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Article · July 2020

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A COOLING POTENTIAL OF FORMULATED BIO-QUENCHANT OILS ON A CAST ALUMINIUM ALLOY MATERIAL

Adebayo Surajudeen Adekunle[1], Adekunle Akanni Adeleke[1], Tajudeen Adelani Gbadamosi[1],
Friday O. Nwosu[2], Jamiu K. Odusote[3], Peter Olorunleke Omoniyi[1],
Tajudeen O. Popoola[1], Kazeem Adekunle Adebiyi[4]

[1]*Department of Mechanical Engineering, University of Ilorin, Ilorin, Nigeria*
 E-mail: adekunlebayo@yahoo.com
[2]*Department of Industrial Chemistry, University of Ilorin, Ilorin, Nigeria*
[3]*Department of Materials and Metallurgy Engineering, University of Ilorin, Nigeria*
[4]*Department of Mechanical Engineering, Ladoke Akintola University of Technology*
 Ogbomoso, Nigeria

ABSTRACT

The biodegradable vegetable oil based quenchants can serve as cooling media alternative to that of the toxic non-biodegradable petroleum based mineral oil in a heat treatment of aluminium and its alloy. 70 vol. % of edible vegetable oil are blended with 30 vol. % of Jatropha oil to form bio-quenchant oils for Aluminium (Al)-alloy probe treated at 500ºC and soaked for 15 min in a muffle furnace. The cooling potential properties such as the cooling rate, the heat transfer coefficient, the Grossman quench severity and the biot number are investigated. The results obtained show that the blended bleached (BB) melon oil provides the highest cooling rate of 49.30ºC s⁻¹, while the blended raw (BR) palm oil ensures the lowest cooling rate of 18.45ºCs⁻¹. Heat transfer coefficients of 704.6 Wm⁻²K⁻¹, 432.3 Wm⁻²K⁻¹, and 394.4 Wm⁻²K⁻¹ are exhibited by the blended bleached melon oil, the blended raw melon oil and the blended bleached groundnut oil, respectively. They are found higher than that of a petroleum based mineral oil, which amounts to 68.7 Wm⁻²K⁻¹. The lowest heat transfer coefficient of 272.11 Wm⁻²K⁻¹ is obtained in case of using a blended raw palm oil. The quench severity of the blended bleached melon oil, the blended raw melon oil and the blended raw groundnut oil refers to a Grossman H-factor of 1.01 m⁻¹, 0.78 m⁻¹, and 0.67 m⁻¹, respectively. The latter values are higher than that obtained in case of a blended raw palm oil, which is equal to 0.37 m⁻¹. However, the heat flow parameters obtained reveal that the blended bleached and the blended raw melon and groundnut oil can be characterized as fast quenching oils, while the blended bleached and the blended raw palm oil can be characterized as medium quenching oils of results comparable to and even better than those of the industrial petroleum based mineral oil.

Keywords: bio-quenchant, cooling rate, fatty acid, Grossman H-factor, heat transfer coefficient.

INTRODUCTION

The heat treatment of aluminium alloys is usually carried out in a solution of a temperature close to their eutectic temperature aiming to obtain a homogenous solution of aluminium and its alloying constituents. As the eutectic temperature approaches the solutioning temperature ranging between 400ºC and 540ºC, the hardening agents (Mg, Si, Mg, Cu, Fe, Zn, Pb, Ti, etc.) dissolve into aluminium decreasing the micro-segregation of the additives in the aluminium matrix [1 - 3]. The rate of dissolution of the additives increases with the solution heat treatment temperature increase but as the value gets close to the eutectic melting temperature, it must be limited to prevent overheating [1]. The early stage of the overheating is not obvious, but it results in mechanical properties deterioration. However, once the aluminium alloy is heated to the desired solutioning temperature, it is then rapidly quenched to obtain a saturated solution

between the solute and the aluminium matrix [4]. During the immersion of the heated probe in the quenching medium, three stages of the quenching process develop: a vapour blanket stage, a nucleate boiling stage and a convection stage. The vapour blanket stage develops when the hot surface of the heated probe meets the quenching medium - the probe becomes surrounded by a blanket of vapours acting as an envelope which insulates it. The quenching heat transfer is slow during this stage and occurs by radiation through the vapour blanket [5-7]. The nucleate boiling stage develops immediately after the vapour blanket stage. It refers to the breakdown of all insulations in contact with the sample leading to an eruption of boiling bubbles. This is the fastest stage of the quenching during which the heat transfer rate produced is the highest and most of the cooling takes place as the vapour envelop collapses. The maximum and minimum cooling rates of the medium are determined during this stage. Finally, the convection stage is encountered when the surface temperature of the sample reaches a temperature below the boiling point of the quenchant in the bath. The cooling rate at this stage is slower as compared to that of the nucleate stage. However, the heat is removed by convection which is controlled by the quenchant specific heat capacity and thermal conduction. The media of the quenching processes are selected depending on the quench sensitivity of the specific probe material and the severity of the quench medium, i.e. the quench cooling rate [8]. The latter is used to classify the quench oils into mar-quench oils (18s - 25s), slow oils (15s - 20s), medium oils (11s - 14s) and fast oils (8s - 10s) [5]. Most of the important properties of the quenching oils refer to their viscosity, volatility, pour point, flash point, wettability, oxidation and thermal stability [9]. However, the volatility of the quench oils is inversely proportional to their flash point. As the average molecular weight of the quench oils increases, their viscosity and flash point temperature increase, while their volatility decreases [6]. The quench severity of the quench oils is directly dependent on the wettability, which is measured by the contact angle between the probe surface and the quench medium. As the viscosity increases, the contact angle decreases, which eventually decreases the cooling rate [6]. The latter is determined to characterize the various bio-quenchant and petroleum based mineral oil on the ground of the data obtained from the cooling temperature-time experiments. The analysis is carried out using

Eq. (1) suggested by Durowoju et al. [8]:

$$\text{Cooling Rate (C.R)} = \frac{dT}{dt} = \frac{T_1 - T_2}{t_2 - t_1} \qquad (1)$$

where dT is the change of the temperature (°C), while dt is the change of time (s).

The heat loss "Q" of the test probe can be expressed in accordance with Eq. (2) using the Lumped method:

$$Q = -h_c A(T_p - T_q) = \ell V C_p \frac{dT}{dt} \qquad (2)$$

The heat transfer coefficient, h_c, of Eq. 2 can be determined by the Lumped heat capacitance method advanced by Fontecchio et al. [4]. Eq. (3) is used:

$$h_c = \frac{\dfrac{\ell V C_p}{A} \dfrac{dT}{dt}}{T_p - T_q} \qquad (3)$$

where hc is the heat transfer coefficient (Wm^{-2}K^{-1}), T_p is the temperature(°C) of the test probe, T_q is the temperature(°C) of the quenching liquid, A is the surface area (m^2) of the test probe being quenched, V is the volume (m^3) of the test probe, C_p is the specific heat capacity of the test probe, $\frac{dT}{dt}$ is the cooling rate (°Csec^{-1}), while ℓ is the density (Kgm^{-3}) of the test probe. The Grossman technique known as the Grossman hardenability factor or the Grossman H-value (m^{-1}) is a numerical way of expressing the quench severity. The hardenability factor H$_G$ can be obtained on the ground of Eq. (4) advanced by Aronov [10]:

$$H_G = \frac{h}{2\lambda} \qquad (4)$$

The generalized Biot number is determined by using Eq. (5):

$$Bi_v = \frac{h l_c}{\lambda} \qquad (5)$$

where h is heat transfer coefficient (Wm^{-3}K^{-1}), λ is the thermal conductivity (Wm^{-1}K^{-1}) of the test probe, while l$_c$ is the characteristic length.

The effectiveness of the vegetable oils as bio-quenchants during the heat treatment of engineering materials has been undergoing several investigations (Tagaya and Tamura [11], Totten et al. [12], Pedisic et al. [9], Prabhu

and Prasad [13], Prabhu and Fernandes [14], Kobasko et al. [15], Simencio [16]). One of the earliest studies, conducted by Tagaya and Tamura [11], focuses on the quench severity of vegetable oils such as castor oils, a rapeseed oil, a soybean oil, a fish/animal oil comparing their viscosity and oxidative stability with those of a mineral oil and a fluid source using JIS K 2242 sliver probe. The results obtained show that the Grossman H-factor of the soybean oil of a value of 0.20 is close to that of the castor oil whose value equals 0.19. Furthermore, the cooling time of the castor oil from 700°C to 300°C is found to be 1.8 s, while that obtained for the soybean oil amounts to 1.42 s. Totten et al. [12] show that cooling curve of the vegetable oils such as soybean oils used in immersion quenching is affected by the sequence of the cooling phase and the heat transfer rate. They also verify that the heat transfer of the vegetable oils (soybean oils) depends predominantly on the bath temperature, the agitation and the cooling characteristics. It is revealed that the soybean oils exhibit a cooling time-temperature dependence and rewetting of the test probe similar to those of a mineral oil used for a comparison, but their cooling behaviour is faster. The effect of the quenching oils (mineral and vegetable oils) composition on the cooling rate is investigated by Pedisic et al. [9] who conduct different tests aiming at the determination of oils viscosity, flash point, boiling point, fluidity, volatility, oxidation, thermal stability, quench power. The cooling curve and the H-value results show that the cooling characteristics are dependent on the oils composition and the additives concentration. The cooling rate and the H-value increase after the addition of additives to the oils. The investigation on the use of a coconut oil, a castor oil, a groundnut oil, a palm oil, a sunflower oil as quench media is done by considering their heat flux and wetting properties using 304 stainless steel cylindrical probes of dimensions of 12 mm x 60 mm. The results obtained reveal that the quench severities and the surface wetting properties of the vegetable oils are comparable to those of the non-agitated mineral oil, while the cooling behaviour observed is similar with the exclusion of the castor oil (Prabhu and Prasad [13], Prabhu and Fernandes [14]). Kobasko et al. [15] investigate the quenching performance of vegetable oil base stocks commonly used for quenchant formulations in North and South America. However, the quenching performance is considered in conjunction with the composition variation of the vegetable oils used as quenchants. The results show that the soybean oil is found the best among the canola, corn, cottonseed and sunflower oils used for quenchants formulation. Although, the cooling profiles are very similar for the different vegetable oils at a lower probe temperature, a greater discrimination of the cooling properties and the cooling curve data observed in case of the different vegetable oils when compared to those of a petroleum based oil. It is also evident that not all vegetable oils exhibit film boiling and transition nucleate boiling. Simencio [16] examines the degradation of the quenching performance of soybean and palm oils with and without the addition of antioxidants. The results obtained show that the soybean oil exhibits a higher total unsaturated fatty acid (linoleic, linolenic and oleic acid) content but a lower oleic acid presence relative to the palm oil. This indicates that the latter has a greater thermal-oxidative stability. It is also observed that the addition of antioxidants, namely Propyl Gallate and Irganox L109, provide greater stabilization of the uninhibited oils. However, the vapour blanket cooling stage is found shorter in the soybean oil-based fluids than those in palm oil-based fluids or petroleum oils. The cooling rates are faster in the vegetable oil-based fluids. There are various studies on the use of raw vegetable oils as quenchants, but only a few focuses on the improvement of the quality of the vegetable oils base stocks performance through bleaching and blending techniques. Hence, the aim of this study is to characterize and compare the cooling potential of formulated bio-quenchant oils in raw and bleached forms through blending of edible vegetable oils with a non-edible one. A comparison with the behaviour of an industrial petroleum based mineral oil is also aimed at.

EXPERIMENTAL
Materials

The materials used in this study referred to cast Al-Si-Cu-Mg alloy, edible vegetable oils (melon, groundnut and palm), a non-edible oil (Jatropha) and a bleaching agent (activated kaolin clay and commercial activated charcoal). The materials were obtained from Ilorin, Kwara State, Nigeria.

Preparation of bio-quench oils

The edible and non-edible vegetable oils were bleached into refined form using the adsorption bleach-

Adebayo Surajudeen Adekunle, Adekunle Akanni Adeleke, Tajudeen Adelani Gbadamosi,

Friday O. Nwosu, Jamiu K. Odusote3, Peter Olorunleke Omoniyi, Tajudeen O. Popoola, Kazeem Adekunle Adebiyi

ing technique. Activated kaolin clay (3 g) and charcoal (5 g) were introduced separately to a 250 ml of melon, groundnut and Jatropha oils. Activated kaolin clay (7 g) and charcoal (3 g) were also introduced to a 250 ml of a palm oil. These mixtures were heated to a temperature of about 90°C under continuous stirring on a hot plate for 15 min and then filtered with a vacuum filtration pump and a filter paper placed in a Buchner funnel after cooling to obtain a bleached oil in accordance with the method of Okolo and Adejumo [17]. The bleached oils collected were stored in an air-tight container to prevent them from oxidation. 70 vol. % of the edible vegetable oils (melon, groundnut and palm) were blended with 30 vol. % of non-edible one (Jatropha) in a raw and a bleached form. The blend and raw oil samples were designated as follows: a blended raw (BR) melon oil, a blended raw (BR) groundnut oil, a blended raw (BR) palm oil, a blended bleached (BB) melon oil, a blended bleached (BB) groundnut oil and a blended bleached (BB) palm oil. The petroleum-based mineral (PBM) oil served as a control sample for a comparison. The percentage decrease of the pigment colour and the concentration of the raw and bleached oils were measured by Ultraviolet/Visible Spectrophotometer with distilled water used as a reference (blank). The wavelength range of 350 nm - 550 nm was studied. The percentage fatty acid compositions of the bio-quenchant oils was determined using a gas chromatographic (GC-MS) system. The physiochemical properties of the bio-quenchants referring to their kinematic viscosity, acid value, saponification value, iodine value, flash point, pour point and free fatty acid were analysed. The kinematic viscosity was determined according to ASTM D445-06 standard at 40°C, while the flash point and the pour point were determined in accordance with ASTM D92-90 standard.

Preparation of the experimental probes

The aluminium alloy probes used for the heat treatment experiments were casted from Al-Si-Cu-Mg alloy material and machined to a cylindrical probe size of a diameter of 10 mm and a length of 200 mm as shown in Fig. 1. Each probe was drilled centrally at one end to a depth of 13 mm and threaded to a depth of 10 mm for easy coupling with K-type thermocouple wire as shown in Fig. 2. The thermocouple sensing tip was screwed tightly to the probe and the gap between the probe and thermocouple sensing tip was sealed using a paste of kaolin clay and sodium silicate, which were furnace hardened in order to prevent the thermocouple sensing tip from wetting during the quenching. The K-type thermocouple wire extending out from the thermocouple sensing tip was connected to a digital data logger for data acquisition of the cooling temperature-time variation.

A solution heat treatment and a quenching process

The probe coupled with the K-type thermocouple was placed in an electric muffle furnace that was heated from a room temperature to 500°C (a solution treatment temperature) and soaked for 15 min in order to homogenize the composition. The heated probe was quickly transferred into the quench bath containing 1000 ml of a quench oil at a room temperature. The cooling temperature versus time dependence was recorded. This provided to determine the cooling curve of each quenching oil in accordance with ASTM D6549 standard.

RESULTS AND DISCUSSION

The results of the analysis show that the blended raw and the blended bleached formulated bio-quenchant oils contain saturated fatty acids (mainly palmitic and stearic) and unsaturated fatty acids (mainly linoleic
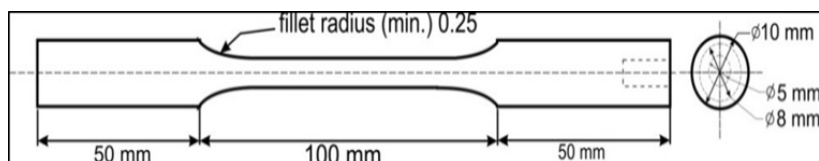

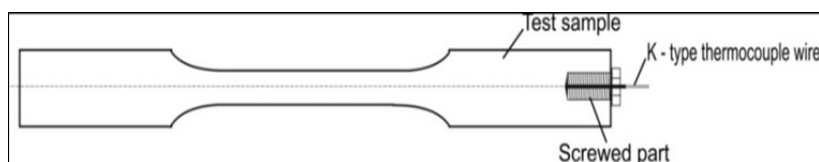Fig. 1. Schematic diagram of experimental test probe.

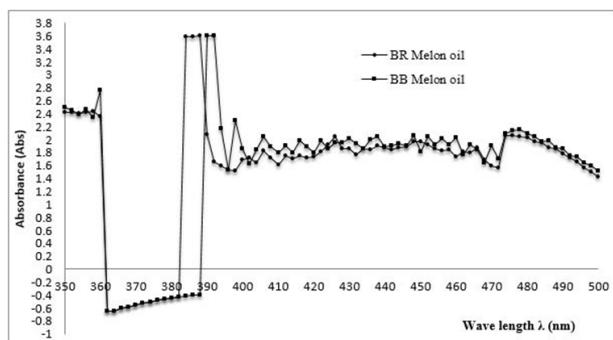Fig. 2. Detail assembling of test probe and thermocouple wire.

Fig. 3(a). Ultra-Violet/Visible Scan of Blended Raw (BR) Melon oil and Blended Bleached (BB) Melon oil.

Fig. 3(c). Ultra-Violet/Visible Scan of Blended Raw (BR) Palm oil and Blended Bleached (BB) Palm oil.
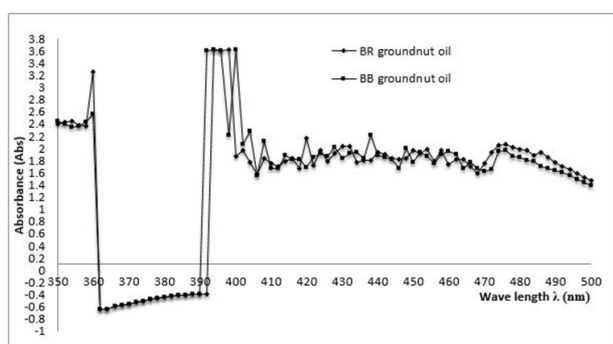

Fig. 3(b). Ultra-Violet/Visible Scan of Blended Raw (BR) Groundnut oil and Blended Bleached (BB) Groundnut oil.

and oleic) as presented in Tables 1 and 2. The bio-quenchant oils having a higher unsaturation of their fatty ester structure exhibit a lower oxidative stability. The blended raw and the bleached melon oil exhibit the highest number of double bonds (unsaturation) such as linoleic one, while the blended raw and the blended bleached palm oil exhibit the highest number of single bonds (saturation) such as palmitic and stearic one, leading to a higher oxidative stability. The effect of
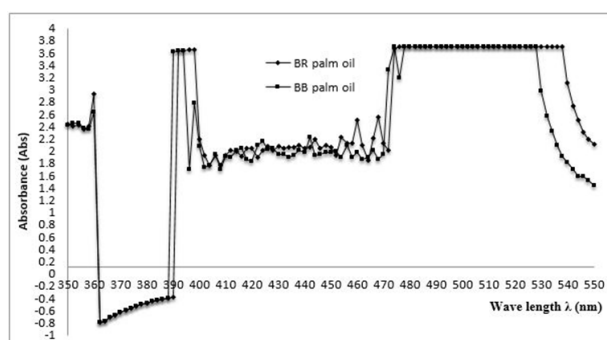
the lipids contributing to the increase of the oxidation rate follows the order: stearic (1) < oleic (10) < linoleic (100) as reported by Kodali et al. [18]. Moreover, the ultra/violet visible spectrophotometic analysis shown in Figs. 3(a) - 3(c) reveals that the blended raw and the blended bleached melon oils exhibit peak absorbance values of 3.602 Abs and 3.608 Abs at peak wavelengths of 388 nm and 392 nm, respectively. The blended raw and the blended bleached groundnut oils show peaks of absorbance values of 3.611 Abs and 3.615 Abs at a peak wavelength of 394 nm and 400 nm, correspondingly. The blended raw and the blended bleached palm oils exhibit the highest peak absorbance values of 3.701 Abs and 3.700 Abs at a wavelength at 534 nm and 528 nm, respectively. The results obtained are observed to correlate with the fatty acid composition of the oils, i.e. the higher peak absorbance and wavelength refer to the higher degree of saturation, while the lower degree of saturation of the formulated bio-oil corresponds to a lower peak absorbance value.

The Jatropha oil used to blend the vegetable oils is

Table 1. Percentage Saturated Fatty Acid Composition of Formulated Blended Raw (BR) and Blended Bleached (BB) Bio-quenchant oils.

Bio - oils	Saturated Fatty Acids					
	Behenic $C_{22}H_{44}O_2$	Myristic $C_{14}H_{28}O_2$	Palmitic $C_{16}H_{32}O_2$	Stearic $C_{18}H_{36}O_2$	Arachidic $C_{20}H_{40}O_2$	Lignoceric $C_{24}H_{48}O_2$
Blended Raw (BR)						
Melon oil	-	-	11.88	10.51	-	-
Groundnut oil	8.43	-	18.85	9.65	4.49	3.80
Palm oil	-	0.78	39.69	7.11	-	-
Blended Bleached (BB)						
Melon oil	-	-	17.86	16.19	-	-
Groundnut oil	7.95	-	19.80	9.87	4.23	3.54
Palm oil	-	1.34	43.16	11.12	-	-

Percentage may not add up to 100 % due to presence of other minor constituents not listed.

Table 2. Percentage Unsaturated Fatty Acids Composition of Formulated Blended Raw (BR) and Blended Bleached (BB) Bio-quenchant oils.

Bio-oils	Unsaturated Fatty Acids		
	Oleic $C_{18}H_{34}O_2$	Linoleic $C_{18}H_{32}O_2$	Gondoic $C_{20}H_{38}O_2$
Blended Raw (BR)			
Melon oil	14.86	51.69	-
Groundnut oil	-	52.35	2.44
Palm oil	41.92	10.49	-
Blended Bleached (BB)			
Melon oil	-	65.94	-
Groundnut oil	-	52.32	2.29
Palm oil	14.95	25.14	-

Percentage may not add up to 100 % due to presence of other minor constituents not listed.

darker in colour after bleaching due to its low oxidation and thermal stability. This fact agrees with the observation of Kapilan and Birdar [19] referring to a change of the blended raw and the blended bleached peak absorbance and peak wavelength value found equal to -0.033 Abs and -88 nm, respectively. This is the cause of the blended raw and the blended bleached melon and groundnut oils to exhibit negative values of the change (Δ) of the peak absorbance and the change (Δ) of the peak wavelength values as shown in Figs. 3(a) and 3(b).

The positive values of the changes of the peak absorbance and the peak wavelength of palm oil are due to its pigment deep red colour as reported by Poku [20]. The highest percentage decrease of the colour intensity between the blended bleached and the blended raw bio-quenchant oils is observed in case of the palm oil where the value is found equal to 0.0270 %. The corresponding lowest decrease is observed in case of the melon oil where the value amounts to 0.1666 %. The values of the specific gravity of the bio-quenchant oils are relatively close. They are in the range from 0.948 to 0.952 as presented in Table 3. The blended bleached (BB) melon oil has the highest flash point of 240°C and the lowest pour point of 9°C, while the blended raw (BR) palm oil has the lowest flash point and the highest pour point equal to 160°C and 19.5°C, respectively. This indicates that the blended raw palm oil is highly flammable at a lower temperature when compared to the other quenchant oils studied.

The chemical composition analysis of the cast aluminium alloy material used for the research work is shown in Table 4. It is evident that the content of Al (70.20 %), Si (27.27 %) and Cu (1.25 %) is the highest, while Mg, Pb, Fe and Ti are present in trace amounts. These values indicate that an aluminium alloy containing Si, Cu, Mg, Pb, Fe and Ti in trace quantities is the object of the present investigation.

Cooling curves and cooling rates

The cooling potential analysis of the cast Al-Si-Cu-Mg alloy probe subjected to a heat treatment at 500°C and quenched in the formulated bio-quanchant oils shows that the cooling curve of each of the oils studied displays three basic regions during the quenching process. The regions refer to film-, nucleate- and convective boiling as shown in Fig. 4. The film boiling region occurs within a short period of between 2 s and 6 s in all quenchant oils. Maximum and minimum cooling rates are observed during the nucleate boiling region, while a slow heat extraction to a room temperature occurs within the convective region. The highest maximum cooling rate of 49.3°C s^{-1} is obtained in case of the blended bleached (BB) melon oil, while the lowest maximum one of 18.45°C s^{-1} is observed in presence of the blended raw (BR) palm oil. Likewise, the highest minimum cooling rate of 24.70°C s^{-1} is achieved by the

Table 3. Physicochemical Characterization of Blended Raw (BR) and Blended Bleached (BB) Bio-Quenchant oils.

Quality Parameter	Blended Raw (BR) oils			Blended Bleached (BB) oils		
	Melon oil	Ground-nut oil	Palm oil	Melon oil	Ground-nut oil	Palm oil
Specific gravity at 35°C	0.95	0.95	0.95	0.95	0.95	0.95
Kinematic Viscosity (mm²/Sec) at 40°C	32.34	33.24	43.95	31.87	32.99	38.33
Flash point (°C)	220.00	220.00	160.00	240.00	230.00	190.00
Pour point (°C)	13.00	15.00	19.50	9.00	12.00	18.70
Acid value (mgKOH/g)	2.33	2.42	5.51	2.10	2.22	4.89
Peroxide value	1.94	1.86	1.74	1.20	1.31	1.55
Iodine value (gI₂/100g)	42.44	46.00	41.30	34.11	32.30	40.04
Saponification value (mgKOH/g)	196.20	193.34	200.14	202.08	197.39	210.18
Moisture content %	0.70	1.50	1.50	0.20	0.80	0.80
Free fatty acid %	1.16	1.21	2.76	1.17	1.26	2.45
pH value	7.46	7.61	6.80	7.26	7.07	6.24

Parameters were determined at 35°C while Kinematic Viscosity was determined at 40°C.

blended bleached melon oil, while the lowest minimum cooling rate of 8.35°C s⁻¹ is obtained in the blended raw palm oil. On other hand, the petroleum based mineral oil provides the highest maximum cooling rate of 25.8°C s⁻¹ as shown in Fig. 5. The petroleum based mineral oil and the blended bleached groundnut oil show no observable minimum cooling rates which could be a result of their heat extraction behaviour. The temperature values of the maximum cooling rate registration in case of the blended bleached melon oil, the groundnut oil and the palm oil refer to 401.4°C, 395.1°C and 378.6°C respectively, while those of the blended raw melon oil, the groundnut oil and the palm oil are found equal to 366.3°C, 387.5°C and 398.6°C, correspondingly. However, the maximum cooling rate of the petroleum based mineral oil is obtained at a temperature of 400.7°C. The quanchant oils time – temperature cooling curves and the cooling rate – temperature curves follow the trend reported in the literature (Kavalco et al. [3]; Durowoju et al. [8]; Kobasko et al. [15])

The cooling rate of each quench medium is observed dependent on the oil kinematic viscosity, peak absorbance value, acid value, total unsaturated fatty acids (linoleic, oleic and gondoic acid) content and that of the total saturated (palmitic and stearic) acids. The higher cooling rate values obtained in the blended bleached bio-quenchant oils are found to have a direct relation to the fatty acid presence in the oils. This means that the cooling rate value increases with a decrease of the kinematic viscosity. The viscous oils such as the blended bleached and the blended raw palm oil offer a highly stable vapour blanket, consequently slowing down the cooling rate [9]. However, the kinematic viscosity decreases with the degree of saturation decrease and vice

Table 4. Chemical Composition (wt %) of the As-Cast Al-Si-Cu-Mg Alloy.

Elements	Al	Si	Cu	Mg	Pb	Fe	Ti
Composition (Wt %)	70.20	27.27	1.25	0.61	0.003	0.14	0.12

Adebayo Surajudeen Adekunle, Adekunle Akanni Adeleke, Tajudeen Adelani Gbadamosi,
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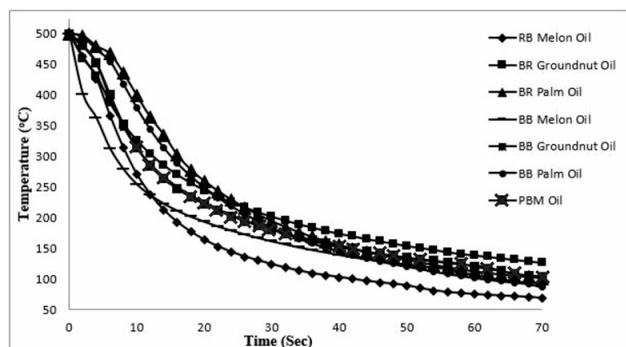Fig. 4. Time – Temperature Cooling curve of various formulated Bio-quenchant oils.

Fig. 5. Cooling Rate - Temperature for various formulated Bio-quenchants oils.

versa, which agrees with the results of Kim et al. [21]. The lower cooling rate value obtained in the blended raw bio-quenchant oils results from the oils higher kinematic viscosity and the lower total unsaturated fatty acid content as reported by Durowoju et al. [8]. Thus, the cooling rate of the formulated bio-quenchant oils decreases in following order: BB melon oil > BR melon oil > BB groundnut oil > PBM oil > BR groundnut oil > BB palm oil > BR palm oil.

A heat transfer coefficient

The heat transfer coefficients of the formulated bio-quenchant oils are calculated using the lumped analytical method presented by Eq. (3). The results obtained show that the highest heat transfer coefficient of 704.56 $Wm^{-2}K^{-1}$ is observed in the blended bleached melon oil, while the lowest one of a value of 272.11 $Wm^{-2}K^{-1}$ is found in the blended raw palm oil as shown in Fig. 6. The blended raw melon oil, the raw groundnut oil, the blended bleached groundnut oil and the palm oil have heat transfer coefficient values of 432.31 $Wm^{-2}K^{-1}$, 316.55 $Wm^{-2}K^{-1}$, 394.44 $Wm^{-2}K^{-1}$ and 277.97 $Wm^{-2}K^{-1}$, respectively, while the petroleum based mineral oil has a value of 368.72 $Wm^{-2}K^{-1}$. The highest heat transfer coefficient is obtained in presence of the blended bleached melon oil due to its low kinematic viscosity and high heat extraction properties. Its temperature and time of reaching the heat transfer coefficient value refer to 401.4°C and 2 s. The corresponding lowest values observed in the blended raw palm oil refer to 378.6°C and 8 s. The petroleum based mineral oil displays its heat transfer coefficient within 6 s at a temperature of 400.7°C.

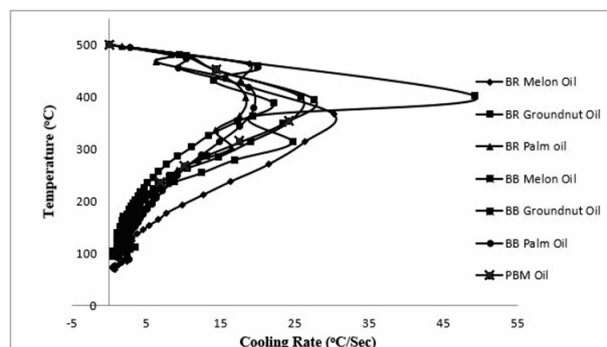The temperature and the time of occurrence of the maximum heat transfer coefficient of the blended raw melon oil, the groundnut oil, the blended bleached groundnut oil and the palm oil refer to 366.3°C, 387.5oC, 395.1°C, and 378.6°C, respectively, and 6 s with the only exception of the blended bleached palm oil whose time of occurrence is found equal to 8 s. The variation of the values of the corresponding blended bleached and the blended raw bio-quenchant oils results from their kinematic viscosity, saponification value and total saturated and unsaturated fatty acid content. The blended bleached bio-quenchant oils offer higher heat transfer coefficients when compared to those of the corresponding blended raw ones due to the former lower kinematic viscosity, higher saponification value as well as lower total unsaturated fatty acid (linoleic, oleic and gondoic) content. However, the variation between the blended bleached and the blended raw bio-quenchant oils is observed to be highly dependent on the oils' kinematic viscosity, which increases with the increase of the saturated fatty acid content. This observation agrees with the results reported by Kim et al. [21]. The heat transfer coefficient of the formulated bio-quenchant oils decreases in following order: BB melon oil > BR melon
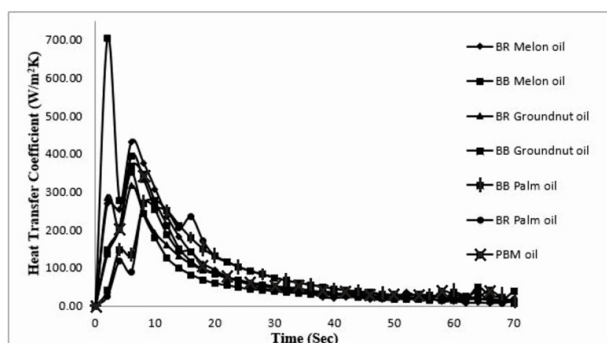

Fig. 6. Heat Transfer Coefficient of various formulated Bio-quenchant oils
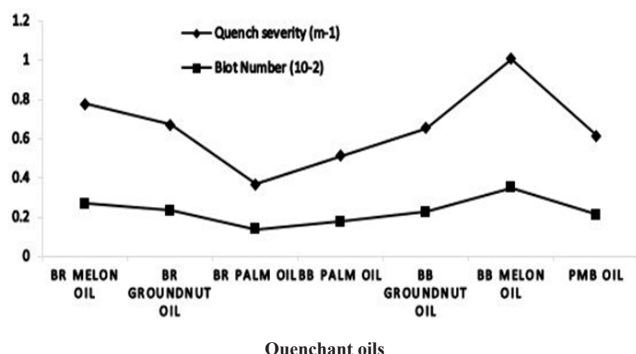
Fig. 7. Grossman Quench severity and Biot Number for varoius formulated Bio-quenchant oils.

oil > BB groundnut oil > PBM oil > BR groundnut oil > BB palm oil > BR palm oil.

Quench severity and Biot number

The Grossman quench severity and the Biot number of the formulated bio-quenchant oils are determined using Eqs. (4) and (5), respectively. The results show that the highest Grossman quench severity value of 1.01 m^{-1} is obtained in presence of the blended bleached melon oil, while the lowest value of 0.37 m^{-1} is observed in case of the blended raw palm oil. It is worth adding that the petroleum based mineral oil has a quench severity value of 0.61 m^{-1} as shown in Fig. 7. Meanwhile, the blended raw melon oil, the groundnut oil, the blended bleached groundnut oil and the palm oil show Grossman H-values of 0.78 m^{-1}, 0.67 m^{-1}, 0.66 m^{-1} and 0.51 m^{-1}, respectively. The biot numbers calculated show that the blended bleached melon oil has the highest value of 0.35x10^{-2}, while the lowest value of 0.14x10^{-2} is obtained in case of the blended raw palm oil. The petroleum based mineral oil offers a biot number of 0.21x10^{-2}.

The results referring to the quench severity and the biot number show that the Grossman quench severity of the formulated bio-quenchant oils is directly proportional to their biot number. This conclusion is in agreement with the observations of Durowoju et al. [8] and Canale et al. [22]. The Grossman quench severity and the biot number are found strongly dependent on the oils' kinematic viscosity as reported by Durowoju et al. [8]. The Grossman quench severity and the biot number follow the decreasing order: BB melon oil > BR melon oil > BR groundnut oil > BB groundnut oil > PBM oil > BB palm oil > BR palm oil.

CONCLUSIONS

The cooling potential of formulated bio-quenchant oils on a heat treated cast aluminium alloy material is sucessfully studied. The blended raw and the blended bleached melon oil have the highest content of unsaturated fatty (oleic and linoleic) acids, while the blended bleached palm oil has the highest saturated fatty (palmitic and stearic) acids content. The cooling potential properties such as the cooling rate, the heat transfer coefficient and the quench severity are strongly dependent on the oils' kinematic viscosity. Higher values are observed in presence of the blended bleached bio-quenchant oils when compared to those of the corresponding blended raw bio-quenchant oils. The heat flow properties obtained characterize the blended bleached and the blended raw melon oil and groundnut oils as fast quenching oils, while the blended bleached and the blended raw palm oil used as quenching media show results comparable and even better than those of the industrial petroleum based mineral oil.

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