Determining the Effect of Carburizing on the Strain Hardening Behaviour of Low Carbon Steel

H. C., Olisakwe[1], I. E. Ekengwu[2], V. I. Ehirim[3]

[1,2]*Department of Mechanical Engineering, Nnamdi Azikiwe University, Awka, Nigeria*

[3]*Department of Mechanical Engineering, Imo State Polytechnic, Umuagwo, Nigeria*

***Abstract*— Fabrication of steel structures such as car bodies, shafts and pressure vessels always involves shaping and surface strengthening (case hardening of the metal). Shaping operations such as bending, drawing and twisting strain hardens the metal as well as the carburizing process. Therefore the strength of the metal required at different stages of metal forming process depends on the operations needed at each stage. Thus, this paper is a presentation of effort made to determine the combined effect of strain hardening and carburizing on the some mechanical properties of plain carbon steel. In this study, seven pieces of tensile test specimens were produced from 0.21 weight percent carbon steel. The gauge length of the specimens was 50mm while the cross-sectional diameter was 10mm, which is in accordance to British Standard Specification. Six pieces of the specimens were carburized using a homogeneous mixture of pulverized charcoal, calcium carbonate and barium carbonate in 70 %(10.5kg), 20 %(3kg) and 10 %(1.5kg) proportions respectively as source of carbon and XKL15 laboratory furnace for heat treatment. The mixture (carbon source) was put into a 12litres steel box and six specimens were buried in the carbon base medium, maintaining uniform spacing of 5cm and was well compacted. Together with its content, the steel box was then put in the furnace and the furnace was then powered and regulated to 950^{o}C. All through the heat treatment time, the furnace was maintained at constant temperature of 950^{o}C (Holding Temperature). One specimen was withdrawn from the furnace at 4 hours intervals; thus, the specimens were carburized 4, 8.12,16,20 and 24 hours soaking times and cooled naturally under atmospheric pressure. They were cleaned and tested together with the non- heat treated specimen using Admet Tensile Test Machine. From the stress-strain curve obtained in each case, stress values at 0.02 strain intervals were deduced. The ultimate tensile stress of each specimen was also determined and recorded. The values obtained were represented graphically and also used to determine the strain hardening coefficient of each specimen, using Least Square Method. The length of each specimen at fracture was also measured using Mitutoyo 500-196-30 digital caliper and the values obtained were used to calculate the percentage elongation. From the results obtained, the strain hardening coefficients are 0.2656, 0.3003, 0.3436, 0.3668, 0.3814, 0.3988 and 0.4141 for the untreated specimen, 4, 8.12,16,20 and 24 hours heat treated specimens respectively. Also, the percentage elongation are 22.00, 18.00, 16.00, 14.10, 13.89, 12.00 and 10.00 for the untreated specimen, 4, 8.12,16,20 and 24 hours heat treated specimens respectively. The ultimate tensile stress are 296.99, 348.07, 370.43, 385.42, 409, 415.48 and 420.82MPa for the untreated specimen, 4, 8.12,16,20 and 24 hours carburized specimens respectively. The results obtained show that strain hardening coefficient and tensile strength of the steel increase with increase in soaking time so also the tensile strength of the steel. On the other hand , the ductility(percentage elongation) decreases with increase in soaking time until it drops to its least and constant value .The results of this study may serve as a guide in controlling of the strain hardening of plain carbon steel in advanced metal processing which is applicable in general metal fabrication. A further study is recommended in which the carburized case depth for each soaking time is determined. It will also be of interest to determine variation of the mechanical properties of the steel with the carburized case depths. The results of this study would be instrumental in predicting the overall quality a finished product in metal forming process.**

Keywords: **Strain Hardening, Low Carbon Steel and Carburizing.**

I. INTRODUCTION

Steel is an alloy of iron and carbon, with some other elements in minute proportions. Carbon composition in steel is in the range (0.008wt.%C - 2.0wt.%C),as shown in iron carbon equilibrium phase diagram[1]. Within this range of composition, steel is classified as hypo eutectoid (0.008wt.%C - 0.83 wt.%C) and hyper eutectoid steel(0.83wt.%C - 2.0 wt.%C). It has Body Centred Cubic (BCC) structure at room temperature, Face Centred Cubic Structure (FCC) at austenite phase and BCC structure at elevated temperature (above the austenite phase). It has good density (about 7860kgm^{-3}), good strength, good thermal properties with solidus temperature of about 1400^{o}C.However, it corrodes in aggressive environment.

Due to its' improved mechanical properties, it has application in virtually all aspect of engineering. It is used in concrete reinforcement, automotives, aircrafts, pipelines, ships, hospital equipment and others. However, its' performance in service depends on chemical composition and processing. On this note, it is classified under certain headings which include: Plain Carbon Steel [2], Alloy Steel, Austenitic Steel, Killed Steel, Martensitic Steel, Pearlitic Steel and others. Generally, the strength of Plain Carbon Steel Majorly depends of the carbon composition of the steel. Based on carbon composition, Plain Carbon Steel is further classified as Low Carbon Steel, Medium Carbon Steel and High Carbon Steel [3]. They have good ductility but weak strength. They are usually employed in metal forming due to

their weak strength and good ductility. In other words, they are shaped, bent, rolled or twisted with relative ease.

However, there may be need to vary the strength of the steel at different stages in metal forming process for adequate performance and desired properties for the finished product. In most cases, the properties of interest are tensile strength, ductility, hardness, corrosion resistance, thermal and electrical properties to mention but a few. Of all the properties mentioned, tensile strength mostly determines the ease for working of steel. Since the strength of Plain Carbon Steel mostly depends on the carbon composition, there is need to investigate the effect of strengthening on the strain hardening behaviour of low carbon steel. One effective and relatively cheap method of strengthening low carbon steel is Pack Carburizing. In this method, carbon atoms from the carburizing medium diffuse into the steel at elevated temperature of 850 to 950^{o}C [4] and occupy the voids and interstitial sites within the matrix and the grain boundaries; thus, increase impediments to dislocation movement. Other methods include Gas Carburizing, Vacuum Carburizing, Liquid Carburizing and Plasma Carburizing. All these methods have similar effect on the steel as Pack Carburizing. However, there are other methods of improving the strength of steel and a method is recommended based on the type of steel and desired properties of the finished product. Water quenching is usually employed for strengthening alloy steel in which austenite - martensite transformation is influenced by the cooling rate of the preheated steel. Based on these considerations, this study is aimed at determining the effect of Pack Carburizing on strain hardening behavior of low carbon steel, using a mixture of pulverized charcoal, calcium carbonate and barium carbonate as the source of carbon and XKL15 laboratory furnace.

II. CARBURIZING

Carburizing is a heat treatment process in which steel absorbs carbon from its surroundings when heated between 850^{o}C to 950^{o}C[5] in an atmosphere of carbon bearing substances, such as charcoal or carbon monoxide with the purpose of increasing the hardness of the steel [4.]. Steel at temperature between 850^{o}C and 950^{o}C is in the austenite phase (γ-phase), has FCC structure, high packing factor and high solubility for carbon. In this process, the strength and hardness of the steel increases as it absorbs more carbon. Carbon content at any depth into the steel is controlled by the carburizing time and temperature. The case depth of the carburized steel is function of carburizing time and the available carbon potential at the surface of the steel in the carburizing atmosphere .When carburizing time is prolonged for deep case depth, a high carbon potential produce a high surface-carbon content, which may thus result in excessive retained austenite or free carbides[4]. Both of these two micro structural elements have adverse effect on the distribution of residual stress in the carburized member. However, a high carbon potential may be recommended for short time carburizing [4.].It is stated in an article [4], the carbon concentration can be controlled by the ratio (vol.%CO)/(vol.%CO_2) in the furnace atmosphere[4]. The basic reactions in carburizing process as stated in a previous work [5] are:

$$2C + O_2 = 2CO \quad (1)$$

$$2C + C = 2C_{active} + CO_2 \quad (2)$$

$$CO_2 + C = 2C \quad (3)$$

In carburizing, the furnace temperature is held at about 900^{o}C, thus, holding the steel in austenite phase for are reasonable soaking time for desired amount of carbon to diffuse from the carburizing medium to the steel. One of the furnaces suitable for this type of heat treatment is XKL15 laboratory furnace, which operates at maximum temperature of 1200^{o}C.Austenite phase in typical part presentation of iron-carbon equilibrium phase diagram, is shown as Figure 1 while a picture of XKL15 furnace is shown as Fig. 2.

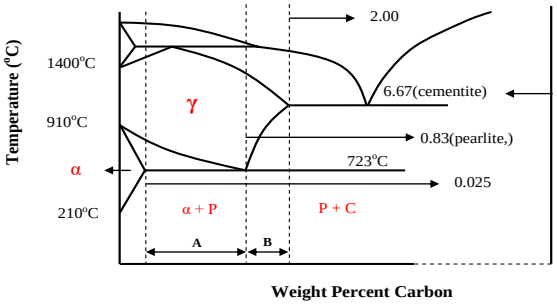

Fig. 1. γ - phase in Part presentation of Iron-Carbon equilibrium phase diagram

In Fig. 1, A is hypo-eutectoid steel and B is hyper-eutectoid steel while α, P, C and γ represent ferrite, pearlite, cementite and austenite phases respectively.

Fig. 2.Picture of XKL15 Laboratory Furnace [6]

The steel strengthening in Pack Carburizing otherwise called Case Hardening is achieved by exposing the steel to a reasonable soaking time, in a carbon enriched medium at elevated temperature of about 900^{o}C [4], but lower than the liquidus. In this environment, the carbon atoms in the medium are energized and diffuse into steel and occupy the vacancies, voids, interstitial sites, thus increase

the level of impediments to dislocation movement within the matrix and grain boundaries of the steel at micro scale. The rate at which the carbon atoms diffuse into the steel varies as they continue to meet obstacles. Thus, this is a non steady state process .As a result of this, there is variation in carbon concentration with depth into the metal. Consequently, the interior of a carburized piece may be soft and ductile while the exterior is hard and brittle. However, this phenomenon may be of engineering importance especially in production of mechanical shafts but makes the product some worth anisotropic especially when the carburized member is massive.

The carbon concentration at any depth , x, into the metal may expressed as Eq. (4).When boundary conditions are specified and surface carbon concentration is known, concentration at any depth , x, may be calculated using Eq. (5) [7].

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial C^2} \tag{4}$$

$$\frac{C - C_0}{C_s - C_0} = 1 - erf\left(\frac{x}{2\sqrt{Dt}}\right) \tag{5}$$

where C is carbon concentration at depth x into the metal, Cs is carbon concentration at depth x into the metal, x is carburized case depth ,D is diffusion coefficient, t is heat treatment time, C_0 is carbon concentration at depth x into the metal and erf denotes error function. Diffusion theory indicates that the diffusion coefficient is determined by activation energy for diffusion and temperature as stated in Eq. (6).

$$D = D_0 \exp\left(\frac{-Q}{RT}\right) \tag{6}$$

where D is diffusion coefficient, D_0 is temperature-independent pre-exponential(m/s^2),Q is activation energy for diffusion(J/mol),R is the gas constant,8.314Jmol.k, T is absolute temperature [7]. The diffusion coefficient of carbon versus temperature is given as Figure 3 whereas the microstructure of carburized AISI 5117 steel is shown as Fig. 4. Looking at Fig. 4, it is observed that carburized layer has a finer structure whereas the inner layer has coarse structure. The finer structure of the carburized layer indicates that the strength and hardness of such zone will be relatively high.

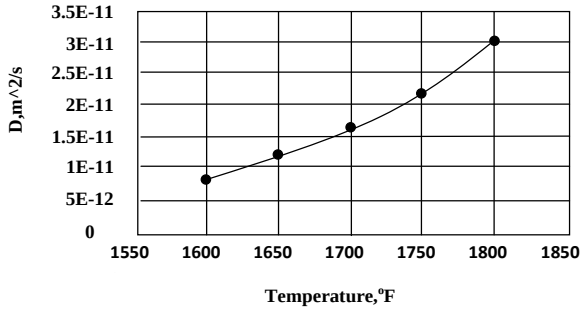

Fig. 3. Diffusion coefficient of carbon versus temperature [7]

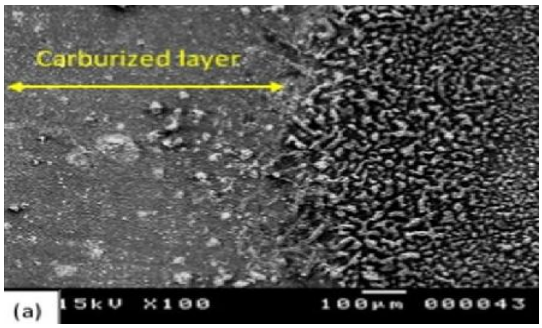

Fig. 4: Microstructure of carburized AISI 5117 steel [8]

Other than carburizing, Strain hardening is another method of increasing the strength of metals. It is achieved by subjecting a metal to tensile or compressive stress below the re-crystallization temperature (cold working). Due to the applied stress in, internal stresses are developed in the metal at microscopic level, resulting to increase in strength and hardness of the metal. Strain hardening may occur in rolling, wire drawing, hammering, bending and other related operations. The response of a material to strain hardening is given as *Strain Hardening Coefficient*. It is usually obtained from stress-strain relationships such as Hollomon's equation and logarithmic stress-strain graph of a material loaded beyond elastic limit. Hollomon's equation is stated as Eq. (7). The failure mechanism of plain carbon steel under tensile or compressive loading depends on the strength and hardness of the steel, which may be related its carbon composition. Brittle failure occurs with high carbon steel while ductile failure occurs with medium and low carbon steel. The investigation of combined influence of carburizing and strain hardening on the workability of low carbon steel is deemed to be of interest in *advanced metal forming* because it will help in selecting suitable processing and predicting the mechanical properties of the finished product.

The deformation of steel within the elastic region may be analyzed using Hooke's Law, whereas the deformation of all metals both in elastic and plastic regions may be analyzed using Eq. (7)[9][10][11].

$$\sigma_t = k\varepsilon_t^n \tag{7}$$

where σt = true stress, K = constant ,ε_t = true strain and n = strain hardening coefficient.

The logarithmic form of equation 7 is given by Eq. (8).

$$In\sigma_t = InK + nIn\varepsilon_t \quad (8)$$

Thus, the slope of the graph of Ino$_t$ against $In\varepsilon_t$ is the work hardening coefficient, n.

III. METHODOLOGY

a) Materials

The materials used in this study are:

i. 19mm diameter rod (without ribs) purchased from Ariaria Scrap Market Aba, Abia State in Nigeria. The full length of the rod was 1500mm
ii. Carbon base medium (homogeneous mixture of pulverized charcoal, calcium carbonate and barium carbonate in the proportions 70%, 20% and 10% respectively).

The equipment used are:

i. Laboratory furnace (XKL15), which has a capacity of 15litres and operates at maximum temperature of 1200^{o}C. The furnace is electrically powered.
ii. pSectrometer (Spectromax).
iii. AAdmet Tensile test machine.

b) Method

Three samples, each of 40mm length were cut from the rod and analyzed in laboratory for chemical composition, using spectrometer (Spectromax). The percentage of each element (average) in the steel is shown in Table 1.

Table 1.Chemical composition of the steel used

Element	C	Si	Mn	Mo	Cr	Ni	p	S	Fe
Wt.%	0.21	0.17	0.36	0.03	0.13	0.11	0.04	0.04	98.91

Seven pieces of bars, each of about 150mm length were cut from the left over rod and were machined in Johnson Express Mile 3 Diodu Port Harcourt, Rivers State Nigeria to produce tensile test specimens. The each specimen has a gauge length of 50mm and cross-sectional diameter of 10mm which is in accordance to British Standard Specification. Schematic diagram of the test piece is shown as shown in Fig. 5.

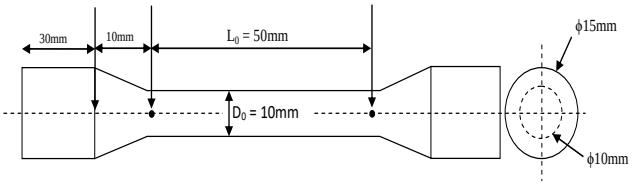

Fig. 5. Schematic representation of the tensile test specimen

Specimen Tagging: For easy identification, each of the specimens was tagged S_i such that S stands for specimen and the subscript i stand for duration of heat treatment otherwise called soaking time[12]. In this study, i = 0, 4, 8, 12, 16, 20 and 24 hours. S_0 stands for non-carburized specimen and S_4 stands for the specimen carburized for 4 hours soaking time.

The carbon base medium was put into a rectangular base steel box of dimensions 40cm×20cm×10cm, to about half the depth and was properly leveled and compacted. Six of the specimens were properly placed on the surface of the compacted material, maintaining uniform spacing of about 5cm. The box, together with its content was then filled to the brim with the carbon base material, properly leveled and compacted. Together with its content, it was then put into the furnace and the furnace was then powered and regulated to constant temperature of 950^{o}C. One specimen was withdrawn from the furnace at 4 hour intervals. Thus, the last withdrawal was after 24hours of furnace the operation. The heat treated specimens were allowed to cool naturally under atmospheric condition and then cleaned. Both the carburized specimens and the non-treated were tested using Admet tensile test machine. From the stress-strain curve obtained in each case, stress values were deduced at 0.02 strain intervals. From each curve also, the ultimate tensile stress and the corresponding strain values were read and recorded. The length of each specimen at fracture was determined by mare joining the two components obtained at fracture and measuring the resulting length using Mitutoyo Caliper. The stress-strain values obtained via the deduction were represented graphically as shown in Figures 6 and 7. The combined results are presented as Figure 8.The stress/strain values were also used to estimate the work hardening coefficients of the tested specimens as shown in Table 4 and Figure 9. The length of the specimens at fracture were used to calculate the percentage elongation as show in Table 4 and presented in Figure 9. The percentage elongation was calculated using equation 10 and the values obtained were compared with the maximum strain for each specimen as shown in Figure 8.

The stress-strain curve of each tested piece was automatically plotted and displayed on the screen of the computer incorporated to the machine. From

c) Characterization

Following the British Standard Specification for Tensile Test Specimen as stated in [13], the gauge length and the cross-sectional area of the specimen used in this study are related as shown in Eq. (9).Using equation the stated equation, a cross-sectional diameter of approximately10mm was obtained for 50mm gauge length.

Gauge Length:

$$L_0 = 5.65\sqrt{A_0} \quad (9)$$

where L_0 = gauge length (mm) and A_0 = cross-sectional area of specimen (mm^2) and L is the length of the specimen at fracture.

i. Percentage Elongation

In Anyanwu [14], percentage elongation was calculated using Eq. (10):

$$\%E = 100In\left(\frac{L}{L_0}\right) \quad (10)$$

ii. Strain Hardening Coefficient

The strain hardening coefficient is calculated using equation 11, as stated in [9].

$$\sigma_t = K\varepsilon_t^n \quad (11)$$

where σ_t = true stress, K = constant ,ε_t = true strain and n = strain hardening coefficient.

From equation 11, strain hardening coefficient was calculated as follows:

$$In\sigma_t = InK + nIn\varepsilon_t \quad (12)$$

The plot of $In\sigma_t$ against $In\varepsilon_t$ is deemed to be straight line whose slope is n and has intercept InK of the $In\sigma_t$ axis. Using Least Square Method, equations 13 and 14 were obtained.

$$n = \frac{N\sum In\sigma_t \times In\varepsilon_t - \sum In\sigma_t \sum In\varepsilon_t}{N\sum In\varepsilon_t^2 - (\sum In\varepsilon_t)^2} \quad (13)$$

$$K = \exp\left(\frac{\sum In\sigma_t - n\sum In\varepsilon_t}{N}\right) \quad (14)$$

where σ_t is True stress, ε_t is True strain, K is constant, n is Strain Hardening Coefficient, N number of sample points, exp denotes exponential and ∑ denotes summation.

IV. RESULTS AND DISCUSSION

The parameters presented in experimental results includes true stress, true strain, ultimate tensile stress, ductility and the work hardening coefficients of the various tested samples. The results were presented in tabular and graphical forms as shown in Tables 2, 3 and 4 and Fig. 6, 7, 8 and 9.

Table 2 Strain Hardening Coefficient of Untreated specimen

σ(Mpa)	ε	$Y=In\sigma_t$	$X = In\varepsilon_t$	X^2	XY
165.6922	0.0200	5.1101	-3.9120	15.3039	-19.9910
197.0423	0.0400	5.2834	-3.2189	10.3612	-17.0067
218.0632	0.0600	5.3848	-2.8134	7.9153	-15.1496
218.0632	0.0800	5.3848	-2.5257	6.3793	-13.6005
247.7676	0.1000	5.5125	-2.3026	5.3019	-12.6930
265.3223	0.1200	5.5809	-2.1203	4.4955	-11.8331
280.5110	0.1400	5.6366	-1.9661	3.8656	-11.0822
292.6599	0.1600	5.6790	-1.8326	3.3584	-10.4073
296.9873	0.1800	5.6937	-1.7148	2.9405	-9.7635
294.6470	0.2200	5.6858	-1.5141	2.2926	-8.6090
sum		**54.9516**	**-23.9205**	**62.2142**	**-130.1358**

Table 3 Strain Hardening Coefficient of 4 Hours carburized specimen

σ(Mpa)	ε	$Y=In\sigma_t$	$X = In\varepsilon_t$	X^2	XY
184.1890	0.0200	5.2160	-3.9120	15.3039	-20.4050
226.7633	0.0400	5.4239	-3.2189	10.3612	-17.4589
256.0944	0.0600	5.5455	-2.8134	7.9153	-15.6019
256.0944	0.0800	5.5455	-2.5257	6.3793	-14.0065
298.5071	0.1000	5.6988	-2.3026	5.3019	-13.1220
320.2892	0.1200	5.7692	-2.1203	4.4955	-12.2323
335.2122	0.1400	5.8148	-1.9661	3.8656	-11.4325
344.7088	0.1600	5.8427	-1.8326	3.3584	-10.7072
348.0709	0.1800	5.8524	-1.7148	2.9405	-10.0357
Sum		**50.7088**	**-22.4064**	**59.9216**	**-125.0019**

Table 4 Summarized Experimental Result

Specimen	t(hrs)	σ_{UTS} (MPa)	K(MPa)	n	L(mm)	Ductility(%E)
S0	0	296.99	456.00	0.2656	62.30	22.00
S4	4	348.07	590.63	0.3003	59.86	18.00
S8	8	370.43	695.70	0.3436	58.68	16.00
S12	12	385.42	789.68	0.3668	57.51	14.10
S16	16	409.00	872.81	0.3814	57.45	13.89
S20	20	415.48	946.94	0.3988	56.37	12.00
S24	24	420.82	1030.26.	0.4141	55.26	10.00

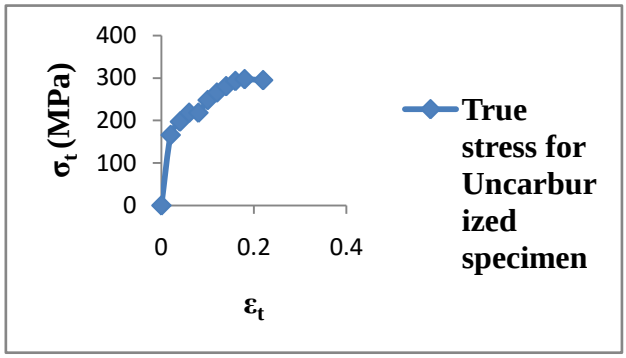

Fig. 6. Stress-Strain Curve for 4hours untreated specimen

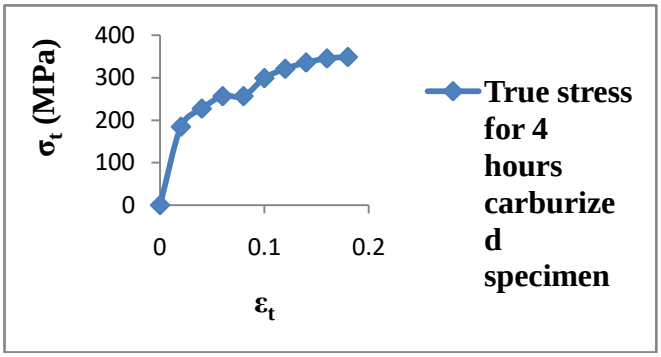

Fig. 7. Stress-Strain- Curve for 4hours carburization

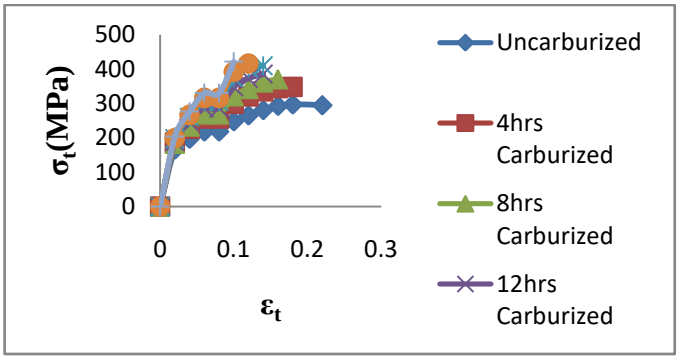

Fig. 8. Stress-Strain curves for all the specimens

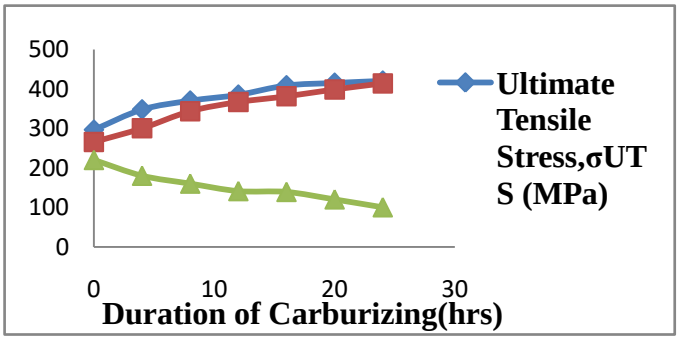

Fig. 9. Variation of mechanical with soaking time

Comparing Figures 6 and 7, it is seen that the 0.21% carbon used show a good ductile behavior before carburization but started losing its ductility through carburization .At the extremes, the untreated' specimen has very good ductility while on the other extremes, the '24hours carburized' specimen show high level of brittleness indicating that increase in carbon content of the steel with corresponding increase in strength. From Figure 9, it is seen that the rate at which strength of the steel increase during carburization decreases with time indicating decrease in carbon solubility as the carburization progresses. Through this phenomenon, it is envisaged that carbon absorption of the steel has a limit and the strength of the steel will not exceed such limit. Looking at the same Figure 9, it is seen on the other hand that the rate of decrease in ductility decreases with time indicating the minimum ductility which invariable should correspond to maximum strength at which the ductility. From Figure 8, it is seen that upper and lower yield occurred for all the specimens, which is peculiar to steel products; For that carburized specimens, this occurred between the stress of 200 to 350Mpa , corresponding to strain of 0.015 to 0.1. It is recommended that this experiment be conducted using carbon steel of different carbon compositions and longer soaking time. In metal forming process, the result of this study may be used as a guide in controlling the strengthening of the steel at different stages of operation. From Table 4, the percentage elongation obtained with equation 10 corresponds to the maximum strain values shown in Figure 8. That is 22% against 0.22 strain, 18% against 0.18 strain and 16% against 0.16 strains for 0, 4 and 8 hours soaking times.

V. CONCLUSION

From the experimental results obtained, it may conclude that carburization increases the strain hardening coefficient of plain carbon steel. From Figure 8, it may also be concluded that the strain hardening exponent increases with soaking time. Conclusion may be drawn that a mixture of pulverized charcoal, calcium carbonate and barium carbonate is a good material medium for pack carburization. Looking at Figure 9, it may be concluded that carburization increases the strength of steel but decreases its ductility. From Figure 8, it may be concluded that carburization turns the failure mode of steel from ductile to brittle; specifically, brittle fracture of carburized plain carbon steel start when the ultimate tensile strength of the steel increases to about 400Mpa.

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