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ORIGINALE ARTICLE

ASSESSING THE EFFECT OF JATROPHA CAKE-DERIVED SOAP ADDITIVES ON THE COLD FORGING BEHAVIOR OF ALuminum ALLOYS VIA SOLID-STATE LUBRICATION MECHANISMS

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ABSTRACT

Background: The utilization of petroleum-based lubricants in metal forming processes often results in the formation of oxide layers on extruded materials due to elevated temperatures and chemical reactions between the base metal and certain components in the lubricant. This phenomenon compromises the surface quality of the final product. Additionally, the non-biodegradable nature of these lubricants contributes to environmental pollution. **Objective**: This study aims to investigate the lubricating properties of Savon (laundry soap) blended with de-oiled *Jatropha* cake additive as a solid lubricant in direct cold extrusion of aluminum alloys. **Methods**: *Jatropha* seeds were dried and processed into powder with a particle size of 0.5 µm, followed by de-oiling using the Soxhlet Apparatus within a temperature range of 65°C to 85°C. Savon soap and de-oiled *Jatropha* cake were blended in varying ratios (90:10, 80:20, 70:30, 60:40, and 50:50) to produce solid lubricant blends denoted as S1, S2, S3, S4, and S5, respectively. De-ionized lukewarm water was used in a 50:50 ratio for blending. An aluminum alloy A6063 billet was machined from a cast dimension of φ26mm x 26mm to test dimensions of φ25.4mm x 25.4mm. A heat-treated axial split steel die with dimensions φ60 mm in diameter and 60mm in length, featuring a tapered entrance of φ16mm and an exit diameter of φ30 mm, was employed in the extrusion rig. The *Savon-Jatropha* lubricant blends were utilized during the direct cold extrusion process on a 2000-capacity UT CO821 machine. A ball-disc type Tribometer was utilized to determine the coefficient of friction for the five solid lubricant samples. **Results**: The findings revealed that the lowest extrusion force of 155.43KN was achieved with lubricant blend S3 (70:30). Furthermore, friction results indicated that lubricant sample S3 (70:30) exhibited the lowest coefficient of friction at 0.717. **Conclusion**: Based on these results, it can be concluded that lubricant blend S3 (70:30) demonstrates superior suitability as a lubricant for cold extrusion of aluminum alloys. It is recommended that the mixture of Savon and de-oiled *Jatropha* cake be processed and stored in dry form to prevent oxidation, and application should occur only when needed for aluminum extrusion. This approach enhances the shelf life of the solid lubricant.

Keywords: *Lubricant Blends; Ball-Disc Tribometer; Friction; Force.*

1. INTRODUCTION

The function of a lubricant is crucial in preventing and managing wear and tear between contacting surfaces. Lubricants, typically complex formulated products, consist of 70-90% base stocks with specific physical properties, complemented by functional additives to optimize performance characteristics [1, 2, 3]. The core principle of supporting a sliding load on a friction-reducing film defines lubrication. Base stocks, which can be mineral, synthetic, or vegetable oils, form the primary constituents of lubricants. Mineral oil-based lubricants, rich in hydrocarbons with traces of sulfur, nitrogen, and various metals, are prevalent in industrial applications due to their commendable properties and cost-effectiveness [4, 5, 6].

Synthetic oils, including polyalphaolefins (PAOs), polyalkylene glycols (PAGs), and synthetic esters, offer alternatives to mineral oils. PAOs, derived from petrochemicals, closely resemble mineral oils, while PAGs, polymerized from ethylene and propylene oxides, exhibit distinct properties. However, both PAOs and PAGs suffer from poor solubility with additives [7, 8, 9].

Industrial lubricants, constituting 32% of the lubricant market, encompass various categories such as hydraulic oils, industrial greases, metalworking fluids, and gear oils [4, 5, 6]. The efficacy of lubricants in metal forming processes hinges upon several factors, including process conditions, die-punch configurations, material properties, and lubricant characteristics [10]. In scenarios where liquid lubrication is impractical, such as high-temperature environments or vacuum conditions, solid lubricants emerge as a promising solution [11].

However, the application of petro-lubricants in metal forming processes often leads to oxide formation on extrudates due to temperature elevation and chemical reactions between the base metal and lubricant constituents, thereby compromising surface quality [12]. Improper lubrication can further exacerbate issues, resulting in oxide lamination within the extruded material, manifesting as the formation of 'annular rings of oxide' in the final product [13, 14]. Surface cracking, a common defect observed during aluminum extrusion processes, particularly in hard aluminum alloys, underscores the significance of effective lubrication [15].

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The intricate interplay of process variables necessitates lubricants with tailored properties to minimize friction and enhance tool-workpiece interactions [16]. Moreover, considerations for environmental impact, biodegradability, and toxicity pose additional constraints on lubricant formulation [17]. Enhancing tool life, product quality, and reducing friction are paramount concerns in metal forming operations, necessitating efficient lubrication systems [18].

The escalating demand for renewable and biodegradable lubricants, driven by regulatory pressures, has spurred interest in alternatives such as solid lubricants [19, 20, 21]. Vegetable oil-based soaps, comprising metal salts of fatty acids, serve as solid lubricants in metal forming applications, offering good adhesion and low friction coefficients [22].

After oil extraction, a significant portion of *Jatropha* seeds (~70%) remains as de-oiled seed cake, presenting an opportunity for value addition and resource optimization [23]. In line with this, the current study evaluates the performance of solid lubricant blends comprising Savon (vegetable oil-based laundry soap) and de-oiled *Jatropha* cake to identify an optimal blend ratio for direct cold extrusion of aluminum alloys.

2. MATERIELS AND METHODES

2.1 Soap Stock and Processing

Soaps may be defined as water-soluble salt of fatty acids which contain more than eight carbon atoms. Soaps are prepared by treating a strong alkaline solution with animal or vegetable fats. The fats are composed of triglycerides; a single molecule of glycerol attached to three molecules of fatty acids. The major composition of in the production of *Savon* soap is as shown in Table 1. Figure 1 also shows the saponification reaction where sodium hydroxide is used to hydrolyze the triglycerides present in the palm oil with end product being glycerine and soap.

Table 1: Composition of the *Savon* Soap

S.No	MATERIAL	FORMULA	FUNCTION
1	Distilled Palm Oil	C_{16} – C_{18}	To provide the needed glycerine
2	Sodium Hydroxide (Caustic Soda)	NaOH	Act as a catalyst in the saponification reaction
3	Distilled Water	H_2O	To ease the mixture
4	Sodium Chloride	NaCl	To reduce viscosity
5	Salt of ethylenediaminetetracetic acid	HDTA (an Acid)	To Chelate any metal contaminants, if present

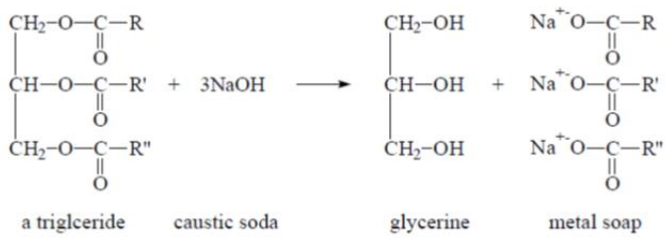

Figure 1: Hydrolysis of a Triglyceride (Fat) [24].

The *Savon* (vegetable oil-based soap), Plate, used in this study is a product of *Azur* Company in Cameroon and was purchased from the soap vendor in Bamenda main market, Cameroon.The 300-gramme *Savon* soap tablet was grated into small particle size as shown in (Plate 2).

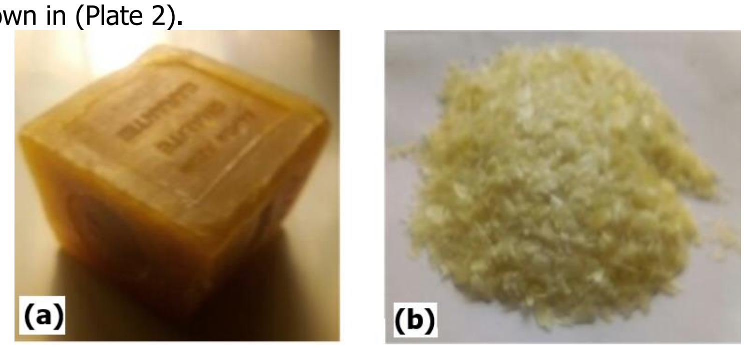

Figure 2: (**a**)- Plate 1: *Savon* (Laundry Soap); (**b**)-Plate 2: Grated *Savon* (Laundry Soap)**.**

2.2 Jatropha Plant, Seed Collection and Processing:

The term *"Jatropha"* is usually used to refer to the species *Jatropha curcas* (Tropical Physic Nut). The fresh fruits have an "American Football" type of shape of about 40 mm length and contains 3 seeds (on average), which look like black beans with similar dimensions, of about 18 mm long and 10 mm wide (Plate 3). *Jatropha* oil has various uses and apart from its use as a biofuel, the oil has been used to produce soap, medicine and pesticides (Shanker and Dhyani, 2006 as reported by [25]. Mature *Jatropha* seeds (Plate 4) were obtained at Ondo town in Ondo State-Akure, Nigeria. The The seeds were further washed and sun-dried for three days until the shells were dried enough to be cracked with the hand. The seeds

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were then de-shelled to obtain the bean (Plate 5). The bean was again oven-dried at 100°C at an hourly interval until constant weight was obtained after which it was allowed to cool at room temperature. The moisture-free bean was then grounded and sieved to 0.5μm particle size powder (Plate 6).

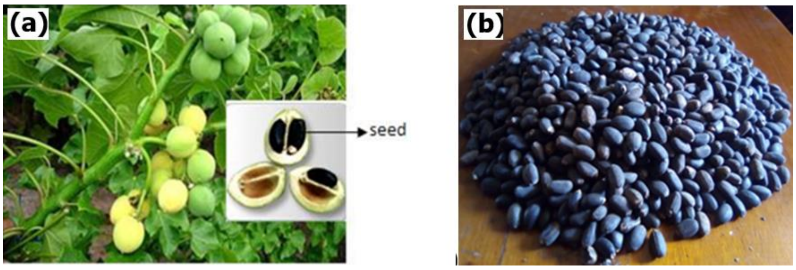
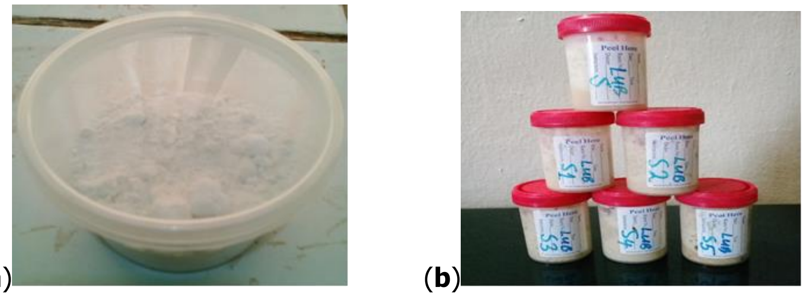


Figure 2: (**a**)- Plate 3: Jatropha Plant with Fruits and Seeds; (**b**)- Plate 4: Jatropha seeds

Figure 3: (**a**)- Plate 5: **Jatropha Beans**; (**b**)- Plate 6: **0.5µm Particle Size *Jatropha* Powder**

2.3 Oil Extraction:

The oil contained in 1200g of *Jatropha curcas* L. powder was extracted in a Soxhlet apparatus for 5 hours, using analytical n-hexene (boiling point of 65°C - 85°C) as an extraction solvent. The evaporating n-hexane condensed into the thimble by the condenser where the oil was leached out of the cake into the round bottom beaker of the apparatus. A change in the solution of the n-Hexane in the thimble from cloudy colour to a clear solution indicated the removal of the oil. The weight of oil extracted was measured to be 493.8g with a percentage oil yield of 41.15%. The de-oiled cake (Plate 7a) was then used as an additive with the *Savon* soap for the solid lubricant formulation.



(**a**) (**b**)

Figure 4: (**a**)- Plate 7: De-Oiled *Jatropha* Cake; (**b**)- Plate 8: Blended *Savon* (Laundry Soap) with de-oiled *Jatropha* Cake.

2.4 Solid Lubricants Blends Formation

Five mixtures were carried out using the grated *Savon* soap and de-oiled *Jatropha* cake in ratio: 90:10, 80:20, 70:30, 60:40 and 50:50 represented by S1, S2, S3, S4 and S5, respectively Mixture was carried out as described by [26]. For each final mixture, 17-gramme of it was measured and the same amount of lukewarm de-ionised water equally measured using an electronic digital scale. The two were then mixed together and blended using a 750-watt blender until a uniform composition of the paste was obtained as shown in (Plate 8) for the solid lubricant (Labelled S1, S2, S3, S4 and S5).

2.5 Physicochemical Analysis of the Blends

Moisture Content MC (%): This was determined in according with DINCEN/TS 14774-3 (2004). 2g each of sample of S-blends were placed in separate crucibles and then transferred into a drying oven and allowed at a temperature of 105°C for 3 hours, after which they were then cooled in desiccators to room temperature before taking the final weight. The weight loss for each of the soiled lubricant blend samples was then calculated using the equation 1 below.

$$MC = \frac{Weight\ loss}{original\ weight} \times 100\% \qquad (1)$$

Chloride Content CC (mg/l): This was determined in accordance with Association of Analytical Chemist, (1996). 2.50g of sample each of samples (S-blends was dissolved in hot water (100ml). for each sample, 10ml of the solution was titrated against 0.0257M $AgNO_3$ using potassium chromate as indicator. The chloride content for each of the blends was determined using equation 2. With TV= Titre value, TVB = Titre value of blank and M_{CL} = molar mass of chlorine

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$$CC = \frac{(TV - TVB) \times M_{Cl} \times 70000}{mole\ of\ Sample} \quad (2)$$

Free Fatty Acid Value FFA (%): This was determined in accordance with the Official Methods of Analysis of the (Association of Official Analytical Chemists, 1998). 0.5g of each of the samples (S-blends) was prepared and boiled with 5 cm^3 of ethanol and allowed to cool. 2 drops of phenolphthalein indicator was then added to each of the solutions and titrated with 0.1M NaOH solutions until the pink colour disappears. The free fatty acid for each of the samples was the calculated using the expression given by equation 3. *TV*= Titre value, *NA* = Normality of acid, *F* = Equivalent weight of free fatty acid and *Ws* = Weight of sample.

$$FFA = \frac{TV \times NA \times F}{W_s} \times 100 \quad (3)$$

Iodine Value IV (mg/g): A 0.50g of each of the sample blanks was dissolved in carbon tetrachloride in 100ml conical flask. 5mls of Wijs iodine was then added to the flask and allowed to stand for 2-hour in the dark at 25^oC. 5ml of potassium iodide (KI) solution was then added to each of them and each of the mixture titrated with 0.1 M sodium thiosulphate using starch indicator. A blank determination was carried out and the iodine value was calculated for each sample using the formula given by equation 5 below. $C_{Na2S2O3}$ = Concentration of sodium thiosulphate, V_1=Volume (ml) of sodium thiosulphate solution used in blank, V_2 = Volume (ml) of sodium thiosulphate solution used in predetermination and *W* = Weight of sample (=0.5g).

$$IV = \frac{12.69 \times C_{Na2S2O3} \times (V_1 - V_2)}{W} \quad (4)$$

Bulk density BD (g/cm^3): This was determined in accordance with Association of Analytical Chemist (1996), 2g of each of the samples were placed into a clean and dry 10cm^3 measuring cylinder and tapped until well compacted, the volume of the sample was taken from the cylinder followed by the determination of bulk densities using equation 6.

$$BD = \frac{weight\ of\ sample}{Volume\ of\ sample} \times 100 \quad (5)$$

2.6 Aluminium Billets Preparation

Alloy 6063 is heat-treatable 0.7% magnesium, 0.4% silicon alloy offering good mechanical properties commonly available in a wide range of extruded sections. Its ready extrudability enables thin walled and intricate hollow shapes to be produced: flats, angles, channels and hollow circular and square sections are all standard profiles. Aluminium wires of known composition were obtained from a cable shop in Jos-Plateau State-Nigeria. Charge calculation was carried out for A6063 alloy and necessary element for the alloy obtained as in Table 2. These were then smelted and cast to sizes of Ø26mm and 26mm length. The billets were then further machined to required billets test diameter of Ø25.4 mm and length 25.4mm, Plate 9.

Table 2: Chemical composition of the aluminium alloy (A6063)

Element	**Si**	**Fe**	**Cu**	**Mn**	**Mg**	**Cr**	**Zn**	**Al**
% Composition	0.50	0.42	0.1	0.90	0.70	0.10	0.10	The Rest

(**a**)  (**b**) 

Figure 4: (**a**)- Plate 9: Machine Aluminium 6063-Alloy Billet; (**b**)- Plate 10: 2000KN Capacity UT CO821 Compress Machine and Extrusion Rig Setup

2.7 Extrusion Setup and Experimental Procedure

Extrusion Setup: A 2000KN capacity Universal Compression Testing Machine shown in Plate 10 was used for the Extrusion performance evaluation study. The extrusion rig in the setup is used for direct and backward extrusion of aluminium and other light alloy billets from an initial diameter of 25.4mm [27]. Tapered split die as shown in figure 5a was used at the bottom part of the extrusion rig

Extrusion Experimental Procedure: Three billets were used for each lubricant blend to ensure consistency of results. Before and after each extrusion run, the container inner wall, tapered die, punch, dummy and billet were first cleaned with Acetone $(CH_3)CO$ using cotton wool to degrease the components before the next extrusion to ensure that the

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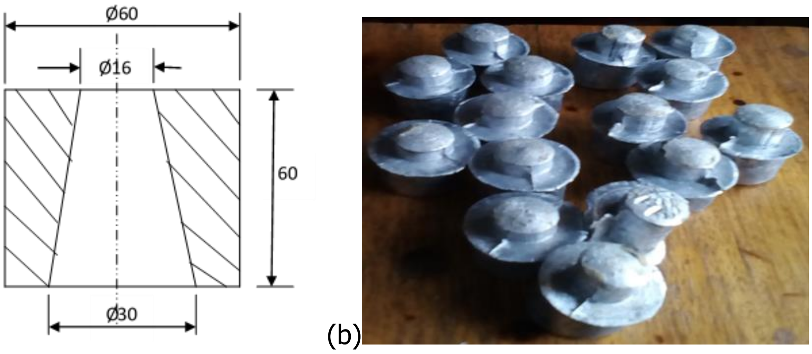
lubricant blend in one extrusion do not affect the results of the next extrusion test. For each billet during extrusion there is increase in the extrusion force (KN) as the ram displacement (mm) increases. The machine automatically stops whenever the maximum compression force is attained. The extrudates from the aluminium alloy billets are as shown in Plate 11.



(a) (b)

Figure 5: (a)- Tapered Die Section View; (b)- Plate 11: Extruded Aluminum Alloy Billets

2.9 Extrusion Force Model

In direct extrusion, an empirical relation proposed by Johnson under friction condition gives the extrusion force in equation (6). Where F=extrusion force (KN), σ_f =average flow stress during deformation (MPa), A_o = cross sectional area of the starting billet (mm^2), L= portion of the billet remaining to be extruded (mm), D_o = original diameter of the billet (mm) and the strain equation (7). The empirical constants a=0.8 and b=1.5 (for a 90^o die angle), r_x = extrusion ratio/reduction ratio and is given by equation (8).

$$F = \sigma_f A_o \left(\epsilon_x + \frac{2L}{D_o}\right) \quad (6)$$

$$\epsilon_x = a + b ln r_x \quad (7)$$

$$r_x = \frac{A_o}{A_f} r_x \quad (8)$$

Where A_o = cross sectional area of the starting billet (mm^2) and A_f = final cross-sectional area of the extruded section (mm^2). From the above relations, the extrusion force and coefficient of friction, 'μ' can then related as obtained in equation (9) and with F_{f} = force of friction (KN).

$$F_f = \sigma_f A_o \left(\epsilon_x + \frac{2L}{D_o}\right) \mu \quad (9)$$

3. RESULTS

The results of relevant physicochemical analysis of the solid lubricant blends are as presented in Table 3. The table presents the percentage of moisture content, concentration of chloride, percentage of fatty acid, concentration of iodine and bulk density for each of the solid lubricant sample blends.

Table 3: Physicochemical Results of the Blends.

Parameter	***Savon-Jatropha* Cake Blend Ration**				
	S1-90:10	**S2-80:20**	**S3-70:30**	**S4-60:40**	**S5-50:50**
Moisture content (%)	47.85	39.75	54.35	50.45	55.50
Chloride Content (mg/L)	2.004	1.525	1.467	0.977	0.796
Fatty Acid (%)	0.6	2.99	9.91	14.43	15.97
Iodine Value	65.02	67.54	62.69	53.32	70.43
Bulk Density (g/cm^3)	0.52	0.52	0.40	0.4	0.48

The maximum extrusion force for unlubricated billets Al (00:00), aluminium billets lubricated with *Savon* S (100:00), grease G (100:00), *Jatropha* J (100:00) and lubricated with *Savon-Jatropha* lubricant samples S1-S5 in which the *Jatropha* in the mix is 10, 20,30, 40 and 50%, respectively as presented in Table 4. Figure 6 showcases aluminium maximum extrusion force variation with lubricants and percentage *Jatropha* cake in *Savon* (Laundry Soap) blends.

Table 4: Aluminium Extrusion Force.

Lubricant	**Al**	**G**	**S**	**J**	**SJ10**	**SJ20**	**SJ30**	**SJ40**	**SJ50**
Force (KN)	195.50	182.53	171.60	170.93	169.83	162.27	155.43	160.50	165.23

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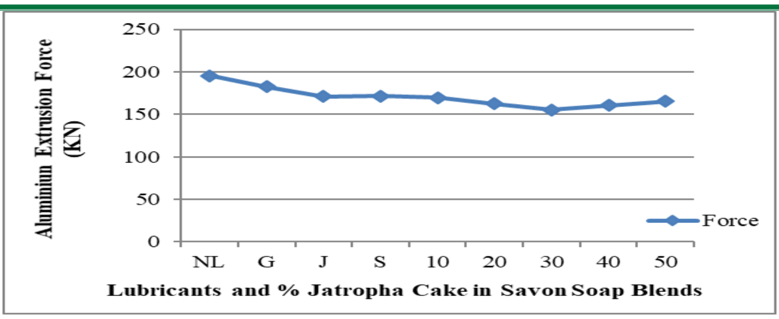

Figure 6: Aluminium Maximum Extrusion Force Variation with Lubricants and percentage *Jatropha* Cake in *Savon* (Laundry Soap) Blends.

Table 5 shows the coefficient of friction in aluminium extrusion with *Savon-Jatropha* lubricant blends while Figure 7 show the variation of coefficient of friction in aluminium extrusion force with percentage *Jatropha* cake in *Savon* (laundry soap) solid lubricant blends. Figure 8 presents the aluminium extrusion load-displacement curves *Savon-Jatropha* lubricants blends.

Table 5: Coefficient of Friction in Aluminium Extrusion in Savon (Laundry Soap) and *Jatropha* Cake Lubricant Blends.

***Jatropha* Cake in Savon (Laundry Soap) (%)**	10	20	30	40	50
Coefficient of Friction in Aluminium Extrusion	0.726	0.822	0.717	0.818	0.845

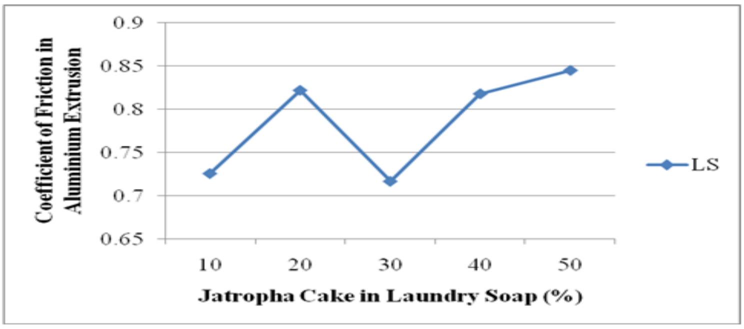

Figure 7: Variation of Coefficient of Friction in Aluminium Extrusion with Percentage *Jatropha* Cake in *Savon* (Laundry Soap).

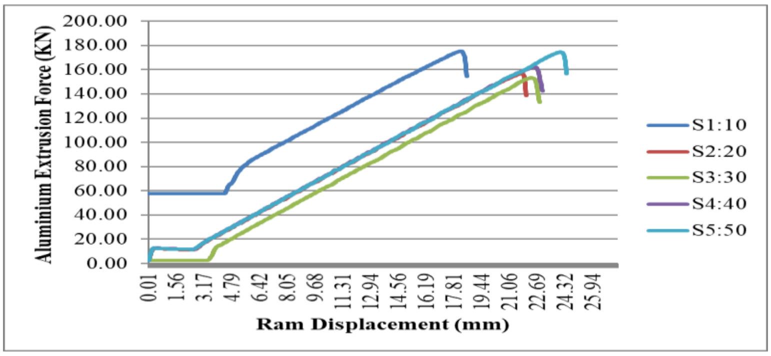

Figure 8: Aluminium Maximum Extrusion Load-Displacement Curves for *Savon* (Laundry Soap) with *Jatropha* Cake Solid Lubricants Samples.

4. DISCUSSION

From Table 3, the largest extrusion force is 195.5 KN and is that obtained with unlubricated aluminium billets Al (00:00) in direct cold extrusion. This high extrusion force is definitely due to excessive friction between the tooling and aluminium billet during material flow. Heat generated also increases during this forming process as there is metal-to-metal contact with sliding motion. On application of grease G(100:00), *Savon* S(100:00) and *Jatropha* J(100:00) paste lubricants on the aluminium billets, the mean extrusion force decreases with mean values of 182.50 KN, 171.60 KN and 170.93 KN, respectively and ranging from 182.27KN -182.73KN, 166.31 – 176.89KN and 165.85KN – 176.01KN, respectively.

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The solid lubricant bends S1 (90:10), S2 (80:20), S3 (70:30), S4 (60:40) and S5 (50:50) recorded mean values of 169.83 KN, 162.27 KN, 155.43 KN, 160.50 KN and 165.23 KN, respectively. The extrusion force range for the blends were obtained as 163.33KN – 176.33KN, 148.34KN – 176.20 KN, 154.33 KN – 156.53 KN, 159.02 KN – 161.98 KN and 157.12 KN – 173.34 KN for lubricant blends S1, S2, S3, S4, and S5, respectively. From Table 4 and Figure 3, it can be observed that there is a percentage decrease in the extrusion force up to S3 (70:30) is in the order of 25.78, 17.44, 10.40, 9.97, 4.31, and 0%, respectively. The extrusion force then starts increasing from lubricant samples S4 (60:40) to S5 (50:50) from 3.26 to 5.31%, respectively.

It can be observed from the curve in Figure 6 that for the unlubricated aluminium, NL; grease, G; *Jatropha* cake paste, J; and *Savon* soap paste, S. the maximum extrusion force decreases to a minimum at the Jatropha cake paste with an extrusion force of 170.93KN The largest extrusion force (195.5kN) for unlubricated billet is in agreement with findings of [13, 14]. It can equally be seen that blend S3 (70:30) recorded the least extrusion force of 155.43 KN after which it started increasing again on application of S4 (60:40) and S5 (50:50). On application of *Savon* and J*atropha* paste, the extrusion force decreases due the presence of moisture content of 54.35% in soap and Jatropha paste as recorded in Table 4. This moisture gets absorbed on the rubbing surfaces, acting as coolant and friction modifiers thereby reducing adhesive wear and friction force as confirmed by Zhe *et al.,* (2018) [28].

The coefficient of friction from Table 5 is displayed in figure7. It can be observed from this figure that the minimum coefficient of friction of 0.717 was obtained at 30% de-oiled *Jatropha* cake additive. This coefficient of friction therefore corresponds to the minimum extrusion force of 155.43 KN as observed in Table 4 and Figure 7. The 30% addition of *Jatropha* cake is consistent with the reports of Theodori, *et al.,* 2004 where the authors stated that lubricants like greases, metalworking fluids and gear oils, base oils account for up to 70% of the end product [29].

The 0.717 coefficient of friction obtained and as observed in Table 5 and Figure 7 is probably due to the combination of moisture content of 54,36%, chloride concentration value of 1.467mg/l and fatty acid value of 9.91% obtained in lubricant blend sample S3 (70:30) as shown in Table 3. The chloride equally reacts with the metal surface to form a metal salt layer between mating surfaces that reduces friction, wear and damage. This is in line with documentation of STLE, 2013 reporting that chlorinated wax and chlorinated paraffin oils are being used as extreme pressure additives (EP) in lubricants as friction modifiers [30]. According to Calton (2013) fatty acid composition within the natural oils has a significant effect on the coefficient of friction [6]. Fox *et al*., (2004); Lundgren *et al*., 2007 and Salih *et al*.; 2011 all noted that fatty acid contributes in limiting the metal-to-metal contact thereby minimizing the friction force [31, 32, 33]. The table also shows the iodine value of 62.59 for the blend with the least extrusion force obtained. This value indicates that the oil in the S3 (70:30) blend is saturated. The bulk density of the blends in the table is observed to vary with extrusion force. The extrusion force decreases from 169.83KN at 0.52 g/cm3 to 153.43KN at 0.4 48 g/cm^3. The force starts increasing again from 160.50KN at 0.4 g/cm^3 to 165.23KN at 0.48 g/cm^3. This shows that shear force in the lubricant increase with increase in bulk density and vice versa.

Figure 8 starts with a flat (horizontal) portion in each curve indicating that on application of the force, the billet first expands to fill-up the wall of the cylinder after which the applied force increases linearly with ram displacement up to a turning point (break-through-pressure). This turning point corresponds to the maximum extrusion for that particular solid lubricant sample. The trend at the point of decrease may be due to the fact that the frictional force decreases linearly once the maximum load is reached as affirmed by Nourani *et al.* (2005) [34].

The turning pointon the curve is as a reduction in frictional force which is possibly due to the presence of palm oil methyl ester in the soap as explained by Liew *et al*., (2014) [35]. Since some oil still remain in the *Jatropha* cake after extraction, it contributes in enhancing the lubricating film forming properties. This could be attributed to its hydroxyl functional group that increased both the viscosity and polarity of this vegetable oil performance, Quinchia *et al*., (2014) [36]. This result is also in agreement with the findings of Moveh and Gambo, 2016 where the authors affirmed that *Jatropha* oil in itself is suitable lubricant in the extrusion of aluminium [12].

5. CONCLUSION

The findings of this study demonstrate the feasibility of formulating a solid lubricant using *Savon* soap as a base stock and de-oiled *Jatropha* cake as an additive. Among the various blends tested, the ratio of *Savon* soap to de-oiled *Jatropha* cake at 70:30 exhibited superior performance, manifesting in a reduced extrusion force of 155.43KN and a coefficient of friction value of 0.717 during the direct cold extrusion of aluminum. This optimized lubricant blend holds promise for enhancing tool longevity by mitigating tool wear in the aluminum forming process.

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