The Viability of Water/Alumino-Silicate Solution as Quenchant for Medium Carbon Steels.

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ABSTRACT

The possibility of using a quenchant consisting of water and alumino-silicate solution for hardening process of medium carbon steels was investigated. The percentage of alumino-silicate was varied from 5 to 25% in the water mixture and 100% water was used as a control for the study. Parameters such as specific latent heat of vaporization, hardness value, impact energy, yield strength, tensile strength, percentage elongation, percentage area reduction and microstructures were analyzed.

The results of the tests and analyses carried out revealed that addition of 5wt% alumino-silicate to water gives the best mechanical property as the hardness value, yield strength and tensile strength did not varied appreciably as compare with the control and no crack was observed. This is due to a uniform release of thermal energy in form of latent heat of vaporization across the dimension of the specimen. However, addition of more than 5wt% gives a sharp decrease of the above mechanical properties. Besides, the impart energy values increases continuously with alumino-silicate addition. The specific latent heat of vaporization decreases as the weight fraction of alumino-silicate in the quenchant increases due to high viscosity. The microstructural examination shows that the quenchant produces predominantly lath martensite.

(Keywords: alumino-silicate, medium carbon steel, water, mechanical properties, metallurgy)

INTRODUCTION

The structure, hardness, and strength resulting from heat-treating operations are partly determined by the actual cooling rate obtained from quenching media (Rayan, 1988). Quenching is a process of rapid cooling of steel from austenizing temperature to room temperature usually in a cooling media. It involves heating steel and cast iron to some temperature above the upper critical temperature, in order to convert it partially or completely to austenite. Holding at this temperature for a specified period of time long enough to ensure the desired austenization after which cooling is carried out at a rate equal to or faster than the critical cooling rate. This is possible only when the steel piece is allowed to come in contact with some media, which can absorb heat from the steel piece within a short period. The effectiveness of a quenching process largely depends on the characteristics of the quenchant used.

Thermal and transformation stresses accompanying fast cooling has been the major concern of most heat treaters (i.e., taking closer look at the various oil-base and polymer quenchants). In the last few years, conventional quenching media such as mineral oils and recently, organic polymers (synthetic) quenchants (Raymond, 1993) have been used for quenching various machine components. Other researchers have come up with special additives to water to provide slow cooling rate when the temperature of the quenched part is under 300°C (Dennis, 1963). In metallurgy, the most frequently used vaporizable liquids are; water, oil, brine, air and organic products (Brain, 1963).

Some of the factors, which control quenching characteristics, are as follows: temperature of the quenchant, specific latent heat of vaporization of the quenchant, Specific heat capacity of the quenchant, thermal conductivity of the quenchant, viscosity of the quenchant, degree of agitation of the quenching bath. In this paper, some of these properties were examined.

In practice, the applicability of water as quenching medium is restricted only to plain carbon steels and a few grades of low alloy steels. The higher cooling rates exhibited by water involves a swift structural transformation varying in intensity from surface to center and, in consequence, produces severe internal stresses where the transformation from one structure to another is imperfect and incomplete. These stresses, in their struggle to achieve relief may produce considerable warping, distortions, dimensional instability and crack formation. Also, water absorbs large quantities of atmospheric gases, and when a hot piece of metal is quenched, these gases have a tendency to form bubbles on the surface of the metal. These bubbles tend to collect in holes or recesses and can cause soft spots that lead to warping. With water as a quenchant is the vapor blanket stage is quite stable for prolonged periods and this reduces further cooling of the steel. One great drawback with water is that the rate of cooling is high in the temperature range of martensite formation. This exposes the steel to simultaneous influence of thermal and transformation stresses, the combined effect is crack formation (Rayan, 1988).

The primary driving force for this research and development on quenching media is a desire to produce a material with desirable mechanical features; characteristic of low thermal and transformation stresses, little or no crack that can be used in engineering applications.

The objective of this study is therefore to develop and test for the viability of a mixture of clay and water aqueous solution(s), which will serve as quenching medium for carbon steels.

This study is aimed at creating awareness as well as to stimulate interest in the use of a mixture of clay and water solution as quenching medium. This consideration is particularly important because of the roles quenched components with improved mechanical properties are now playing in engineering and many other applications, in more recent times.

MATERIALS

The alumino-silicate material used is white, fine powder particles. These particles are not synthetic, being obtained from natural geological deposits found in abundance in Kankara Village, Katsina State-Nigeria (Aigbodion, 2007). The composition of the alumino-silicate is shown in Table 1 in weight percentage.

The medium carbon steel specimens used was obtained and a chemical analysis was carried out on the steel (Oghenevweta, 2008) and the result is shown in Table 2 in weight percentage.

Table 1: Chemical Composition of Alumino-Silicate Material used.

Kankara Clay	Wt %
SiO_2	56.50
Al_2O_3	24.95
Fe_2O_3	Nil
CaO	1.00
MgO	2.32
Na_2O	> 0.000003
K_2O	> 0.000003
FeO	Nil
TiO_2	> 0.000000
L.O.I	15.32

Table 2: Chemical Composition of the Medium Carbon Steel used.

Elements	C	Mn	Si	Ni	Cr	Mo	Al	P	Co
Wt%	0.33	0.84	0.29	0.05	0.08	<0.005	0.012	0.037	0.015

Elements	Nb	Ti	V	W	Pb	Sn	Zn	S	Cu	Fe
Wt%	<0.005	0.0025	0.007	<0.001	<0.005	<0.005	0.0016	0.046	0.073	98.21

Equipment

The equipment used for the purpose of austenizing the medium carbon steel samples include an electric furnace with operating temperature up to 1400°C before quenching in the media. The apparatus used in the determination of the specific capacity by the method of mixtures include: copper piece, beaker, copper calorimeter and stirrer, heater, thermometer, insulating jacket, and weighing balance (Hariharan, 2007). Also, the apparatus used in the determination of the specific latent heat of vaporization include: steam broiler, steam trap, copper calorimeter and stirrer, insulating jacket, heater, thermometer, and chemical balance.

All tensile tests were carried out on a Hounsfield strength-testing machine. Brinell hardness testing machine using 2.5mm diameter of ball indenter and 187.5kg load application was used for all the hardness measurement of the quenched specimens and the as-cast. Besides, an Izod Impact-testing machine was used for the entire impact test done on the as-received and quenched specimens.

A polishing machine, etchant and metallurgical microscope with an in-built camera were used to examine the microstructure of all the steel specimens.

METHODS

Preparation of the Alumino-Silicate (Kankara Clay)

Preparations of the alumino-silicate test samples involved grinding of the dry lump sizes into powdered form and then sieved. The percentage of alumino-silicate ranging from 5 to 25% were thoroughly dissolved in the corresponding weight percentage of (95 to 75% water respectively) water, the mixed blend was poured into five (5) steel buckets and 10litres of water without alumino-silicate dissolution (100% water) was poured into another bucket to be used as the control. In all, six quenching media were prepared and the physical property i.e. specific latent heat of vaporization were determined.

Determination of Specific Latent Heat of Vaporization of Water with Alumino-Silicate Dissolution

The specific latent heat of vaporization of water with alumino-silicate dissolution is defined as the heat required to convert unit mass of it, at its boiling point, into vapor at the same temperature. The procedure for its determination is as follows:

Step 1 – fill the steam boiler with 0.5Kg (5%) fraction of alumino-silicate dissolved in 9.5Kg (95%) of water, fit into it the cork and the steam trap and boil the mixture.

Step 2 – the calorimeter and stirrer were weighed.

Step 3 – fill the calorimeter half way with water and re-weigh.

Step 4 – the initial temperature of the water is noted.

Step5 – steam from the steam jacket is passed through a steam trap to remove any condensed moisture. Dry steam is passed into the water in the calorimeter until the temperature of the water rises to about 10°C above the room temperature.

Step 6 – the steam source is removed from the calorimeter and the water source is stirred continually until a steady final temperature is reached.

Step 7 – the calorimeter and the mixture is weighed to find the mass of the condensed steam.

Measurements:

Mass of calorimeter and stirrer
$m_1 =$ Kg

Mass of calorimeter and stirrer + water
$m_2 =$ Kg

Mass of calorimeter and stirrer + water + steam
$m_3 =$ Kg

Initial temperature of calorimeter and contents
$\theta_1 =$ °C

Final temperature of calorimeter + contents
$\theta_2 =$ °C

The experiment is repeated for other weight fractions of alumino-silicate dissolved in water following the above procedure. Assuming that the heat lost by steam condensing and the heat loss by condensed steam in cooling from 100°C to temperature θ_2 is equal to the heat gained by water and calorimeter (Okeke, 1987).

Let, S1 = specific heat capacity of calorimeter

S_2 = specific heat capacity of water

L = unknown specific latent heat of vaporization of the quenchant.

The temperature of steam is assumed to be 100°C. From the measurement above:

Mass of water = $m_2 – m_1$

Mass of steam = $m_3 – m_2$

Heat lost by steam condensing = $(m_3 – m_2)L$

Heat lost by condensed steam in cooling from 100°C to .θ_2 = $(m_3 – m_2)(100 - \theta_2)S_2$

Heat gained by water = $(m_2 – m_1)(\theta_2 - \theta_1)S_2$

Heat gained by calorimeter = $m_1S_1(\theta_2 - \theta_1)$

This implies that:

$$(m_3 – m_2)L + (m_3 – m_2)(100 - \theta_2)S_2 = [(m_2 – m_1)S_2 + m_1S_1](\theta_2 - \theta_1)$$

$$(m_3 – m_2)L = [(m_2 – m_1)S_2 + m_1S_1](\theta_2 - \theta_1) – (m_3 – m_2)(100 - \theta_2)S_2$$

$$L = \frac{[(m_2 – m_1)S_2 + m_1S_1](\theta_2 - \theta_1) – (m_3 – m_2)(100 - \theta_2)S_2}{(m_3 – m_2)}$$

$$L = \frac{[(m_2 – m_1)S_2 + m_1S_1](\theta_2 - \theta_1)}{(m_3 – m_2)} - (100 - \theta_2)S_2$$

Heat Treatment

One tensile test specimen and one impact test specimen were put in small cast iron chips. The crucibles were covered and sealed with clay. This was done to eliminate decarburization during austenization. The crucibles were then placed in an electric furnace and heated to a temperature of 1000ºC. The specimens were soaked at his temperature for one hour, after which one of the austenized tensile and one impact test specimen per batch were quenched in the various quenching media. It was ensured that the specimens were adequately submerged in the quenchant.

Tensile Test

The tensile tests were carried out on a Hounsfield Tensometer using the standard machined tensile test specimen of 5mm diameter and a gage length of 30mm.

The results obtained were used to calculate the yield strength, tensile strength, percentage elongation and percentage area reduction.

Impact Test

The impact tests were also carried out on an Izod impact-testing machine to measure the toughness of the specimens. The dimensions of the standard sample used are 2.5mm notch diameter and a length of 30mm.

Hardness Test

The hardness values of the carbon steels were taken at least at three different points to obtain an average hardness result using the Brinell hardness testing machine of 2.5 mm diameter of ball indenter under 187.5 kg load application. The time for the load carrying capacity of the equipment is 10 secs. The equipment has a built-in screen that displays the hardness value after the indentation has been made.

Microstructural Determination

Each of the seven (7) specimens that were prepared with as-received and heat treated conditions were used for microscopic examination.

RESULTS

Table 3 shows the specific latent heat vaporization of the quenchant and Table 4 shows the mechanical properties of the as-received and quenched medium carbon steel. Figures 1 to 4 shows the variations of mechanical properties with percentage alumino-silicate. The microstructures are presented in Plates 1 to 7.

DISCUSSION

The Effect of Alumino-Silicate on the Specific Latent Heat of Vaporization

From the results of the specific latent heat of vaporization, it can be seen that as the weight percent of alumino-silicate dissolved in water increases, the property investigated decreases. The decrease in the values of the property as the percentage of alumino-silicate addition increases is due to high degree of plasticity and viscosity of the alumino-silicate in water (Raham, 2007). As expected, the higher the viscosity, the lower the value of the specific latent heat of vaporization of the quenchant (Hassan, 2005). However, at relatively lower viscosity, there will be easier generation of conventional currents and this seems to stabilize the cooling power at the vapor transport stage in the quenching operation.

The Effects of the Quenchants on the Yield and Tensile Strength

The yield and the tensile strength of the quenched specimen decrease with increasing alumino-silicate in water as showed in Figures 2 and 3. However, at 5%wt fraction of alumino-silicate, both properties do not change appreciably in value as compare to when 10%wt of alumino-silicate or more was added.

This demonstrates the fact that at 5% the vapor transport stage was stabilized. This is in agreement with the specific latent heat of vaporization which determined the stability of the stage of fast cooling and the release of the thermal energy was uniform across the specimen. Besides, it was also observed that there were no noticeable cracks at 5% which implied that there were little thermal and transformation gradients across the dimensions of the specimen that could cause cracks.

This suggests that the stable film of vapor that formed and which enveloped around the work piece during this stage is eliminated quickly (Edwin, 1966). The rapid decrease in yield and tensile strength beyond 5% weight fraction alumino-silicate is due to high viscosity and vaporization of the quenchant forming stable films of vapor, which cannot be reconverted into liquid in the shortest possible time as observed in the sharp decrease in values obtained from the specific latent heat of vaporization (Avner, 1934).

The Effects of the Quenchants on the Hardness Value

The hardness values decreased as the weight fraction of alumino-silicate increases but there were little change in the hardness value at 5% weight fraction of alumino-silicate as compare with the control and as showed in Figure 1.

Table 3: Specific Latent Heat of Vaporization.

Quenchants	Specific Latent Heat of Vaporization (j/kg) x 10^6
Water without alumino-silicate	2.33
Water with 5% alumino-silicate	2.03
Water with 10% alumino-silicate	1.70
Water with 15% alumino-silicate	1.57
Water with 20% alumino-silicate	1.29
Water with 25% alumino-silicate	1.06

Table 4: Mechanical Properties of the Medium Carbon Steels.

QUENCHANT	Hardness Value (BHN)	Yield Strength (N/mm^2)	Tensile Strength (N/mm^2)	% Elongation	% Area Reduction	Izod Impact Energy (J)
Water without alumino-silicate dissolution	368	1208	1443	2.0	5	12.0
Water with 5% alumino-silicate	360	1200	1440	2.5	15	16.0
Water with 10% alumino-silicate	297	752	989	2.5	20	18.0
Water with 15% alumino-silicate	286	702	968	2.5	22	19.0
Water with 20% alumino-silicate	279	650	884	3.0	22	24.0
Water with 25% alumino-silicate	250	515	760	3.0	33	25.0
As-received	121	211	408	8.0	50	32.0

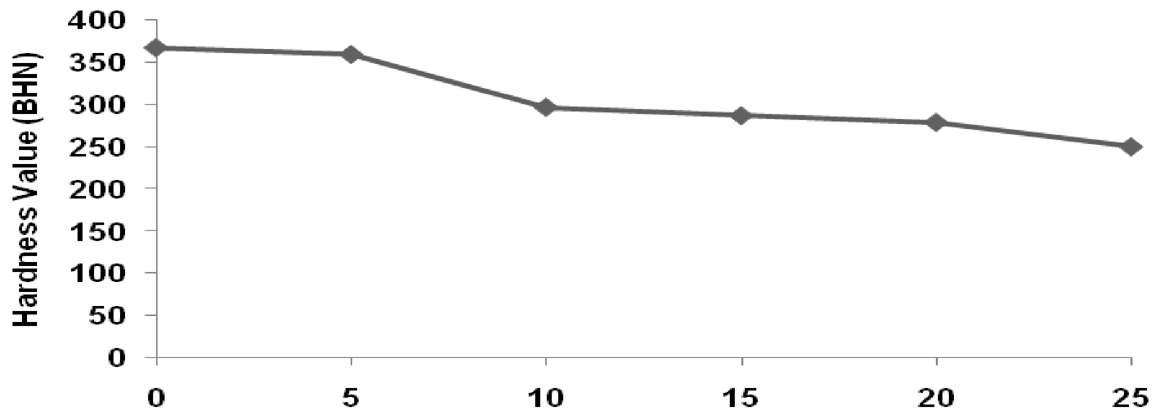

Figure 1: Variation of Hardness Value with % Addition of Alumino-Silicate.

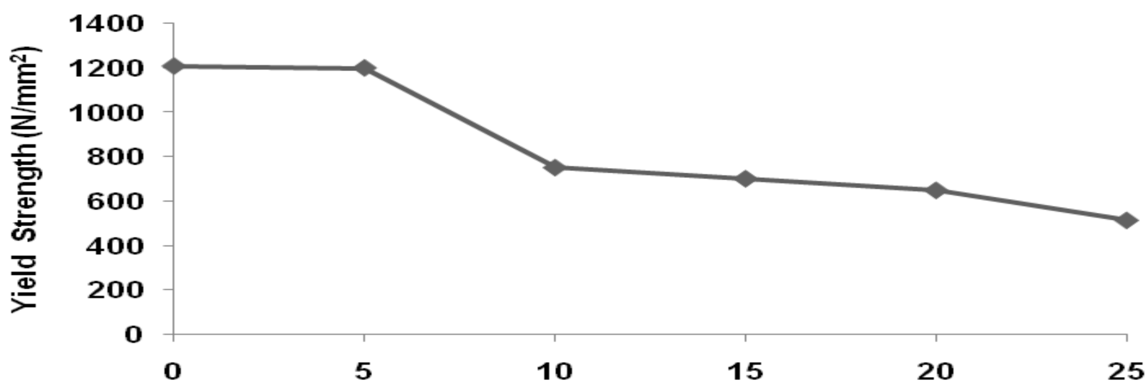

Figure 2: Variation of Yield Strength with % Addition of Alumino-Silicate.

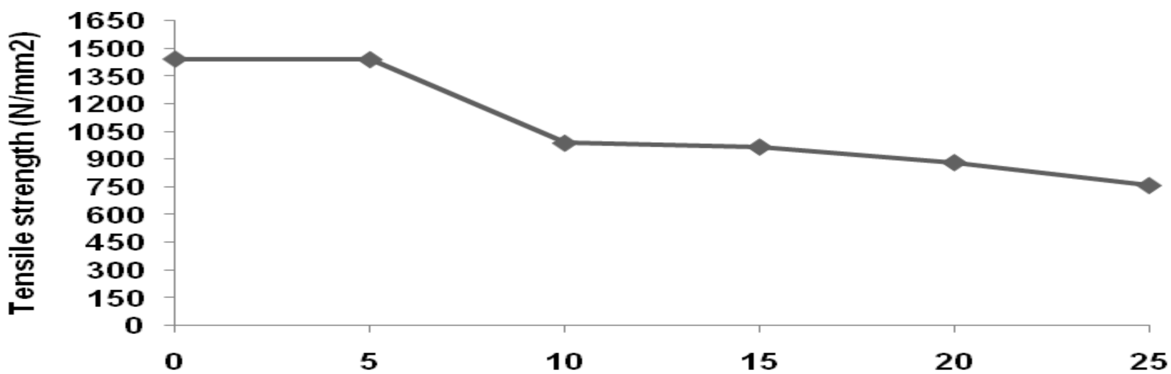

Figure 3: Variation of Tensile Strength with % Addition of Alumino-Silicate.

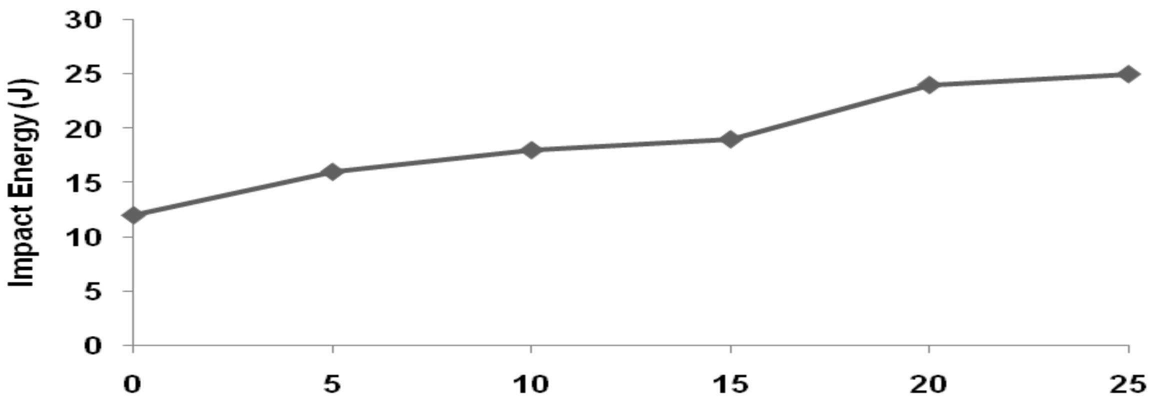

Figure 4: Variation of Impact Energy with % Addition of Alumino-Silicate.

This is in agreement with specific latent heat vaporization value obtained at 5% which probably stabilizes the rate of the vapor transport cooling stage where very rapid cooling takes place (William, 1997). This suggests that hard lath martensite particles are formed. This is in agreement with the microstructural observation in Plate 3 when 5% was added. The sharp decrease in the hardness value beyond 5 wt% alumino-silicate addition may be due to the formation of relatively high percentage of untransformed austenite in the matrix. The reason is that the severity of the quenching or rate of cooling has been reduced drastically due to high viscosity (David, 1981). This is also in agreement with the microstructural observation in Plates 4 to 7. This is also in the agreement with sharp decrease of values obtained from the specific latent heat of vaporization (Hassan, 2005).

The Effects of the Quenchants on the Impact Energy

The impact energy values of the quenchants increased with increase in alumino-silicate additions. The continuous increase in the impact energy (toughness) is due to the formation of more soft and ductile particles [13]. This is in agreement with the microstructural observations.

Microstructural Analysis

The different microstructures developed as a result of addition of alumino-silicate to the quenchants and as-received are shown in Plates 1-7.

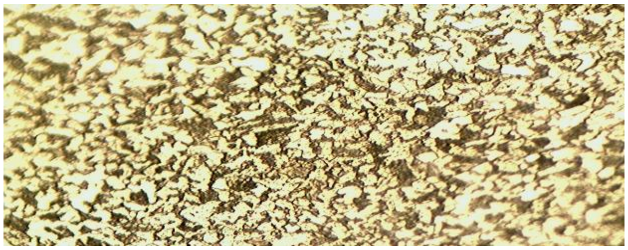

Plate 1: As-received microstructure of 0.33%C steel (medium carbon steel) showing pearlite (dark region) in ferrite (white region) matrix. Etched in 2% Nital. Magnification x 400.

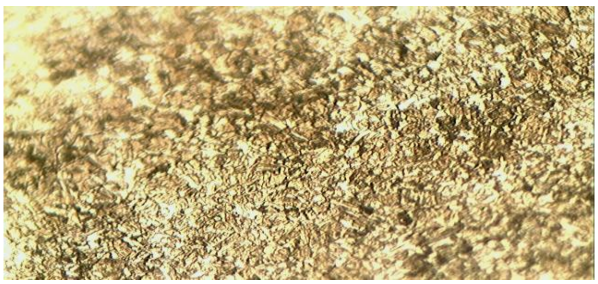

Plate 2: Water quenched (100% water) microstructure of 0.33%C Steel showing Lath Martensite. Etched in 2% Nital. Magnification x 400.

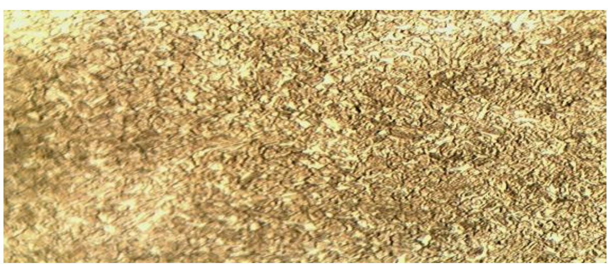

Plate 3: 95% water + 5% alumino-silicate quenched microstructure of 0.33%C Steel showing high proportion of full lath Martensite. Etched in 2% Nital. Magnification x 400.

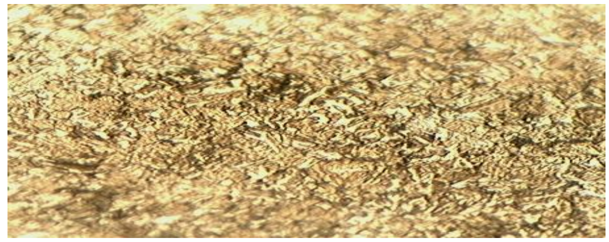

Plate 4: 90% water + 10% alumino-silicate quenched microstructure of 0.33%C Steel showing Martensite and low proportion of untransformed Austenite. Etched in 2% Nital. Magnification x 400.

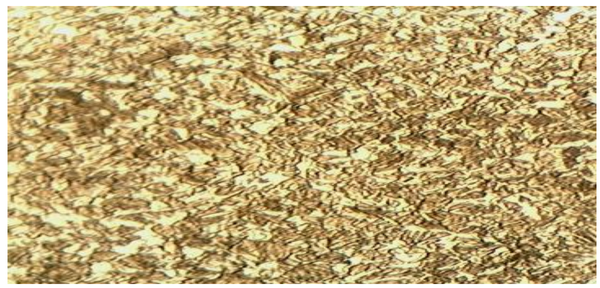

Plate 5: 85% Water + 15% alumoni-silicate quenched microstructure of 0.33%C Steel showing low proportion of Martensite and untransformed Austenite. Etched in 2% Nital. Magnification x 400.

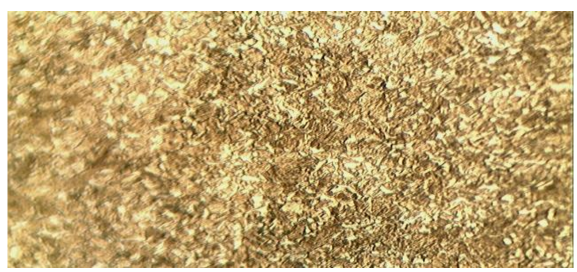

Plate 6: 80% Water + 20% alumino-silicate quenched microstructure of 0.33%C Steel showing fewer Martensite in higher proportion of untransformed Austenite. Etched in 2% Nital. Magnification x 400.

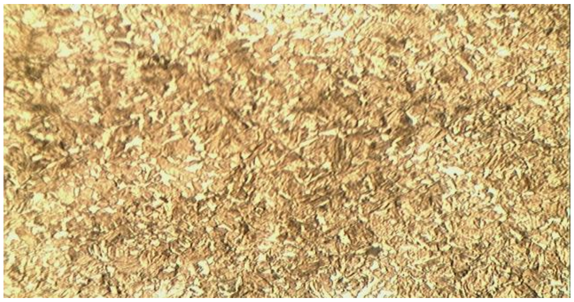

Plate 7: 75% water + 25% alumino-silicate quenched microstructure of 0.33%C Steel showing very low Martensite in high proportion of untransformed Austenite. Etched in 2% Nital. Magnification x 400.

The microstructural studies revealed that the as-received medium carbon steel was made up of pearlite in ferrite matrix as showed in Plate 1. Plate 2 shows the microstructure of martensite and untransformed austenite i.e. 100% water (control). Moreover, Plate 3 reveals the microstructure of fine lath martensite i.e. 5% alumino-silicate. Plates 4, 5, and 6 show predominantly few lath martensite and untransformed austenite at respectively 10%, 15% and 20% while Plate 7 reveals high proportion of untransformed austenite and small lath martensite (i.e., 25%).

From the microstructure developed at 5wt% of alumino-silicate addition, it can be seen that fine lath martensite dominates the structure of the medium carbon steels hence, the addition of alumino-silicate to water as a quenchant is an effective means of producing martensite structure which is characteristic of producing considerable high hardness and little or no warping as compare with the control and these steels could be applied where wear resistance is needed. The reason for this dominant martensite structure and no cracks is because the quenchant were able to minimized vaporization during cooling.

CONCLUSIONS

The effectiveness and viability of water with percentage fractions of alumino-silicate additions as quenching media in the hardening process of the medium carbon steel has been quantitatively assessed using microstructural characterization, mechanical properties and hardness in particular. From the results obtained in this study, it can be concluded that:

1) The addition of alumino-silicate particles to water increases the impact strength of the Carbon Steel.

2) The addition of alumino-silicate particles to water give appreciably high value of yield strength, tensile strength and the hardness values of the medium carbon steels at 5wt% alumino-silicate addition as compare to the control but it is accompanied by a general reduction in these properties as the percentage additions exceed 5%wt alumino-silicate due to high viscosity.

3) For optimum service performance and quench hardening purposes of these carbon steels, alumino-silicate addition should not exceed 5wt% in order to avoid any compromise in the mechanical properties.

4) The specific latent heat of vaporization decreases as the weight percentage of alumino-silicate increases. This is due to high viscosity of the quenchant.

5) For practical purposes, the selection of quenching medium is dictated by the resulting mechanical properties of the steel products required, which are dependent on the cooling rates. The most suitable quenchant was obtained at 5wt% alumino-silicate because it developed appreciably high hardness value and tensile strength without considerable cracking. Hence, it can be used as alternative to water for hardening purposes in carbon steels.

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