Effect of Quench Immersion Speed in Water on the Mechanical Properties of C30 Carbon Steel

S.M. Adedayo, A.S. Adekunle, and T. Oladimeji

Abstract - A C30 carbon steel was quenched in a special bath under conditions of constant bath temperature and a variable immersion speed. Time versus temperature data was collected during the quench and mechanical properties such as hardness and tensile strength of material were examined thereafter. Immersion speed variation was by a variable weight-force application acting on the quench specimen falling freely through an extended height quench bath. At immersion speeds of 0.106 m/sec, 0.697 m/sec, 0.853 m/sec, 1.065 m/sec and 1.139 m/sec. yield strength of the material are 310.40, 496.12, 500.56, 565.40 and 579.92 MN/m^2 respectively. At a typical location of radius 15 mm on specimen mid-height the corresponding hardness values are 275, 293.40, 454.60, 408 and 594 VHN respectively. There is an enhancement of mechanical strength with immersion speed increase.

Index Terms: Quench, Immersion speed, hardness, tensile strength, temperature

I. INTRODUCTION

Heat treatment is a multi-parameters process. Selection of the appropriate parameters helps in predicting possible behaviours of treated components. The kind of quenching medium, selection of quenching medium temperature and the selection of the medium state (unagitated, agitated) are determining factors [1, 2]. Quenching is an essential element in developing the desired properties of many steel and aluminum alloys. Agitation, or forced circulation of the quenchant, is required to shorten the cooling times. Without agitation, natural convection of the quenchant [3, 4, 5] and quenchant vaporization limit the heat transfer rate through the fluid film boundary at the surface of parts. Under these conditions, changes in the quenchant medium temperature have little effect on the cooling rate. Obtaining a forced convection fluid regime greatly reduces the resistance to heat flow at the fluid film boundary layer [6]. This can be accomplished by mechanically moving the parts through the bath, pumping to recirculate the quenchant, or mechanically inducing agitation/circulation of the fluid. Where control over the cooling rate is important, mechanical agitation provides the best performance at the lowest energy costs. The cooling rate is however influenced by such factors as bath temperature, quenchant type, immersion temperature, agitation and immersion speed [7, 8, 9].

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Agitation during quenching generally enhances heat transfer at all cooling stages. Liscic found that hardness of AISI 4135 steel across its entire thickness in a conventional oil quench increased with agitation [10, 11]. Quench severity is dependent on agitation rate, tank size, fluid viscosity, type and placement of agitators [12, 13]. Agitation affects the hardness and depth of hardening during the quench because of the rupture of the relatively unstable film boiling cooling process that always occur in vaporizable quenchants such as oil, water and aqueous polymers. An early breakdown of the vapour blanket results in transition into the nucleate boiling [2, 15]. This process results into a time reduction of the slow cooling stage thus resulting in rapid heat transfer. Agitation enhances recirculation of quenchant unto the metal surface with consequent higher temperature difference between quenchant and the surface. Direct quenching and tempering (DQ-T) combined with controlled rolling has been widely used in the production of low and medium carbon steel for plates and rods. The steel produced by DQ process has an advantage of attaining better combination of strength, toughness and weldability in comparison with the steels produced by conventional reheating and quenching (RQ) process , In DQ process, the reheating temperature before rolling is much higher than austenitizing temperature used for the RQ process, so that it will be important to control austenite grain size (AGS). It is obvious that hot deformation of austenite refines ferrite, (in controlled rolled steels) and martensite (in ausformed martensite) [15]. The influence of microstructure on mechanical properties of low alloy steels has been a subject of considerable research interest in physical metallurgy [14, 16]. Most researchers do not quantify the speed of immersion of materials into the quenchants; this works attempts to examine the effect of immersion speed during quenching on strength of the material, study microstructural evolution and mechanical behavior of the steels in the series of quenching in order to characterize the material after different settings (speed) in quenching.

II EXPERIMENTAL METHODS

A *Quench Materials and Bath Specifications*

A C30 carbon steel material with chemical composition as indicated in Table 1 is preliminarily annealed at 900^{o}C and soaked for 1 hour before machining to tensile and hardness tests specifications. Fig.1 (a & b) shows the as –

quenched test pieces. The quench bath consists of an extended height square base tank of 305 x 305 mm base and 2134 mm height. A separate immersion weight-force carrier is also constructed.

Table 1: Chemical Composition (wt %) of the C 30 Steel Used.

Symbol	wt%
C	0.311
Si	0.028
S	0.026
P	0.007
Mn	0.742
Ni	0.202
Cr	0.172
Mo	0.017
V	0.001
Cu	0.035
W	0.004
As	0.010
Sn	0.001
Co	0.0057
Al	0.004
Pb	0.001
Zn	0.004
Fe	97.76

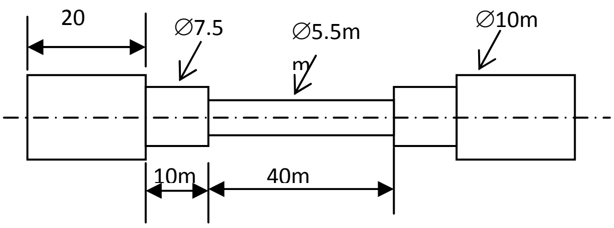

Fig.1(a) : Tensile test specimen

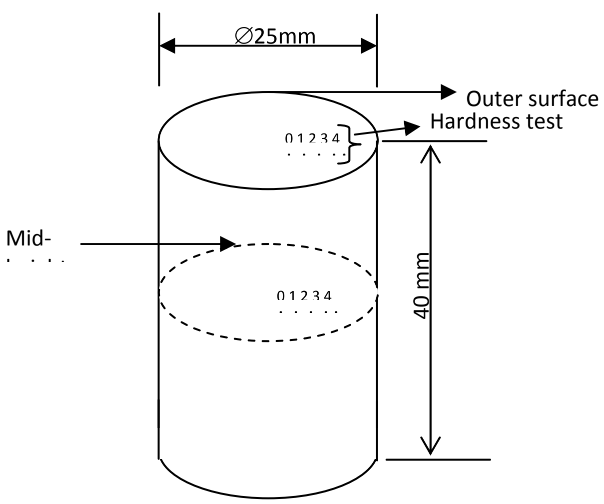

Fig.1(b):Hardness test specimen

A weight-force carrier having pyramidal shape with dimension 300 x 300mm square base was constructed as shown in Fig.2. The pyramidal shape allows smooth movement through the extended height quench tank bath. Different quench immersion speeds was effected by weights placed inside the carrier falling freely through the quench bath height. Weights of 3.35, 11.05, 13.05, 16.85 and 18.35 Kg were used with corresponding immersion speeds of 0.106, 0.697, 0.853, 1.065 and 1.139 m/sec respectively. Calibration of weight-force against speed was done by noting the time it takes for specified weights to travel vertically through known liquid heights. Five different speeds were calibrated. The cylindrical probe of 0.31%C steel specimens of 25 mm dia x 40 mm fitted with a K thermocouple to the geometric centre, were heated in electric Muffle furnace at the rate of 25^oC/min to a temperature of 840 $^oC \pm 2^oC$ and soaked at that temperature for about 1hour. The heights of these probes were five times their diameters to ensure heat transfer in the radial direction. The thermocouple was inserted in a hole of diameter 3 mm drilled on the top surface of the probe and quickly transferred laterally under 2sec into 2,000ml of bioquenchants having a temperature of 25^oC at static condition. The specimen was positioned at exterior side of the pyramidal shape in a metallic net thus allowing free quenchant flow around the probe during immersion Fig. 2. The probe temperature and cooling times was captured using SD card datalogger digital thermometer Model MTM-380SD in order to establish a cooling temperature versus time curve of each immersion speed tested. The quench process was repeated three times and average values reported.

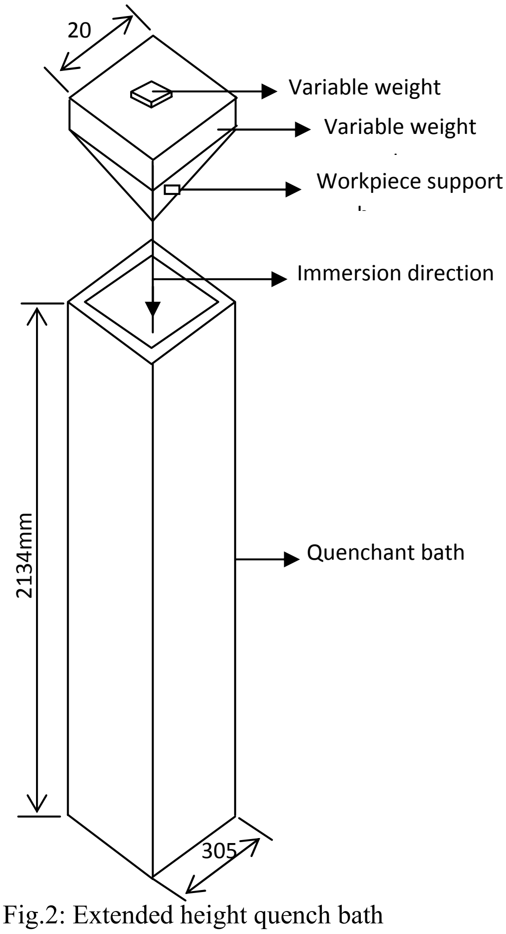

Fig.2: Extended height quench bath

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B Mechanical and Microstructural Property Tests

Room temperature uniaxial tension tests were performed on round tensile samples machined from the carbon steel material with dimensions of 5.5 mm gauge diameter and 40mm normal length. Computerized Universal Tensile Testing Machine (Model:3369) was used to conduct the test. The samples were tested at a nominal strain rate of 10–3/s until failure. Multi tests were performed for each test condition to ensure reliability of the data generated. The tensile properties evaluated from the engineering stress-strain curves developed from the tension test are –the ultimate tensile strength (σu) and the yield strength (σy). Hardness measurement was taken along the radial direction at 5 mm intervals at exterior top or bottom surface and a sectioned mid – height surface (see Fig.1 (b). The hardness of post treated quenched-tempered samples was evaluated using a Vickers Hardness (LECO AT700 Microhardness Tester). Prior to testing, the steel specimens were mounted using phenolic powder, grinded and polished to obtain a smooth surface finish. A direct load of 490.3mN (50.03kg) was thereafter applied on the specimen for a dwell time of 10 seconds, The machine, which is automated, evaluated the diamond -like impression on the surface of the sample and subsequently displays the hardness value digitally. Multiple hardness tests were performed on each sample and the average of the best values taken as a measure of the hardness of the specimen. Optical micrographs of quenched specimens were carried out on sectioned surface using Daheng microscope, grinded with silicon carbide papers of different sizes. They were subsequently polished using a cloth impregnated with alumina until a mirror surface was obtained. Grinded surface were cleaned with water and ethanol. Etching with 2% Nital was done and microstructures observed using a high powered optical microscope.

III RESULTS AND *DISCUSSION*

A Cooling Curves and Microstructures

Cooling curves at different immersion speed at quenchant temperature of 25^{o}C under dynamic quenching conditions show two of the three stages of quenching mechanism Fig.3. which are film boiling and convective cooling. However, with increasing speed the film boiling stage time reduces. Maximum cooling rates of 53.88, 63.80, 73.88, 90.76 and 97.70 ^{o}C/sec with corresponding immersion speed of 0.106, 0.697, 0.853, 1.065 and 1.139 m/sec was obtained Fig. 4. Thus, cooling rates increases with immersion speed; this was attributed to rapid destruction of the film boiling stage due to rapid movement of workpiece through the quenchant.

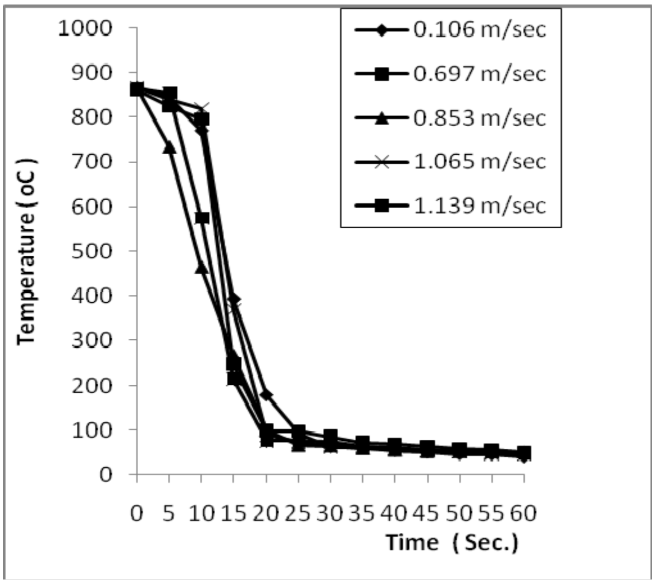

Fig 3 Cooling curve at different immersion speeds

The microstructures for the as-received, minimum and maximum immersion speeds are as shown in Fig.5 (a – c) respectively. The as-received specimen comprises of ferrite and pearlite predominantly. At highest speed of 1.139 m/sec the steel material showed traces of martensite structures while at lowest immersion speed of 0.065 m/sec bainitic structures with a mixture of pearlite are observed thereby making the hardness of the material to increase as the immersion speed increases. With maximum immersion speed of 1.139 m/sec, maximum cooling rate of 97.7^{o}C/sec occurred at 534.3^{o}C which falls within the pearlitic transformation temperature and this was high enough to suppress diffusional transformation in this range such that transformation was delayed till the martensitic range of about 330^{o}C to 120^{o}C was reached.

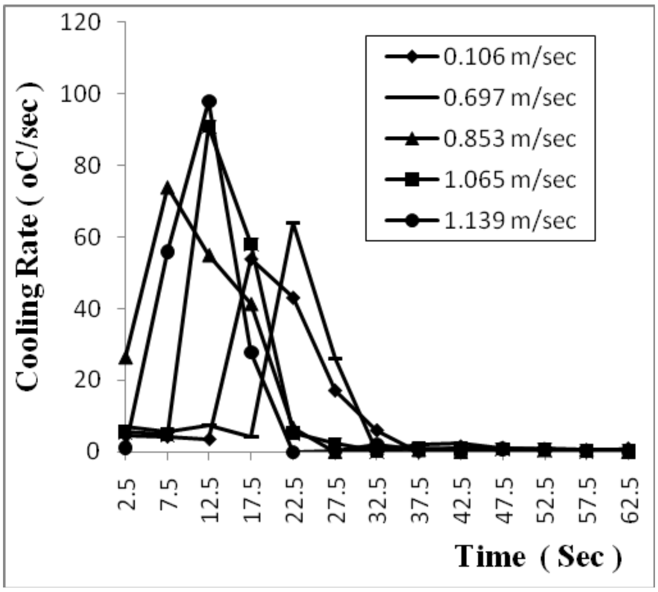

Fig.4 Variation of cooling rates with immersion speed

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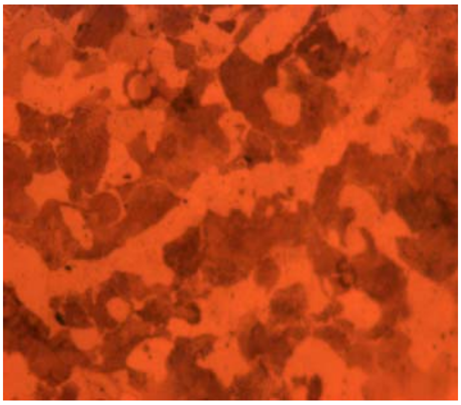

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Fig. 5(a) Microstructure of as-received material

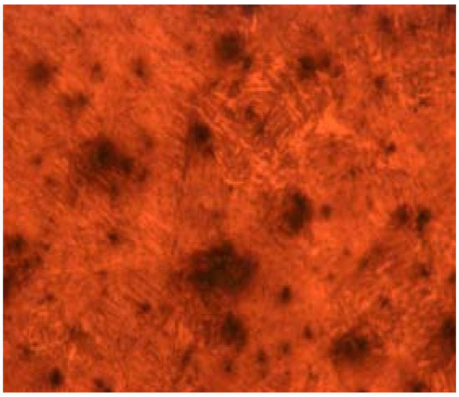

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Fig.5(b) Microstructures at minimum immersion speed (0.106 m/sec)

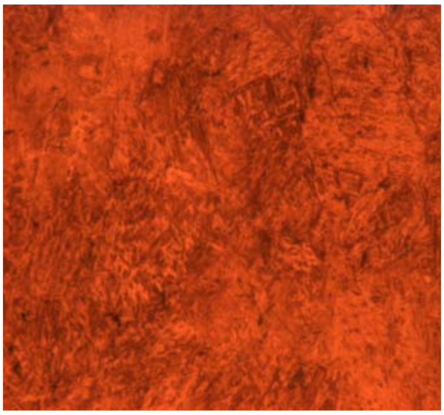

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Fig.5(c) Microstructure at maximum immersion speed (1.139 m/sec).

B Mechanical Properties

Fig. 6 shows the yield strength and ultimate tensile strength of the C30 material at different immersion speeds. Material strength increased with immersion speed as much as 19.30% when immersion speed increased by 63.41% (from 0.697m/sec to 1.139m/sec.). The enhancement in the property of the steel was as a result of increased cooling rate resulting from disruption of both film and nucleate boiling stages at higher speeds.

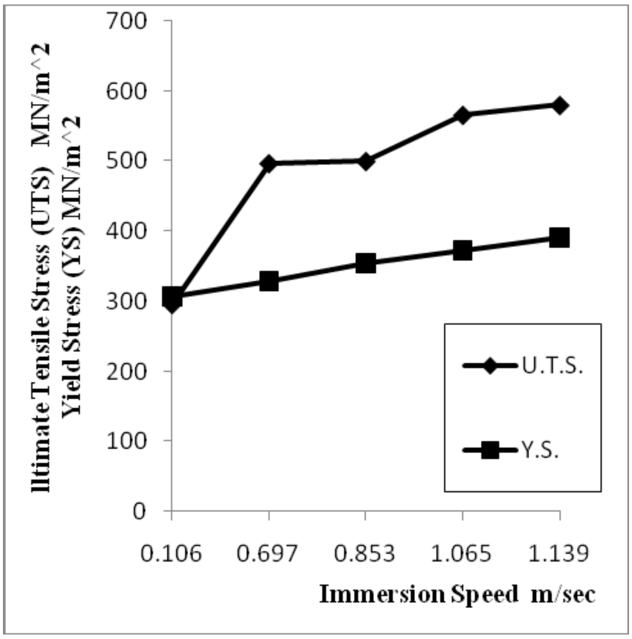

Fig.6: Variation of material strength properties with immersion speed

Fig.7 shows the variation of material hardness across the radial direction taken at top and mid-height points. In both cases hardness increased with immersion speed which was as a result of higher cooling rate resulting from the collapse of the film boiling and nucleate boiling stages. Hardness tends to increase with increasing radius at both mid and top surfaces. This was due to the higher severity of quenching towards the exterior cylindrical boundaries.

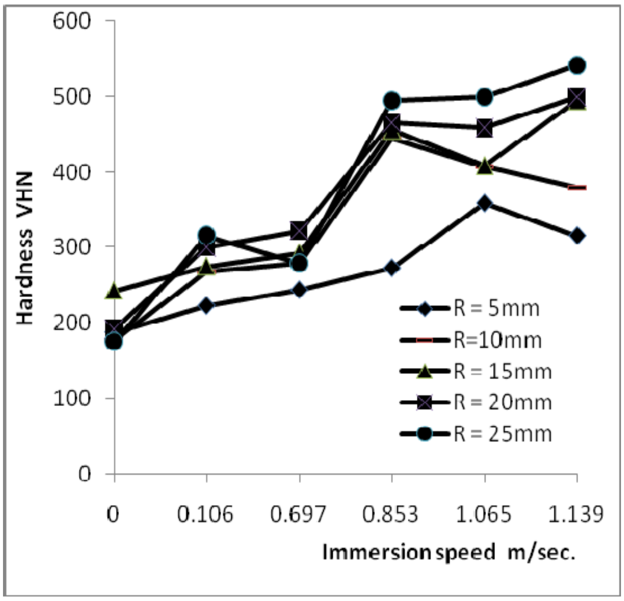

Fig 7 Variation of metal hardness with immersion speed

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IV. CONCLUSION

The main conclusions from the present study are the following:

1. Cooling rates increased with immersion speed due to rapid transformation of the film boiling to convective cooling.
2. At highest quench immersion speed of 1.139 m/sec, the C30 steel material showed traces of martensite microstructures formation.
3. Material strength increased by as much as 19.30% with 63.41% increase in immersion speed.
4. Material hardness increased steadily with immersion speed and also towards the outer diameter.

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