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Empirical Relationship between Hardness and Tensile Strength for Medium Carbon Steel Quenched in Different Media

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Abstract

The possibility of predicting the ultimate strength of medium carbon steel sample quenched in different media has been investigated. A 0.4%C steel was austenitized in a carbolite furnace, quenched in water, hydraulic oil and olive oil and later tempered while some samples were normalized. All experimental samples were tested in a computer controlled Testometric universal materials testing machine and Rockwell hardness tester and later viewed in an optical microscope. The results show that a linear relationship exists between the ultimate tensile strength and the hardness of the steel material and it is of the type: UTS=ao+a1HRC where the regression constant (ao) and regression coefficient (a1) have been evaluated for the steel sample to be equal to 241.4 and 10.97 respectively. Stress Vs strain curves revealed that the normalized samples showed a yield point phenomenon while the hardened samples did not. The microstructure of the normalized sample is constituted by combination of ferrite and pearlite while microstructure of the hardened samples is predominantly martensitic. The water- quenched samples showed the highest ultimate tensile strength and hardness while the sample, quenched in olive oil showed the least strength and hardness.

Keywords: Tensile strength; Hardness; Steel; Martensite; Pearlite; Heat treatment; Microstructure

Introduction

Despite constant development of new materials, the steel is still one of the most reliable, most used and most important materials of today [1]. The steel material is a versatile engineering material with diverse applications in civil engineering constructions, automobile manufacturing and railroad constructions due to its wide range of attractive properties, ease of fabrication and relatively low manufacturing cost and for the fact that it is second only to concrete in annual production tonnage [2]. Steels can be broadly classified as: plain carbon; low alloy; stainless and tool steels depending on their chemical compositions [3]: The plain carbon steels can further be categorized into three groups depending on their carbon content as follows: the low carbon/mild steels-containing up to 0.3% carbon; the medium carbon steels between 0.3-0.6% carbon; and the high carbon steels which contain between 0.6-1.0% carbon [3]. Applications for medium carbon steels include but are not limited to the following: gears, shafts, axles, rods and a multitude of machine parts [4].

The mechanical properties of plain carbon steels are strongly connected to their carbon composition and microstructures which are obtained after various thermo-mechanical treatments such as heat treatment and controlled cooling after hot deformation [5]. Higher cooling rates during heat treatment processes of steels lead to a decrease in ferrite grain size, and formation of high strength, hardness, dislocation density and fine phases because it suppresses the atomic diffusion whereas slow cooling rates lead to transformation into soft, coarse and less dislocated phases like the ferrite [6]. A variety of microstructures such as ferrite, pearlite, bainite and martensite can be obtained in medium carbon steels and the size and percentage distribution of these microstructural phases play an important role in the final mechanical properties such as tensile strength, hardness and toughness of the steel material [6].

The hardness and strength are the important material properties of structural steels [7]. Experimental methods for determining the tensile strength of a material are destructive in nature. Therefore non-destructive methods for estimating the tensile properties especially yield strength and tensile strength have been of interest to process engineers [8]. One of the most common techniques for estimating yield strength and tensile strength have been hardness testing because of its non- destructive (or semi destructive) nature, leaving behind only an indentation [8]. A simple equation that correlates tensile strength (TS) and hardness (H) can be stated as follows [9]:

$$TS=H.k \tag{1}$$

where k is coefficient. Cahoon et al. [10,11], offered expression relating hardness (H) and tensile strength (T.S) as follows:

$$TS=\left(\frac{H}{2.9}\right)\left(\frac{n}{0.217}\right)^{2} \tag{2}$$

$$YS=\left(\frac{H}{3}\right)(0.1)^{n} \tag{3}$$

where n is strain hardening exponent. The use of Cahoon's model requires prior knowledge of the strain hardening exponent either directly from uniaxial tensile test or indirectly through Meyer's index or empirical methods [12]. This can be cumbersome. Hence there is need to explore simpler methods for estimating the tensile strength of a steel material by means of measurement of its hardness only. The aim of this investigation, therefore, is to find an empirical correlation between tensile strength and hardness for medium carbon steel hardened in different quenching media.

Materials and Experimental Procedures

The steel material used for this study was obtained from Ajaokuta

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Steel Company limited in Kogi State of Nigeria and has composition (obtained from Ajaokuta Steel company limited) shown in Table 1. The quenchants used during the hardening processes to obtain different microstructures and properties include water, olive oil (vegetable oil) and hydraulic oil (SAE J1703 Manufactured by Oando Plc, Nigeria), which is a synthetic clutch and brake fluid and composed of a mixture of polyoxyalkylene glycols. The quenchants were chosen to give different degrees of hardening and strengthening of the steel material.

Heat treatment

The medium carbon steel samples were subjected to normalizing, quenching and tempering treatments in a carbolite furnace prior to micro examination and mechanical property testing. The furnace was pre- heated to 500°C and held for 1 hour to remove moisture and later heated to 900°C. During normalizing heat treatment, the samples were soaked at the temperature of 900°C and, thereafter, removed from the furnace and cooled in air after soaking for 10, 20 , 30, 40, 60 and 80 minutes. During quenching operation, the samples were soaked at 900°C and soaked for same incremental times as normalizing treatment and differently quenched in water, olive oil (vegetable oil) and hydraulic oil (synthetic). For tempering, the water quenched samples were soaked at 300°C for the same periods of time and cooled in air. All the experiments were repeated for three times.

Micro examination

The as- received and heat treated samples were successively ground in a grinding desk using silicon carbide papers of numbers 180, 240, 320, 400, and 600 grit sizes and polished in a rotating disc polishing machine having synthetic velvet polishing cloth impregnated with 1 micron alumina powder until very smooth surfaces were achieved and dried in an oven operated at 80°C. The samples were etched in 2% Nital solution by swabbing them with cotton wool, soaked with the etchant and examined using a Nikon optical microscope which is equipped with a CMEX digital camera (KL1500-T) for image capturing.

Tensile testing

Tensile test was performed on as- received and heat treated samples using a M500-25CT model of computer controlled Testometric universal materials testing machine which features winTest™ analysis software running under the windows™ operating system. The samples were mounted and subjected to tensile loading at an extension speed of 1 mm/min and were loaded until fracture occurred.

Hardness testing

A standard Rockwell C hardness tester was used in determining the hardness of the as- received and heat treated medium carbon steel samples. The tests were conducted on carefully ground and polished samples using a minor and major load of 10 and 100 Kg respectively and 10 mm diameter steel ball. Each hardness test was performed six times and the average determined.

Results and Discussion

Microstructure

The microstructure of as received and normalized medium carbon steel are shown in Figures 1A and 1B while the microstructure of the medium carbon steel, soaked at 900°C and quenched in water and tempered at 300°C are shown in Figures 1C and 1D respectively. As can be seen in Figure 1A, the microstructure of the as-received medium carbon steel consists of ferrite and pearlite. Similarly the microstructure of the normalized samples is made of ferrite and pearlite but with more volume fraction of pearlite than ferrite when compared with that of the as- received sample. It has been reported that in steel, austenite transformed to ferrite on cooling between 910°C and 723°C [13] while pearlite is formed by cooling an austenitized steel through the eutectoid temperature by the following reaction:

Element	C	Si	Mn	S	P
Wt%	0.4	0.18	0.65	0.02	0.02

Table 1: Chemical Composition of Medium Carbon Steel sample.

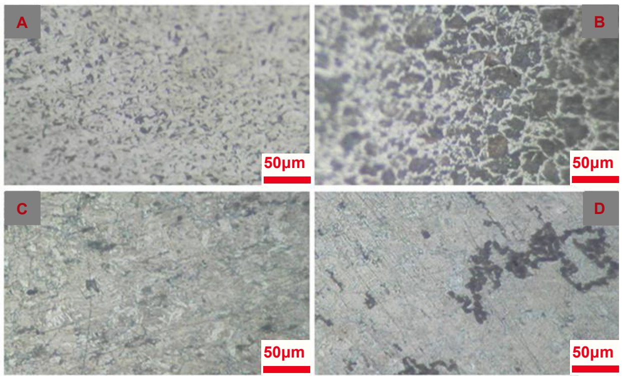

Figure 1: The microstructure of the medium carbon steel in: (A) as received condition; (B) normalized condition; (C) water- quenched condition; and (D) water quenched and tempered condition.

$$\text{Austenite} \leftrightarrow \text{Ferrite+Cementite} \quad (4)$$

The ferrite and cementite form as parallel plates called lamellae which is essentially a composite microstructure containing a very hard carbide phase, cementite, and a very soft and ductile ferrite phase. Equbal Md Israr et al. [14] reported that the volume fraction of ferrite decreases while that of pearlite increases as the cooling rate of medium carbon steel was increased during normalizing treatment in still and forced air.

The microstructure of steel sample shown in Figure 1C is constituted by martensite lath which is essentially super saturated solid solution of carbon in ferrite iron as a result of very rapid cooling from the austenite phase region leading to the formation a body centered tetragonal (bct) structure [15]. The microstructure of water- quenched and tempered medium carbon steel sample shown in Figure 1D consists of laths of tempered martensite structure in which epsilon carbides and cementite (Fe_3C) are expected to have been precipitated from the supersaturated martensitic structure [15].

Mechanical properties

Figure 2 shows the stress versus strain curve of the as- received medium carbon steel sample while Figure 3 shows the variation of stress with strain for the normalized medium steel sample. It can be seen that the medium carbon steel sample showed similar response to tensile loading conditions by showing plastic deformation while the normalized sample exhibited a yield point phenomenon in which the load increases steadily with elastic strain, drops suddenly, fluctuates about approximately constant value of load and then rises with further strain. The yield point behaviour did not, however, occur in the tensile loading and fracturing of the hardened and tempered samples as shown in Figures 4 and 5. The yield point phenomenon is reported [16] to be associated with relatively small amounts of interstitial or substitutional

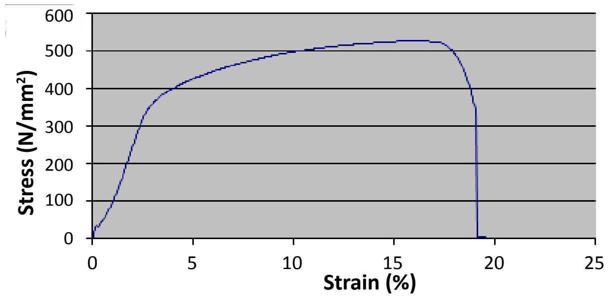

Figure 2: Stress versus strain graph of the as- received medium carbon steel sample.

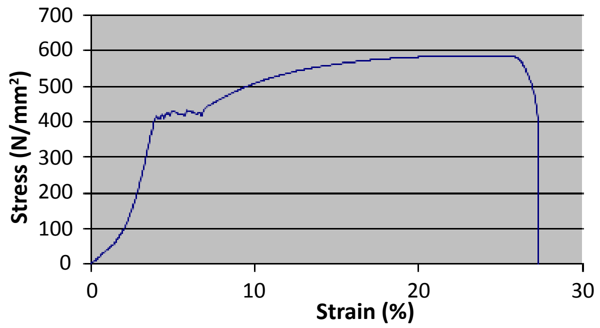

Figure 3: Stress versus strain graph of normalized medium carbon steel sample.

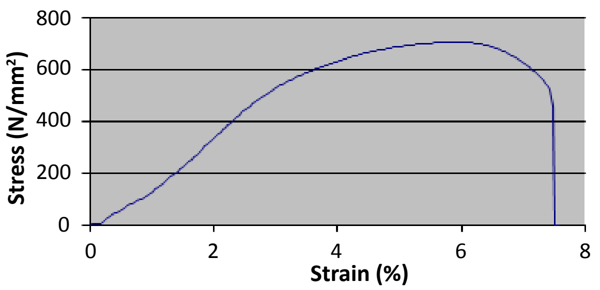

Figure 4: Stress versus strain graph of a water quenched medium carbon steel sample.

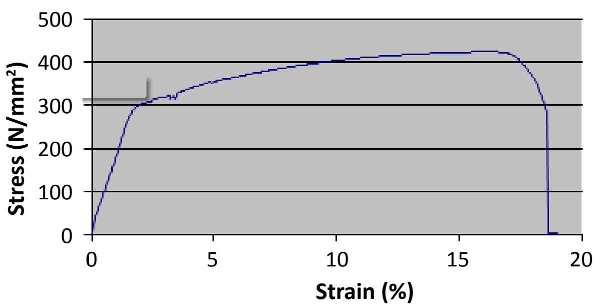

Figure 5: Stress versus strain graph of a water quenched and tempered sample.

impurities in iron which pin down dislocations and this is followed by the unlocking of the dislocations by a higher stress leading to the formation of upper and lower yield points.

It can also been seen from Figures 2 and 3 that the ultimate tensile strength of the normalized sample is greater than the one for the as-received sample. This is probably because normalizing treatment results in the formation of more pearlitic structures as seen in Figure 1B which is harder and stronger than ferrites that predominantly constitute the microstructure of the as received sample as shown in Figure 1A. As seen in Figure 6, the water quenched samples showed the highest strength, which is followed by the hydraulic oil quenched samples while the tempered samples showed the least strength property.

These effects are generally associated with the effect of cooling rate on the type and volume of microstructures formed in the samples. The trend in the mechanical properties can be attributed to the fact that water produced the highest severity of quench and hence fastest cooling rate which caused more volume fraction of martensite to be formed in the water- quenched samples than in the other samples [14]. Also, water quenching induces the highest amount of dislocation density in the quenched samples [17]. Figures 7 and 8 show the variation of strength and hardness respectively with time for the water- quenched samples which were soaked at austenitizing temperature of 900°C. As seen, both the strength and hardness of the samples decrease as the soaking time was increased. The decrease in strength and hardness of the quenched samples with time can be explained from the fact that coarser martensite laths and packets are formed from coarser austenite grains as the soaking time is increased and it follows from the Hall-Petch [16] relationship that the yield strength will decrease with the grain size of the microstructure.

Strength and hardness relationship

Figure 9 shows the variation of teansile strength with hardness

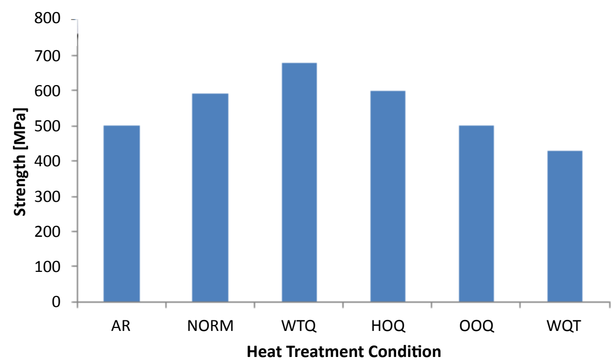

Figure 6: The effect of heat treatment on the tensile strength of medium carbon steel.

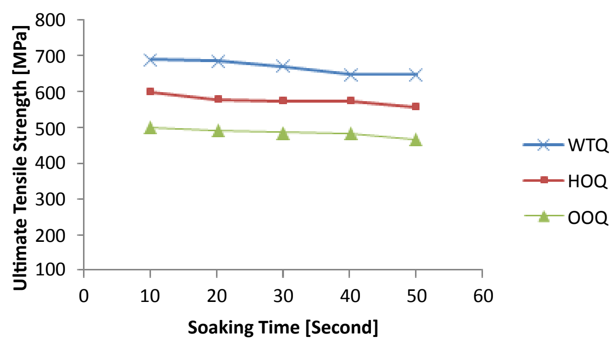

Figure 7: Effect of soaking time on the tensile strength of medium carbon steel quenched in different media.

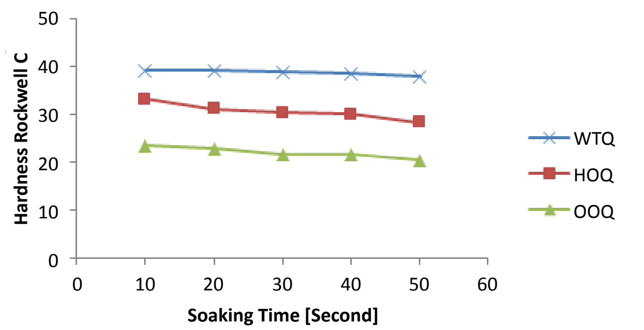

Figure 8: Effect of soaking time on the hardness of medium carbon steel quenched in different media.

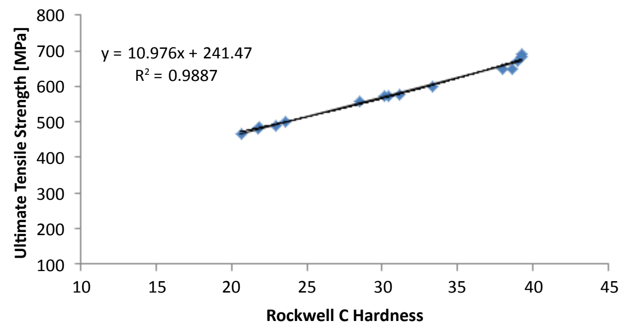

Figure 9: Correlation between tensile strength and hardness.

(Rockwell C) of medium carbon steel quenched in different media. As seen, the tensile strength of the medium carbon steel shows a linear relationship with Rockwell C hardness for the strength range covered by the experiment. A least square linear regression gives the correlation for tensile strength as:

$$TS=241.4+10.97H_{RC} \qquad (5)$$

Regression analysis shows that equation 5 has a coefficient of determination of 0.988 which indicates that over the range of hardness examined, the tensile strength of the hardened medium carbon steel is linearly correlated with hardness.

The estimated strength (ultimate tensile strength, calculated from equation 5) in comparison with the strength based on tensile strength measurement is in the range of UTS ± 18.2 MPa. From the measured results in this work, it can be said that the possibility to predict strength of the hardened steel materials by means of measured values of hardness may be limited because of the number of experimental data. The work, however, established that the interdependence between strength and hardness for hardened steel material is relatively good.

Conclusions

In this work, the possibility of prediction of tensile strength from the measurement of Rockwell C hardness was verified. It was shown that a linear relationship exists between strength and Rockwell C hardness number for a 0.4% carbon steel sample hardened in different quenching media. The result of the work further shows that the normalized sample shows a yield point phenomenon while the hardened and tempered samples show stress versus strain behavior of a typical ductile material. It can also be inferred that the water- quenched samples show the highest strength while the steel materials quenched in olive oil exhibited the least strength and hardness values.

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