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EFFECTIVENESS OF BIODEGRADABLE OILS AS QUENCHING MEDIA FOR COMMERCIAL ALUMINIUM

UČINKOVITOST BIORAZGRADLJIVIH OLJ KOT SREDSTEV ZA GAŠENJE KOMERCIALNEGA ALUMINIJA

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The effectiveness of biodegradable oils such as palm oil, shea-butter oil and jatropha oil, compared to the conventional mineral oil, in the quenching of commercial aluminium was investigated. Pure commercial aluminium was solutionized in an electric furnace at (200, 250, 300 and 350) °C. The mechanical properties of the samples of commercial aluminium were determined while the cooling rate and quench severity of the oils were studied. The results showed that the quench severity of the oils is directly proportional to the heat-transfer coefficient; jatropha oil, palm oil, shea butter and conventional mineral oil had heat-transfer coefficients of (648.80, 621.38, 447.80 and 520.72) W/m^{2}K at the nucleation region, while their quench severities were (0.861, 0.752, 0.630, and 0.758) m^{-1}, respectively. The hardness values of the pure commercial aluminium after quenching in jatropha oil, shea-butter oil, palm oil and mineral oil were (116.7, 121.9, 116.0 and 91.1) HVN, with tensile strengths of (96.59, 127.60, 100.86 and 84.35) MPa, respectively. Shea-butter oil and palm oil are better quenching media for pure commercial aluminium when high ductility is required, while jatropha oil can be used when low ductility, or brittleness, is of importance.

Keywords: biodegradable oils, quenching, aluminium, mineral oil

Avtorji v pričujočem prispevku opisujejo raziskavo učinkovitosti biorazgradljivih olj, kot so jatrofino olje, palmino olje, karitejevo maslo in karitejevo olje za gašenje (hitro ohlajanje) komercialnega aluminija v primerjavi s konvencionalnim mineralnim oljem. Tehnično čisti komercialni aluminij so raztopno žarili v električno-uporovni peči pri (200, 250, 300 in 350) °C. Določili so mehanske lastnosti vzorcev aluminija v odvisnosti od ohlajevalne hitrosti in študirali ostrost (intenzivnost) hladilnih sredstev. Rezultati raziskave kažejo, da je ostrost ohlajevalnega medija direktno proporcionalna koeficientu prenosa toplote; jatrofino olje, palmovo olje, karitejevo maslo in mineralno olje imajo namreč naslednje koeficiente prenosa toplote: (648,80, 621,38, 447,80 in 520,72) W/m^{2}K pri področju nukleacije, medtem ko je njihova intenzivnost ohlajanja (0,861, 0,752, 0,630 in 0,758) m^{-1}. Izmerjene trdote in natezne trdnosti vzorcev iz komercialnega aluminija po hitrem ohlajanju v jatrofinem olju, karitejevem maslu, palmovem olju in mineralnem olju so bile (116,7, 121,9, 116,0 in 91,1) HVN ter (96,59, 127,60, 100,86 in 84,35) MPa. Jatrofino olje in palmovo olje sta boljši za hitro ohlajevanje čistega aluminija v primeru zahtev po njegovi boljši trdoti in trdnosti, medtem ko ima karitejevo maslo prednost, ko se zahteva dobra duktilnost in manjša trdnost aluminija.

Ključne besede: biorazgradljiva olja, gašenje (hitro ohlajanje), aluminij, mineralna olja

1 INTRODUCTION

Materials are the core of all technological advances, and essential for human survival on earth. Aspects of daily life, such as clothing, transportation, construction, communication, are influenced by materials. The advancements of societies are tied to the ability to manufacture materials to meet the needs.[1] Mastering the development, synthesis and manufacture of these materials provides opportunities that were scarcely thought of a few decades ago. Every day, new limits and heights are attained in engineering applications. This has forced materials science into a rapid development ranging from the very heavy-weight machine beds to the flyweight of electronic circuit boards, high temperature performance of super alloys and the versatility of ductile steels.[1]

Aluminium is widely used in electrical, chemical, food-packaging, petrochemical and construction industries on account of its excellent corrosion resistance, high thermal and electrical conductivities and good formability. Pure commercial aluminium possesses weak matrices, resulting in low strength and this has caused a drawback to its use.[2,3] The desire to develop new materials with improved wear resistance and better tribological properties without compromising the strength-to-weight ratio, can be realised using metal-matrix composites and heat treatment.[4,5] However, the choice of an effective quenching medium used after heat treatment is very critical for ensuring the achievement of desired mechanical properties.[6]

Quenching has been regarded as an essential element in the development of the desired properties of many steels as well as aluminium alloys.[7] According to J. B. Agboola et al.,[8] quenching has been used as a heat-treatment method for several years and it still finds relevance

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today. It helps us to alter the microstructures of metals; hence, their mechanical properties. Water, air and oils have been the major quenching media for altering the properties of any engineering material. Oils are complex mixtures that are made up of different molecules that should not be altered so as to maintain the synergy to produce their effects.[9] Mineral oils have been in use as the traditional source of quenching fluids for metals and alloys because of its excellent cooling capacity.[10] However, the growing environmental concerns such as renewability, biodegradability, safety and health of workers demand serious attention; thereby looking for an alternative quenching oil such as vegetable oil. Although the price of vegetable oils is relatively higher compared with the mineral oils,[11] their biodegradability, availability and numerous benefits of by-products of vegetable oils have made them more suitable and economical for use in quenching. A study conducted by A. Petterson[12] showed that bio-based fluids have better lubricities and their viscosities are reduced significantly better at high temperatures than those of mineral-based oils. However, with these advantages, there are also a few challenges associated with the use of vegetable oils as quenching fluids. These include their low-temperature viscosities, oxidative problem and hydrolytic instabilities associated with the triglycerides naturally present in them.[13] These triglycerides are present in vegetable oils as free fatty acids (FFA) and their effect can be neutralised by an effective antioxidant used as an additive.[14] The carbon cycles of mineral oil-based products are not closed but open and this leads to an increase in the content of atmospheric carbon dioxide, thus contributing to global warming, an issue of concern to the entire globe.[15]

Several researchers have worked on the heat treatment and quenching of various materials (mild steel, medium-carbon steel, aluminium, etc.) in various media in order to investigate the effects of these quenching media on the mechanical properties and microstructure of the materials quenched.[7,16–25] However, there are few reference studies on the heat treatment and quenching of aluminium alloys in biodegradable oils. Therefore, it is important to investigate and evaluate the effects of quenching aluminium alloys in biodegradable oils that have not been utilized before. Their quenching ability is determined by their heat-removal ability as well as the ability to improve the hardenability of the material quenched. The present study aims at determining the effects of local biodegradable oils, replacing mineral oils, on the mechanical properties of pure commercial aluminium during quenching carried out after solution heat treatment.

2 EXPERIMENTAL PART

2.1 Materials

The materials used in this research include pure commercial aluminium, vegetable oils (such as shea-butter oil, jatropha oil and palm oil) and conventional mineral oil.

2.2 Characterization of vegetable oils

Vegetable oils (jatropha oil, shea-butter oil and palm oil) used for this work were purchased from the Ilorin market, Nigeria. They were characterized and used in the as-purchased condition. The quenching performance of these oils was compared with a commercially available mineral oil designated as quintolubric 888-46 (conventional slow oil). The chemical structures of the bio-quenchants used in this work were characterized with fluid viscosity which was measured at 40 °C according to the ASTM D445-06[26] standard test. The fatty acid ester composition of the vegetable oils was determined with a gas-chromatography analysis using methyl-ester derivatives of different vegetable oils prepared using a Model HP 6890 gas chromatograph equipped with a flame-ionization detector (FID) set to 300 °C and a split-injection-system ratio of 1:30 at 280 °C.

2.3 Sample production, heat treatment and quenching

In determining the cooling curves of the oils, 99.83 % commercial aluminium was cast and cylindrical probe samples with dimensions of 13.5 mm diameter × 100 mm long were cut from the cast and the geometric centre of each sample was fitted with a type-K thermocouple. Similar samples with the same dimensions were machined for a tensile test, as shown in **Figure 1**. The cast aluminium samples were then solutionized in the electric furnace at a rate of 25 °C/min to solutionizing temperatures of (200, 250, 300, and 350) °C and soaked at each temperature for about 1 h. The heights of these probes were five times their diameters to ensure the heat transfer in the radial direction during solution treatment. The thermocouple was carefully inserted in a hole with a diameter of 3 mm, drilled into the top surface of the probe having a good contact. The solutionized specimens were manually and quickly (under 2 sec) transferred laterally into a 1000-mL quenching bath containing bio-quenchants. The probe temperature and cooling times were captured using an SD-card data-logger digital thermometer, model MTM-380SD, in order to establish the cooling temperature versus time curve. In order to determine the heat-transfer coefficient, the methodology as stipulated by A. S. Adekunle et al.[13] was adopted.

2.4 Mechanical test

The hardness of the specimens was determined using a LM700AT microhardness tester so that the Vickers

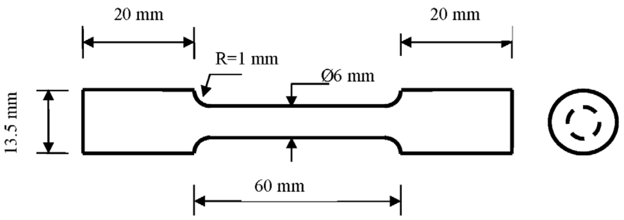

Figure 1: Specimen for mechanical properties

hardness number was obtained. The hardness test was done in triplicates, using the mean result as the hardness value for each corresponding sample. The tensile test of each specimen (**Figure 1**) was carried out on a Testometric machine (M500-50AT model) until fracture. The method used by P. P. Ikubanni et al.[20] was adopted. The tensile strength and the elongation of each sample were determined from the data generated.

2.5 Microstructural examination

A microstructural examination was carried out on the quenched samples using an optical metallurgical microscope. The surfaces of the heat-treated aluminium cast were grinded and subsequently polished with emery paper until a mirror surface was obtained. The polished surfaces were later cleaned with water and ethanol. Thereafter, the surfaces were etched using 2 % Nital. The microstructures were then observed under a high-powered metallurgical microscope.

3 RESULTS AND DISCUSSION

3.1 Physical and chemical properties

The analysis of the oils with gas chromatography using methyl-ester derivatives shows that the vegetable oils possess triglyceride structures, which are completely saturated, mono-unsaturated, di-unsaturated and tri-unsaturated (**Table 1**). The two most common saturated fatty esters in the vegetable oils used for this study are palmitic and stearic, while the mono-unsaturated ester is oleic and di-unsaturated ester is linoleic. The physical properties of the oils are shown in **Table 2**. The densities of the biodegradable oils are higher than that of the mineral oil. Palm oil has the highest density of 0.925 kg/m^3, followed by jatropha oil, shea-butter oil and mineral oil with (0.916, 0.880, and 0.868) kg/m^3, respectively. However, at 40 °C, mineral oil has the highest viscosity of 159.20 m^2/s, while the lowest was observed to be that of shea-butter oil, being 39.98 m^2/s. Palm oil also has a high viscosity of 130 m^2/s. Shea-butter oil and mineral oil have the lowest and highest flash-point values of 175 °C and 275 °C, respectively. The moisture content is large in palm oil and jatropha oil with 2.39 % and 2.75 %, respectively. The iodine values for the vegetable oils are within (18.30 and 23.37) cgI$_2$/g.

Table 1: Composition percentage of fatty acids present in vegetable oils

Fatty acids	Palm oil	Jatropha oil	Shea-butter oil
Decanoate, C10:0	–	–	–
Lauric, C12:0	–	–	–
Myristic, C14:0	0.76	–	–
Palmitic, C16:0	36.50	48.34	4.62
Stearic, C18:0	3.69	19.81	74.56
Arachidic, C20:0	1.03	3.68	1.24
Oleic, C18:1	45.66	31.85	18.84
Linoleic, C18:2	12.36	20.26	0.74

Table 2: Physical characterization of oils

Oils	Density (kg/m^3)	Viscosity 40 °C (m^2/s)	FP (°C)	SV	IV (cgI$_2$/g)	AV (%)	MC (%)
Palm oil	0.925	130.00	192	144.74	23.37	0.29	2.39
Jatropha oil	0.916	52.60	240	102.00	18.30	5.63	2.75
Shea-butter oil	0.880	39.98	175	115.01	21.59	2.61	1.83
Mineral oil	0.868	159.20	275	180.00	–	2.60	0.05

*FP – flash point, SV – saponification value, IV – iodine value, AV – acid value, MC – moisture content

In addition, the chemical composition of the pure commercial aluminium used for the investigation can be seen in **Table 3**.

Table 3: Chemical composition (in mass fractions, *w*/%) of the commercial aluminium

Al	Cu	Si	Mn	P	S	Cr	Zn	Ni
99.83	0	0.07	0.02	0.02	0.002	0.00	0.04	0.002

3.2 Cooling curves and rates

A film boundary region occurred in all the oils for a short period. Palm oil and mineral oil had their film boiling with nucleation and convection regions occurring at periods of (4, 18, and 28) s, respectively. However, jatropha and shea-butter oils had their film boiling with nucleation and convection regions occurring at (2, 16 and 32) s, respectively (**Figure 2**). These three stages were also observed in the study by J. B. Agboola et al.[9] for all the quenchants used. This showed that the cooling rates of oils are different from one another. Among all the vegetable oils used as the quenchants, jatropha oil has the highest cooling rate, while shea butter has the lowest cooling rate. It was revealed that mineral oil has the lowest cooling rate among the quenchants used in the study, as shown in **Figure 3**. However, the maximum cooling rates of jatropha oil, palm oil, shea-butter oil and mineral oil are (36, 34, 24.2 and 23.1) °C/s, respectively. The cooling rate of shea butter is close and comparable to that of mineral oil, which makes it a slow quenching oil, while jatropha oil and palm oil are fast quenching oils. However, the low flash point of shea butter is a drawback

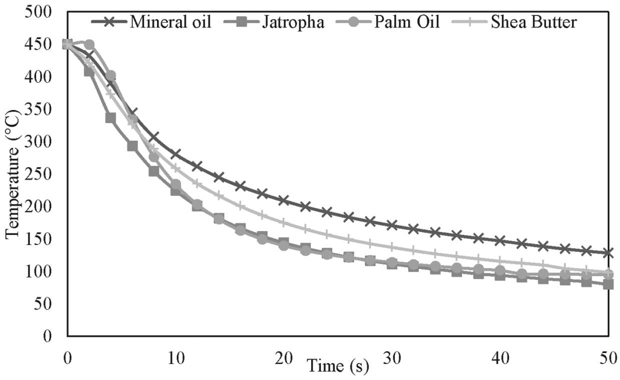

Figure 2: Cooling curve for the oils

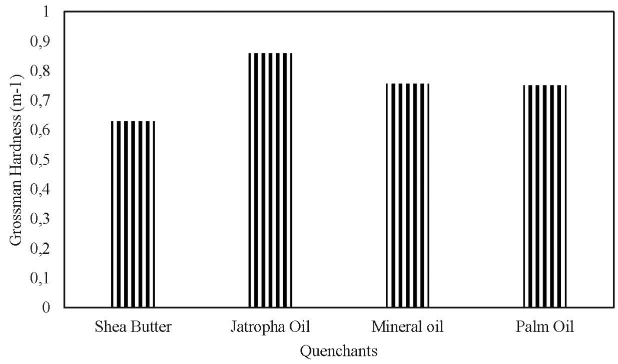

Figure 4: Quench severity of various quenchants

when considering it for the use in the heat-treatment industry because it is highly inflammable. The cooling rates exhibited by various oils used in this study follow each other in this order: jatropha oil > palm oil > shea butter oil > mineral oil.

3.3 Heat-transfer coefficient

The cooling-curve data was used to determine the time-dependent heat-transfer coefficient, while the Grossman method was used to determine the time-averaged heat-transfer coefficient[13]. At the film region, palm oil and shea-butter oil had the same heat-transfer coefficient of 374.57 W/m^{2}K, which was the lowest when compared to those of jatropha oil and mineral oil of (502.34 and 475.23) W/m^{2}K, respectively. The heat-transfer coefficients obtained for the oils showed that jatropha oil exhibits the highest value of 648.80 W/m^{2}K for the heat-transfer coefficient at the nucleation region, while palm oil and mineral oil have heat-transfer coefficients of (621.37 and 520.72) W/m^{2}K at the nucleation region. However, shea butter has the lowest heat-transfer coefficient of 447.80 W/m^{2}K at the convection region, as displayed in **Table 4**, indicating that shea butter has a low wettability and thus also a low quench severity. The highest heat-transfer coefficients of the bio-quenchants were found to be higher than that of the conventional oil. This was in agreement with the work by Adekunle et al.[13] Furthermore, the heat-transfer coefficient at the convection stage showed convergence at 73.08 W/m^{2}K for the vegetable oils, while mineral oil exhibited a higher value.

The quench severity, indicated by the Grossmann hardness, which was calculated from the experimental data for jatropha oil, mineral oil, palm oil and shea butter was (0.861, 0.758, 0.752 and 0.63) m^{-1}, respectively (**Figure 4**). The quench severity for each oil is directly proportional to its heat-transfer coefficient.

3.4 Mechanical properties

The mechanical properties of the pure commercial aluminium quenched in various oils show that shea-butter oil, palm oil and jatropha oil have high tensile strengths of (127.6, 100.86 and 96.59) MPa, while mineral oil has the lowest tensile strength of 84.35 MPa (**Figure 5**). The extension showed by the pure commercial aluminium quenched in various bio-quenchants revealed that shea-butter oil exhibits the highest extension of 5.4 mm, while palm oil and jatropha oil exhibit extensions of 3.9 and 3.11 mm, respectively. Mineral oil exhibits the lowest extension of 1.8 mm. This implies that all the quenchants improved the elasticity and ductility of the material. Ductility and elasticity were also improved when steel was quenched in bio-quenchants and conventional oil as reported by several studies.[9,13,19] According to the tensile-test results, quenching commercial cast aluminium in shea-butter oil makes the material

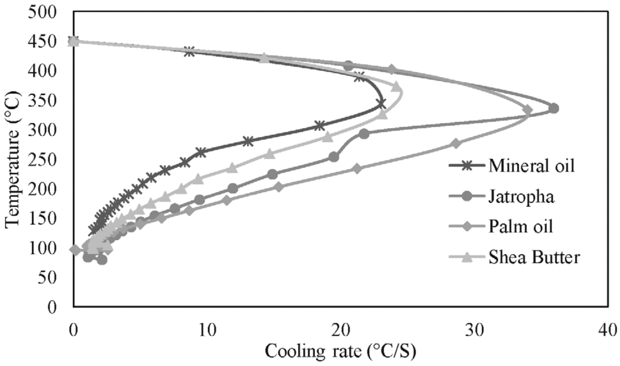

Figure 3: Cooling rates for various bio-quenchants

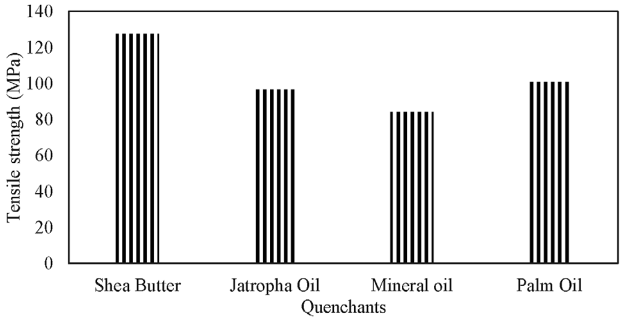

Figure 5: Tensile strength of commercial aluminium in various quenchants

ductile, while quenching it in jatropha oil and palm oil causes less ductility, and mineral oil makes the commercial aluminium brittle.

The hardness of the pure commercial aluminium after quenching indicated that quenching with shea butter provides the highest hardness value of 121.9 HVN, while palm oil and jatropha oil provide hardness values of (116 and 116.7) HVN, respectively, and mineral oil provides the lowest hardness value of 91.1 HVN. The percentage values of oleic and linoleic esters, that is, the unsaturated acids present in the bio-quenchants are related to the hardness values attained by the materials quenched.[13] Based on the improvement in the mechanical properties of the cast aluminium quenched in the bio-quenchant oils, compared with the mineral oil, it can be said that bio-quenchant oils will be a good replacement for mineral oil. The results of this study confirm that the mechanical properties of materials always improve when quenched in biodegradable oils.[7,17,19]

Table 4: Heat transfer at different regions

Region (W/m^2K)	Palm oil	Shea butter	Jatropha oil	Mineral oil
Film region	374.57	374.57	502.34	475.23
Nucleation	621.38	447.8	648.8	520.72
Convection	73.09	73.08	73.09	82.24
Average	356.35	298.48	408.08	359.35

3.5 Microstructure

The microstructure at 200× of the commercial cast aluminium quenched in various oils showed the existence of two major formations that are decisive factors in determining whether a material is brittle or ductile. According to **Figure 6a** showing the structure after quenching in mineral oil, the grains are long, small and loosely packed, thereby making the material brittle. According to the micrograph of the material quenched in jatropha oil shown in **Figure 6b**, the grains are larger but closely packed when compared with the grains obtained after quenching in the remaining oils. Thus, this makes the material slightly ductile. With palm oil, the grains are evenly packed as seen in **Figure 6c**. However, the grains are smaller compared to those obtained with jatropha oil but larger than the grains obtained with mineral oil. Hence, this implies that the material is more ductile than that quenched with jatropha. With shea-butter oil, the grains are smaller when compared to those obtained with the other oils and they are more evenly distributed (**Figure 6d**). This means that the material is much more ductile than that obtained with palm oil. In order to produce materials whose ductility, strength and hardness are of utmost importance, shea butter and palm oil are more appropriate and beneficial as quenching media. Conse-

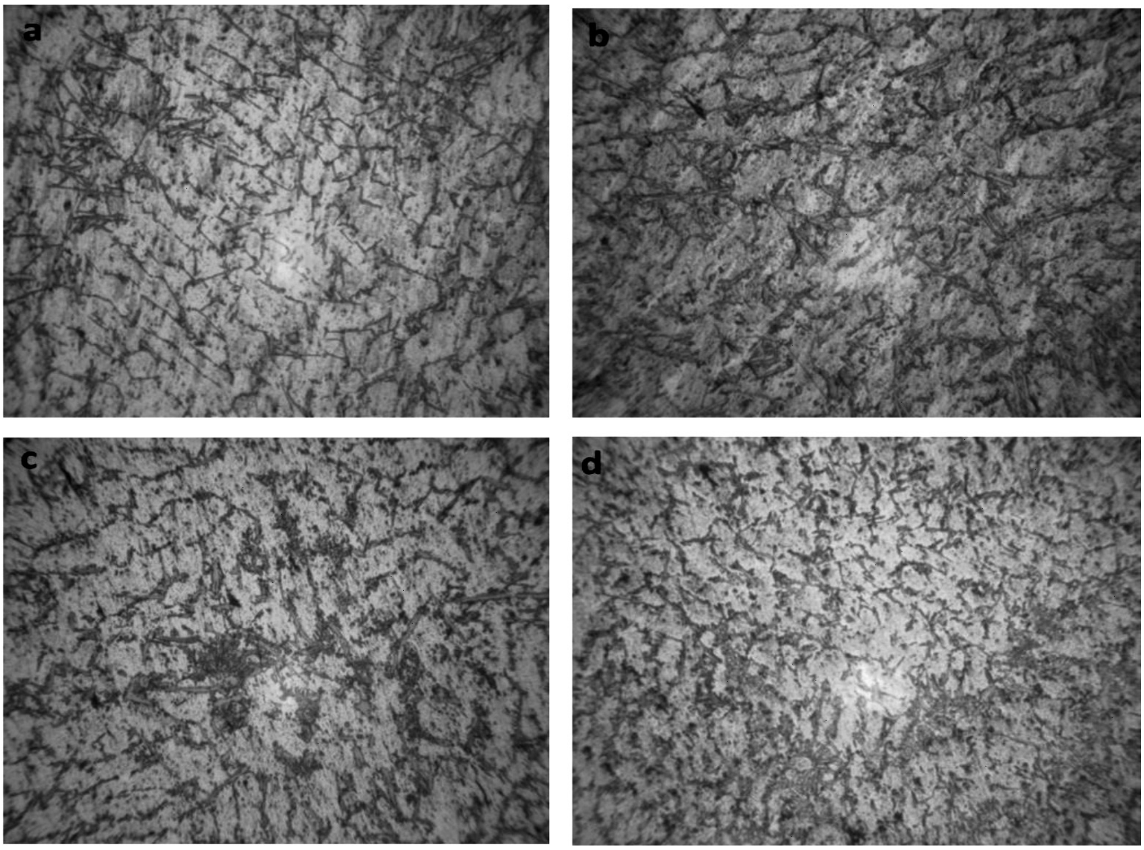

Figure 6: Microstructure of commercial aluminium treated with various quenchants: a) mineral oil, b) jatropha oil, c) palm oil and d) shea-butter oil

quently, jatropha oil is useful for the materials whose low ductility and/or brittleness are desired.

4 CONCLUSIONS

Among biodegradable oils, non-edible oil (jatropha) has the highest heat-transfer coefficient and cooling rate of 648.80 Wm^2/K and 36 °C/s at the nucleation region, respectively. Jatropha can be used as a fast quenching medium because of its rapid cooling rate. The quench severity for each oil is directly proportional to the heat-transfer coefficient and quenching with shea butter provides the highest hardness value of 121.9 HVN. The hardness, elongation and tensile strength of commercial aluminium using jatropha, palm oil and shea butter as quenchants were higher than those obtained with mineral oil. Excellent hardening properties and tensile strength were obtained with vegetable oils when used for quenching commercial aluminium in comparison with the conventional mineral oil. The grains of pure commercial aluminium quenched with jatropha oil were small and closely packed. Shea-butter oil and palm oil are better quenching media when ductility is required, while jatropha can be used as the quenching medium when low ductility and/or brittleness are of importance.

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