2nd International Engineering Conference (IEC2017)
Federal University of Technology, Minna, Nigeria

Evaluation of Distortion in Vegetable Oil Quenched Medium Carbon Steel

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ABSTRACT

The effect of selected vegetable oil quenchant on distortion of medium carbon steel parts was investigated. Modified C-ring specimens of medium carbon steel were quenched in four different vegetable oils and the dimensions of the specimens were measured before (G_o) and after (G_1) heat treatment with the aid of a digital vernier caliper. Distortion that arises after quenching was calculated. The results were compared to carbon steel quenched in SAE 40 under the same condition. Dimensional variation values were higher for samples quenched in melon oil and SAE40. Lower values were obtained for samples quenched in walnut oil and palm oil.

Keywords: *Distortion; Medium carbon Steel; Quenching; Vegetable oil*

1 INTRODUCTION

Quenching of steels to develop martensitic structures involves the process of heating a part above upper critical temperature to austenitizing temperature and holding at this temperature for a specified soaking time followed by intense cooling in a suitable quenching medium (Agboola, *et al.*, 2015).

Quenching medium serves two primary functions. It facilitates hardening of steel by controlling heat transfer during quenching, and it enhances wetting of steel during quenching to minimize the formation of undesirable thermal and transformational gradients which may lead to distortion and cracking (Aronov, 2005).

Distortion can be defined as irreversible and usually unpredictable dimensional changes that take an object outside of its profile tolerance both in size and shape as a result of heat-treatment operation (Adedayo, *et al.*, 2014). When heat-treated parts suffer from distortion beyond the allowable limits, it may lead to scrapping of the article, thereby rendering it useless for the service for which it was intended (Durowoju, *et al.*, 2013).

Distortion in heat treatment can be classified into two categories: size distortion, which denote the net change in volume between the parent and transformation product produced by phase transformation without a change in geometrical form. Shape distortion or warpage is a change in geometrical form and is revealed by changes in curvature, bending, twisting, and/or non-symmetrical dimensional change without any volume change (Civera *et al.*, 2014). Usually both types of distortion occur during a heat-treatment cycle. From the practical viewpoints, warpage in water- or oil-hardened steels is normally of greater magnitude than is size distortion and is more of a problem because it is usually unpredictable (Grinberg, *et al.*, 2015)

Over the years, water, brine and mineral based oils are the most commonly used to harden steel because they are readily available. The relative severity of quench of these media rates brine as having the highest severity while oil is considerably less drastic (Gunstone, 2004). Because of environmental concerns and growing regulations over contamination and pollution, associated with petroleum based oils, the need arises for a more eco-friendly renewable and biodegradable fluids as quenching medium. Vegetable oils have been identified as safer, renewable and biodegradable alternative to petroleum based oil (Agboola, *et al.*, 2016).

Quenching occurs in three stages. The first stage of cooling is characterized by the formation of a vapour film around the component. This is a period of relatively slow cooling during which heat transfer occurs by radiation and conduction through the vapor blanket. Upon further cooling, the nucleate boiling stage begins during which the vapour film collapses and cool quenchant comes into contact with the hot metal surface resulting in violent boiling and high extraction rates. Maximum part distortion occurs during this stage due to difference in heat extraction from the part surfaces. As cooling continues, the surface temperature is below the boiling point of the quenching fluid and the metal surface is completely wetted by the fluid. At this point, the cooling rate is low and determined by the rate of convection and the viscosity of the quenching fluid. Heat transfer rates in this region are affected by various process variables, such as agitation, quenchant viscosity and bath temperature. The duration of the vapour phase and the temperature at which the maximum cooling rate occurs have a critical influence on the ability of the steel to harden fully (Adeyemi & Adedayo, 2009).

Although quenching results in high hardness values, one of the major drawbacks associated with quenching is high thermal and transformational stresses which may lead to distortion and possibly cracking. This can lead to rejected component and production losses (Adekunle, *et al.*, 2013). Therefore, the technical challenge of quenching is to select the quenching medium which gives optimum mechanical properties with least amount of distortion. To tackle this challenge, several studies have been carried out focusing on the quenching characteristics, such as cooling mechanism and heat transfer during quenching of selected vegetable oils. However, there is little information on the distortion values or dimensional changes that arises after quenching of steels in different vegetable oil quenchant.

The objective of this work is to measure and compare the dimensional changes that arise after quenching medium carbon steel in four selected vegetable oils and using conventional petroleum derived oil SAE 40 as control.

METHODOLOGY

In this work, dimensional variations were measured on modified C-ring test specimens as described by Civera *et al,* (2014) (see figure 1). The flat sheets for C-ring were punched out from a 150×150mm sheet plate of 1.5mm thickness using a pneumatic punching machine, bored to specification and sam-papered to give a good surface finishing. The chemical composition of the steel is shown in Table 1

TABLE 1: CHEMICAL COMPOSITION (WT %) OF THE MEDIUM CARBON STEEL USED.

Element	C	Si	Mn	P	S	Cr	Fe
% Composition	0.357	0.16	0.75	0.032	0.041	0.1	98.2

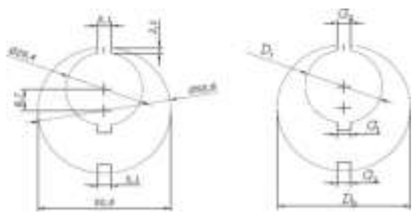

Figure 1: Shape and dimensions (mm) of the modified C-rings used.

The dimensions (D_1, D_0, G_0, G_1, and G_2) of the C-ring test specimens were measured before and after quenching using a digital vernier caliper. The individual measuring points were marked with lower case letters "a", "b" and "c". Measuring point „"a"" permitted measurement of the changes in size and of the shape, that is the distortion of the shape of the left and right legs of the ring. Measuring points „„b"" and „„c"" permitted measurement of the dimensional deviation as well as assessment of the crack susceptibility of steel in heat treatment. The major advantage of the modified C-ring is that it enables a simple measurement of dimensional change at the upper notch of the ring that is in the place of the lesser wall thickness.

The C-ring was austenitized at 860 ^oC and quenched in melon seed oil, groundnut oil, palm oil and atili oil. Distortions in SAE 40 and water were used to compare with that obtained with the vegetable oils used in this work. The gap openings of the C-ring were measured before and after quenching and the average percentage gap openings ΔG_o (%) was calculated.

Viscosity of the oils was measured at 40°C and 100 ºC using viscometer baths according to American Society of Testing and Materials (ASTM) D445-06. The VI was calculated according to ASTM D2270-10 Standard Practice for Calculating Viscosity Index from Kinematic Viscosity at 40° and100°C.

Cooling curves were obtained at room temperature, in a non–agitated condition according to ASTM D6200-01: Standard Test Method for Determination of Cooling Characteristics of Quench Oils by Cooling Curve Analysis].

The longitudinal section was selected as the section for the evaluation of the microstructure and hardness in the different regions of the modified C-ring sample. The hardness values were obtained using a Digital Micro Hardness testing machine (Model: LecoLM700AT) under

applied load of 490.3 MN and dwell time of 10 s using a "C" scale (HRC). Hardness numbers taken at four (4) points of the C-ring (see Figure 3) were automatically read from the digital counter and the average value was taken. Four repeat tests were performed on each specimen and the average taken as representative of the hardness obtained for the corresponding treatment. The polished surfaces of the steel samples were etched in 2% HNO_3 (nital) for 10s, dried with rectified spirit to remove moisture. Metallographic observations were performed with a metallurgical microscope.

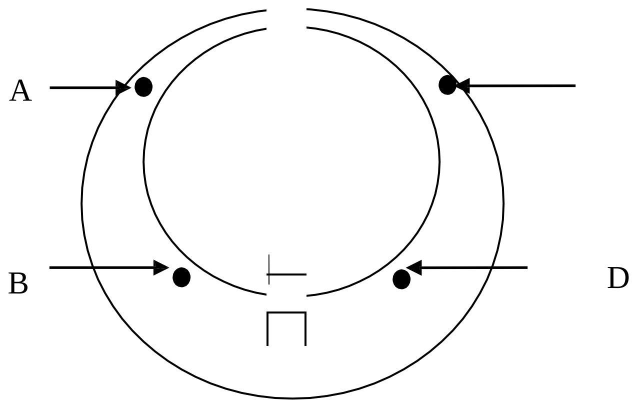

Figure 2: Hardness Measurement on the C-ring Sample

RESULTS AND DISCUSSION

The various properties of the quenching media used in this work are summarized in table 2

TABLE 2: PHYSICAL PROPERTIES OF THE QUENCHING MEDIA

Quenching Media	Viscosity at 40°c	Acid Value (mgKOH/g)	Iodine Value (g I_2/100 g)	Flash Point (°C)	Oxidation Stability (meq/kg)	Specific Gravity
						CR
Wal nut Oil	36.2	22.44	19.1	117	57.70	0.971
Melon Oil	31.5	4.48	19.4	149	35.00	0.897
Palm Oil	42.9	30.86	18.5	249	23.80	0.889
Groundnut Oil	34.8	5.6	18.4	249	57.60	0.922
Water	-	-	-	-	-	1.019
SAE 40	117	28.05	9.7	182	17.10	0.778

Cooling curve obtained during quenching of carbon steel probe in the selected quenchant is shown in Figure 2. Cooling rate curves (see Figure 3) were obtained by taking the slope at each temperature of time vs temperature curves. Critical cooling parameters are summarized in Table 3.

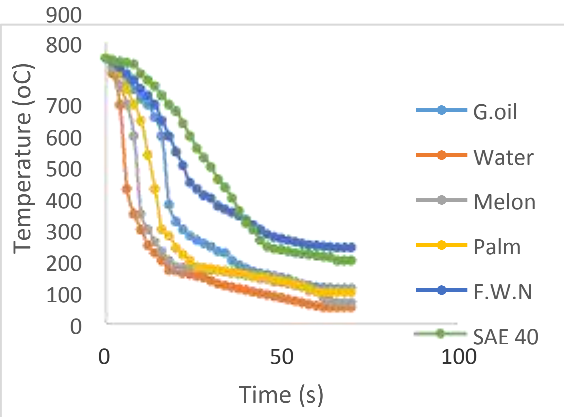

Figure 2: Cooling curve of various quenching media

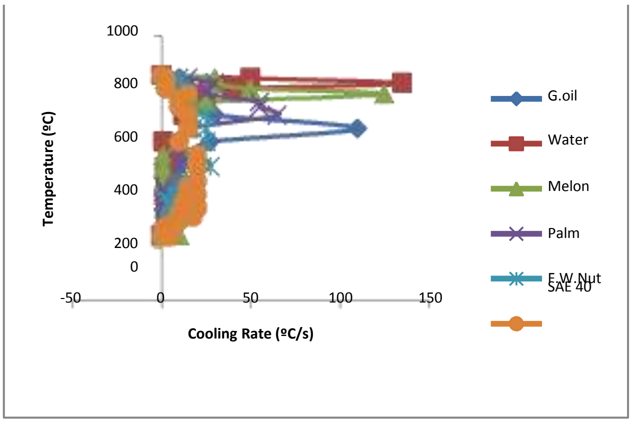

TABLE 3: CRITICAL COOLING PARAMETER

	Vegetables				Fast	Slow
Cooling Parameter	Walnut oil	Melon oil	Palm oil	Groundnut oil	Water	SAE 40
t_{A-B}(s)	16	10	12	18	8	10
T_{A-B}(°C)	650	350	540	380	350	800
CR_{DHmin}	25	25	55	27.5	25	10
CR_{max}	27.5	125	65	110	135	17.5
T_{CRmax}	505	600	430	600	700	435
	25	50	25	20	135	10
700(°C/s) CR	7.5	20	15	10	25	17.5
300(°C/s) CR 200(°C/s)	-	10	10	7.5	15	-
$t_{300°C/s}$	41	12	16	22	10	42
$t_{200°C(s)}$	-	18	24	36	16	66

All the vegetable oils exhibited a very short film boiling stage, thus providing rapid cooling at high temperatures. The predominant cooling mechanism for the vegetable oils is convection. Thermal gradients due to transitions between boiling processes is less pronounced. Therefore more uniform cooling and reduced distortion would be expected. This behaviuor supports earlier work in the literature with respect to quench severity (Adekunle, *et al*, 2013).

Dimensional changes

The values of the percentage distortion of gap opening G_0 % versus the viscosity of the oil at 60 ºC are shown in figure 4. It can be seen that as the viscosity decreases, the percentage distortion G_0 % increases.

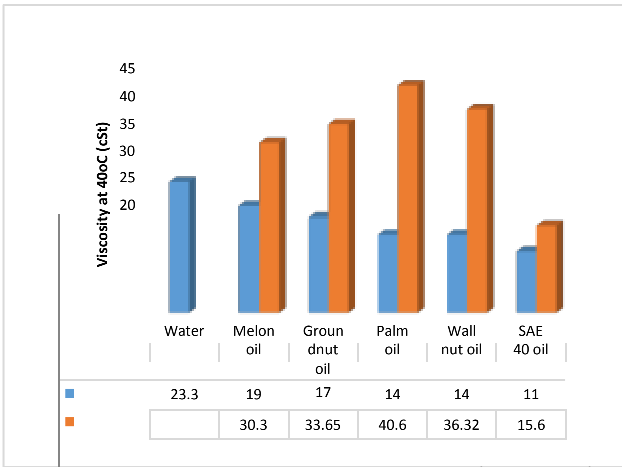

Figure 4: percentage distortion G_0 % as a function of kinematic Viscosity (cSt)

Figure 3: Cooling rate curves of the quenching media

TABLE 4: CORRELATION BETWEEN DISTORTION AND HEAT TRANSFER COEFFICIENT (W/M^{2}K)

Quenchants	Heat transfer coefficient (w/m^{2}k)	Distortion (%)
Water	4777	23.3
Melon oil	3588	19
Groundnut oil	2058	17
Palm oil	1587	14
False wall nut oil	580	14
SAE 40 oil	284	11

Melon oil exhibits the highest heat transfer coefficient of 3588w/m^{2}k with corresponding distortion of 19 % among the vegetable oils investigated. Since the heat transfer is related to the temperature field in the component, if the heat transfer coefficient is high, the temperature distribution in the part tends to be less uniform thus producing greater distortions.

Figure 5 shows the average distortion of the steel sample according to the quenching oil used.

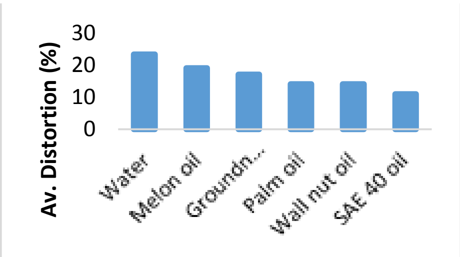

Figure 5.: Average Distortion (%) of the Steel Samples according to the quenching oil used

Figure 5 shows that melon seed oil exhibited the highest percentage distortion of 19% among the oils investigated in this work. It is closely followed by groundnut oil (17%). False walnut oil and palm oil exhibits the least percentage distortion of 14%.

The results of the hardness test of the specimens are presented in Table 5.

TABLE 5: HARDNESS VALUES

Quenching Media	Average Hardness Value (HC)
Melon oil	49.23
Groundnut oil	48.36
Wal nut oil	46.01
Palm oil	46.27
SAE 40 oil	39.57
Water	51.68
As-received	14.22

The hardness values of the quenched specimens were found to be higher than of the unquenched specimen. With respect to the vegetable oil quenched specimens, the hardness values increased with increased oil saturation with highest value obtained for melon oil.

4.6 MICROSTRUCTURE ANALYSIS

Micrographs of the carbon steel quenched in different media are shown in Plates 1-6.

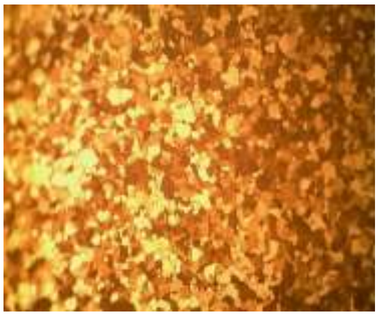

Plate 1 Microstructure of as-received C-ring steel sample. The structure consists of pearlite (dark) in the matrix of ferrite (light) .(×400)

Plate 2 Microstructure of C-ring steel sample quenched in SAE 40. Structure consists of martensite (dark) with retained austenite (light) (×400)

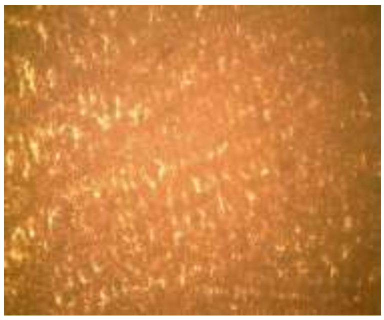

Plate 3 Microstructure of water quenched C-ring steel sample. Structure consists of predominantly martensite (dark) .(×400)

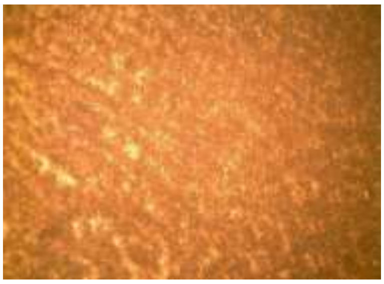

Plate 4 Microstructure of sample quenched in melon seed oil .The structure consist of predominantly martensite (dark) and ferrite (light) (×400)

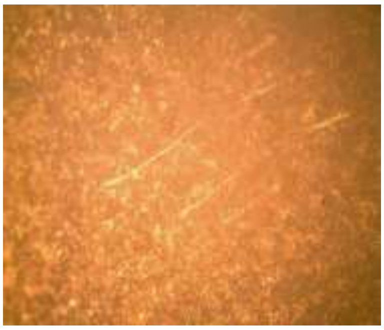

Plate 5 Microstructure of sample quenched in palm oil. The structure consists of predominantly martensite (dark) and ferrite (light) structure (×400)

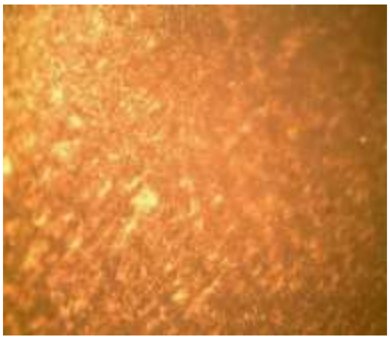

Plate 6 Microstructure of sample quenched in wall nut oil. The structure consists of martensite (dark) and ferrite (light) at the boundaries (×400)

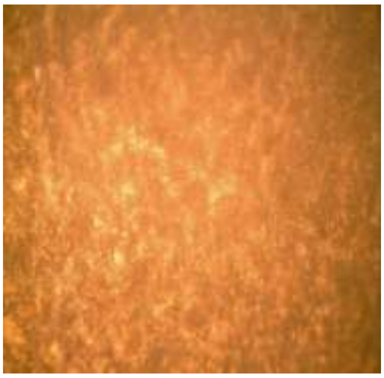

Plate 7 Microstructure of medium carbon steel sample quenched in groundnut oil. Structure consists of a random disribution of martensite (dark) and ferrite (light) (×400)

CONCLUSIONS

The experimental study was performed to investigate the level of distortion in Medium Carbon Steel quenched in selected vegetable oil. On the basis of the results of the investigation,the following conclusions were drawn:

- The highest cooling rate was obtained for samples quenched in melon seed oil. Cooling rate was found to be strongly dependent on the viscosity of the quenching oils and acid values.
- The highest distortion rate was obtained for samples quenched in melon oil and groundnut oil whereas wall nut oil and palm oil gave rise to the least distortion value
- Hardness value increases with increasing
- Mechanical properties, such as hardness were highly dependent on heat transfer coefficient and the final structure of the material which supports earlier work in the literature with respect to quench severity
- Among the oils investigated, melon oil assures high hardness value (51.68HC), least distortion, and uniform hardness variation in the entire volume of the specimen.

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