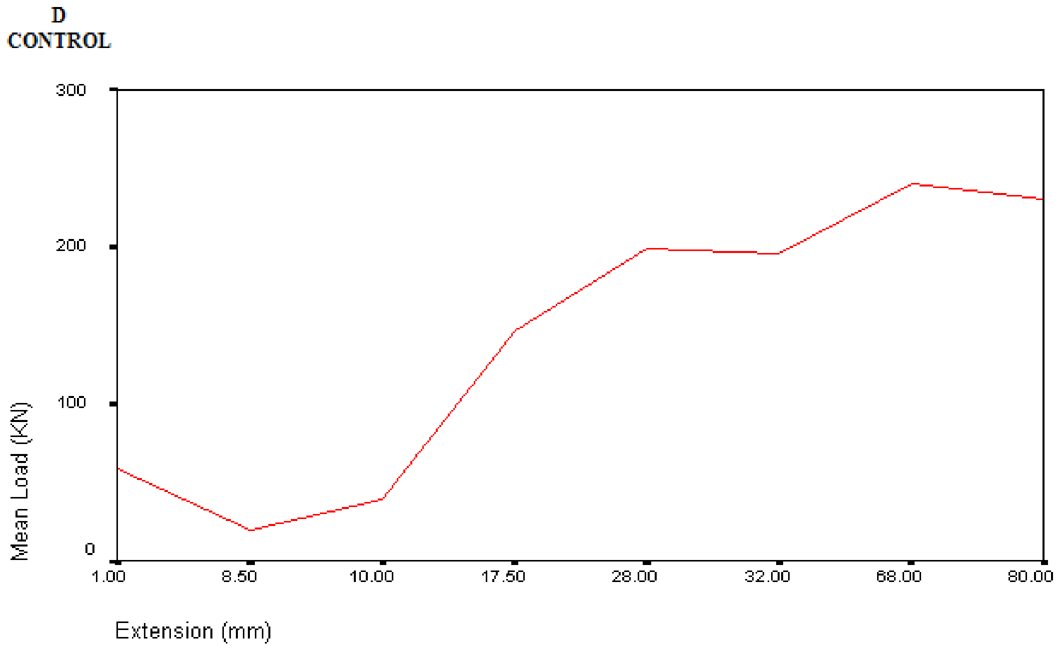

Figure 4 A: Load vs. Extension Graph for Control D.

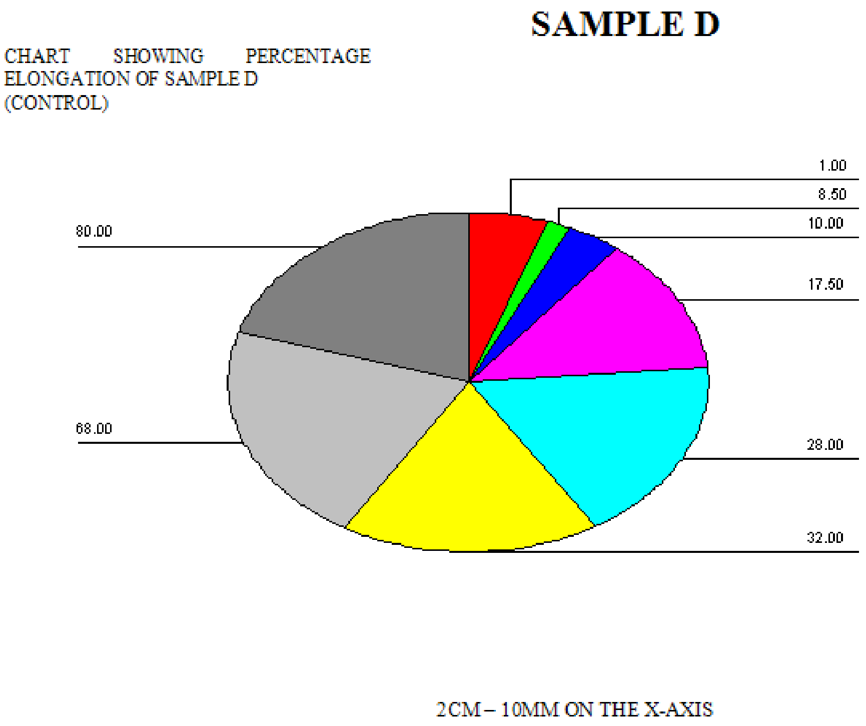

Figure 4 B: Percentage Elongation of Sample D (Control).

b. Between 650ºC - 700ºC there was no serious transformation although the carbon has started precipitating as seen in fig 700ºC (the dark part) (“patches”). But the structure is still revealing ferrite and pearlite. The dark part is the pearlite containing mounting carbon while the white part is ferrite containing mainly ferrous part. The grain size is relatively the same between 650ºC - 700ºC

c. Between 700ºC - 850ºC there is a serious transformation. There the grain boundaries could no longer be seen vividly, the ferrite has precipitated with the pearlite as well forming grey color instead of clear white and black. The grain size is the largest. The implication is that the longer or coarse the grain size, the softer the material.

The grain essence of this metallographic is to make us gain access to the microstructure of the material and understand bow they behave to heat treatment at various temperature range.

A spot of the sample was magnified hundred times (100 x) Etchants are chemical used in attacking polished surface to reveal its microstructure.

<u>Discussion of Tensile Test Results</u>: From the tensile test results, it is observed that the samples A and D get to their fracture point much faster than sample B and C is more compared to samples A and D. This goes to show that there is decrease in ductility in samples A and D as expected. This further shows that A and D has more strength than examples B and C as expected. Both yield and tensile stresses for samples A and D should be higher than their corresponding values for samples B and C.

<u>Hardness Test Result</u>: From the hardness test result, it was observed that sample A has 2.5 as the indent diameter, then B has 2.7 indent diameters, sample C has 2.85 while the control, sample D has 2.4 indent diameters. This shows that as the annealed temperature increases, the material gets softer and softer.

The control which is 2.4 diameter, with the Brinel hardness test result 219 HB means that the control which is D is harder than the annealed samples which are with hardness test result 200.38HB, 173.08HB and 155.2HB, respectively.

Table 5: Load Extension Readings for Graphs.

Sample	Load (KN)	Extension (mm)
A 650°C	20 40 60 135 Yield pt. 200 200 223 Max pt. 212 Fracture pt.	4 6 7 13 31 34 68 83
B 700°C	20 40 60 122 Yield pt. 200 204 209 Max pt 203 Fracture pt.	4 6 6.5 8 40 43 70 81
C 850°C	20 40 60 112 Yield pt. 200 200 199 Max pt 194 Fracture pt.	5 6.5 7.5 12.5 27 31 77 89
D Control	20 40 60 147 Yield pt. 200 196 240 Max pt. 230 Fracture pt.	8.5 10 11 17.5 28 32 68 80

CONCLUSION

From the analysis of the experimental result, it can be seen that, the various alloying elements of steel have different effects on mechanical properties on metal. The various properties installed by the alloying elements determine to a great extent their application. Treatment to which the metal was subjected affect the properties and hence application. Thus required application determines treatment carried out on the metal. Also steel alloys generally have higher strength than the pure metal in the same condition and relatively inexpensive alloy when compare with non-ferrous alloys generally, hence steel is by far the most important engineering alloy.

Annealing has a considerable influence on the stress-strain relationship and properties of practically every engineering material. It even affects it compression strength in the case of an engineering metal the ultimate strength, yield strength and stiffness decreases appreciably with increasing temperature, while percentage elongation (ductility) and malleability as the temperature rises. The reverse is generally true as the temperature is lowered.

APPENDIX A

TENSILE TEST CALCULATIONS

SAMPLE 650 A steel bar (123744) of compositions C 41. Sio 22, Co.04 Mn 1.09. P 0.048S 0.008, Cu 0.02, Ni
Length of sample = 524mm
Gauge length = 120mm
Weigh of sample = 1350g

$$\text{Cross Sectional Area} = \frac{\text{(Weigh (g) x 0.1275)}}{\text{Length}} \times 1000 = 328.48$$

$$\text{Cross Sectional Area} = 328.48$$

650 sample calculation
Gauge length (Li) = 200mm
Yield load = 78KN
Initial Area = (Ao) = 328.5
Maximum Load = 223KN
Fracture Load = 212KN
Initial gauge length = 200mm
Increase gauge length = 26.1mm

$$\text{Yield Stress} = \frac{\text{Yield load}}{\text{Initial Sectional Area}} = \frac{78 \times 1000}{328.2} = 411.33\text{N/m}$$

$$\text{Tensile Stress} = \frac{\text{Maximum load}}{\text{Initial Area}} = \frac{223 \times 1000}{328.2} = 679.46$$

$$\text{Fracture Stress} = \frac{\text{Fracture load}}{\text{Initial Area}} = \frac{212 \times 1000}{328.2} = 645.95$$

$$\%\ \text{Elongation} = \frac{\text{Maximum gauge length}}{\text{Initial gauge length}} \times 100 = 13.05\%$$

APPENDIX B

SAMPLE ANNEALED AT 700°C
The sample composition 0.41c, 0.22Si, 1.09mm P 0.48 – C) 0.04 Cu 0.02 Si 0.22 – Mn 1.09 P 0.048 S 0.008, Cu 0.02

Length of Sample = 520mm
Gauge length = 200mm
Weight of sample = 1320(g)
Area = 323.4mm²
Yield load = 122KN
Maximum Load = 209KN
Fracture Load = 203KN
Initial Gauge Length = 200mm
Increase in length = 31.6mm

$$\text{Yield Stress} = \frac{\text{Yield load}}{\text{Initial Sectional Area}} = \frac{122\text{KN}}{328.2} = 371.72\text{N/mm}$$

$$\text{Tensile Stress} = \frac{\text{Maximum load}}{\text{Initial cross sectional Area}} = \frac{209 \times 1000}{323.4} = 646.26\text{N/mm}$$

$$\text{Fracture Stress} = \frac{\text{Fracture load}}{\text{Initial cross sectional area}} = \frac{212 \times 1000}{328.5} = 645..35$$

$$\%\ \text{Elongation} = \frac{\text{Maximum gauge length}}{\text{Initial gauge length}} = \frac{31.6 \times 100}{200} = 15.8\%$$

APPENDIX C

Sample Annealed at 850°C
A steel bar (123774) of composition 0.41 C, 0.22 Si, 1.09Mn, P 0.048 0.04Cr 0.02Cu Si 0.08

Length of Sample = 520mm
Gauge length = 200mm
Weight of sample = 1320(g)
Area = 323.4mm²
Yield Load = 112KN
Maximum Load = 199KN
Fracture Load = 194KN
Initial Gauge length = 200mm
Increase in length = 36.4mm

$$\text{Yield Stress} = \frac{\text{Yield load}}{\text{Initial Area}} = \frac{112 \times 1000}{323.4} = 364.32\text{N/mm}$$

$$\text{Tensile Stress} = \frac{\text{Maximum load}}{\text{Initial Area}} = \frac{199 \times 1000}{323.4} = 615.34\text{N/mm}$$

$$\text{Fracture Stress} = \frac{\text{Fracture load}}{\text{Initial Area}} = \frac{194 \times 1000}{323.4} = 599.88$$

$$\% \text{ Elongation} = \frac{L2 - L1}{L1} \times 100 = \frac{36.4 \times 100}{200} = 18.2\%$$

APPENDIX D

AS RECEIVED SAMPLE:
A Steel bar (123774) of composition 0.41 C, 0.22 Si, 1.09Mn, P 0.048 0.04Cr 0.02Cu Ni T

Length of Sample = 520mm
Gauge length = 200mm
Weight of Sample = 1320(g)
Cross Sectional Area = 323.4mm^2
Yield Load = 147KN
Maximum Load = 240KN
Fracture Load = 230KN
Initial Gauge length = 200m
Increase Gauge length = 25.6mm

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ABOUT THE AUTHORS

Patrick Adebisi Olusegun Adegbuyi, is a Nigerian who undertook his university education in Romania between 1979 and 1987 where he obtained his B.Sc. and M.Eng. in Mechanical Engineering. He has served as a Senior Lecturer in the Department of Mechanical Engineering, Lagos State University, Ojo, Lagos, Nigeria since 1995 and has been the Head of Department many times. He was also the Acting Dean of the Faculty between 2002 and 2004. His area of research interest is in Mechanical Metallurgy.

Andrew Atiri is a Nigerian who attended the Lagos State University where he obtained a B.Sc. in mechanical engineering. He is currently an engineering assistant at the Delts Steel rolling mills, Aladja-Delta State, Nigeria His area of research interest is in Mechanical Metallurgy.

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