Performance assessment of vegetable oil and mineral oil blends during heat treatment of medium carbon steel

Joseph Babalola Agboola*, Oladiran Kamardeen Abubakre, Edeki Mudiare and Michael Bolaji Adeyemi

Department of Mechanical Engineering, Federal University of Technology, P.M.B. 65, Minna, Niger State, Nigeria
Email: joe_agboola@yahoo.com
Email: diranabubakre@gmail.com
Email: edekimudiare@yahoo.com
*Corresponding author

Abstract: Cooling effect of palm kernel oil and mineral oil (SAE 40) with their blends as quenching media for heat treatment of medium carbon steel was investigated. Palm kernel oil was blended with SAE 40 in the ratio of 1 : 3, 1 : 1 and 3 : 1. Medium carbon steel probe of diameter 12.5 mm and 60 mm height was used to determine the cooling intensities of the oils and their blends. Mechanical properties and microstructure of the quenched steel samples were determined. Quench severity of pure palm kernel oil was found to be greater than that of SAE 40. The blend consisting of 75% palm kernel oil and 25% mineral oil showed higher cooling power as compared to other blends. Samples quenched in 100% palm kernel oil showed higher hardness values than the blends whereas samples quenched in 100% mineral oil (SAE 40) showed the least hardness value.

Keywords: vegetable oil; mineral oil; blends; quenching; quench severity.


Biographical notes: Joseph Babalola Agboola is an accomplished Engineer with over 28 years of experience in Industry, Lecturing and Research Conduct. He holds an MSc in Metallurgical Engineering from Donetsk, Ukraine and a PhD in Mechanical Engineering (Metallurgy and Materials option) from Federal University of Technology, Minna, Nigeria. He has more than 10 publications in reputable National and International Journals. He is currently a Senior Lecturer in Metallurgy and Materials Engineering in Mechanical Engineering Department, Federal University of Technology, Minna, Niger State, Nigeria. His research interest covers: heat treatment/quenching of steels and metal forming.
1 Introduction

Heat treatment is defined as heating a metal to a specified temperature and holding at this temperature for required time followed by controlled cooling (Agboola, 2014). Mechanical properties of steels are strongly connected to their microstructure obtained after heat treatments (Adnan, 2009).

Quenching of steel during heat treatment consists of raising the temperature of steel above austenitising temperature usually in the range of 850–870°C, holding it at that temperature for a fixed time and then rapidly cooled in a suitable quench medium to room temperature. Quenching to develop martensitic structures without warping or cracking depends on the hardenability of the steel part, the cooling rates needed to achieve the desired microstructure, the quenching temperature and the severity of quenching medium (Jagannath and Prabhu, 2011).

The mechanism of heat removal during quenching is in three stages (Agboola et al., 2008). In the first stage, as soon as a work-piece comes into contact with a liquid medium, the surrounding liquid layer is instantaneously heated up to the boiling point and gets vapourised and forms the vapour blanket. This vapour film is a poor conductor of heat and cooling of work-piece takes place by conduction and radiation through the vapour film. The stable vapour film collapses and quenchant comes into contact with the hot metal surface causing nucleate boiling and resulting in higher heat extraction rates. This second stage reduces hardness and the degree of softening depends on the rate
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of cooling. As cooling continues, the surface temperature is reduced and metal surface is completely wetted by the liquid resulting in low cooling rate. The third stage if slow enough tempers the steel and minimises distortion in this temperature range where volume changes occur (Totten et al., 1993).

The steel composition, section thickness and the type of quenchant all have a major influence on the properties obtained in the heat treated condition (Liscic, 1993). Some steels, particularly those having high alloy content do not require rapid cooling or quenching in their heat treatment to develop hardness. A fast enough quenchant is used that will achieve the desired properties, but slow enough that cracking or distortion will not occur (Sogerberg and Troell, 1996). In search for a suitable medium for hardening such steel effectively, many efforts have been made to increase the initial quenching speed of oils.

Many components use oil quenching to achieve enhancement of mechanical and metallurgical properties (Fernandes and Prabhu, 2013). Oil quenching facilitates hardening of steel by controlling heat transfer during quenching, and it enhances wetting of steel during quenching to minimise the formation of undesirable thermal and transformational gradients which may lead to increased distortion and cracking (Nik et al., 2005). The most widely used quenchant for ferrous alloys are petroleum-based quenchant due to its favourable heat extraction characteristics (Fernandes and Prabhu, 2008). The environmentally hazardous, toxic gases which are produced when the metal part is quenched in mineral oils and the fact that they are extracted from non-renewable sources necessitates considering alternative quenchant which can replace or reduce the usage of mineral oil (Chandler, 1995).

As an alternative to mineral oil generally used for quenching, vegetable oils are used as quenching media. They are cheap, abundantly available, biodegradable and environmentally friendly. However, they have poor oxidation properties (Totten et al., 1991).

To be a viable alternative, the quenchant must have high oxidation resistance, low sludge formation, maximum cooling rate to achieve maximum hardness and depth of hardening, high flash temperature that is approximately 50°C above the expected use temperature, maximum thermal and oxidation stability besides being environmentally friendly (Singh, 2012). Mineral–vegetable oil blend is being investigated in this work as important alternative to replace mineral oil as quenchant.

Mixed oils have been found in practice to be more effective than their isolated principal constituents and with minimal side effects (James and Davidson, 2004). Apart from the synergy produced by the components of single oil, there is also an enhancement of effect when two or more oils are mixed together (Cahn and Haasen, 1996). In line with this reasoning, a wide range of quenching characteristics can be improved through careful blending.

Oils are complex mixtures, containing several hundreds of different molecules which act in synergy to produce their effect, but if the composition is altered the effect of the individual constituents is diminished. Unwarranted characteristics and side effects can be removed enabling the oil to be used more effectively. Minor components of essential oils can modify the activity of main components (ASTM D256, ISO 180, 2008).

The high boiling temperature of vegetable oil which is almost 166°C above the boiling temperature of most petroleum quench oils provides for an increased transition temperature between nucleate boiling and convection (Pranesh Rao and Prabhu, 2015).
This is very important in reducing the temperature gradients, which results in residual stresses during transformation. The higher flash point of 332°C gives greater safety during quenching (Cazabat and Cohen Stuart, 1986). Higher oxidative stability of the petroleum oils as compared to that of vegetable oil is a beneficial physical property for quenching oil. Combining these characteristics of both oils is hoped to produce better alternative quenching oil than the individual components.

The aim of the present study is to develop a quenching medium which is not only effective in hardening carbon steel, but which will also have a cooling rate in the lower temperature ranges so as to avoid warping or cracking steel parts. In this work, vegetable oil (palm kernel oil) is blended with mineral oil (SAE 40) as quenching media for heat treatment of carbon steel. The various performances of different proportion were compared with that of the individual components.

One way to evaluate the performance of a quenchant is to relate it with the quenchant’s ability to remove away heat from the work piece. The other way is to relate it to the results given when hardening a metal work piece in the quenchant (Prabhu and Fernandes, 2007).

2 Materials and methods

2.1 Materials

The blended oils were prepared by mixing palm kernel oil with mineral oil (SAE 40) in the ratio of 1:3, 1:1 and 3:1. The mixing was done with the aid of a mechanical stirrer.

The experimental setup for the quenching treatment consisted of an electric furnace Model HAS 1508-0611NH. Cylindrical quench probes having 12.5 mm diameter and 60 mm height were prepared from medium carbon steel for assessment of quench severity. The composition of the carbon steel used is shown in Table 1.

<table>
<thead>
<tr>
<th>Element</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Cr</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>% Composition</td>
<td>0.357</td>
<td>0.16</td>
<td>0.75</td>
<td>0.032</td>
<td>0.041</td>
<td>0.1</td>
<td>98.2</td>
</tr>
</tbody>
</table>

The quench probes were instrumented with chrome/Alumel thermocouples of 0.45 mm diameter. All the thermocouples were connected to a data-logger model (RD 8900) by means of compensating cables through a cold junction apparatus maintained at a constant temperature of 0°C.

2.2 Methods

2.2.1 Cooling curves

Direct dip quenching method under static condition was adopted. The test specimens were heated in the electric furnace at a heating rate of 25°C/s to a temperature of 850°C and soaked at this temperature for about 10 min and then rapidly transferred into a stainless steel container containing 1000 ml of the quenchant placed directly
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beneath the furnace. The temperature data acquired during quenching of specimen was used to plot cooling curve. Cooling rate curves were obtained by taking the slope at each temperature of time vs. temperature curves.

2.2.2 Measurement of mechanical properties

The hardness impressions were taken transversely in two perpendicular directions along the cross section of the quenched specimens by a Digital Micro Hardness testing machine (Model: Leco LM 700 AT) under applied load of 490.3 MN and dwell time of 10 s using a ‘C’ scale (HRC). Hardness numbers taken at different points were automatically read from the digital counter and the average value was taken. Two repeat tests were performed on each specimen and the average taken as representative of the hardness obtained for the corresponding treatment.

Tensile tests on the specimens were conducted using a digital electron universal testing machine (Model: INSTRON 3369). The cylindrical test specimens used were of 5 mm in diameter and gauge length of 20 mm. In all, five tensile specimens were machined for tensile properties test. The tensile load was hydraulically applied. The input and output display of applied load unit in the control unit indicated magnitude of applied load. The load was gradually increased until specimen broke off and corresponding extension was noted and recorded. The automatically generated test data were shown on the display unit. The tensile strength, percentage reduction in area and percentage elongation was determined from the load–extension curves.

The impact energy test was carried out on an Izod impact testing machine Model IT-30 to measure the toughness of the quenched steel specimens according to ASTM D256. Five standard impact test specimens of 10 mm square by 55 mm long were machined for the impact test (Cahn and Haasen, 1996).

2.2.3 Microstructure of quenched samples

Optical micrographs of quenched steel samples were carried out on sectioned surface ground with silicon carbide papers of different sizes. They were subsequently polished using a cloth impregnated with alumina until a mirror surface was obtained. Polished surface were cleaned with water and ethanol. Etching with 2% Nital was done and microstructures observed using a high powered metallurgical microscope.

3 Results and discussion

3.1 Properties of palm kernel oil, mineral oil and their blends

The various properties of palm kernel oil, mineral oil (SAE 40) and their blends are given in Table 2.

3.2 Cooling curve analysis

Cooling curve obtained during quenching of carbon steel probe in palm kernel oil, mineral oil (SAE 40) and their blends is shown in Figure 1. Cooling rate curves (see Figure 2) were obtained by taking the slope at each temperature of time vs. temperature curves.
Table 2  Properties of palm kernel oil, mineral oil and their blends

<table>
<thead>
<tr>
<th>Quenching media</th>
<th>Viscosity at 40°C</th>
<th>Viscosity at 100°C</th>
<th>Flash point (°C)</th>
<th>Iodine value (g I₂/100g sample)</th>
<th>Acid value (mg KOH/g sample)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Palm kernel oil</td>
<td>41.69</td>
<td>8.94</td>
<td>246</td>
<td>19.59</td>
<td>0.22</td>
</tr>
<tr>
<td>Mineral oil (SAE 40)</td>
<td>56</td>
<td>15.03</td>
<td>260</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>75% SAE 40, 25% palm kernel oil</td>
<td>42</td>
<td>7</td>
<td>266</td>
<td>18</td>
<td>0.21</td>
</tr>
<tr>
<td>50% SAE 40, 50% palm kernel oil</td>
<td>43</td>
<td>6</td>
<td>265</td>
<td>16</td>
<td>0.20</td>
</tr>
<tr>
<td>25% SAE 40, 75% palm kernel oil</td>
<td>45</td>
<td>8</td>
<td>268</td>
<td>15</td>
<td>0.21</td>
</tr>
</tbody>
</table>

Figure 1  Cooling curve during quenching of carbon steel probe in different blends of palm kernel oil and SAE 40 (see online version for colours)

Figure 2  Cooling rate during quenching of carbon steel sample in different blends of palm kernel oil and SAE 40 (see online version for colours)
The three stages of quenching namely vapour blanket, nucleate boiling and convective cooling stages were observed in all quench media. Vegetable (palm kernel oil) showed higher cooling rates compared to mineral oil. Maximum cooling rate of palm kernel oil (50°C/s) at 700°C was higher than mineral oil (28°C/s) at 520°C. Among blend oils, the highest maximum cooling rate of 42°C/s at 540°C was obtained for 25% mineral oil and 75% palm kernel oil blend whereas 75% mineral oil and 25% palm kernel oil showed a lowest maximum cooling rate of about 26°C/s at 570°C.

3.3 Mechanical properties

Figure 3 shows hardness variation across the quenched specimen surface.

**Figure 3** Hardness variation across the quenched specimen surface (see online version for colours)

![Hardness variation across the quenched specimen surface](image)

Figure 3 indicates a higher hardness closer to the edge of the steel sample compared to the core in all the media.

The Rockwell hardness data obtained for carbon steel specimens quenched with different blends are shown in Table 2. Quenched specimens in Palm kernel oil showed higher hardness values compared to that obtained with other quenched samples. The 25% blend of palm kernel oil with mineral oil resulted in quenched specimens having lower values of hardness compared to that obtained with 50% and 75% blend of palm kernel oil. However, sample quenched in 75% palm kernel oil blend showed lower depth of hardness (see Figure 3).

3.4 Microstructure analysis

Micrographs of the carbon steel quenched in different blends of Palm Kernel oil and mineral oil (SAE 40) are shown in Plates 1–6.
Plate 1  Microstructure of as-received medium carbon steel. The structure consists of pearlite (dark) in the matrix of Ferrite (light); (X400) (see online version for colours)

Plate 2  Microstructure of medium carbon steel quenched in 100% palm kernel oil, predominantly martensite (dark) with some bainite (grey); (400X) (see online version for colours)

Plate 3  Microstructure of medium carbon steel quenched in 75% Palm Kernel oil and 25% SAE 40. Full martensite structure (X400) (see online version for colours)
Plate 4  Microstructure of medium carbon steel quenched in 100% SAE-40. Structure consists of martensite (dark) and retained austenite structure (light); (400X) (see online version for colours)

Plate 5  Microstructure of medium carbon steel quenched in blend of 50% palm kernel oil with 50% SAE 40. Structure of martensite and retained austenite (X400) (see online version for colours)

Plate 6  Microstructure of medium carbon steel quenched in 25% palm kernel oil with 75% SAE 40 (see online version for colours)
4 Conclusions

The experimental study was performed to investigate the effect of blending palm kernel oil with SAE 40 on the quenching performance of the oil and their blends. On the basis of the results of the investigation, the following conclusions were drawn:

- The highest cooling rate was obtained for samples quenched in 100% palm kernel oil whereas mineral oil (SAE 40) yielded the lowest cooling rate.
- Hardness value increases with increasing percentage of palm kernel oil. However, 75% palm kernel oil blend showed lower depth of hardness compared to other blends.
- The tensile strength for samples quenched in 100% SAE 40 was on average smaller than those obtained for samples quenched in 100% palm kernel oil and their blends.
- The impact value for samples quenched in 100% palm kernel oil was smaller than those obtained for SAE 40 and the blends.
- Mechanical properties, such as hardness, tensile strength and impact value, were highly dependent on the percentage of blend and the final structure of the material which supports earlier work in the literature with respect to quench severity.

References


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