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Effect of Heat Treatment on Microstructure and Mechanical Properties of SAE 1025 Steel: Analysis by one-way ANOVA

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Abstract

The effect of heat treatment at 850°Con the microstructure and mechanical properties of SAE 1025 carbon steel has been studied. Annealing, normalizing and age-hardening heat-treatments at 850°C were used for the experimental work. Hardness tests, tensile tests and metallography were carried out on the heat-treated and control samples. The results were further analyzed using the one-way ANOVA test. 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. A microstructure of enhanced quality was obtained with normalizing heat-treatment. A higher tensile strength of 313.55MPa was obtained with annealing heat treatment in comparison to age-hardening (212.94MPa), normalizing (167.79MPa) and the control test (269.12MPa). ANOVA test confirmed the results at 90% confidence and further showed that there was significant difference amid the four test conditions.

Keywords: Heat treatment, mechanical properties, ANOVA, steel

1. Introduction

Over 500 million tonnes of low carbon steels are produced yearly around the world; they are used for most of the engineering applications. 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 [1]. Furthermore, low carbon steel also called mild steel have carbon content below 0.2 per cent, and manganese content below 0.7 per cent, with maximum values for silicon, phosphorus and sulphur at 0.6, 0.05 and 0.05 per cent respectively. The performance of low carbon steel in service depends on inherent factors which include its grain size, presence of defects, its chemical composition, ultimate Tensile strength, etc. as well as extrinsic factors.

In addition, 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 production methods, use of substandard material, poor design, manufacturing errors due to poor machining, or failure from a phenomenon called fatigue [2, 3]. Sequentially, to forestall these failures, the mechanical properties can be changed as desired by heat treatment or cold working. [4] Defined heat treatment 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 [5] 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, generally 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 [6]; the mechanical properties of medium carbon steel under different quenchants [7]; the mechanical properties of medium carbon steel in different quenching media [8]; the mechanical properties of medium carbon steel subjected to annealing, normalizing, hardening and tempering [9]; multi-regimes of annealing temperatures on mechanical properties [10]; amongst others. Nevertheless, 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, analysis of the fatigue behavior of packable composites [11]; optimal designs for estimating variance components with ANOVA in one-way classification under non-normality [12]; application of ANOVA to image analysis results of talc particles produced by different milling [13]; and application of ANOVA to the study of thermal stability of micro-nano silica epoxy composites [14]. However, the application of this statistical tool for evaluating the effect of heat treatment on low carbon steels is scarce.

Consequently, in this present work, a limited experimental result for investigation of the mechanical properties of heat treated SAE 1025 low carbon steel is presented. In addition, the use of one-way ANOVA test for the analysis of its mechanical properties has been discussed.

2. Experimental Procedure

12mm SAE 1025 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 SAE 1025 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 cooled in the furnace, samples for normalizing in air and hardening samples in SAE 40 engine oil. After these treatments, tensile and compression tests were carried out by a type W Monsanto Tensometer on samples so as to investigate their mechanical properties. Samples for metallography were prepared and etched in 2% nital and the microstructures were revealed at a magnification of X640 under an Accuscope metallurgical microscope. In addition the hardness profile was determined using Brinell ball indenter.

3. Results and Discussion

3.1 Effect of heat treatment type on the microstructure of SAE 1025 Carbon steel

The microstructures of SAE 1025 steel before and after various heat treatment modes at constant temperature (850^{o}C) and soaking time (1hr) are presented in Figure 1.

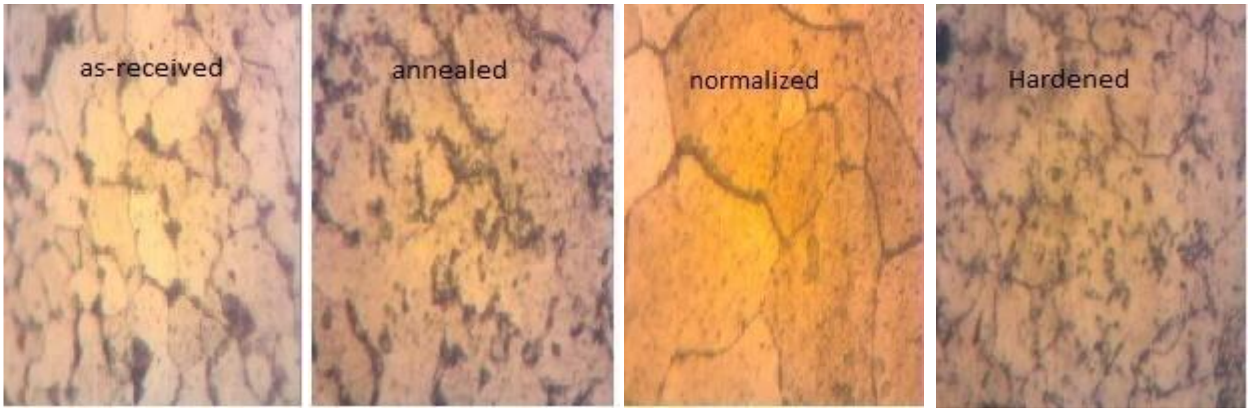

Figure 1: Microstructure of a) As-received b) annealed c) normalized d) age-hardened steel samples at 850^{o}C.

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.

3.2 Effect of heat treatment type on the microhardness of SAE 1025 Carbon steel

The results of Brinell microhardness test in quadruplicates for each heat treatment is presented in Fig.2.

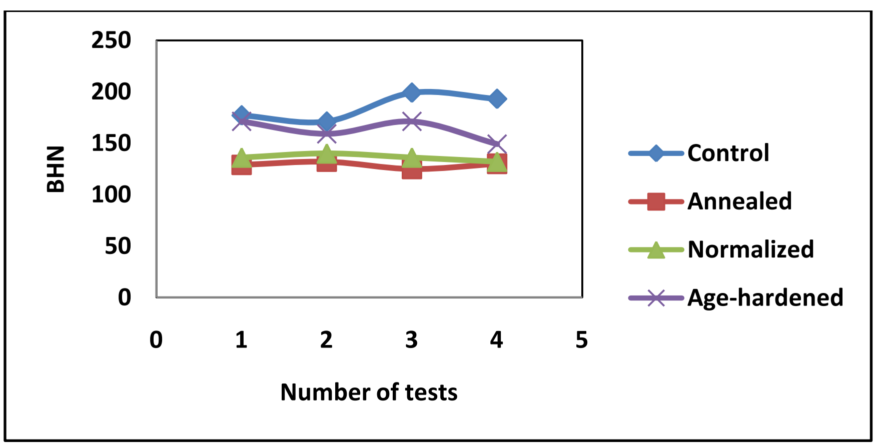

Figure 2: Brinell hardness values for heat treated samples

The microhardness of the steel varied with the heat treatment method. In comparison with the hardness results for all the heat treated samples, the average hardness of the control (as-received) sample, 185HB was significantly high. This was followed by the age-hardened samples with 162.5HB, the normalized samples having 136HB and the annealed samples with 129HB. The decrease in hardness when compared with the control was expected for annealed, normalized and age-hardened samples.

3.3 Effect of heat treatment type on the tensile properties of SAE 1025 Carbon steel

The tensile strength and yield strength of SAE1025 steel increased with annealing heat treatment at 850^{o}C (Fig.3). This was observed when compared with the behaviour of the as-received samples under tensile loading signifying that annealing SAE 1025 steel at the stated temperature improves its tensile strength. The normalized samples and age-hardened samples exhibited lower tensile strengths under the same loading conditions.

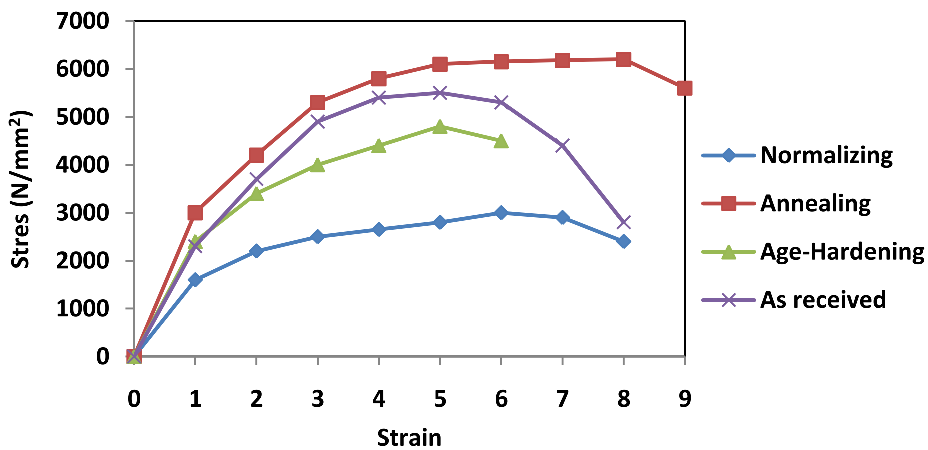

Figure 3: Stress-strain diagram showing the tensile properties of heat treated 1025 steel at 850^{o}C

The comparison between the properties of the annealed, normalized and age-hardened steels in respect of their ultimate tensile strengths and yield strengths are shown in Figures 4 and 5.

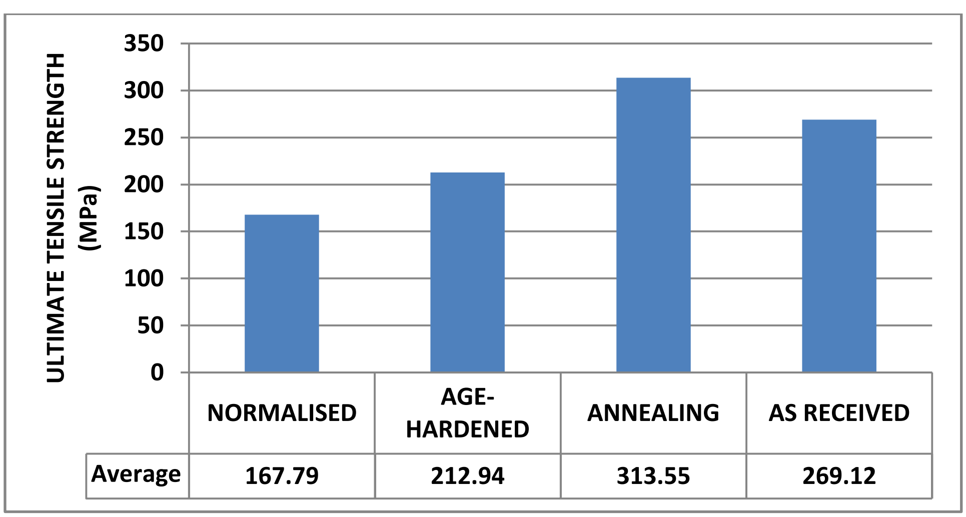

Figure 4: Ultimate tensile strength of heat treated SAE 1025 steel samples

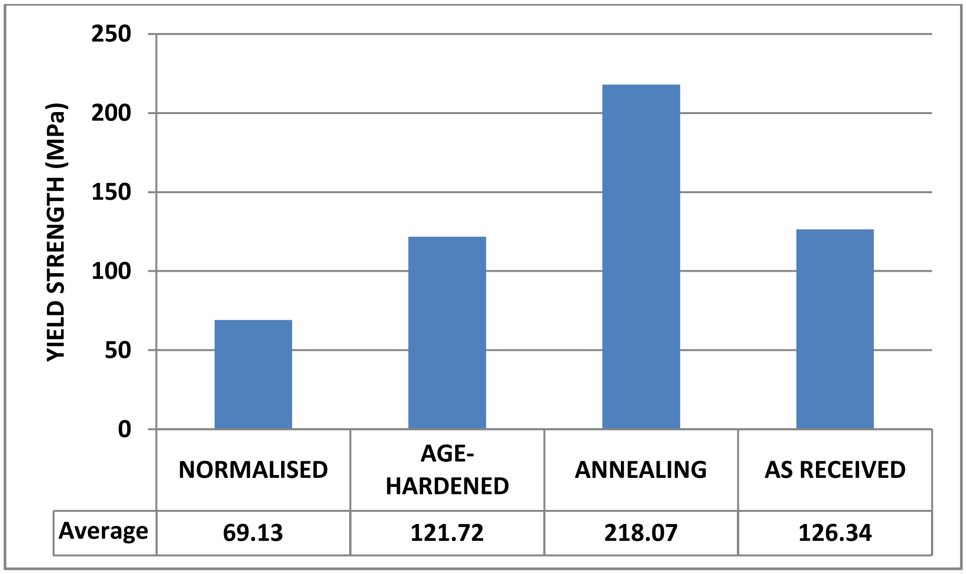

Figure 5: Yield strengths of heat treated SAE 1025 steel samples

As shown in Fig. 4, the lowest ultimate tensile strength of 167.79MPa was exhibited by the normalized samples whereas the highest tensile strength of 218.07MPa was obtained from annealing heat treatment.

3.4 Statistical Analysis

Statistical analysis using the ANOVA 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 [15]. 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 [15].

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

Residual Sum of Squares:

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

Total Sum of Squares:

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

The calculation using the ANOVA test is tabulated (Table 2) as shown.

Table 2: Summary of ANOVA analysis for tensile strength measurements

Source of Variation	SS	Df	MS	F	Significance F
Heat treatment type	48801.93	3	16267.31	13.98	2.61
Residual	13962.71	12	1163.559		
Total	62764.64	15			

As shown in Table 2, the mean-square ratio experimentally derived (13.98) 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).

Conclusion

1. A higher tensile strength was obtained for the annealed samples than for the control, normalized and age-hardened samples.
2. A microstructure of better quality was obtained with normalizing heat treatment whereas a lesser quality was obtained by age-hardening.
3. The hardness values of the heat-treated samples were lower than those of the unheat-treated as was expected.
4. 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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