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Edible and Non-Edible Bioquenchants: Analysis and Comparison of Mechanical Properties in Pure Commercial Aluminium

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Abstract: The imbibed properties of pure commercial Aluminium were evaluated after being heated and quenched in various bio quenchants (edible and non-edible oils). These metals were subjected to various material testing processes. The data obtained showed the existence of three regions (i.e., film, nucleate and convective) on the cooling curves with Jatropha noted to exhibit the maximum cooling rate and heat transfer coefficient than the other oils. The quench severity of the oils was found out to be directly proportional to their respective heat transfer coefficients. Of all the oils, pure commercial Aluminium quenched with the use of Shea butter and Palm oil exhibits better mechanical properties and could be recommended for use in industrial quenching process.

Keywords: Bioquenchants, Quench Severity, Cooling Curves, Aluminium, Heat Transfer

1. Introduction

Strengthening process depends on heat treatment such as hardening of metals and their alloys [1-3]. Rajput (2004) asserts that they have close connections to theories because of their dependence on phase diagrams and the knowledge about their atomic mechanism that leads to strengthening. Heat treatment is the best-known material strengthening process, and it is done for the purpose of improving the properties and structure of metals through stress relief, quenching, tempering, and surface hardening [1-3, 10].

Furthermore, Albert and John (1992) affirmed that heat treatment is the process by which metal in its solid state is subjected to one or more temperature cycles to confer desired properties. According to Odebiyi *et al. (*2013), application of heat to metal during hot working process slows down the cooling rate, enhanced toughness, and microstructure constituents among others.

Quenching is a process of rapid cooling of metal(s) from an austenitizing temperature which results in the transformation of austenite to martensite (non-equilibrium constituents). It is usually done to maintain mechanical properties that could be lost with slow cooling and commonly applied to metal objects to which it gives hardness. According to Rajan, T. V et al. (1999), quenching media and the type of agitation during quenching are selected to obtain specific physical properties with minimal internal stresses and distortion.

The medium used for quenching is referred to as “quenchant,” and the effectiveness of the quench process depends on the characteristics of the quenchant used (which include specific heat, thermal conductivity, viscosity, flash point, pour point etcetera); and other factors such as the chemical composition, design component and surface condition of the metal component which controls the efficiency of the quenching process [4].

There have been various investigations on the use of vegetable and animal oils as quenchants. One of the earliest studies involving cooling curve and heat transfer analysis of the quenching properties was conducted by Rose in 1940 with rapeseed oil [9].

The rapidity with which the heat absorbed by the quenching bath has a considerable effect on the hardness of the metal; for instance, clear cold water is very often used while the addition of salt increases the degree of hardness. Oil, however, gives the best balance between hardness, toughness, and distortion for standard metals [4].

The quenching velocity of oil is less than that of water [6]. Obviously, the eventual properties are determined by composition and structure of the material which is the result of given processing that could be altered through the composition constituents. Thus, the property of the material is determined by the processing parameters which control the microstructure along with the composition [1, 5, 10].

2. The objective of the Study

The objective of the study is to determine and compare the mechanical properties of pure commercial aluminum in the various bio-quenchants with that of the petroleum (mineral) oil.

3. Methodology

Edible and non-edible oils were used for this work. The edible oils used were purchased at a local market in Ilorin, Kwara state and the non-edible oil was purchased in a processing factory in Lagos state, Nigeria. The edible oils purchased include Palm oil and Shea butter while the non-edible oil purchased is Jatropha. The quenching performances of these oils were compared to that of the mineral oil purchased that is SAE 40.

The specimen used was pure Aluminium with a specific dimension. The temperature of the column was maintained isothermally at 450°C for pure Aluminium for a set length of time of about 40 minutes. Viscosities of the various oils were determined at different temperatures ranging from 20, 30, 40 & 100°C. The acid value density, iodine value, moisture content, specific gravity, saponification value and flash point were all determined.

The cooling rate curves were obtained for the pure Aluminium cylinder probe with a k-type thermometer inserted into the geometric center and end. The purpose for inserting the k-type thermometer to the end and center of the probe is to determine the region of heat concentration that is of it flows inward or outward after the probe is been heated in the furnace to 450°C for Aluminium. The terminal of the thermocouple is connected to the 3-channel thermometer monitor while the standard k-type temperature probe is immersed into the quench medium of about 1000ml while the heated probe was then manually and rapidly inserted into the quench bath. The probe temperature read at the center is marked as T1 while the end is marked as T2 with the cooling time and rate studied on the 3-channel thermometer in order to establish a temperature versus cooling rate curve.

3.1. Calculation of Effective Heat Transfer Coefficients

A most conventional cooling process involving vaporizable quenchants possess four distinct cooling mechanisms: a) Shock boiling; b) Film boiling; c) Nucleate boiling & d) Convection boiling processes. Since standard probe provides cooling rate and temperature versus time at the core of the probe, we can only evaluate the average heat transfer coefficients which are widely used in heat treating industries. During quenching, the heat transfer coefficient is dependent on the surface temperature of the metal, mass and flow velocity of the quenchants, a variation of the average value (h). These coefficients are calculated using the Lumped System Analysis with the governing equation as:

$$h = \frac{\frac{C_p \rho V}{A}\left({dT_p}/{dt} \right)}{T_p - T_q}$$

Where, h = heat transfer of the coefficient
C_p = specific heat capacity of the probe
ρ = density of the probe
V = volume of the probe
A = area of the probe
T_q = temperature of the quenchant
T_p = temperature of the probe
dt = change in time

3.2. Material Testing Equipment

3.2.1. Tensile Test

The universal testing machine was used in determining the tensile strength of the probe. The work piece was fixed to the lower and upper grip of the machine while the pulling force was applied to the work piece metal axially. The elastic limit, yielding stress, ultimate tensile stress, breaking load and elongation of the metal were determined from the graph obtained or recorded from the Universal testing machine.

3.2.2. Micro Hardness Test

The Vickers machine model of micro hardness tester LM700AT was used. A sample is cut from the work piece and grinded to a smooth mirror-like surface. The surface of the work piece was indented with the Vickers diamond indenter at any clear view of the work piece grains. The hardness of the work piece was displayed by the Vickers machine and recorded. The hardness value of the material was determined with an applied load of 490.3mN and a dwelling time of 10 seconds.

4. Results and Discussion

The properties of the oils used in the course of the study were analyzed in order to ascertain the differences between their individual constituents. The densities of the oils were close to each other except for Palm oil which has a density of 915kg/m^3. The flash point of Jatropha is discovered to be close to that of SAE 40 which has a flash point of 260°C.

The edible oils under study had a close range of specific gravity, and the moisture content of each of the oils falls within the range of 0.1 – 10% with Shea butter having the highest moisture content value of 10%.

Table 1. *Properties of the Oils used.*

Oils	Density (kg/m^3)	Viscosity	Flash Point (°C)	Saponification Number	Iodine Value	Acid Value	Specific Gravity	Moisture Content (%)
Palm Oil	915	130 @ 20°C	162	190 – 205	50 – 55	0.1 – 1.0	0.952	0.10
Jatropha	0.916	52.6 @ 30°C	240	188 – 198	90.8 – 112.5	1.0 – 3.82	0.917/0.923	5.54/101
Shea Butter	0.91	39.98 @ 30°C	110	190	59.5	3.62	0.920	10
SAE 40	0.868	159.2 @ 40°C	260	Not Analyzed				

The result of quenching using the different edible and non-edible oils is shown in Table 2 below.

Table 2. *Temperature Variations (°C) of Oils during quenching.*

Time (s)	SAE 40	Jatropha	Palm Oil	Shea Butter
0	450.0	450.0	450.0	450.0
2	432.6	408.8	449.7	421.4
4	389.8	336.9	402.0	373.0
6	343.7	293.4	334.0	326.7
8	306.8	254.4	276.7	288.6
10	280.6	224.6	234.2	259.2
12	261.5	200.7	203.4	235.4
14	244.8	181.8	180.4	216.7
16	231.1	166.6	163.0	200.5
18	219.4	154.4	149.8	186.7
20	209.0	144.3	139.8	175.1
22	199.5	135.7	132.3	165.2
24	191.2	128.4	126.3	156.6
26	183.6	122.1	121.5	149.3
28	176.9	116.6	117.5	142.8
30	170.7	111.7	114.0	137.2
32	165.1	107.4	111.0	132.0
34	159.9	103.5	108.2	127.2
36	155.3	100.0	105.8	123.1
38	151.1	96.2	103.7	119.3
40	147.1	93.9	101.6	115.8
42	142.7	91.3	96.4	112.8
44	138.5	88.8	96.2	109.8
46	134.7	86.5	95.8	104.6
48	131.4	84.3	95.4	101.7
50	128.4	80.0	95.0	98.7

Table 3. *Cooling Rate of the Oils.*

Time (s)	SAE 40	Jatropha	Palm Oil	Shea Butter
0	0.00	0.00	0.00	0.00
2	8.70	20.60	0.15	14.30
4	21.40	35.95	23.85	24.20
6	23.05	21.75	34.00	23.15
8	18.45	19.50	28.65	19.05
10	13.10	14.90	21.25	14.70
12	9.55	11.95	15.40	11.90
14	8.35	9.45	11.50	9.35
16	6.85	7.60	8.70	8.10
18	5.85	6.10	6.60	6.90
20	5.20	5.05	5.00	5.80
22	4.75	4.30	3.75	4.95
24	4.15	3.65	3.00	4.30
26	3.80	3.15	2.40	3.65
28	3.35	2.75	2.00	3.25
30	3.10	2.45	1.75	2.80
32	2.80	2.15	1.50	2.60

Time (s)	SAE 40	Jatropha	Palm Oil	Shea Butter
34	2.60	1.95	1.40	2.40
36	2.30	1.75	1.20	2.05
38	2.10	1.90	1.05	1.90
40	2.00	1.15	1.05	1.75
42	2.20	1.30	2.60	1.50
44	2.10	1.25	0.10	1.50
46	1.90	1.15	0.20	2.60
48	1.65	1.10	0.20	1.45
50	1.50	2.15	0.20	1.50

Table 4. *Heat Transfer at different region.*

Heat Transfer Coefficients	Palm Oil	Shea Butter	Jatropha Oil	SAE 40
Film Region (W/m^{2}K)	374.572	447.803	648.800	475.226
Nucleate (W/m^{2}K)	621.377	374.572	502.337	520.723
Convection (W/m^{2}K)	73.087	73.076	73.087	82.238
Average (W/m^{2}K)	356.345	298.484	408.075	359.345
Grossman Hardness	0.752	0.630	0.861	0.758

Table 5. *Mechanical Properties of Aluminium in different media.*

Oils	HARDNESS (VHN)	TENSILE STRENGTH (Mpa)	MAXIMUM LOAD (N)	EXTENSION (mm)
Jatropha	116.70	96.59	1734.85	3.11
SAE 40	91.10	84.35	1281.98	1.82
Shea Butter	121.90	127.58	2261.97	5.35
Palm Oil	116.00	100.86	1795.85	3.86

From the result of the quenching tabulated in Table 2, it was observed that all the used oils showed three (3) basic regions on their cooling curves which are: the film, nucleate, and convection regions respectively Figure 1.

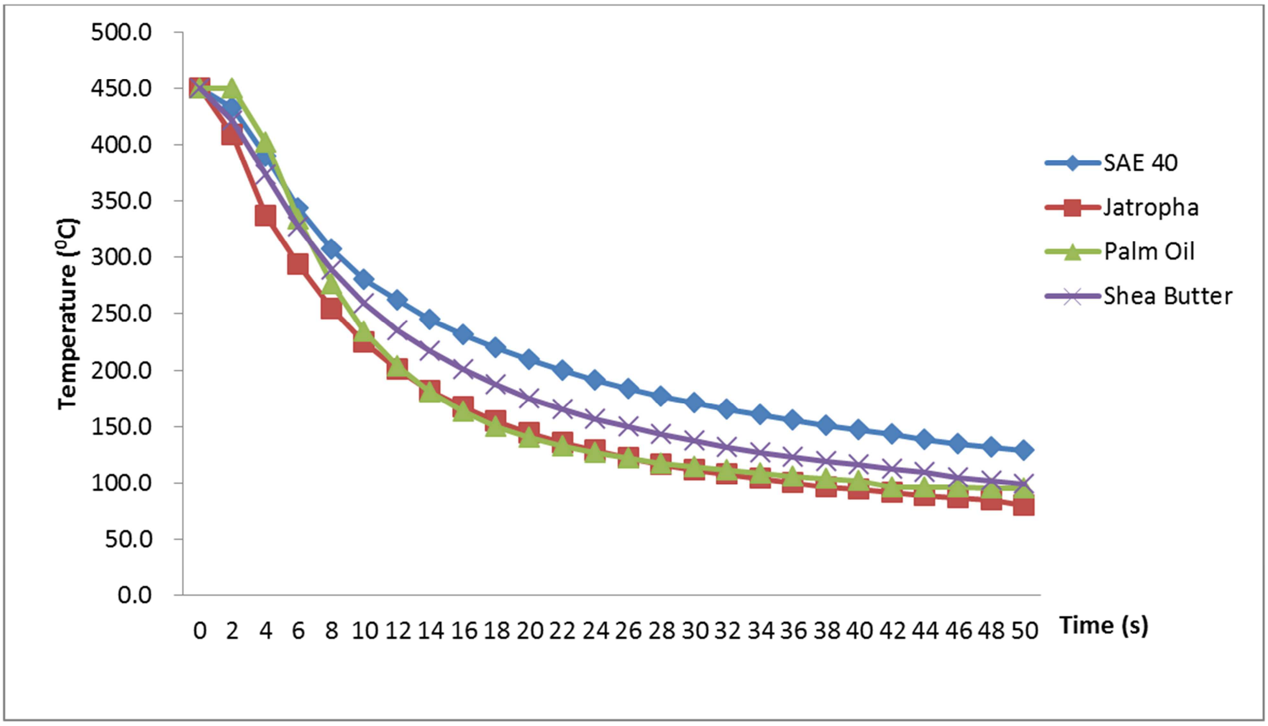

Figure 1. *Cooling curves of Oils.*

The film boundary region in all the oils occurred for a short period. Palm oil and SAE 40 had their film boiling, nucleate and convective regions are occurring at 4secs, 18secs, and 28secs respectively while Jatropha and Shea butter had their film boiling, nucleate and convective regions at 2secs, 16secs and 32secs respectively.

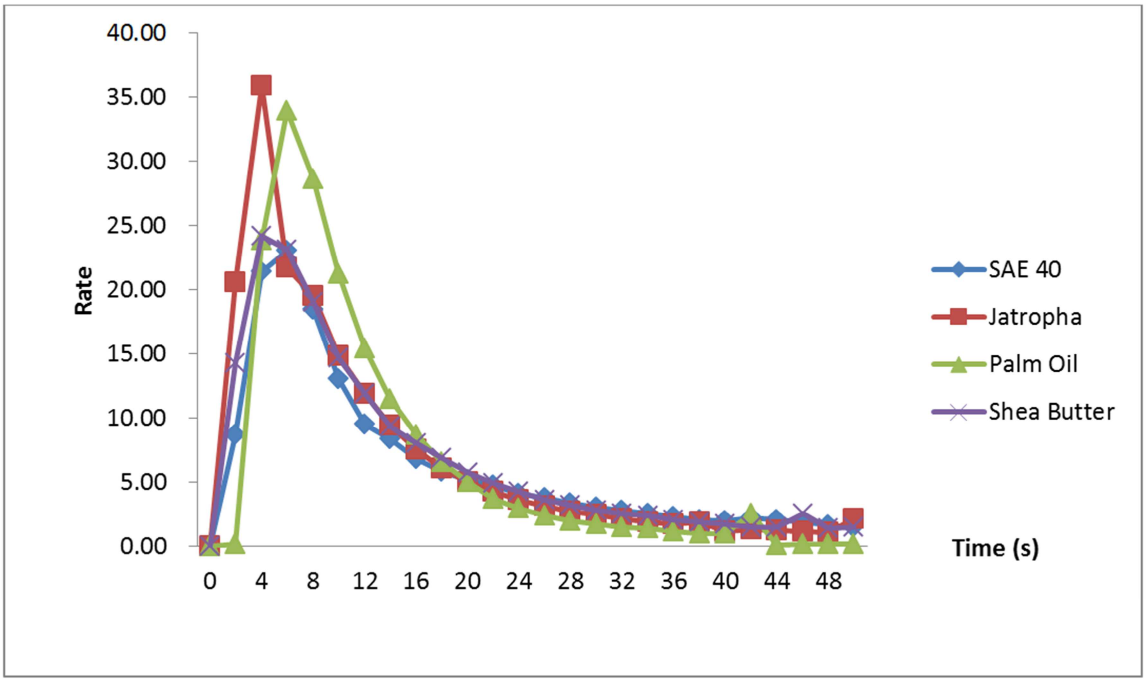

***Figure 2.** Cooling rates of the Oils.*

The cooling rate of the oils has distinguishing differences. Jatropha and Shea butter have the highest and lowest cooling rates respectively. The result of the cooling rate of these oils shows that SAE 40 and Shea butter fall into the category of slow quenching oils while Jatropha and palm oil are fast (rapid) quenching oils. However, the low flash point obtained for Shea butter is a drawback for its consideration on a large scale heat treatment process because of its high flammability.

The calculated Grossman hardness as seen in Table 5. indicates the low wettability properties of Shea butter thus making its quench severity to be low. The quench severity for Jatropha, SAE 40, Palm oil and Shea butter are 0.861, 0.758, 0.752 and 0.630m^{-1} respectively. The quench severity for each of the oils is directly proportional to their heat transfer coefficients.

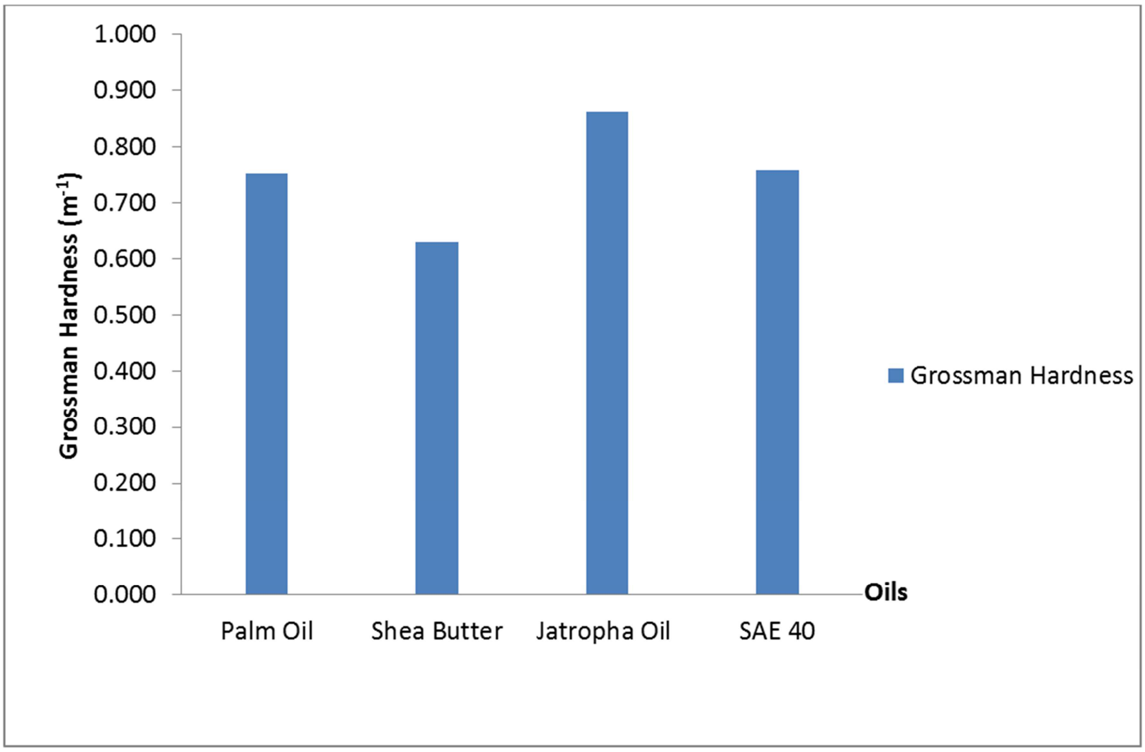

***Figure 3.** Quench Severity of the oils.*

The mechanical properties of the pure commercial Aluminium been quenched in the various oils showed that Jatropha and Palm oil had a tensile strength greater than 100MPa while SAE 40 has the lowest tensile strength (Table 5). The extension chart revealed that Aluminium quenched with Shea butter has the highest expansion ability which further explains the fact that quenching pure commercial Aluminium with Shea butter gives the material a better ductile attribute than the use of Palm oil and Jatropha in like proportion (Figure 4). In respect to the hardness value gotten from the pure commercial Aluminium quenched with these edible and non-edible oils; the hardness value is shown in the order below:

Shea butter > Jatropha > Palm oil > SAE 40

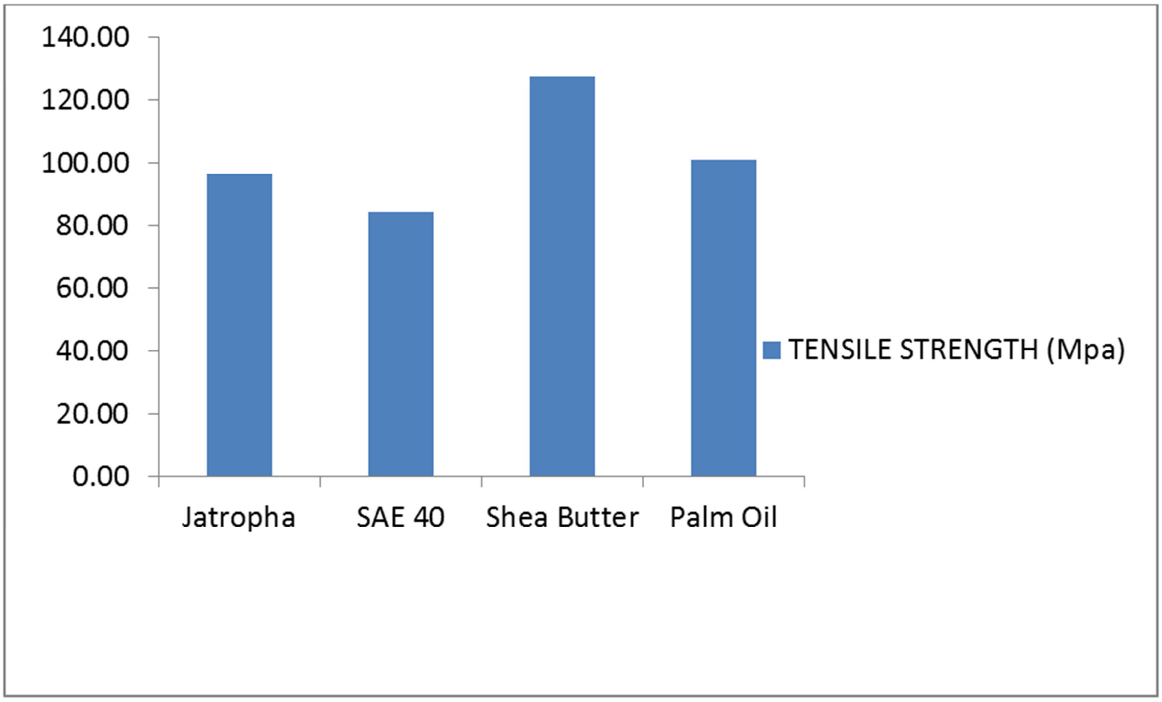

Figure 4. *Tensile Strength for Aluminium using various quenchant.*

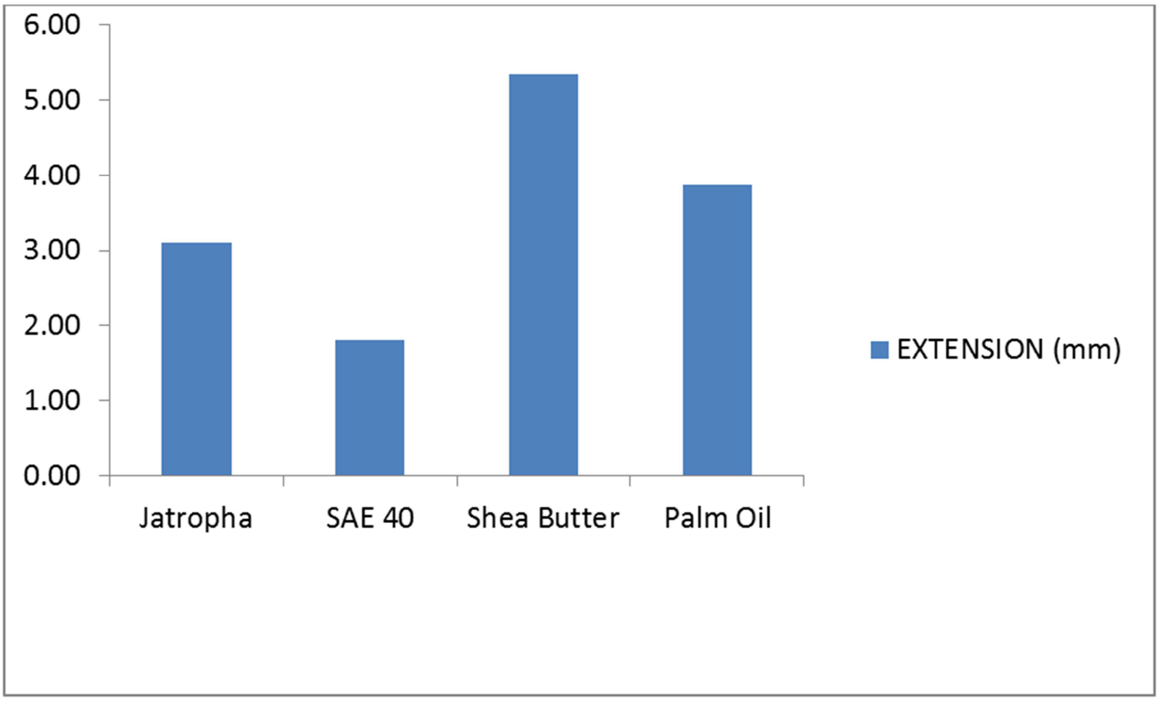

Figure 5. *Extension values for Aluminium using various quenchant.*

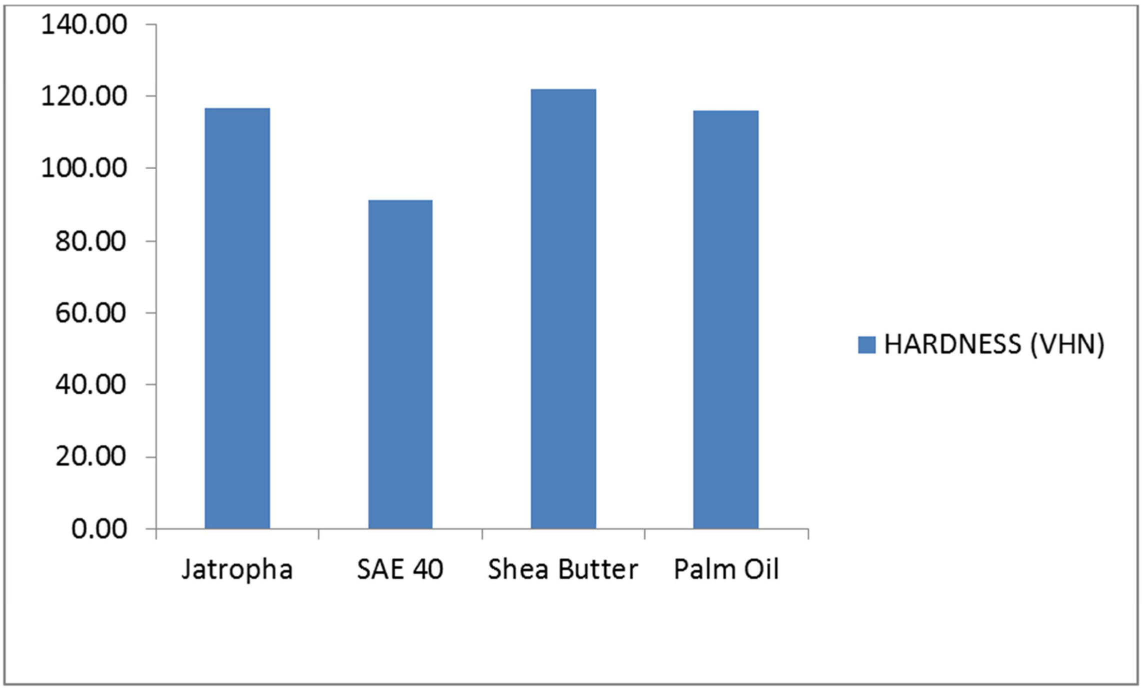

Figure 6. *Hardness Value of the various quenchants.*

5. Conclusion

Four edible and non-edible oils were obtained from the commercial source, and their composition was determined. Based on the composition of the oils, their cooling rates, curves and the mechanical properties they imbibe into the pure commercial Aluminium were analyzed. The quench severity for each of the oils is directly proportional to their heat transfer coefficients, and Jatropha can be used where fast/rapid quenching medium is required because it has a rapid cooling rate.

It could be concluded that in materials (especially pure commercial Aluminium) where mechanical properties such as ductility, hardness, and strength are of more consideration, Shea butter and Palm oil will be a more suitable quenching medium while Jatropha should be of notice when properties such as low ductility/brittleness are of paramount interest.

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