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Microstructural Features and Mechanical Behaviour of Unalloyed Medium Carbon Steel (EN8 Steel) after Subsequent Heat Treatment

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Abstract—**This study reports the results of an experimental investigation of the effect of microstructural features on mechanical properties of unalloyed medium carbon (EN8) steel with emphasis on the effects of grain size within solid phase mixtures and the mechanical response of the material. Specimens with a range of microstructures (grain size and phase) were prepared by heat treatment. The microstructures were carefully characterized using both optical electronic microscope (OEM) and scanning electron microscope (SEM) and the mechanical properties were studied using tensile and hardness tests. The results indicated that tensile strength and hardness of unalloyed medium carbon (EN8) steel increases with decrease in grain size while elongation decreases.**

Keywords: grain sizes; microstructures; mechanical properties; medium carbon steel

I. INTRODUCTION

The prediction of mechanical properties of materials is more complicated because of different mechanisms that come in play such as chemical composition, the evolution of deformation microstructure, amount of deformation, heat treatment profile, and average grain size distribution. Many of the important mechanical properties of steel, including yield strength and hardness, the ductile-brittle transition temperature and susceptibility to environmental embrittlement can be improved considerably by refining the grain size [1]. [2, 3] . With the knowledge of dynamical interplay between deformation and grain microstructures size, it is possible to predict the behavior of steel when subjected to various working conditions [4, 5] . Numerous aspects of microstructures and their effects on mechanical behaviour of metals have been studied, including grain size [6, 1] , grain boundary [7, 8, 9] , crystal structure [10], crystal orientation [11].The production of different Materials with the controlled manipulation of their microstructure in order to improve properties is an active field of study in materials science. [1, 12, 13]. In general, as the average grain size decreases, the metal becomes more resistant to plastic flow (yield strength increase) and as the grain size increases, the opposite effect on strength occurs (yield strength decreases) [12, 1, 8, 13] .

EN8 steel is an unalloyed medium carbon steel with good tensile strength. This steel is suitable for the manufacture of parts such as general purpose axles and shafts, gears, bolts and studs. The materials is usually recommended by the suppliers to carried out heat treatment after initial stock removal to achieved better mechanical properties toward the core. The aim of this study is to investigate the microstructure of EN8 steel by the size and morphologies of constituent phases and or grains after subsequent heat treatment, also using a tensile and hardness tests to study the effects of heat treatment on the mechanical property of this material From this study, the influence of grain size on mechanical behaviour of steel based on heat treatment history can be understood

II. MATERIAL AND METHODS

The test specimen used in this investigation was unalloyed carbon steel designated as (EN8), the steel was received as rolling bar. The chemical composition was determined and is given in table 1. Tensile specimens were machined in standard dimensions and prepared using heat treatment experiments. They were divided into four sets for tensile tests. These sets were shown in Table 2. Scanning electron microscopy (SEM) and optical electronic microscope (OEM) were used for phase identification and microstructure characterization of these samples. The test specimen was examined for the following features: The size, shape and type of grain present. The aim of the heat treatment is to obtain a range of microstructures (grain size and phase). The mechanical properties were determined through tensile test and hardness test.

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Table I: Chemical composition of EN8

Elements	Compositions wt %
C	0.036
Si	0.02
P	0.025
Mn	0.54
S	0.05
Fe	Balance

Table II: Heat treatment regime used produces various microstructural features

Specimen	Heat Treatment
A	Austenised at 950^0C , held for 180 minutes and cooled in furnace.
B	Austenised at 914^0C, held for 10 minutes, cooled in furnace to 680^0C
C	Austenised at 914^0C, held for 10 minutes, cooled in furnace
D	Austenised at 914^0C held for 3 minutes cooled in furnace to 715^0C and quenched in oil

III. RESULTS AND DISCUSSION

A. Metallographic studies

Figures 1a show the SEM and figure 1b OEM image of as-received EN8 steel used for this experiment, while figures 2 show the SEM images of the specimens A, B, C and D prepared and figure 3 shows the OEM images of the specimens A, B, C and D prepared according the heat treatment regime described in table 2. It can be observed from these figures that the heat treatment regime employed produced five different microstructures. The images show both grains and phase present in the specimens. Another interesting feature that can be observed with SEM and OEM is the individual grain boundaries, which can be distinguished quite easily at higher magnifications (see figure 4).

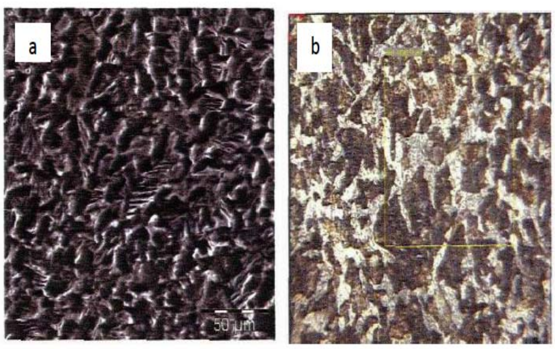

Figure 1: (a) SEM and (b) OEM images of the as received EN8 steel samples

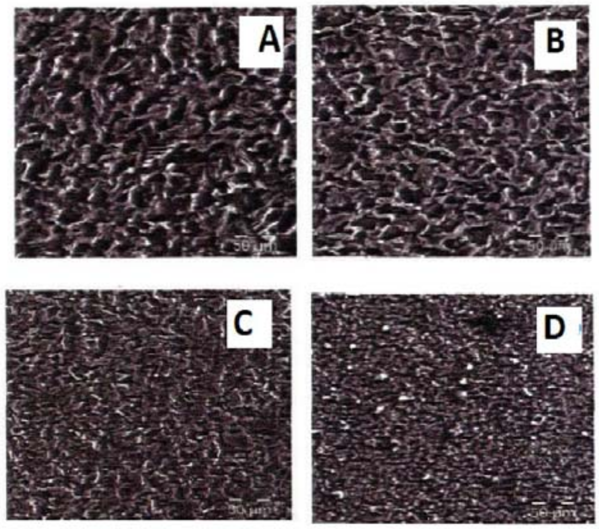

Figure 2: SEM images of samples prepared according the heat treatment regime described

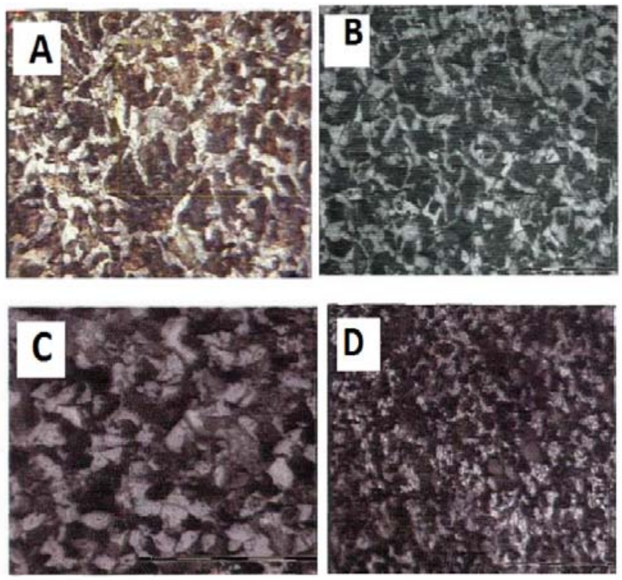

Figure 3: OEM images of samples prepared according the heat treatment regime described

It can be observed that the images shown in figures 2 and 3 are populated by different phases. The heat treatment processes employed produced multiphase microstructures with different morphologies. The microstructures of specimens A and B (figure 2a and figure 3a) are mainly composed of ferrite and pearlite. However, a slight change in morphology and marked coarsening of microstructure are observed in specimen B. Micrograph B, presented in figure 2c, has a similar microstructure to micrograph D, basically a ferritic matrix with second phase islands. However, the heat treatment temperature and soaking/holding time provided two interesting effects: heating steel at 914^0C and reducing holding time at this temperature resulted in formation of small grains in micrograph D (figure 2d). On the other hand, increasing holding time at this temperature produced relatively large grains in micrograph C. The fast cooling rates in heat treatments C and D favoured the formation of the phases of martensite and bainite, in comparison with heat treatment B. whereas heat treatment B did not favour the formation of bainite and martensite. The microstructure obtained in heat treatment C presented a similar fourth phase volume fraction in comparison to the microstructure obtained in treatment D. This is suspected to be martensite.

Table III shows the volume fraction of the steel phases obtained from statistical analysis of OEM for all the microstructures obtained by the heat treatments A, B, C and D investigated in this study and table 4 shows the average grain size and hardness test results of the specimen. It can be observed that an increase in time at an inter-critical temperature increased the grain size. Heat treatment of specimen D produced microstructure with small grains, while heat treatment of specimen B promoted grain growth. From micrograph C results, it can be observed that the soaking time above critical temperature had a major influence on the microstructure. Heat treatment either at or above the critical temperature caused metallurgical changes and soaking time favoured the growth of grains. The distribution of the phases and grains also showed a continuous change of the microstructure with increasing temperature and soaking time. As reported by [14] grains generally grow, coalesce and coarsen with increasing temperature and soaking time, [15] reported that nucleation of micro-void in ductile material is generally governed by large strains of the material. They initiate at discontinuities soon after the onset of plastic yielding and grow due to plastic deformation [16] of the surrounding matrix material [17]. Upon further plastic deformation of the material the micro-voids tend to grow and possibly change shape by means of deviatoric and volumetric strain [18, 19, 20] which may result in the formation of micro-cracks as micro-voids start to combine micro-void nucleation at the areas of large strains (at the necked area) was distinctly evident (see figure 5). Figure 6 also shows the micrographs of EN8 showing variation in grain size where specimen A with larger grain sizes and Specimen D with smaller grain sizes.

Table III: Phase volume obtained from OEM analysis

Specimen	phase 1	Phase 2	Phase 3	Phase 4
	% volume	% volume	% volume	% volume
A	21.05	74.94	3.91	0.13
B	17.18	75.95	6.71	0.16
C	16.09	73.56	7.00	3.35
D	23.04	61.62	8.38	6.96

Table IV: Grain size and Brinell hardness values of EN8 studied.

Specimen	Average grain size (um)	Hardness (Brinell)
A	123.46	164
B	156.25	147
C	46.3	194
D	39.6	206

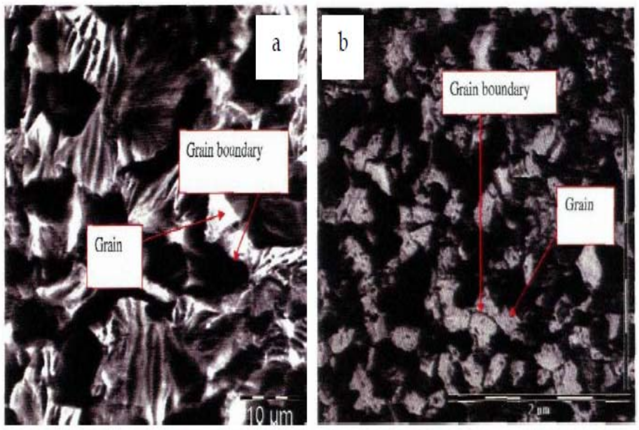

Figure 4: (a) SEM micrography showing individual grains and grain boundaries. (b) OEM micrography showing individual grains and the grain boundaries obtained in the heat treatment B. Ferrite (clear), martensite and bainite (dark)

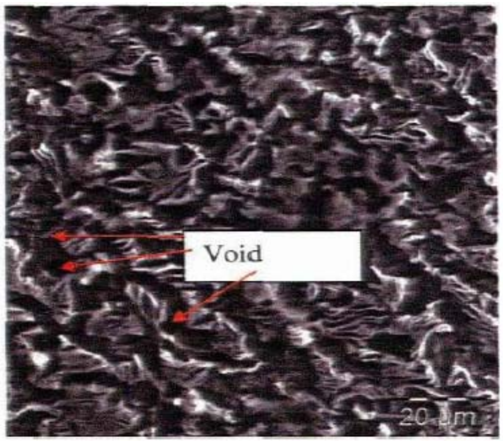

Figure 5: SEM micrography showing micro-void nucleation

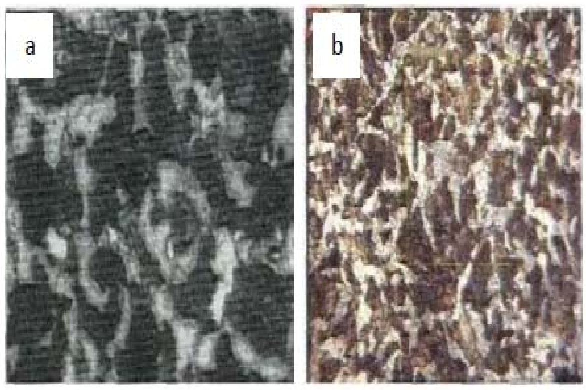

Figure 6 : Micrographs of EN8 showing variation in grain size (a) specimen A with larger grain sizes (b) Specimen D with smaller grain sizes .

B. Mechanical properties

Figure 7a shows the stress vs strain curves of En8 austenised at 9500C , held for 180 minutes and cooled in furnace and figure 7b shows the stress vs strain curves of En8 austenised at 9140C, held for 10 minutes, cooled in furnace to 6800C. The yield strength (YS), ultimate tensile strength (UTS) and the corresponding elongation of the En8 austenised at 9500C , held for 180 minutes and cooled in furnace were 475.22 MPa, 694.68 MPa and 13 %, respectively, as shown in figure 7(a) and figure 8b show the result of En8 steel austenised at 9140C, held for 10

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minutes, cooled in furnace to 6800C. The The YS, UTS and the corresponding elongation were 397.86 MPa, 492.59 MPa and 16.9 %, respectively.

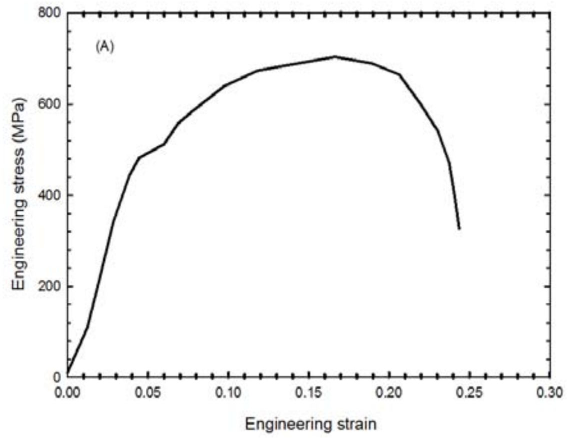

Figure 7a: stress vs strain curve of En8 austenised at 950^{0}C , held for 180 minutes and cooled in furnace.

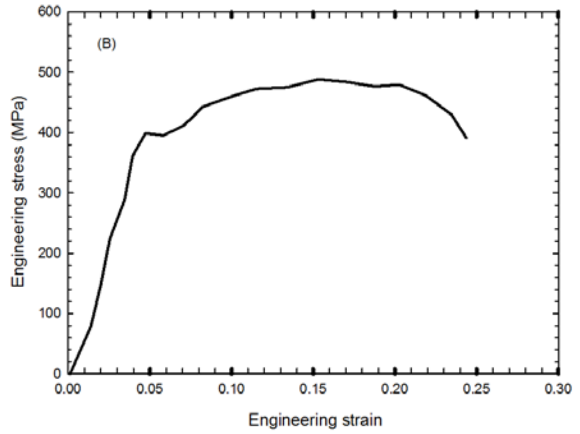

Figure 7b : stress vs strain curve of En8 austenised at 914^{0}C, held for 10 minutes, cooled in furnace to 680^{0}C.

The reduction of the strength values observed in specimen B can be attributed, among other factors, to coarse grains. The reduction in the yield strength and tensile strength values in specimen B was worsened by small volume fraction of the harder phase (martensite). Specimen B exhibits relatively lower strength and higher ductility as compared to specimen A. This can be attributed to relatively large grains of specimen as there is very little difference in the volume fraction of the fourth phase between specimens A and B.

Figure 8a shows the stress vs strain curve of En8 austenised at 914^{0}C, held for 10 minutes, cooled in furnace and figure 9b shows the stress vs strain curve of En8 austenised at 914^{0}C held for 3 minutes cooled in furnace to 715^{0}C and quenched in oil. The YS, UTS and the corresponding elongation of En8 austenised at 914^{0}C, held for 10 minutes, cooled in furnace were 762.26 MPa, 762.57 MPa and 11.8 %, respectively. For En8 steel austenised at 914^{0}C held for 3 minutes cooled in furnace to 715^{0}C and quenched in oil , The YS, UTS and the corresponding elongation 789.41 MPa, 781.41 MPa and 9.4 %, respectively.

The results of hardness test carried out on the steel samples were shown in table 4. it is observed that increase in austenising temperature soaking time and slow cooling rate in heat treatment B induced a marked decrease in hardness in specimen B . This reduction in hardness may be attributed to two microstructural aspects: grain coarsening and reduction in fourth phase observed in specimen B. The maximum hardness values were obtained in heat treatments C and D. This confirmed the suspicion of the presence of harder phases (martensite and bainite) in specimens C and D as alluded to above. However, from the analysis of the phase volume fractions, grain size and hardness values of specimens A, B, C and D; it is observed that grain size has a major influence on variation in the hardness values observed.

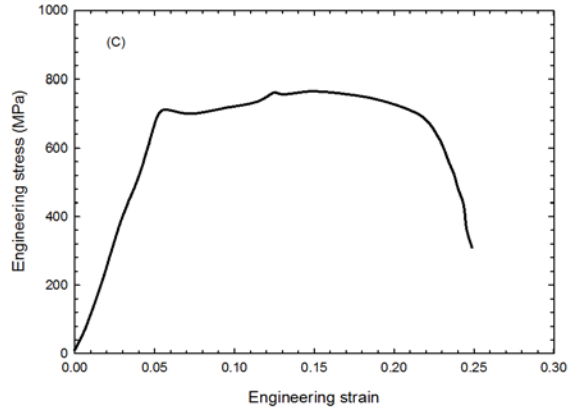

Figure 8a: stress vs strain curve of En8 Austenised at 914^{0}C, held for 10 minutes, cooled in furnace.

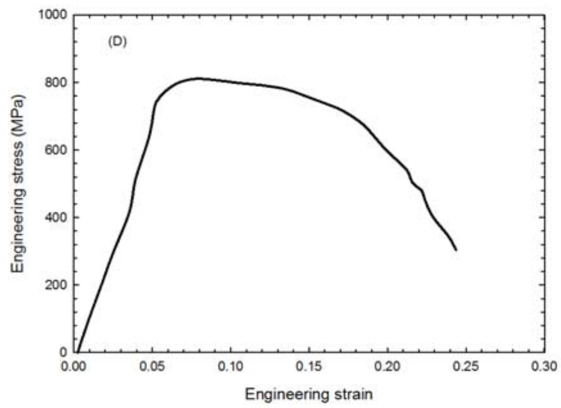

Figure 8b : Stress vs strain curve of En8 austenised at 914^{0}C held for 3 minutes cooled in furnace to 715^{0}C and quenched in oil.

The yield strength of the specimen B was measured to be 391MPa, which is a significant decrease from that of specimen A (475 MPa). As the holding time was reduced, the yield strength increased significantly whereas elongation at failure decreased as evident in Figure 8. Further decrease in the holding time at critical temperature temperatures resulted in increase in the yield strength, values and reduction in elongation at failure (Ef) values. The yield strength of specimen D (781MPa) is found to be equivalent to over 8% enhancement compared to that of the specimen C. This is in agreement to the findings reported in [10]. They also reported that a number of factors such as heat treatment, alloying content and impurities affect the relationship between grain size and mechanical properties of steels. It is therefore imperative to control the heat treatment process and keep impurities in the steel to minimum acceptable levels. In this study, the heat treatment regime was designed in such a way that formation of martensite and bainite phases was limited to a bare minimum level.

A. Effects of Phase volume fraction on yield strength

It has been observed that the yield stress and work hardening of steel depend on individual phases present in the material .Considering the variation of yield strength with grain size and phase volume fractions [21].
Based on the experimental results, the effects of microstructural features such as grain size and phase volume fraction and mechanical properties (Young's modulus, the yield strength, the ultimate tensile strength, and elongation at failure) on the deformation behaviour of the steel studied can be predicted. Since any structural parameter that directly controls the yield strength, the ultimate tensile strength and elongation at failure, should have some influence (direct or indirect) on the stress flow and formability of the material.

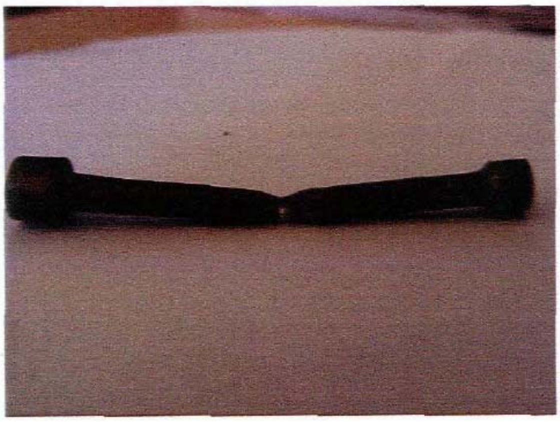

Figure 9: Fracture specimen showing a cone and cup fracture mode

IV. Conclusion

In the study, the plastic deformation behavior and experimental methods used to quantify grain size and mechanical properties were described and following the analysis of the results obtained, the following conclusions were drawn;

1. Grain size and its distribution have a significant impact on the yielding characteristics of steel. It was observed that when a structure is composed of multiphase with different grain size distribution, the maximum plastic deformation will occur within the "weaker" phase. While the 'stronger" phase will experience higher von Mises stress.

2. The annealing temperature and holding time have great influence on the grain size and phase distribution. The increase in annealing temperature and soaking time promotes the coarsening of grains and even an increase in formation of second phases (bainite and martensite) upon cooling.

3. Since the yield strength, increased linearly with decreasing grain size in conventional materials and, elongation at failure decreasing with decreasing grain size, coarse grains obtained in heat treatment B would be beneficial for manufacturing processed that depend on material flow (for example cold forming). Heat treatment C and D would be ideal for applications where high strength and high hardness values are required.

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