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Hardening and characterisation of 0.45%C steel using clay/water media as quenchant

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Abstract: Hardening and characterization of 0.45%C steels using clay/water media as quenchants were investigated. Different weight percent of clay was added to water to form clay/water quenching media and water was equally use as the control. The steel specimens were heated to the austenizing temperature and quenched in these liquid media. The specific latent heat of vapourization of the liquid media, hardness value, impact energy, yield strength and tensile strength of the specimen were analyzed. The morphologies of the as-quenched steels were observed by using SEM. The results revealed that addition of 2-4wt% clay to water gives the best mechanical properties. This may probably be due to a uniform release of thermal energy in form of latent heat of vapourization across the dimension of the specimen and prevention of the oxide film formation on the surface of the workpiece. However, further addition of clay greater than 4% result to decrease in the mechanical properties of the specimen tested. The specific latent heat of vapourization decreases as the weight fraction of clay in water increases. Results from the microstructural examination indicate predominantly formation of martensite and retained austenite phases.

Keywords: Clay, 0.45%C Steel, Water, Microstructures and Mechanical Properties

1. Introduction

Historically, quenching of steels as a heat treatment operation dates back to about 3500 years where the ancient Egyptians civilization uses hardened steels to build foundations [1]. The basics of quenching involved rapid cooling of work piece especially low-alloyed or medium carbon steel in a media such as water. There are a wide variety of other quenchants available other than water such as salt solutions (brine), aqueous polymers vegetable oils and mineral oils. Brine and water remain the most dominant quenching media since both possesses high rate of cooling and a wide range of quenching characteristics can be obtained [2, 11].

Quenching is a tool used to improve the performance of steels however side effects such as induced thermal and transformational stresses causes changes in size and shape of the work piece which usually result to cracks, warping and flaws formation [2, 15]. One of the technical challenges of quenching as a heat treatment process is to select a quenchant medium that could minimize or eliminate these side effects while at the same time provide an interface for heat to be transfer from the work piece to the medium in order to produce the desired properties [1, 15]. Properties such as hardness, impact strength, tensile strength and fatigue bending strength of as-quenched parts of machines has been reported to depend on mode of quenching [2].

In most quenching operations, it has been stated that rapid quenching is required to develop the best properties however; lower quench rates are normally used to minimize residual stresses being induced during quenching [3, 17]. Hassan *S.B* [9] reviewed methods of evaluating the effects of quench rate on mechanical properties, and concluded that the simplest and most effective method was to use media that will result to enhanced microstructural properties with minimal distortions of the material.

The performance of a series of mineral oil based quenchants has been investigated by Totten *et al* [3] and the results revealed that the maximum cooling rate increases with decrease in quenchant viscosity. The use of vegetable and mineral oils have been studied extensively by different researchers and their observations indicate that as the viscosity of these oils decreases, the heat transfer coefficient increases with the increase in hardening power and maximum cooling rate [4,5,8,13,14]. Oghenevweta *et al* [7] uses combination of alumino-silicate and water to hardened a medium carbon steel and discovered that there is decrease in the tensile strength and hardness value of the specimen tested. The decrease in properties was attributed to the high amount of clay added to water which increases the viscosity of the media resulting to relatively poor mechanical properties [15].

In this present investigation, the weight of the clay added to water was reduce from 5-25% to 2-12%. The essence of this reduction was to test the severity of quenching and the resultant morphologies and mechanical properties of the as-quenched steels. The continuation of the investigation is necessary because of the novelty of the approach of using a refractory material with water for quenching operation. It has been stated earlier that using water alone could introduced some defects which probably render the quenched work piece either unusable or witness drastic failure during application [11]. This method may probably hold the key to prevent the limitation pose by using water alone.

2. Experimental

Dried lump of Kankara clay was ground into fine powders and then sieved unto a set of seizes arranged in descending order as described in BS 1377:1990. Particles retained in 80μm mesh size were used for the investigation. The percentage of clay ranging from 2-10% at an interval of 2 was dissolved in the corresponding weight percentage of water. A quenching medium consisting of 10 litres of water without clay dissolution was used as the control. In all, six quenching media were prepared and the specific latent heat of vapourization of these media was measured and calculated [8]. The steel samples were heated to a temperature of 1000ºC in an electric furnace and austenized at the austenizing temperature. The specimens were soaked at his temperature for one hour and then discharged. The discharged samples were quenched in the quenching media. The strengths and the impact energy of the specimen were measured by using the Instron machine (model 5564) in accordance with standard ASTM D 638-90 and PN-EN 10045- 01 method respectively. The morphologies of the as-quenched specimens were examined by using scanning electron microscope (SEM)

3. Results and Discussion

3.1. Results

Table 1 shows the results of the specific latent heat vapourization of the quenching media and the mechanical properties of the as-quenched specimen respectively. Figure 1 shows a graph illustrating the hardness values of the as-quenched specimen. It was observed that the hardness of the as-quenched steel increased in value as the weight of clay to water increase from 2-4% however, there was a progressive decrease in the hardness value as the amount of clay added to water increases from 6-12%. The trend of the hardness value as compared to the previous work of Oghenevweta *et al* [7] was different in the sense that in the previous research there was a continuous degree in the value of hardness even when 10-15wt% of clay was added.

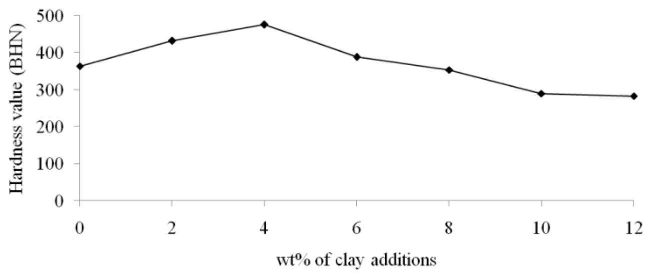


Figure 1. *Variation of hardness value with weight percent of clay additions*

Table 1. *Specific latent heat of vaporization of the quenching media and the mechanical properties of the as-quenched 0.45%C steel*

Quenchants	Hardness Value (BHN)	Yield Strength (N/mm^2)	Tensile Strength (N/mm^2)	Izod Impact Energy (J)	Specific latent heat of vaporization ((J/Kg)x10^6)
Water	364	1204	1442	13.0	2.31
2% clay + 98% water	432	1298	1582	12.0	2.00
4% clay + 96% water	476	1338	1653	10.0	1.80
6% clay + 94% water	388	1240	1500	11.0	1.67
8% clay + 92% water	354	1201	1457	12.0	1.34
10% clay + 90% water	290	1156	1349	14.0	1.22
12% clay + 88% water	283	1103	1206	18.0	1.14
As-received	123	214	411	31.0	-

Fig. 2 shows the the yield and tensile strength of the as-quenched steel specimen. Obviously, both properties indicate a sharp increase in the strength of the specimen when 2-4wt% of clay was added. However, further increase of clay in water reduces the strength of the workpiece continously. Figure 4.3 shows the graphical representation of the impact energy of the as-quenched workpiece. It was observed that the initial addition of 2-4wt% of clay reduces the ability of the workpiece to absorb shock and formation of cracks and flaws. When the impact energy of the specimen was acquired at 6-12wt% of clay additions in water, there was a corresponding increase in the impact energy value of the as-quenched specimen.

The micrographs 1-2 show the morphologies of the as-received 0.45%C steel (see Micrograph 1(a)) and the as-quenched workpiece. The structure of the as-received carbon steel indicate a composite composition of ferrite (white) and pearlite (dark) microconstituents while the as-quenched workpiece consist different microstructural phases. The specimen that was quenched in water (control) indicate three phases and these phase are accicular ferrite, retained austanite and martensite. A closer view of the microstructure of the water quenched workpiece indicate evident of combination of cementite and dislocated ferrite which is probably a non-equilibrium structure of bainite. However, the sructure of this bainite looks very similar to that of martensite. It might take TEM to clearly differentiate this observed bainite from martensite. However, the microstructures of the as-quenced workpiece when 2-4wt% of clay was added to water indicate large proportions of martensite with probably non-equilibrium bainite. Also, the micrograph shows evident of small proportions of retained austensite which we believe is always associated with high severity quenching operation. The micrographs obtained when 6-12wt% of clay was added indicate the formation of Widmanstaten ferritic structure especially at 6wt% additions (see Micrograph 3a), dislocated and dendritic ferrites and pearlite strcutures.

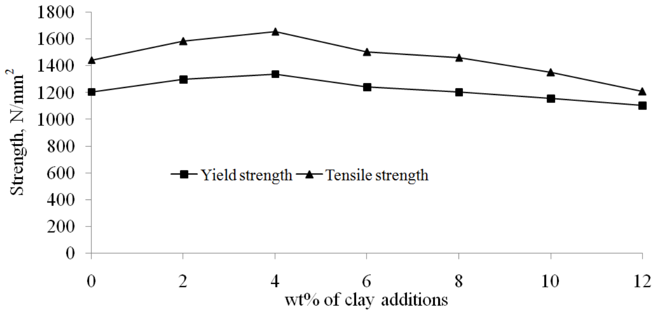


Figure 2. *Variation of yield and tensile strength with weight percent of clay additions*

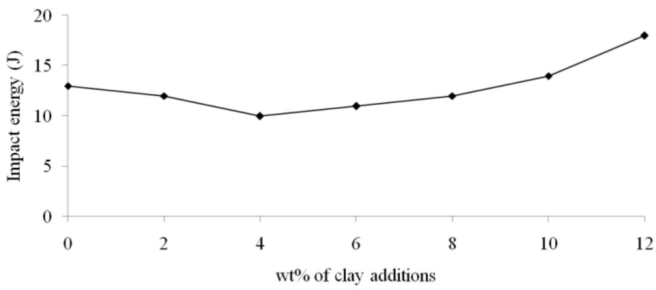
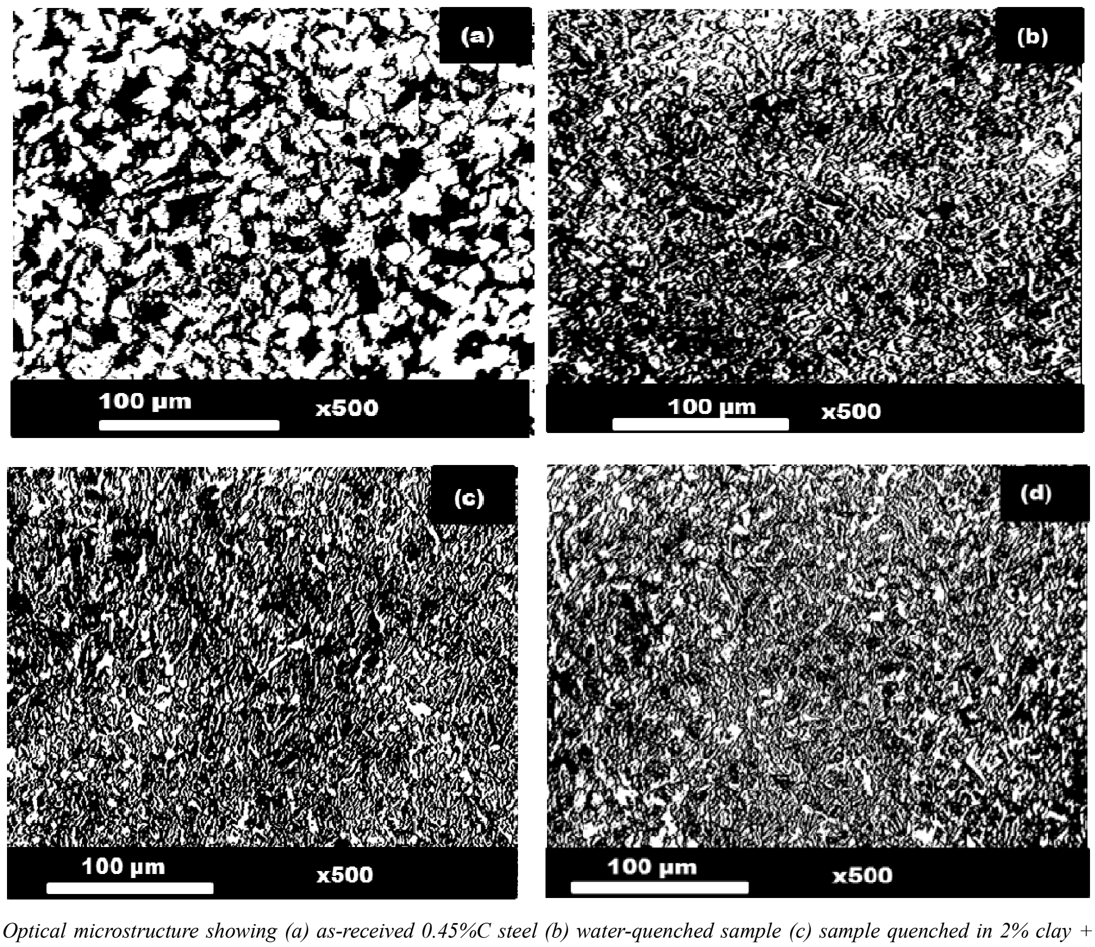
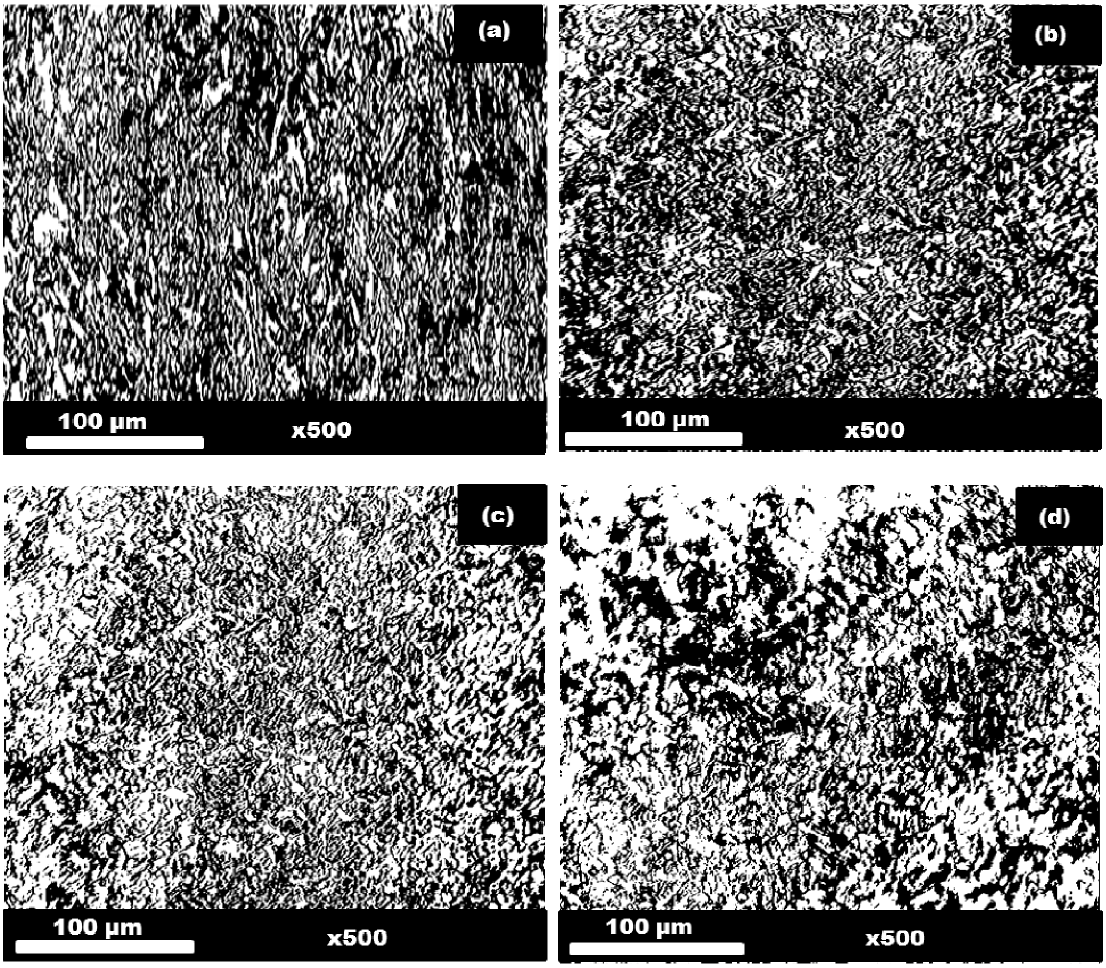


Figure 3. *Variation of impact energy with weight percent of clay additions*



Micrograph 1. *Optical microstructure showing (a) as-received 0.45%C steel (b) water-quenched sample (c) sample quenched in 2% clay + 94% water (d) sample quenced in 4% clay + 92% water.*



Micrograph 2. *Optical microstructure showing (a) sample quenched in 2% clay + 98% water (b) sample quenced in 4% clay + 96% water (c) sample quenched in 10% clay + 90% water (d) sample quenced in 12% clay + 88% water.*

3.2. Discussion

The specific latent heat of vapourization of the various prepared quenching media as shown in Table 1 indicate a decrease in its value as the clay content in water increases. The decrease is probably due to increase in the viscosity of the liquid [7, 13]. It has been shown that the higher the viscosity, the lower the value of the specific latent heat of vapourization [6]. However, if the viscosity is within a critical range (2.1-1.82), the conventional currents generated at high heat generation could probably stabilize the cooling power of liquids at the vapour transport stage during quenching operation [1].

During quenching, there are three basic stages which the work piece passes before it will eventually cool down to room temperature and these stages include the vapour blanket, vapour transport and the convective cooling stages. It is worth mentioning that the vapour blanket stage involves the formation of unbroken oxide films that usually surround and insulate the workpiece. These oxide films are usually formed when the heat generated by the work piece is more than the heat which the quenching medium can absorb. Among other factors that affect this stage and the stability of the oxide film include the nature of the oxide formed, surface-enhanced additives, work piece surface and formation of more volatile oxide films. The vapour transport stage involves the rigorous boiling of the quenching media resulting in rapid heat transfer from the workpiece to media in form of heat of vapourization. It usually starts when the temperature of workpiece has cooled down resulting to breakdown of the initially formed oxide film. This stage usually records the highest heat transfer rate during the quenching operation. Finally, the liquid cooling stage starts when the temperature of the workpiece has been reduce to the boiling point of the quenching media [15, 16]. When the temperature of the workpiece has been reduced below the boiling point of the media, slow cooling of the workpiece will be by convection and conduction. The cooling stage is majorly affected by the viscosity of the medium. An ideal quenching media is the one that exhibit high quenching speed at the first and the second stage while slower quenching speed at the third. Thus, the ideal quenchant is one that exhibits little or no vapor stage, a rapid boiling stage, and a slow rate during convective and conduction cooling [14].

The as-quenched microstructure obtained at 2-4wt% of clay added to water shows that there are high proportions of martensite structures as shown in Micrograph 1(c & d). It has been theoretically shown that time and temperatures are the major factors that affect phase transformation. Probably, the evolution of more martensite during addition of 2-4wt% of clay to water as compared to when water was use alone may suggest that the time spent by the workpiece during the vapour blanket stage is very short. It may likely also indicate that the oxide film formed during the vapour blanket stage collapses at a shortest possible time [13]. This is only a presumption of the likehood of this taking place however; there might be high possibilities that when 2-4wt% of clay was added to water, the introduction of these percentages of clay prevent moisture build up around the workpiece. The prevention of oxide build up as presumed around the workpiece might speed up the onset of the boiling stage. It may be suggested that the addition of 2-4wt% of clay to water may increase the probability of the boiling range as compared to water that has shorter boiling range. If this is true then there is a high possibility of these two media to extend the duration of the high cooling stage which may enable more time for martensite to form and also enable the transformation stresses generated to be release [10]. The extension of the boiling stage may prevent the slower convective stage to start sooner. However, increase in the amount of clay added to water more than 4wt% indicates that the microstructures contained lower proportion of martensite and other constituents such as bainite and retained austenite forming. The development of these microstructures may probably suggest that the time and temperature available for transformations to take place are longer as compared to when 2-4wt% of clay was added to water. Moreover, addition of more clay to water increases the viscosity of the liquid. It has been shown that the higher the viscosity of liquid media, the lower the probability of the high transfer rate from the workpiece to the liquid media if other factors such as the ability of some quenching media to decrease in viscosity due to increase of temperature of the bath are presumed to be constant [11]. Surprisely, it was also observed that the outward appearance of the workpiece of all the composition of clay added to water, there was no visible crack and distortion of the workpiece found however, when the workpiece was examined for water-quenched, the surface indicate slight crack formation and warping of the workpiece. These observations clearly indicate that there were little thermal and transformation gradients across the dimensions of the specimen that could cause cracks during the addition of clay to water [6].

The hardness value and yield and tensile strength of the as-quenched steel indicate that there was initial increase in these properties when 2-4%wt of clay was added to water (see Table 1). The initial increase in the hardness value may probably due to the presence of high proportion of hard martensite particles contained in the microstructures (see Micrograph 2). Moreover, the initial increase in the yield and tensile strength of the as-quenched may probably due to formation of high dislocation densities which are associated with martensite structures. The presence of high amount of dislocation contained in these microstructures may probably resist the application of tensile load resulting in the initial increase of these mechanical properties. However, when the amount of clay dissolved in water was increase further than 4wt%, there is resultant decrease in the hardness, yield and tensile strength of the as-quenched steel. The progressive decrease in these mechanical properties may point to the fact that softer and ductile microstructures such ferrites are being developed. This decrease in the hardness value, yield and tensile strength is believed to be in agreement of the earlier research of Oghenevweta *et al* [7]. However, the impact energy values of the as-quenched steels follow the opposite trend to that of other mechanical properties tested. The initial decrease in the impact energy of the as-quenched 0.45%C steel may be due to the brittleness of martensite phase contained in the microstructures acquired when 2-4wt% of clay was added to water.

4. Conclusion

This current research was able to assess the morphologies and mechanical properties of 0.45%C steel when different amount of clay was added to water for quenching operation. The results obtained in this present research as compared to the earlier work shows a great improvement on the mechanical properties. It is believed that the development of this novel liquid media for quenching heat treatment may stir up scientific discussion in the coming years. Quenching is a complex process because it is affected by many process parameters and this research might be a platform where these parameters can be measured and scientifically characterised. Statistical modelling of these parameters in the nearest future might be explored however; a novelty quenching media is believed to be added to the numerous types we have now for commercial purposes. Because of the poor mechanical properties recorded for higher additions of clay to water, lower amount of clay in water should be considered.

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