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Effect of copper addition and solution heat treatment on the mechanical properties of aluminum alloy using formulated bio-quenchant oils

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Abstract

Addition of copper and use of solution heat treatment solution with bio-degradable vegetable oils as quenchants has great potential to improve the mechanical properties of aluminum and its alloys. In this study, copper was added to as-received Al-Si-Mg alloy to produce Al-Si-Cu-Mg alloy. The specimens were quenched with blended bleached bio-quenchant oils and a petroleum-based oil after solution heat treatment. The alloy was heat treated at 500℃, soaked for 20 minutes in a muffle furnace before quenching in the formulated bio-quenchant oils. The cooling properties, mechanical properties and microstructure of the solution treated specimens were determined. Blended bleached melon (BBM) oil was observed to have offered a higher cooling rate of 49.3 ℃ s^{-1} compared to the petroleum-based (PB) oil with a cooling rate of 25.8 ℃ s^{-1}. Blended bleached melon oil exhibited the highest quench severity value of 1.0074 m^{-1}, while petroleum-based oil was 0.6133 m^{-1}. The as-received alloy and as-cast alloy specimens exhibited tensile strength values of 125.33 and 131.37 N mm^{-2}, respectively, while a higher tensile strength value of 139.30 Nmm^{-2} was obtained using the blended bleached melon oil. The highest Rockwell hardness number, 61.00 HRB, was obtained using blended bleached melon oil. The overall mechanical properties of specimens improved after the addition of copper and heat treatment in various bio-quenchant oils.

Keywords: Bio-quenchants, Cooling rate, Quench severity, Mechanical properties, Microstructure

1. Introduction

Pure aluminum is not usually chosen for structural applications due to its light weight, softness and low strength. However, it found applications in areas such as aluminum foil, chemical tanks, electric wire, and pipe systems, among many others [1]. Alloying pure aluminum with other elements is necessary to provide improved properties such as strength and hardness. This enables its use in structural applications in industries such as aerospace, automobiles, ship, and vessel construction. The physical, chemical, mechanical properties of aluminum alloys, as well as their corrosion resistance, strength-to-weight ratio, non-toxicity, desirable appearance, and high electrical and thermal conductivity [2] make them desirable and suitable materials in many engineering applications. Alloying elements that can be added to pure aluminum to bring about desired properties include antimony, silicon, chromium, bismuth, arsenic, copper, magnesium, manganese, iron, lead, zinc, zirconium and calcium [3]. Aluminum association systems [4] developed two major alloy nomenclatures for cast and wrought alloy. Wrought alloys are classified into heat treatable and non-heat treatable types. Wrought heat treatable alloys include the 2xxx series (Al-Cu, Al-Cu-Mg), 6xxx series (Al-Mg-Si), 7xxx series (Al-Zn-Mg and Al-Zn-Mg-Cu) and 8xxx alloy series, where lithium is the major alloying element. Wrought non-heat treatable alloys include the 1xxx series (pure aluminum), 3xxx series with Mn as the major alloying elements, 4xxx series with Si being the major alloying elements and 5xxx series where Mg is the major alloying element [3-5]. Cast alloys include the 2xx.x series (Al-Cu), 3xx.x series (Al-Si-Cu or Mg), 4xx.x series (Al-Si), 5xx.x series (Al-Mg), 7xx.x series (Al-Zn) and 8xx.x series (Al-Sn).

The addition of copper to aluminum to form an aluminum-copper system is the basis for wrought 2xxx and cast 2xx.x alloys [3], one of the many heat treatable alloys. In commercial aluminum-copper alloys, some of the copper chemically combines with aluminum and iron to form tetragonal Al_7Cu_2Fe constituent particles [5]. During heat treatment of aluminum-copper alloys containing a small amount of magnesium, and Al_2Cu precipitates as a strengthening phase. The addition of copper and silicon help to modify the crystal structure of the alloyed aluminum to increase its hardness and tensile strength, usually at the expense of ductility (i.e., deformability) [5-6]. Addition of magnesium to aluminum-rich aluminum-copper alloys results in the formation of Al_2CuMg phase by eutectic

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decomposition, which is used to strengthen different structural alloys so that they may be employed in the automobile and aerospace industries. This is because they offer a desirable combination of strength, toughness and resistance to fatigue cracks [6]. Selection of an effective quenching medium for solution heat treatment is also critical in ensuring attainment of the desired mechanical properties [7]. The most common industrial quenching medium for steel and aluminum alloys is petroleum-based mineral oil, which possesses excellent cooling capability [8]. However, this oil is relatively expensive, non-biodegradable and toxic. Hence alternative inexpensive, biodegradable and non-toxic quenching media are required as replacements. Numerous studies have focused on the possibility of reducing or replacing mineral oil with eco-friendly vegetable oil derivatives, which are less expensive, non-toxic, bio-degradable and renewable [9-12]. Vegetable oils are lipids obtained from plants. These oils are composed of triglycerides with chains of fatty acids containing about 14 to 20 carbon atoms with varying degrees of unsaturation compared with wax which lack glycerides in their structure [13]. Bleaching process is important in refining vegetable oils to improve their performance as bio-quenchants in heat treatment operations. It also enhances the economic value of the bio-oils by increasing their purity and quality.

Bleaching also helps to reduce the level of oxidation and contaminants such as soot, salt, water and sludge, which find their way into the oils during production or use as quench oils [13]. Contamination of quench oils with substances such as water leads to test specimen's distortion, cracking, spotty work and non-uniformity of properties. This is because water has properties that are different than those of bio-oil [14]. Contamination eventually causes foaming, explosion, or fire. Also, the soot in quench oil initial increases the quenching rate of a bio-oil, but its accumulation eventually reduces the quenching its speed. This occurs because higher concentrations of soot alters heat transfer features and causes a more rapid oxidation of the oil. Numerous studies on quenching using single biodegradable and petroleum-based mineral oils have been done on several metals including aluminum and its alloys [10-11, 15-20]. However, little attention has been paid to the bleaching and blending of biodegradable oils used for quenching to determine their effects on the engineering material properties.

Cooling rate is a parameter which affects the mechanical properties of heat treated aluminum. Adeleke *et al.* [17] noted changes in the microstructure and impact resistance. Finer microstructure was observed at faster cooling rates. Likewise, a higher impact resistance energy was observed with a faster cooling rate. Therefore, this study aims at investigating the effect of copper addition to Al-Si-Mg and solution heat treatment on the mechanical properties and microstructure of cast aluminum alloy Al-Si-Cu-Mg when bleach blended biodegradable oils are utilized as quenchants. It examines the effects of cooling rate on the microstructure, tensile strength and hardness of quenched aluminum.

Water, which is an economical and readily available quenchant, causes rapid cooling of metals, resulting in thermal shock, distortion of the metal's morphology, and ultimately corrosion of the metal [8]. Another commonly used quenchant is petroleum based oils, but they are expensive and not environmental friendly. Thus, the use of specially formulated bio-quenchants will mitigate the cost and create a protective film around material been quenched, thereby reducing the rate of corrosion.

2. Materials and methods

2.1 Preparation of bio-quenchant oils

2.1.1 Bleaching

Raw vegetable oils were bleached into refined form using an adsorption bleaching technique. For raw vegetable oils, 250 ml volumes melon oil, groundnut oil and Jatropha oil in a beaker were added to activated kaolin clay and activated charcoal in a ratio of 3 g:5 g, respectively. Concurrently, 7 g: 3 g of this mixture were measured into a beaker containing 250 ml of palm oil. Different mixing ratios were required due to the varying colour pigments contained in the oils. The mixture was heated to a temperature of about 90℃ under continuous stirring on an electric hot plate for 15 minutes. It was then filtered using vacuum filtration through a filter paper placed in a Buchner funnel to obtain the refined oil [21].

2.1.2 Blending

An amount, 70% by volume, of each of the bleached vegetable oils (melon oil, groundnut oil and palm oil) were blended with a bleached 30% by volume of Jatropha oil to formulate three bio-quenchant media. These are referred to as blended bleached melon (BBM) oil, blended bleached groundnut (BBG) oil and blended bleached palm (BBP) oil while petroleum based (PB) oil served as control for comparison. Fatty acid methyl ester (FAME) analysis of the bio-quenchant oils was done using gas chromatography-mass spectrometry (GC-MS) (Model, 7890A GC, 5675C, Agilent, USA). The physiochemical properties of the bio-quenchant oils including specific gravity, kinematic viscosity, flash point, pour point, acid value, moisture content, and saponification value as well as free fatty acid composition were analyzed in accordance with ASTM standards.

2.2 Preparation of test specimens

The chemical composition of the as-received and as-cast alloy materials was analyzed using Olympus Delta Professional XRF (Model 540723). The results are presented in Table 1. Tensile test specimens were prepared from the as-received and as-cast alloy samples using a sand casting method and machined to a test specimen shape and size (Figure 1) following the ASTM E8 standard on a Colchester Student 1800 lathe.

2.3 Solution heat treatment and quenching

The 10 mm diameter × 200 mm length as-cast alloy specimens were drilled centrally at one end to a depth of 13 mm and threaded to a depth of 10 mm for coupling with a K-type thermocouple, as shown in Figure 2. The thermocouple was screwed in and the gap between the thermocouple and specimen covered with paste of kaolin clay and sodium silicate hardened in a furnace to prevent the quenchant from entering the thermocouple sensing tip. The thermocouple was then plugged to a digital SD card data logger (Model MTM 380SD) to capture variation in temperature with time data [22-23]. The prepared specimens were then placed into a muffle furnace its working temperature held at 500℃ since solution heat treatment for

Table 1 Chemical composition (wt%) of the as-cast and Ai-Si-Cu-Mg alloy

Material	Composition (%)						
	Al	**Si**	**Cu**	**Mg**	**Ti**	**Pb**	**Fe**
Al-Si-Mg (As-received)	86.57	12.23	-	0.53	-	0.003	0.199
Al-Si-Cu-Mg (As-cast)	70.20	27.27	1.25	0.61	0.12	0.003	0.140

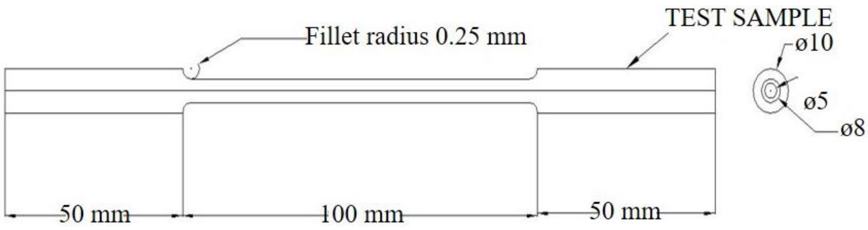

Figure 1 Schematic diagram of tensile test specimen of Al-Si-Mg and Al-Si-Cu-Mg alloys

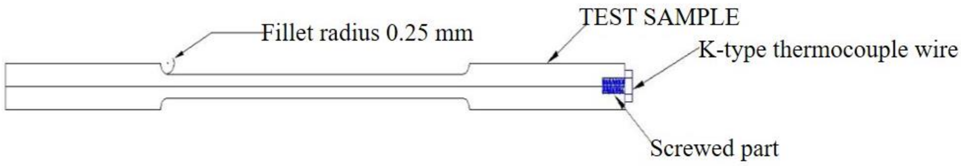

Figure 2 Schematic diagram of coupled specimen with thermocouple wire

aluminum alloys is carried out within the temperature range of 450 to 500°C [24] for 20 minutes. For soaking time, a rule of thumb [22] is one hour for every inch of cross-sectional thickness. This allows homogeneity of alloy before the samples are rapidly transferred into a quenching bath.

2.4 Determination of cooling performance

Control of cooling properties, such as cooling rate and quench severity, is essential to characterize the bio-quenchant oil behaviours. Therefore, the average cooling rate can be calculated from the temperature-time data acquired during quenching using Equation (1) as presented by Durowoju *et al.* [24]:

$$\text{Cooling Rate (CR)} = \frac{dT}{dt} = \frac{T_1 - T_2}{t_2 - t_1} \quad (1)$$

where dT (°C) is the change in temperature, dt (sec) is the change in time.

The Grossman hardenability factor (m^{-1}) is a numerical way of expressing quench severity of bio-oils. It can be calculated as expressed in Equation (2) in accordance with Aronov et al. [25]:

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

where h (W/m^3K) is a heat transfer coefficient, λ (W/mK) is the thermal conductivity of the test sample.

2.5 Mechanical tests

2.5.1 Tensile test

Tensile tests were carried out on the as-received, as-cast and quenched specimens using a Universal Testing machine Model 38140, ADMET. Each of the specimens was mounted to the jaw of the machine and a gradually increasing was load applied until fracture occurred. The data generated for tensile strength and percentage elongation on each specimen were recorded. The tests were done in duplicate.

2.5.2 Hardness test

A Rockwell hardness tester with steel ball indenter, Model HR-150A, was used for the determination of the hardness value of the as-received, as-cast and quenched specimens. Tests were done in duplicate. Prior to testing for hardness, a rough grinding was done using 180-grit SiC pre-grind paper to prepare the surface of the sample. A small piece from each test specimen was placed on the anvil of the machine and then loaded to create a round indentation. The impression created was automatically recorded as hardness value measured on a gauge.

2.6 Microstructure analysis

The as-received, as-cast and quenched Al-alloy specimens, after being kept at room temperature for 5 days to allow for natural aging, were subjected to microstructural inspection using an Accuscope metallurgical microscope with a built-in camera (Model 0524011). A small specimen sample, 10 × 3 mm, was removed and ground under running water using various grades of silicon carbide abrasive paper of 220, 320, 400 and 600 - grits to obtain a smooth finished surface. This was followed by polishing. Final polishing was done using a 0.5µm silicon carbide paste until a mirror-like surface was attained. Specimens were then etched in 2% (HNO_3) Nital. The surface was washed, dried and viewed under the Accuscope microscope.

3. Results and discussion

3.1 Bio-Quenchant oils analysis

Table 2 shows the fatty acid methyl ester (FAME) analysis of the bio-quenchant oils. The primary saturated fatty acids identified in the oils are stearic and palmitic acids,

Table 2 Percentage fatty acid composition of formulated blended bleached (BB) oils

Bio-oils	Saturated acids						Unsaturated 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 $C_{24}H_{48}O_2$	Oleic $C_{18}H_{34}O_2$	Linoleic $C_{18}H_{32}O_2$	Gondoic $C_{20}H_{38}O_2$
BBM	-	-	17.86	16.19	-	-	-	65.94	-
BBG	7.95	-	19.80	9.87	4.23	3.54	-	52.32	2.29
BBP	-	1.34	43.16	11.12	-	-	14.95	25.14	-

*Blended Bleached Melon oil (BBM); Blended Bleached Groundnut oil (BBG); Blended Bleached Palm oil (BBP).
***Percentages may not add up to 100% due to presence of other minor constituents not listed.

Table 3 Physicochemical characteristics of bleached blended oils

	Blended Bleached oils		
Quality parameter	**Melon oil**	**Groundnut oil**	**Palm oil**
Specific gravity at 35℃	0.951	0.950	0.949
Kin. Viscosity at 40℃ (mm^2/s)	31.87	32.99	38.33
Flash point (℃)	240	230	190
Pour point (℃)	9.0	12.0	18.7
Acid value (mg KOH/g)	2.098	2.224	4.890
Peroxide value	1.20	1.31	1.55
Iodine value ($gI^2/100g$)	34.11	32.30	40.04
Saponification value (mg KOH/g)	202.08	197.39	210.18
Moisture content (%)	0.2	0.8	0.8
Free fatty acid (%)	1.169	1.262	2.446
pH value	7.26	7.07	6.24

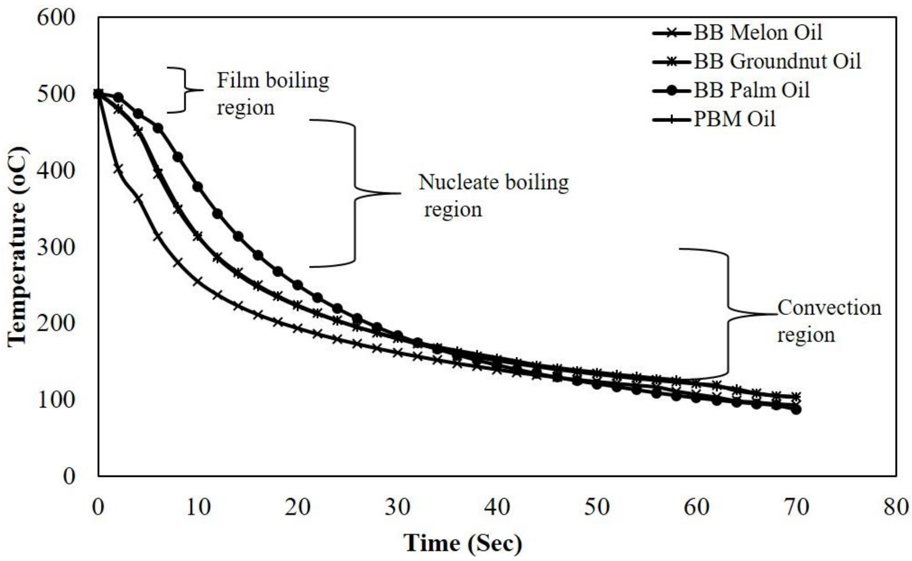

Figure 3 Cooling curves of various quench oils

while the unsaturated acids were identified as oleic and linoleic acids. Table 3 show the physicochemical characteristics of the blenched oils. The kinematic viscosities at 40°C of the bio-quenchant oils were obtained to determine the flow rate in mm^2/s. The highest kinematic viscosity, 38.33 mm^2/s, was obtained in blended bleached palm (BBP) oil, while the lowest value, 31.87 mm^2/s, was obtained for blended bleached melon (BBM) oil. The results indicated that bio-quenchant oils with the highest total saturated fatty acid content (palmitic and stearic acid) exhibited the highest kinematic viscosity. Bio-quenchant oils with the highest total unsaturated fatty acid (oleic and linoleic acid) exhibited the lowest kinematic viscosity. This observation is in agreement with the results of Kim *et al*. [26]. The highest flash points, 240 and 230°C, were obtained in blended bleached melon oil and blended bleached groundnut oil, respectively, with blended bleached palm oil offering the lowest flash point, 190℃, while that of petroleum-based oil was 194℃. Oil with high flash points have low volatile contents, which assists in reducing the risk of fire during quenching, as reported by Prabhu and Prasad [27].

3.2 Cooling performance evaluation

The cooling potential of each formulated bio-quenchant oil was evaluated and results obtained compared to petroleum based (PB) oil. The bio-quenchant oils exhibited three basic regions of quenching in the cooling curves, film boiling, nucleate boiling and a convection region. The film boiling region of the quenchant oils was observed to have occurred within an average period of 6 seconds for both the blended bleached groundnut oil and PB oil, showing similar cooling curve trend as those in Figure 3. The cooling curves obtained showed similar trends with the work of Kavalco *et al.* [28]; and Kobasko *et al.* [12]. The maximum cooling rate was observed to have occurred in the nucleate boiling region

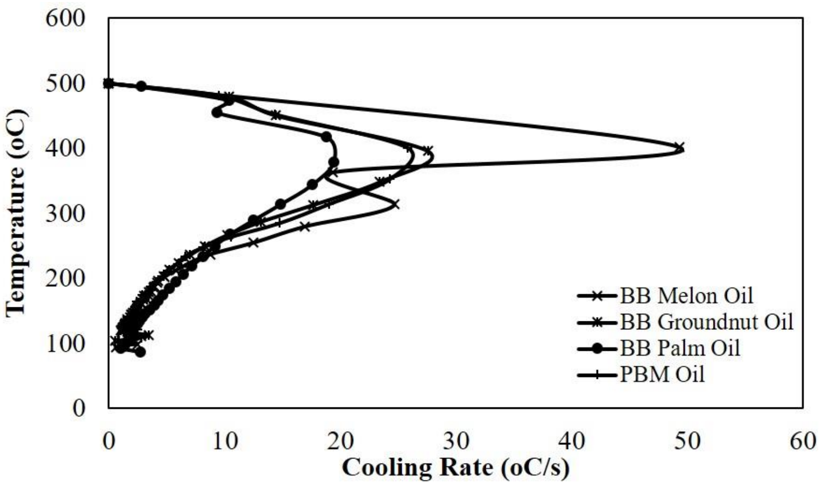

Figure 4 Cooling rate of various quench oils

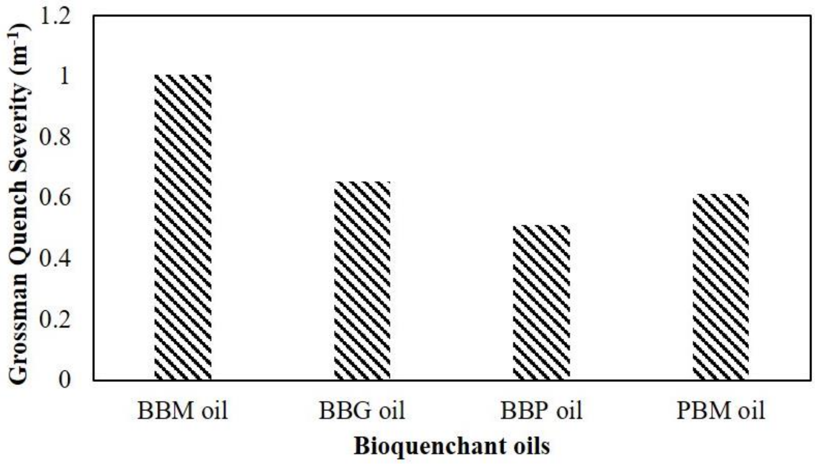

Figure 5 Grossman quench severity for the quenchant oils

for all the quench oils. Blended bleached melon oil had the highest maximum cooling rate, 49.30 ^{o}C/s, occurring at 2 seconds. Blended bleached palm oil offered a lower cooling rate, 19.45 ^{o}C/s, at 10 seconds, while the PB oil exhibited a maximum cooling rate value of 25.80 ^{o}C/s at 6 seconds. However, blended bleached groundnut oil was observed to have maximum cooling rate of 27.60 ^{o}C/s occurring at 6 seconds, as shown in Figure 4. The variation in results can be attributed to the kinematic viscosity exhibited by the individual oils.

The Grossman quench severity of various formulated bio-quenchant oils was calculated using Equation (2). The results showed that blended bleached melon oil had the highest value, 1.007 m^{-1}. Blended bleached palm oil had the lowest value, 0.5112 m^{-1}, while PB oil had a quench severity value of 0.6133 m^{-1}, as shown in Figure 5. Concurrently, the blended bleached groundnut oil had a quench severity value of 0.6552 m^{-1}. The cooling rate and quench severity of the quench oils were observed to be dependent on kinematic viscosity and their fatty acid content. Bio-quenchant oils with higher cooling rates and quench severities, such as blended bleached melon oil and groundnut oil, were influenced by their lower kinematic viscosity resulting from their lower total saturated fatty acid (palmitic and stearic acid) content vs. blended bleached palm oil with the lowest cooling rate and quench severity, resulting from its higher kinematic viscosity. The maximum cooling rate and quench severity exhibited by the bio-quenchant oils decrease in the order of: BBM oil > BBG oil > PB oil > BBP oil.

3.3 Mechanical test analysis

3.3.1 Tensile strength

The tensile strengths for both the as-cast (Al-Si-Cu-Mg) alloy and solution treated cast alloys were higher compared to that of the as-received (Al-Si-Mg) alloy specimen. After addition of 1.25% copper (Cu) to the as-received alloy, the solution was used to heat treat the as-cast alloys at a soaking temperature of 500^{o}C for 20 minutes in the various formulated bio-quenchant media. As depicted in Figure 6, the results show that tensile strength of the as-cast specimen was 131.37 N/mm^{2} vs. the as-received specimen with a value of 125.33 N/ mm^{2}. The specimen quenched in BBM oil gave the highest tensile strength, 146.22 N/mm^{2}. These values may have been due to the influence of heat treatment temperature and the soaking time used. They may be attributed to the quench oil properties such as high cooling rate. This observation is in line with the works of Abubakre *et al*. [10], Adekunle *et al*. [29], Ndaliman [30]. However, specimens quenched in BBP oil exhibited the least tensile strength compared to the as-cast alloy. This may have been due to its slow cooling rate and quench severity that consequently were influenced by high kinematic viscosity.

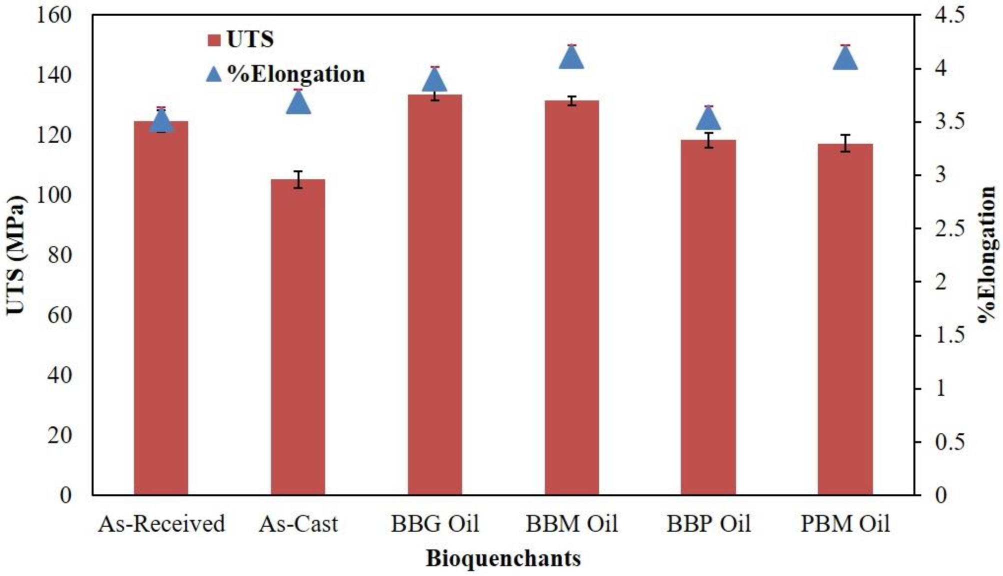

Figure 6 Ultimate tensile strength and %elongation of Al-alloy specimens

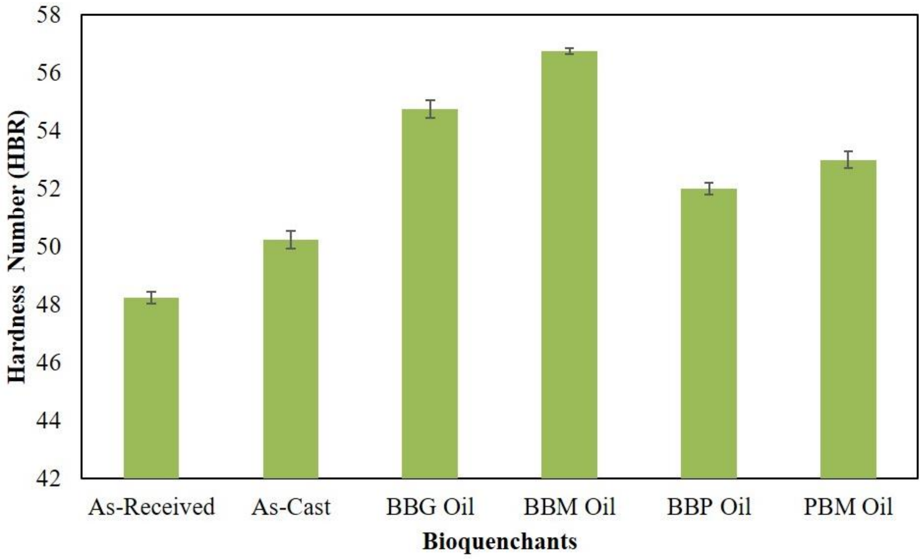

Figure 7 Hardness number of Al-alloy specimens

The results obtained from specimens quenched in bio-quenchant oils show that oils with higher levels of total unsaturated acids (linoleic and oleic acid) gave the highest tensile strengths. The tensile strengths of specimens analyzed decreased in the order of: BBM oil >PB oil > BBG oil > As-cast > BBP oil > as-received.

3.3.2 Percentage elongation

The percentage elongation of as-cast alloy specimens decreased drastically to 2.90% after the addition of copper (Cu) to the Al-Si-Mg alloy material compared to the as-received specimens with an elongation of 3.51% (Figure 6). The decrease could have been a result of the influence of copper addition as reported by Goncalves and Silva [31]. It could also have been due to low fragmentation of silicon after casting or the presence of contaminants such as titanium, which is present in the copper used for casting, as shown in Table 1. However, the specimens' elongation tends to improve after quenching, with BBG oil offering the highest elongation, 3.760%. BBM oil offered the lowest elongation value, 3.187%, while PB oil presented an elongation of 3.299%.

The specimens quenched in formulated bio-oil media, elongation may have been influenced by the fatty acids present in the oils. Concurrently, the faster cooling rate and higher quench severity of the BBM oil may have resulted in a lower elongation as fast cooling negatively affects elongation, as reported by Gündüz and Capar [32]. The overall increase in the elongation of solution treated specimens as against the as-cast alloy specimen was in agreement with the work of Odusote *et al*. [11] and Sharma *et al*. [33]. The percentage elongation decreases in the order of BBG oil > as-received > BBP oil > PB oil > BBM oil > as-cast.

3.3.3 Hardness number

The hardness number results presented in Figure 7 depict that the as-cast alloy specimen has a higher hardness

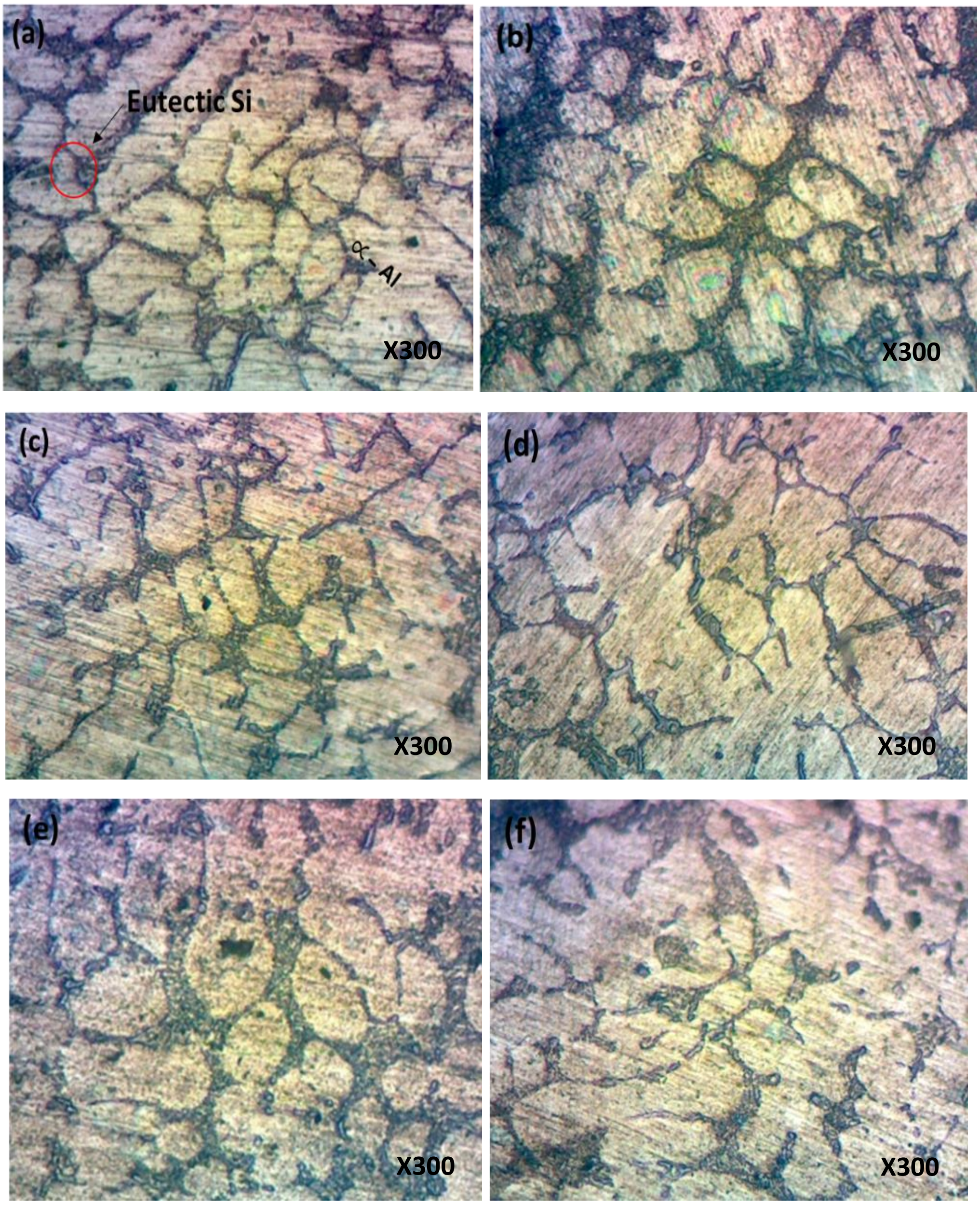

Figure 8 Micrographs (X300) of (a) as-received Al-Si-Mg, (b) as-cast Al-Si-Cu-Mg, (c) Al-Si-Cu-Mg quenched in BBM oil, (d) Al-Si-Cu-Mg quenched in BBG oil, (e) Al-Si-Cu-Mg quenched in BBP oil, and (f) Al-Si-Cu-Mg quenched in PB oil

number, 50.25 HRB, compared to the as-received specimen, 48.25 HRB. This may have been due to the presence of Cu in the as-cast sample. The hardness value of the as-cast specimen increased after treatment in the formulated bio-quenchant oils. BBM oil exhibited the highest hardness number, 61.00 HRB, while BBG and BBP oils displayed hardness numbers of 54.75 and 52.00 HRB, respectively. Petroleum based oil offered a hardness number of 53.00 HRB. The bio-quenchant oils with lower saturated fatty acid (palmitic and stearic acids) levels offered the highest hardness numbers. BBM oil, with a higher hardness number, yielded a faster cooling rate. This is in agreement with the report of Gündüz and Capar [32]. The hardness results of specimens treated in quench media were observed to have a similar decreasing order as the cooling rate and quench severity as BBM oil of > BBG oil > PB oil > BBP oil > as-cast > as-received.

3.4 Microstructural analysis

The microstructure of the as-received, as-cast and solution treated alloy specimens in formulated quench oil presented two major phases, light patches “a silicon in aluminum (α-phase)” and dark patches “eutectic (α+silicon phase)” [34-35]. The grain size of silicon in the as-cast alloy specimens increased considerably after sand casting compared with the as-received specimen as presented in the optical images shown in Figure 8(a-b). The increase in grain size was due to slow cooling rate in the sand mould, which corroborates the work of Raji [34]. The results show increased mechanical properties, such as tensile strength and hardness number, of as-cast alloy compared to the as-received alloy specimen. This was due to the addition of copper and increased silicon content, while the increased coarseness and porosity led to a decreased percentage elongation. The optical images of the as-cast alloy specimens quenched in the formulated bio-oils are shown in Figure 8(c-f). A great reduction in grain size and better re-distribution in grain structure is observed. This may have resulted in increased tensile strength, hardness and percentage elongation. However, BBP oil quenched specimens offer lower tensile strengths compared to the as-cast alloy specimen. This was due to slow cooling exhibited by this quenching oil.

A general improvement in mechanical properties of the quenched specimens resulted from improved refinement and re-distribution of the grain structure as the alloying element dissolved to form precipitates under very short solution treatment times from rapid cooling during quenching [35]. The fragmentation of the eutectic Si-particles into needle-like particles in the aluminum matrix contributed to the improved mechanical properties after quenching. The higher tensile strengths, percentage elongation and hardness numbers obtained in specimens quenched in BBM oil and BBG oil were due to the greater levels of unsaturated fatty acids present in the oils. This produced faster cooling of the dissolved alloying elements in the aluminum matrix. However, lower tensile strengths and hardness numbers produced by BBP oil quenching were influenced by its high kinematic viscosity lowering its cooling potential. The higher levels of total saturated fatty acids present in the oil resulted in lesser fragmentation of the eutectic Si-particles and other alloying elements after quenching. Specimens treated in PB oil with faster cooling potential presented microstructure with fragmentation of eutectic Si-particles into smaller sizes with even distribution in the aluminum matrix, resulting in improved mechanical properties.

4. Conclusions

In this study, the effect of copper (Cu) addition to Al-Si-Mg and various formulated bio-quenchant oils on Al-Si-Cu-Mg alloys considering their cooling rate and quench severity were determined. The mechanical properties and microstructure of the resulting specimens was carefully examined. It can be concluded that the as-cast alloy specimen and specimens quenched in various formulated bio-quenchant oils showed improved mechanical properties compared to the as-received specimen. The overall improvement in mechanical properties of as-cast alloy compared to the as-received alloy was traced to the introduction of copper (Cu) as alloying element. This caused better re-distribution of the grain particles after casting, but led to decreased percent elongation in the as-cast alloy specimens. After heat treatment, the cooling behaviour of bio-quenchant oils, i.e., cooling rate and quench severity, also led to better re-distribution and refinement of the eutectic silicon-particles and other alloying elements in their aluminum matrix.

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