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An Assessment of the Microstructure and Mechanical Properties of 0.26% Low Carbon Steel under Different Cooling Media: Analysis by one-way ANOVA

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Abstract

This study reports the effect of heat treatment on the microstructure and mechanical properties of 0.26% low carbon steel at 850°C using different cooling media. Annealing, normalizing and age-hardening heat-treatments were used for the experimental work. Hardness tests, fatigue tests, compression tests and metallography were carried out on the heat-treated and control samples. The results were further analyzed using the one-way ANOVA test. The results obtained showed significant differences in the microstructure and mechanical properties of the different heat-treated samples. The hardness profile determined using a Brinell ball indenter showed decrease in hardness of the heat-treated samples when compared with the control. Normalizing heat-treatment yielded a microstructure of better quality than annealing and age-hardening. A higher compressive strength of 155.97MPa and 151.52MPa was obtained with normalizing and annealing heat treatments respectively in comparison to age-hardening (149.93MPa), and the control test (150.56MPa). Improved fatigue strength was also obtained with annealing heat treatment. ANOVA test confirmed the results at 90% confidence and further showed that there was significant difference between the four test conditions.

Keywords: Heat treatment, mechanical properties, fatigue, ANOVA, steel

1. Introduction

Low carbon steel is the most common form of steel due to the fact that its material properties are acceptable for many applications (Al-Qawabah *et al*. 2012). Low carbon steel also called mild steel have 0.2% carbon content, and manganese content below 0.7%, with maximum value for silicon, at 0.6%. Low carbon steels are utilised to produce cars body panels, tubes, domestic appliance side panels and other engineering applications because they are readily available, workable and weldable (Fish, 1995).

The performance of low carbon steel in service depends on intrinsic factors which include its grain size, presence of defects, its chemical composition, ultimate tensile strength, etc. as well as extrinsic factors. Furthermore, the mechanical properties of low carbon steel such as strength, formability, ductility, fatigue strength and surface hardness, amongst others enhances its performance in service. Studies have also shown that failure of carbon steels can result from poor design, use of inferior material, fabrication methods, manufacturing errors as a result of poor machining, or failure from a phenomenon called fatigue (Ajayi *et al*. 2013; Joseph *et al*. 2013). In order to forestall these failures, the mechanical properties can be changed as desired by heat treatment which fundamentally alters the microstructure of the steel (Raji & Oluwole, 2012). Heat treatment was defined by Singh (2011) as a controlled process of heating and cooling a metal or alloy in its solid state to change its metallurgical and mechanical properties. The findings of Dossett & Boyer (2006) also revealed that, amongst various heat treatment processes (hardening, annealing, normalizing, tempering, etc.), annealing causes softening of the steel followed by a resulting increase in ductility and relief of residual stresses. It is of necessity to note that all the different heat treatment processes consists of three stages: heating of the material, holding the temperature for a stipulated period and cooling, usually to room temperature.

Previous works carried out in this regard, include the investigations of: the mechanical properties of 0.13% C steel after intercritical normalizing heat treatment (Offor *et al*. 2010); the mechanical properties of medium carbon steel under different quenchants (Ndaliman, 2006); the mechanical properties of medium carbon steel in different quenching media (Odusote *et al*. 2012); the mechanical properties of medium carbon steel subjected to annealing, normalizing, hardening and tempering (Senthikumar & Ajiboye, 2012); multi-regimes of annealing temperatures on mechanical properties (Al-Qawabah *et al*. 2012); amongst others. However, such extension in the material modification of carbon steels requires the investigation to analyze how low carbon steels behave under annealing, normalizing and age-hardening heat treatments. This will be achieved by a statistical analysis of experimental data using the one-way ANOVA F-test. The approach of ANOVA test is based on the breakdown of the total variation within an experiment into variations due to each main factor, interacting factors and residual (experimental) error. This statistical tool has been recently used by many authors in various fields, for example, a study of the inhibiting effect of Vernonia amygdalina on the corrosion of mild steel reinforcement in concrete (Loto *et al*. 2013); analysis of the fatigue behavior of packable composites (Abe *et al*. 2005); optimal designs for estimating variance components with ANOVA in one-way classification under non-normality (Guiard *et al*. 2000); application of ANOVA to image analysis results of talc particles produced by different milling (Ulusoy, 2008); and application of ANOVA to the study of thermal stability of micro-nano silica epoxy composites (Saavedra *et al*. 2011). However, the application of this statistical tool for evaluating the effect of heat treatment on low carbon steels is scarce.

Therefore, in this present work, a limited experimental result for investigation of the mechanical properties of the heat treated low carbon steel is presented. Furthermore, the application of one-way ANOVA test for the analysis of its mechanical properties has been discussed.

2. Experimental Procedure

12mm low carbon steel samples were machined to standard dimensions for hardness, tensile, compression and fatigue tests. The chemical composition of the steel is shown in Table 1.

Table 1: Elemental composition of low carbon steel

Element	C	Si	S	P	Mn	Ni	Cr	Mo	Cu	W	Sn	Co	Fe
Composition %	0.26	0.08	0.07	0.11	0.34	0.17	0.09	0.03	0.64	0.04	0.21	0.01	97.95

In order to investigate the mechanical properties and microstructure of the steel, samples were annealed, normalized and hardened using a Carbolite muffle furnace 7B9162E. Steel samples were heated to 850^{o}C, soaked for 1 hour and then cooled using various media. Samples for annealing were furnace cooled; samples for normalizing were cooled in air whereas age-hardened samples were quenched in SAE 40 engine oil. After these treatments, compression and fatigue tests were carried out on all samples by a Universal Testing Machine and an Avery Denison fatigue tester respectively in order to investigate their mechanical properties. Samples for metallography were prepared and etched in 2% nital. Microstructural examination was further carried out at a magnification of X640 using an Accuscope metallurgical microscope. In addition, the hardness profile was determined with the aid of a Brinell ball indenter.

3. Results and Discussion

3.1 Effect of heat treatment type on the microstructure of 0.26% carbon steel

The microstructures of 0.26% carbon steel before and after various heat treatment modes at constant temperature (850^{o}C) and soaking time (1hr) are presented in Figure 1.

The microstructure of the as-received sample showed ferrite in the grain boundaries of the acicular pearlite grains. For this reason, the microstructure of the steel can be described as having a ferrite-austenite duplex phase. Subjecting the steel to annealing heat treatment at 850^{o}C affected the spatial distribution of ferrite at the grain boundaries, and scales were observed to be present in ferrite (Fig. 1b). This was due to oxidation at the metal surface. On the other hand, normalizing yielded a uniform fine grained microstructure of ferrite and pearlite with large grain sizes. Furthermore, age-hardening heat treatment revealed the presence of scales more widely distributed on the metal surface and highly dispersed ferrite.

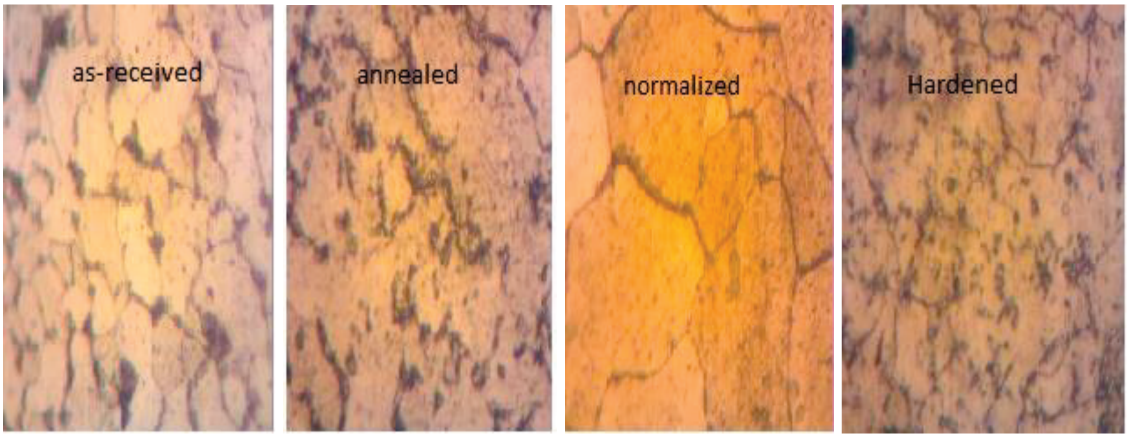


Fig.1. Microstructure of a) As-received b) annealed c) normalized d) age-hardened steel samples at 850^{o}C. Magnification: 640x

3.2 Effect of heat treatment type on the microhardness of 0.26% carbon steel

The results of Brinell microhardness test in quadruplicates for each heat treatment is presented in Fig.2. The microhardness of the steel varied with the heat treatment method. In comparison with the control (as-received) samples which had an average hardness of 162.5HB, the strength of the steel increased to 185HB by age-hardening heat treatment. This signifies that age-hardening improves the strength of 0.26% carbon steel. Normalizing and annealing heat treatments resulted into lower strengths of the carbon steel, that is, 136HB and 129HB respectively. The decrease in hardness when compared with the control was expected for annealing and normalizing heat treatments.

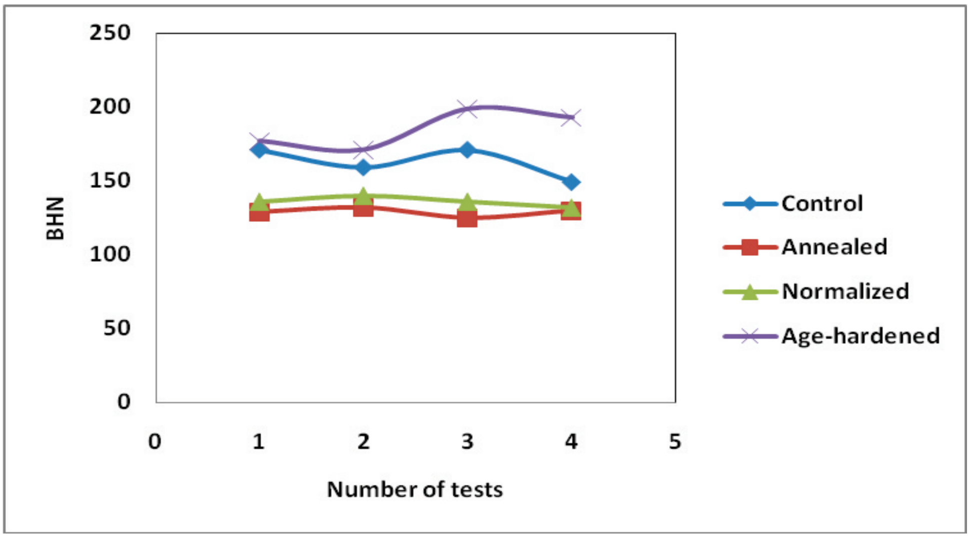


Fig.2: Brinell hardness values for heat treated samples

3.3 Effect of heat treatment type on the compressive strength of 0.26% carbon steel

The compressive strength of 0.26% carbon steel increased with normalizing and annealing heat treatments at 850^{o}C (Fig.3). This was observed when compared with the behaviour of the as-received samples under compressive loading signifying that annealing and normalizing 0.26% carbon steel at the stated temperature improves its compressive strength. An explanation for this lies in the fact that annealing and normalizing heat treatments have altered the nature of the microstructural grains as shown in Figure 1, thereby manipulating the overall mechanical behaviour of the material. The age-hardened samples exhibited initially increasing compressive strengths and a subsequent decrease was observed with the third and fourth samples under the same loading conditions.

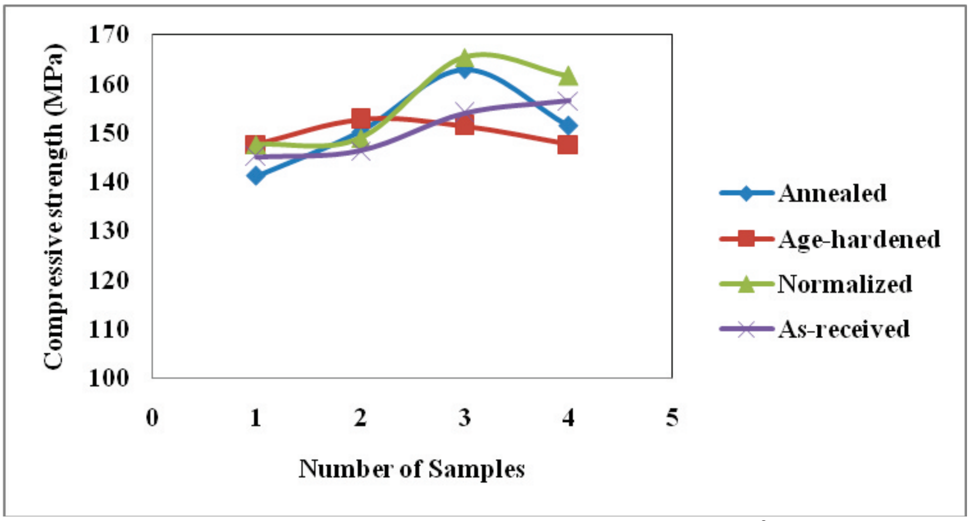


Fig.3: Compressive strengths of heat treated 0.26% carbon steel at 850^{o}C

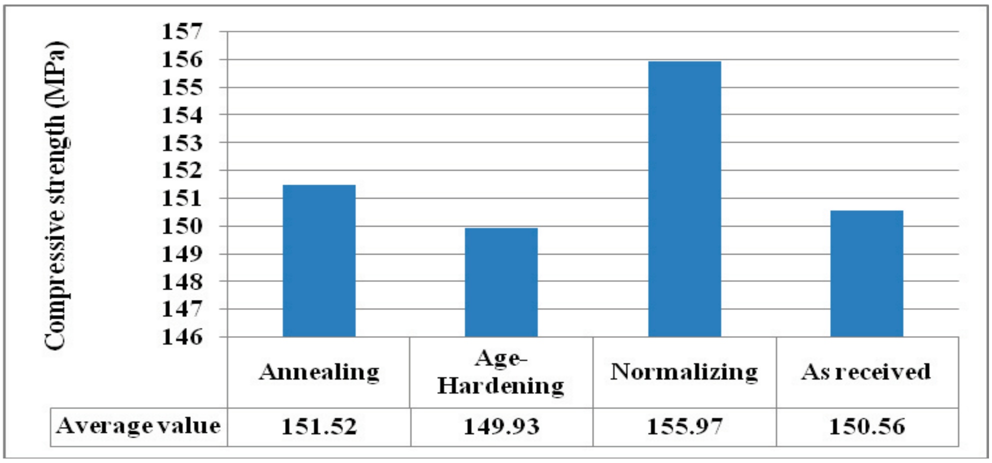


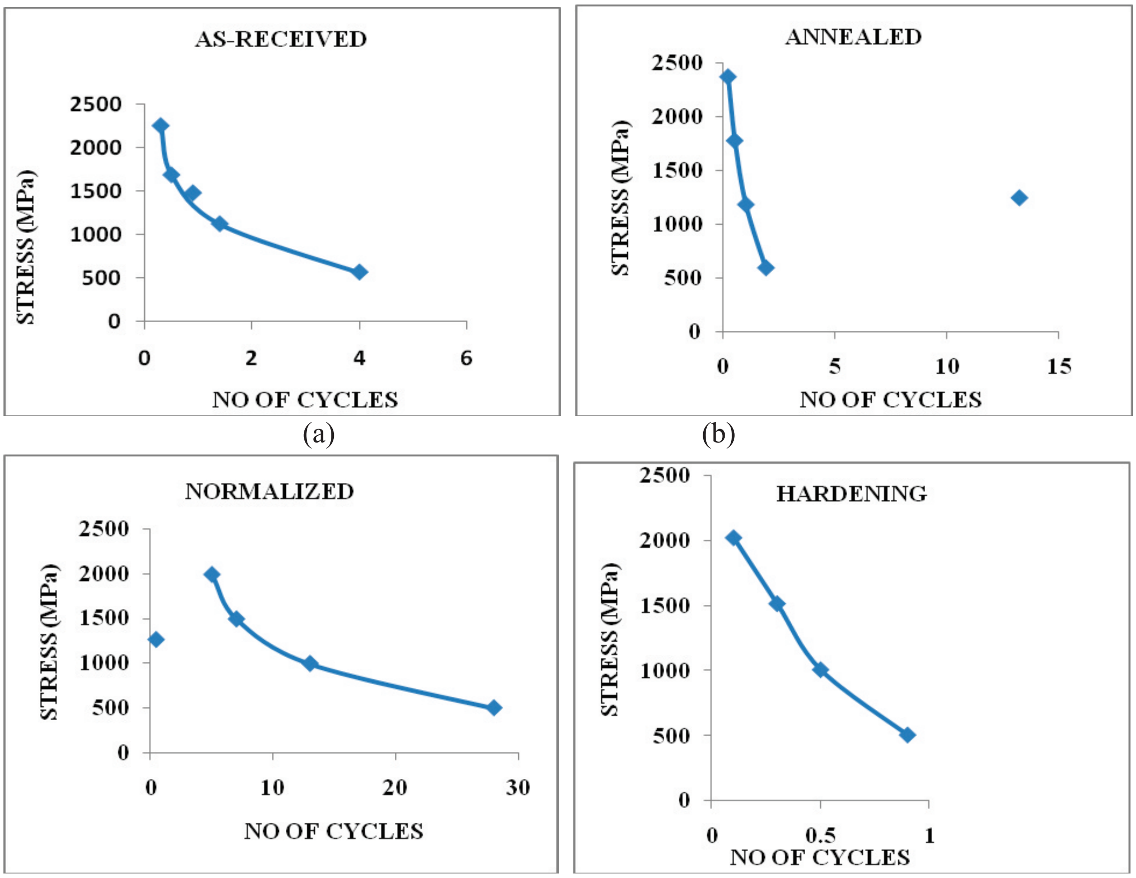
Fig.4: Compressive strengths of heat treated 0.26% carbon steel samples

The comparison between the properties of the annealed, normalized and age-hardened steels in respect of their compressive strengths is further shown in Figure 4. The highest compressive strength of 155.97MPa was exhibited by the age-hardened samples whereas the lowest compressive strength of 149.93MPa was obtained from normalizing heat treatment.

3.4 Effect of heat treatment type on the fatigue strength of 0.26% carbon steel

The essence of fatigue testing was to ascertain the actual load the heat treated steels could withstand before failure in service. Upon the application of bending load the fatigue strength of each sample conditions for 0.26% carbon steel are shown in Figures 5. For each material condition, the fatigue strength declined with increasing cycles. The average number of cycles obtained for each material condition is as shown in Figure 6.

The fatigue strength of as-received samples declined to 567MPa from 2254MPa resulting into failure at the 4th cycle. When compared with the heat-treated samples, higher fatigue strength of 592MPa was achieved with the annealed samples at 1.9 cycles, whereas the normalized samples exhibited the least fatigue strength (497MPa) at 28 cycles. It was also noted that the average highest number of cycles (13.25) was obtained with normalized samples whereas the hardened samples gave the least number of cycles (0.45). Furthermore, all the samples exhibited significant amount of deformation within relatively short lives. It can therefore be concluded that for the four material conditions, the failure mechanism was by low-cycle fatigue.



(a) (b)

(c) (d)

Fig. 5: S-N Curve for 0.26% carbon steel in a) As-received, b) Annealed, c) Normalized, d) Age-hardened conditions.

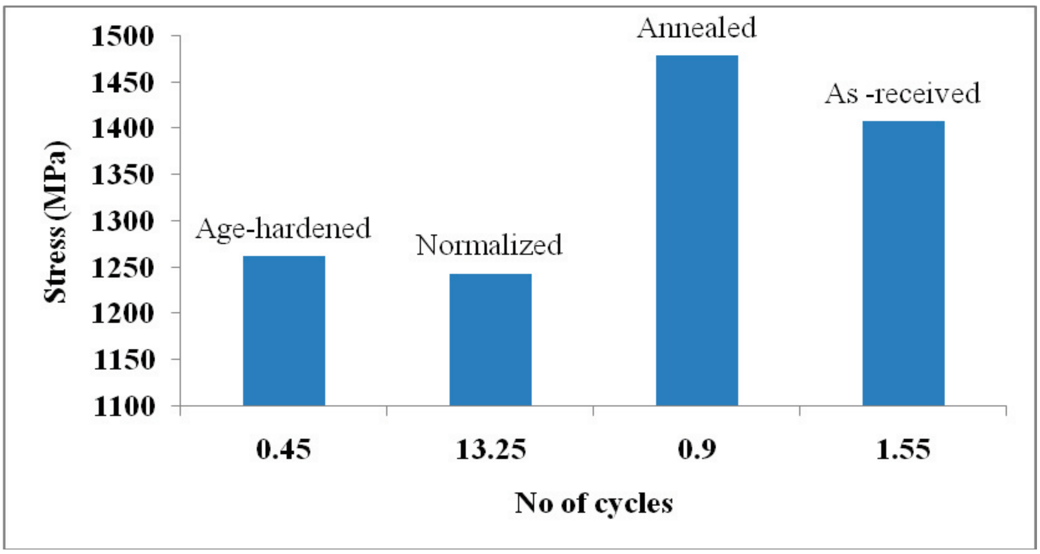


Fig. 6: Variation between fatigue stress and number of cycles to failure for 0.26% carbon steel.

Statistical Analysis

Statistical analysis using the ANOVA test was performed on the results obtained in this work. ANOVA is a powerful technique for analyzing experimental data involving quantitative measurements. It is useful in factorial experiments where several independent sources of variation may be present (Loto *et al*. 2013; Loto *et al*. 2014). One-factor single-level experiment ANOVA test (F-test) was used to evaluate the separate and combined effects of annealing, normalizing and age-hardening heat treatment methods on the tensile strength of the steel. The F-test was used to examine the amount of variation within each of the samples relative to the amount of variation between the samples. When the F-test is applied to the ratio of Mean Square (MS) of columns to MS of residual, it will indicate whether a significant difference exists between the columns (or various levels of a factor). The sum of squares was obtained with Equations (1) – (3) as previously used by (Loto *et al*. 2013).

$$SS_c = \frac{\sum T_c^{\,2}}{n} - \frac{T^2}{N} \qquad (1)$$

Residual Sum of Squares:

$$SS_{residual} = SS_{total} - SS_c \qquad (2)$$

Total Sum of Squares:

$$SS_{Total} = \sum x^2 - \frac{T^2}{N} \qquad (3)$$

The calculation using the ANOVA test is tabulated in Table 2.

Table 2: Summary of ANOVA analysis for fatigue strength measurements

Source of Variation	SS	Df	MS	F	Significance F
Heat treatment type	455.09	3	151.6967	5.43	2.61
Residual	335.45	12	27.95417		
Total	790.54	15			

As shown in Table 2, the mean-square ratio experimentally derived (5.43) is higher than the F ratio (2.61) for 90% confidence. Hence, on the basis of the above test data it can be concluded with 90% confidence that there is significant difference between the four test conditions (that is, control, annealed, normalized and age-hardened steel samples).

4. Conclusion

In this work, the differences between unheat-treated (control) and heat-treated test conditions were evaluated using one-factor single-level ANOVA test. From the results of the mechanical tests, it can be concluded that the compressive strength of 0.26% carbon steel increased with annealing and normalizing heat treatments at 850^{o}C while improved fatigue strength was obtained with annealing heat treatment. Furthermore, a microstructure of better quality was obtained with normalizing heat treatment. The hardness of the steel was improved by age-hardening treatment. ANOVA test confirmed the results at 90% confidence and further showed that there was significant difference between the four test conditions.

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