PRELIMINARY STUDY OF SELECTION OF ENVIRONMENTALLY BENIGN LUBRICANTS FOR CONVENTIONAL AND SEVERE PLASTIC DEFORMATION PROCESSES

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ABSTRACT

The purpose of this paper is to investigate the suitability of some environmentally benign lubricants for the processing of conventional and severe plastic deformation operations. Al 6063 bar was annealed at 350^0C for 1hr, machined and cut to billets size of 14 mm x 14 mm x 44 mm. These specimens for extrusions were machined to the specified dimensions to visibly good finishes. The billets were extruded through a twisted and direct equal channel angular extrusion (ECAE) dies of 14 x 14 mm^2 channel cross-section area. The channel angle was 120^0, the angle of the outer arc of the channels was 30^0 .The deformation area of the die was slightly twisted to impact additional strain. The punch and container used for the experiment were made of tool steel alloy AISI D2, and were chromium-coated and polished. Seven lubricants such as palm oil, tropical coconut oil, palm kernel oil, soya oil, mustard oil, groundnut oil and sesame oil were used in this study. Also, a double cup extrusion test (DCET) was performed using the same aluminum, but for annealed and non-annealed billets to represent, respectively, the normal and adverse conditions that exist in conventional and ECAE processes. The results obtained from the experimental works show that red palm oil has satisfactory lubrication performance in both conventional metal forming processes and severe plastic deformation. But groundnut oil performs satisfactorily well in conventional metal forming processes but failed under severe plastic deformation (SPD) whereas, olive oil performed poorly in conventional processes but suitably well in severe plastic deformation. The higher the strain rate the higher the load during severe plastic deformation processes. Also, it is found that while the values of strain hardening exponent, n, decreases with increasing deformation rate, strength coefficient, k, increases. The current experimental work successfully select, simultaneously, some vegetable-based oils such as soya, red palm, mustard, tropical coconut, and palm kernel oils as good replacements for petroleum-based lubricants for conventional and SPD metal forming operations.

Keywords: Aluminum, ECAE, Lubricants, Viscosity, Ductility, Hardness,

INTRODUCTION

Severe plastic deformation (SPD) is a generic term describing a group of metalworking techniques involving very large strains typically involving a complex stress state or high shear, resulting in a high defect density and equiaxed grain Valiev (2000); Valiev et al. (1993); Valiev et al. (2006); Rosochowski (2005); Tsuji (2003) and Maki (2001). The presence of a high hydrostatic pressure, in combination with large shear strains, is essential for producing high densities of crystal lattice defects, particularly dislocations, which can result in a significant refining of the grains leading simultaneously to high hardness and ductility which is the main advantage of SPD over other metal forming operations. Grain refinement in SPD processes occurs by dislocations which are distributed throughout the grains to reduce the total strain energy. As deformation continues and more dislocations are generated, misorientation develops between the cells, forming "subgrains". The process is repeated until subgrains can rotate into high-angle grain boundaries, typically with an equiaxed shape Wu (2002). The mechanism by which the subgrains rotate is not well understood. The process in which dislocation motion becomes restricted due to the small subgrain size and grain rotation becomes more energetically favorable Wu (2002). Mishra (2007) propose a slightly different explanation, in which the rotation is aided by diffusion along the grain boundaries which is much faster than through the bulk. Some definitions of SPD describe it as a process in which high strain is applied without any significant change in the dimensions of the work piece permitting several repetition of the process for higher plastic strain induction, resulting in a large hydrostatic pressure component Valiev (2006). The presence of a high hydrostatic pressure, in combination with large shear strains, is essential for producing high densities of crystal lattice defects, particularly dislocations, which results in a significant refining of the grains. In order to impose an extremely large strain on the bulk metal without changing the shape, many SPD processes have been developed Azushima (2008). The ultra-fine grained metals created by the SPD processes exhibit high strength Bay (1994) and Zairi (2006), and thus they may be used as ultrahigh strength metals with environmental harmony. The decrease of grain size leads to a higher tensile strength without reducing the toughness, which differs from other strengthening methods such as heat treatment. To accomplish this, a very large extrusion force is often involved resulting into adverse interface conditions which can lead to tool wear and consequent tool failure even in the presence of seemly good lubrication.

Bay (2010) stated that tribological systems depend strongly on the kind of metal forming process. Cold forging operations, especially, SPD requires a very large load which poses a high risk on tool life. This large load illustrates the need for different special lubricants capable of material/tool separation to efficiently maximize tool life. Quality and type of lubrication which are required to realize tool workpiece separation and friction reduction depend strongly on the tribological loads that appear in a specific process. By this separation reduced tool wear is achieved because the risk of adhesion coming as a result of sticking friction is minimized. Additionally, in most cases frictional forces are reduced. The use of conventional, petroleum-based synthetic oil as lubricants is an issue due to environmental problems; consequently, it has become imperative for researchers to be proactive in establishing safe and healthy working conditions while limiting the strain on the environment. Since about a decade ago, many countries such as Europe, Japan and the US have been increasingly restrictive to the industrial application of hazardous lubricants Schrader (2007) and Abdulquadir and Adeyemi (2008). Regarding cold forging the substitution of zinc phosphate plus soap with environmentally benign lubrication systems is of concern due to sludge accumulation in the baths and its associated content of heavy metals Bay (2010). Although DCET is the most acceptable and famous in selecting lubricant for bulk forging operations, previous works Ajiboye (2014) and Ajiboye and Okuofo (2014) show that this selection by DCET may prove inadequate for both conventional and severe plastic deformations. These previous works show that lubricants that performed well in conventional operations may fail or performed poorly in severe plastic deformation.

The present study, therefore, focuses on selection of vegetable-based lubricants that can effectively maintain separation between tool and work piece in both severe plastic deformation and conventional deformations. Such environmentally benign lubricants become imperative judging from the beneficial extraordinary combination of high strength and ductility achieved using SPD but with equally enormous extrusion load which can have serious consequence on tool life. To effectively ameliorate the adverse conditions of high pressure and temperature at the interface between the tool and workpiece, the appropriate lubricant should not only possess the ability to consistently separate the tool and the workpiece but extract heat from the interface to prevent grain growth.

Performance of Lubricants in Cold Forging Using Double Cup Extrusion Test

As reported and described by Schrader (2007), there are so many tribological tests used to evaluate lubricity performance of different lubricants used in metal forming operations. Such tests includes spike test, forward and backward extrusion, ring compression test, double cup extrusion test and many others. Of these tests double cup extrusion test (DCET) is considered to emulate severe deformation conditions similar to those occurring in actual cold bulk forging operations better than other tests.

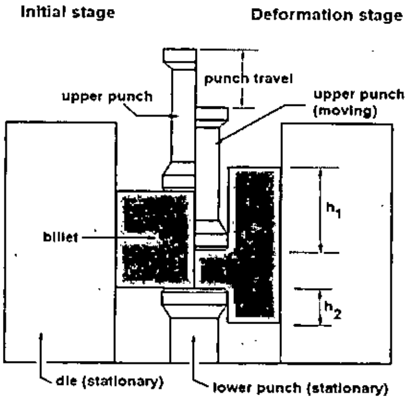

Fig. 1. Double cup extrusion test (DCET).

As reported and described Schrader (2007) the principle of DCET is illustrated in Fig. 1. The advantage of these tests is that the final geometries of the specimen are dependent on the interface friction and the lubricity of the lubricant used. The ratio of the cup heights after deformation, h_1/h_2, is an indication of lubricity. This ratio increases as friction factor increases. Thus, if there is no friction, the cup heights are the same and the ratio, h_1/h_2, is equal to 1. It has been reported Schrader (2007) and Bay (1994) that in cold forging operations, tool-workpiece interface pressures can reach 2500 MPa with interface temperatures of up to 600°C, while surface enlargement can be as large as 3000%. If this is so, with conventional forming, severe plastic deformation will be much higher. Since the friction at the tool-workpiece interface plays such enormous role in the process, it is essential that the lubricants used in cold forging withstand the interface conditions present in production, in order to form well and defects free parts. Failure of the lubricant can lead to part surface defects and significant die wear or even die failure.

METHODOLOGY

In the current study, six vegetable based oils, such as palm, palm kernel, soya, mustard, coconut and sesame oils were used as lubricants in the double cup extrusion test of aluminum 6063. The thirty six (36) specimens were divided into two categories with eighteen specimens annealed and eighteen unannealed to represent conventional and severe plastic deformation (adverse) conditions, respectively. For each oil and category, three specimens were extruded and the average value (h_{ave}) recorded. The ratio of the cup heights after deformation, h_1/h_2, is an indication of lubricity and it increases as the friction factor increases. Thus, if there is no friction, the cup heights are the same and the ratio, h_1/h_2, is equal to one. The upper punch moves down with the ram while the lower punch and container are stationary. Thus, the container has relative velocity with respect to the upper punch, but not with the lower punch. Therefore, the material flow towards the lower punch is more restricted. In the presence of friction, the height of the upper cup is larger than the height of the lower cup. In the double cup extrusion test, the ratio of the height of the upper cup to the lower cup is extremely sensitive to friction. Theoretically, if there is no friction $m = 0$ on the interface, both cups will have the same height. The higher the friction ($m>0$) the shorter the lower cup will be.

RESULTS

The value of the cup height ratio for both annealed and non-annealed specimens for each lubricant was experimentally measured and recorded as shown in Table 1.

Table 1: Results of DCET of AA6063

	Oil specimen	h_1		h_2		CHR	
		Annealed	Non-annealed	Annealed	Non-annealed	Annealed	Non-annealed
1	Palm oil	22.1	11.93	15.7	8.32	1.41	1.43
2	Soya oil	10.2	11.32	9.2	6.80	1.11	1.66
3	Mustard oil	15.0	10.50	11.4	5.13	1.32	2.04
4	Coconut oil	12.6	11.55	10.2	5.67	1.24	2.04
5	Sesame oil	10.8	10.35	9.5	5.18	1.14	1.99
6	Palm kernel oil	11.8	10.18	9.8	6.37	1.20	1.60

Key: *h_1 =upper cup height; h_2 = lower cup height; CHR =cup height ratio*

For the annealed specimens, it is seen that the cup height ratio for Soya oil gives the least, followed by sesame oil, then palm kernel, coconut oil, mustard oil while palm oil has the highest cup to height ratio. This shows their order of performance when used as lubricants in conventional plastic deformation (see figure 2). However, when these oils were used for non-annealed specimen, palm oil gives the best lubricity, followed by palm kernel oil, then soya oil, sesame oil while mustard and coconut were the worst of the six oils under severe deformation conditions. The high value of cup height ratio for, palm oil, mustard oil, coconut oil and palm kernel oil is an indication of high friction generated between the billets/container wall interfaces for annealed specimens. These are probably due to failure of the oil to absolve the temperature generated during the test and reduction in lubricating capacity of the oil due to its structural breakdown.

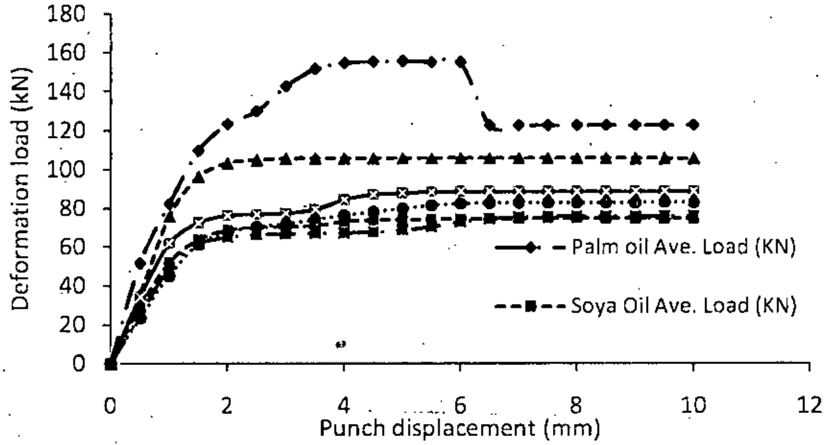

Fig. 2 Plots of extrusion load versus punch stroke

Table 2: Lubricant properties

Test Method	Palm oil	Coconut oil	Soya oil	Mustard oil	Sesame oil	PKO
Viscosity	46.21	16.33	17.47	21.87	19.43	36.36
Viscosity index	155	181	279	196	199	175
Water content	0.6%	3.65%	<1%	<1%	<1%	0.093%
Flash point	228	190	265	220	260	210
TAN	89.6	16.83	5.6	11.22	16.83	65.2
Density and specific gravity	0.896	0.8892	0.900	0.88	0.855	0.907
Colour	>7.5	>0.5	>0.5	>2.0	>1.5	2.0

Table 2 above, showing the properties of the oils, shed light on the results of Table 1. It is a known fact that viscosity index is a good parameter in assessing the suitability or otherwise of any lubricant. The oils with the highest viscosity index (VI) will remain stable and not much variation in viscosity over the temperature range. From Table (1), going by viscosity index alone, soya oil gives the best oil as lubricant, followed by sesame oil, then mustard oil, coconut oil, palm kernel oil with palm oil given the worst lubricant for the annealed aluminum alloy. This is consistent with DCET evaluation of these oils for the annealed specimens (Table 1). Again, since flash point is the lowest temperature at which it can vaporize to form an ignitable mixture in air, the higher the flash point, the better the oil. Again, this selects soya oil as the best of these oils and the least total acid number makes soya oils very suitable as metal forming lubricant. How this oils fair under severe plastic deformation is worth investigating.

Performance of lubricants in cold forging using equal channel angular extrusion

For severe plastic deformation, commercial 6063 aluminum-magnesium alloy provided by Nigeria Aluminum Extrusion Co. was used in this research. The chemical composition of the alloy is shown in Table 1. Before extrusion, the specimen was annealed at 350°C for 1hr. The billet size was 14 mm x 14 mm x 44 mm.

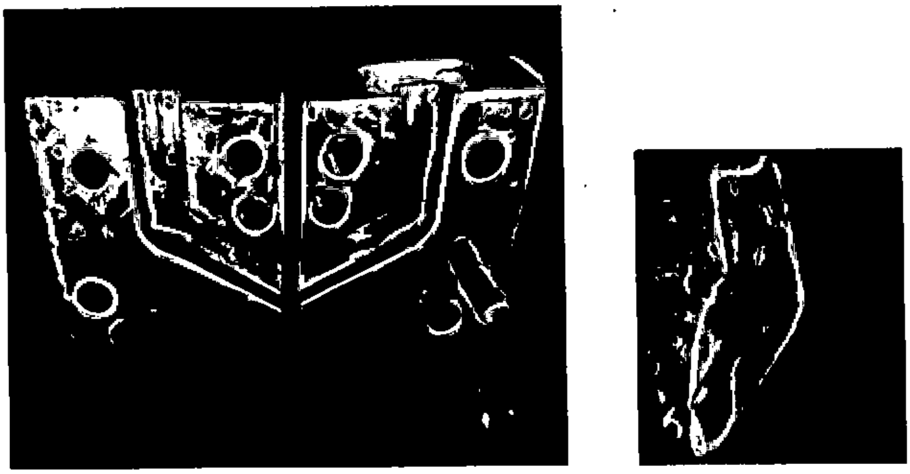

Fig. 3 The die used in this study with $\phi = 120$ and $\psi = 30$ and the extrudate

Specimens for extrusions were machined to the specified dimension to a visibly good finish. The die used was with 14 x 14 mm^2 channel cross-section, the channel angle was 120°, the angle of the outer arc of the channels was 30° (Fig. 3) (Ajiboye, 2014). The punch and container used for the experiment were made of tool steel alloy AISI D2, and were chromium coated and polished. A split die was used to avoid stress concentration at the corners and to facilitate easy removal of the ECA extruded specimen (Fig. 3). Specimens were ECA extruded at room temperature in one pass. All extrusions were conducted using a hydraulic press of 600 KN capacity. During extrusion, the die was first centrally located on the bed of vertical hydraulic testing machine; the billet was then inserted into the entrance channel. Before a billet was inserted into the ECAE entry channel, lubrication was applied to the billet to decrease its friction with the channel inner wall. The ram/plunger speed was about 1mm/s. Before applying each lubricant, the surfaces of the punch and dices were cleaned by a wiper soaked with methylated spirit to avoid adulteration among lubricants. For each lubricant, four experiments were carried out.

Table 3: The chemical composition of the Al alloy used in this study

Element	Al	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Sr
wt.%	Base	0.45	0.35	0.03	0.04	0.6	0.007	0.04	0.006	0.005

Effects of Strain Rate on Extrusion Load

Figures 4-7 show the extrusion load versus stroke/ punch displacement curves at different strain rates of 1.5 x 10^{-3}/s, 2.0 x 10^{-3}/s, 2.5 x 10^{-3}/s and 3.5 x 10^{-3}/s using different vegetable oil-based as lubricants. Generally, it is seen that the increasing strain rate leads to increasing extrusion load for all the oils. However, close examination reveals that the performance of palm kernel and red palm oils is superiors to that of groundnut and tropical coconut oils.

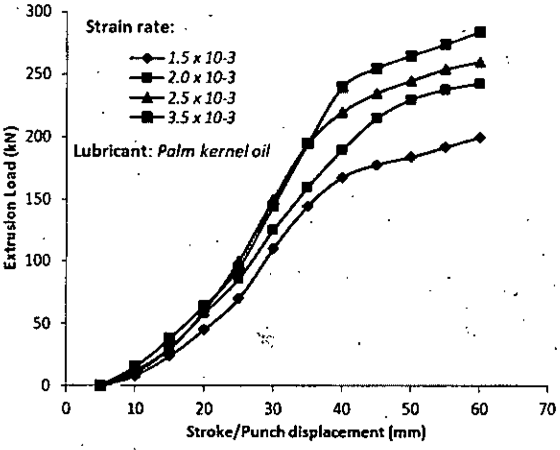

Fig. 4: Extrusion load versus punch displacement at different strain rates using palm-kernel oil as lubricant

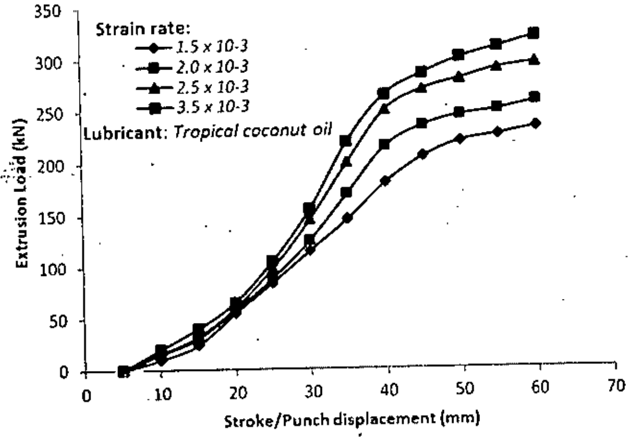

Fig. 5: Extrusion load versus punch displacement at different strain rates using tropcial coconut oil as lubricant

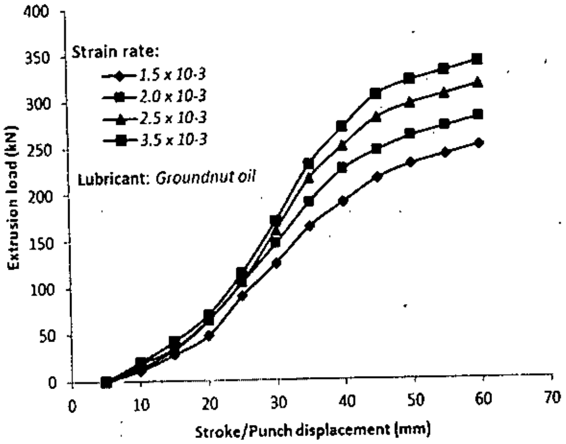

Fig. 6 Extrusion load versus punch displacement at different strain rates using groundnut oil as lubricant

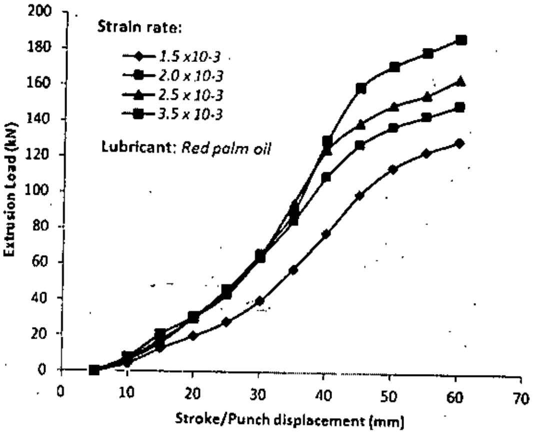

Fig. 7 Extrusion load versus Punch displacement at different strain rates using red palm oil as lubricant

Effects of lubricant on extrusion load

Figures 8, 9, 10 and 11 show the experimental readout of the extrusion load versus Punch displacement curves using different lubricants at the strain rate of 1.5 x 10^{-3}/s, 2.0 x 10^{-3}/s, 2.5 x 10^{-3}/s and 3.5 x 10^{-3}/s, respectively. From the plots, red palm oil gives the least extrusion load, followed by palm kernel oil, then tropical coconut oil with groundnut oil given us the highest load. The current experiment based on equal channel angular extrusion, selects palm oil as the best lubricant, followed by palm kernel oil, then tropical coconut oil with groundnut oil the worst of the four oils tested. Although the palm kernel is the second of these four oils, the difference in the extrusion load between it and palm oil is about 125kN, which is very significant. Also the gap between red palm oil, which is the best and that of the groundnut oil which is the worst, is highly appreciable.

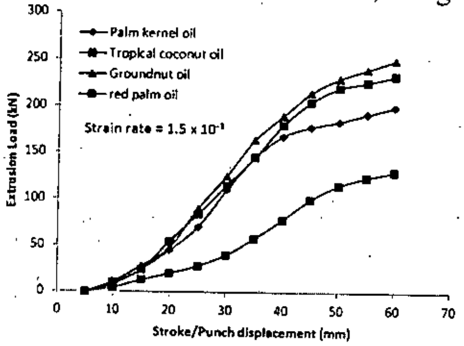

Fig. 8 Extrusion load versus Punch displacement using different lubricants at the same Strain rate of 1.5 x 10^{-3} (s^{-1})

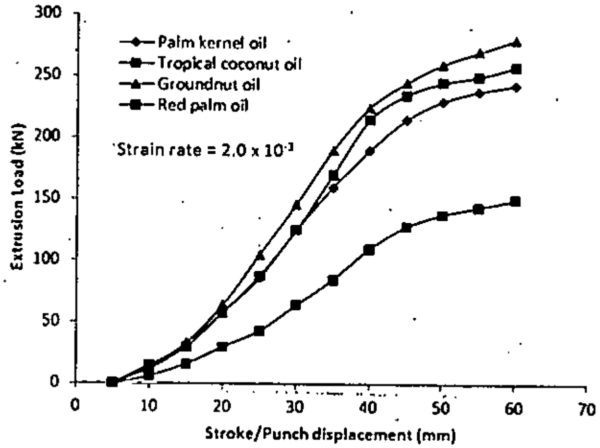

Fig. 9 Extrusion load versus Punch displacement using different lubricants at the same Strain rate of 2.0 x 10^{-3} (s^{-1})

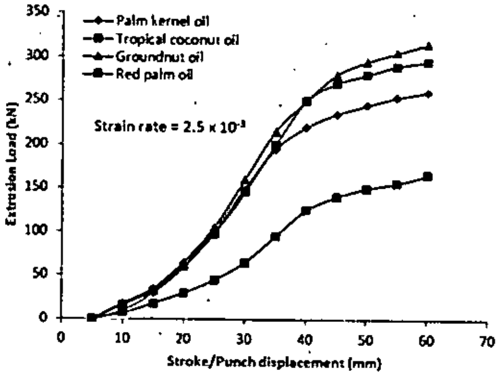

Fig. 10 Extrusion load versus Punch displacement using different lubricants at the same Strain rate of 2.5 x 10^{-3} (s^{-1})

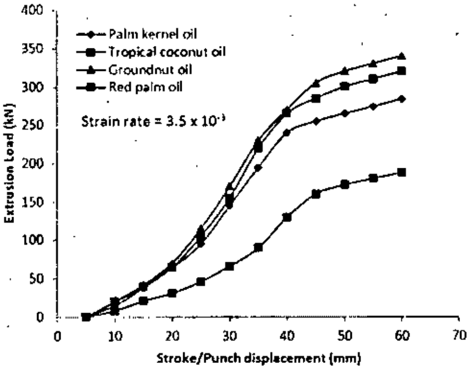

Fig. 11 Extrusion load versus Punch displacement using different lubricants at the same Strain rate of $3.5 \cdot x\ 10^{-3}$ (s^{-1})

A virtual observation of the products formed showed that a much finer surface finish of the extruded material formed with a low strain rate and good lubrication than with a higher strain rate and relatively poor lubricity. This shows that with good lubrication, a good surface finish of the product is guarantee.

Stress – Strain Curves

Figure 12 shows the results of the stress versus strain curves (flow curves) at different strain rates of 1.5 x 10^{-3}/s, 2.0 x 10^{-3}/s, 2.5 x 10^{-3}/s and 3.5 x 10^{-3}/s using red palm oil as lubricant. It can be seen that while strength coefficient increases with increasing strain rate, the strain hardening exponent decreases with increasing strain rate. It has been reported [Segal, V.M. (1995)], that the friction associated with cold forming is responsible, to a large extent, for the increased tool working stresses. Further, friction influences the densification of the compacts, as a result of which the values of strength coefficient, *K*, and strain hardening exponent, *n*, are affected.

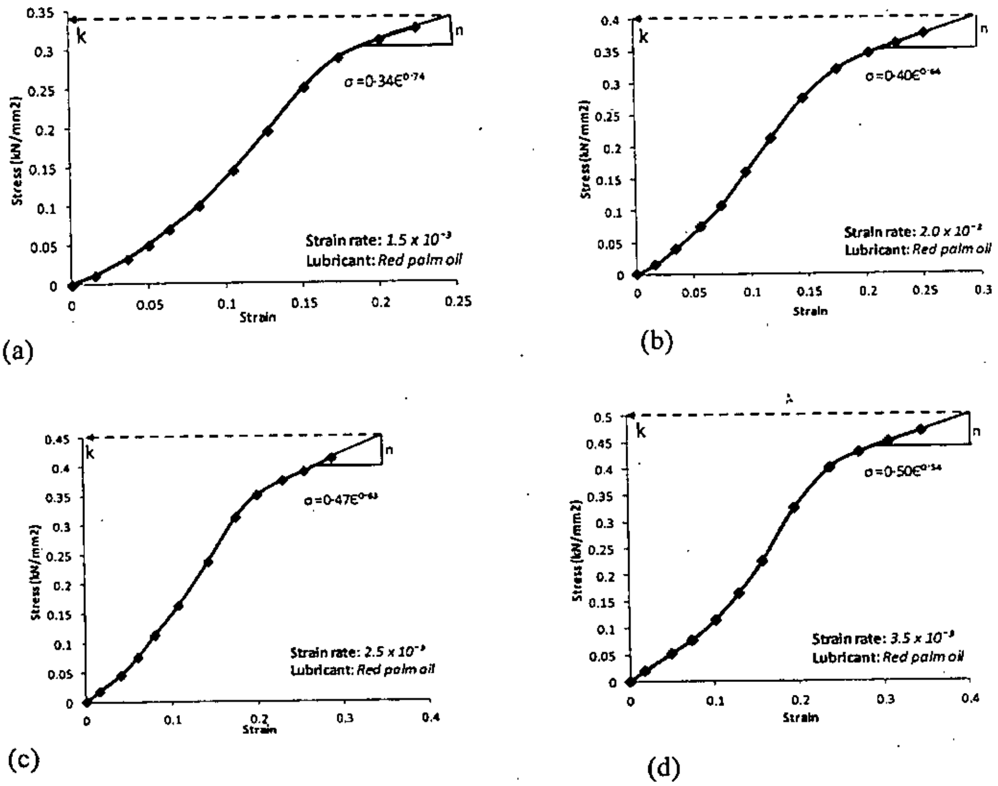

Fig. 12 Stress-strain curves showing the effects of deformation rate on the strength coefficient and strain hardening exponent

Hardness measurement obtained

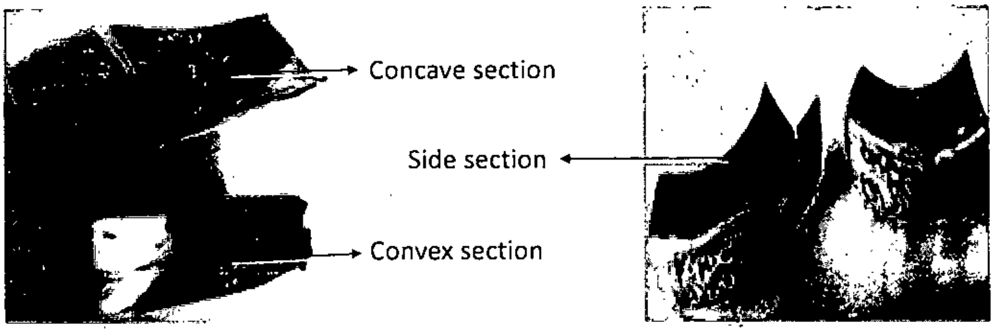

Figure 13: Extruded products showing sections for surface hardness evaluation

Figure 13 shows the work material with which hardness measurement was carried out using the Rockwell hardness tester with a hardness scale of H. the measurement was made on three sections: Side, Convex and Concave sections. These sections were selected to check the degree of surface hardness due to applied strain during extrusion.

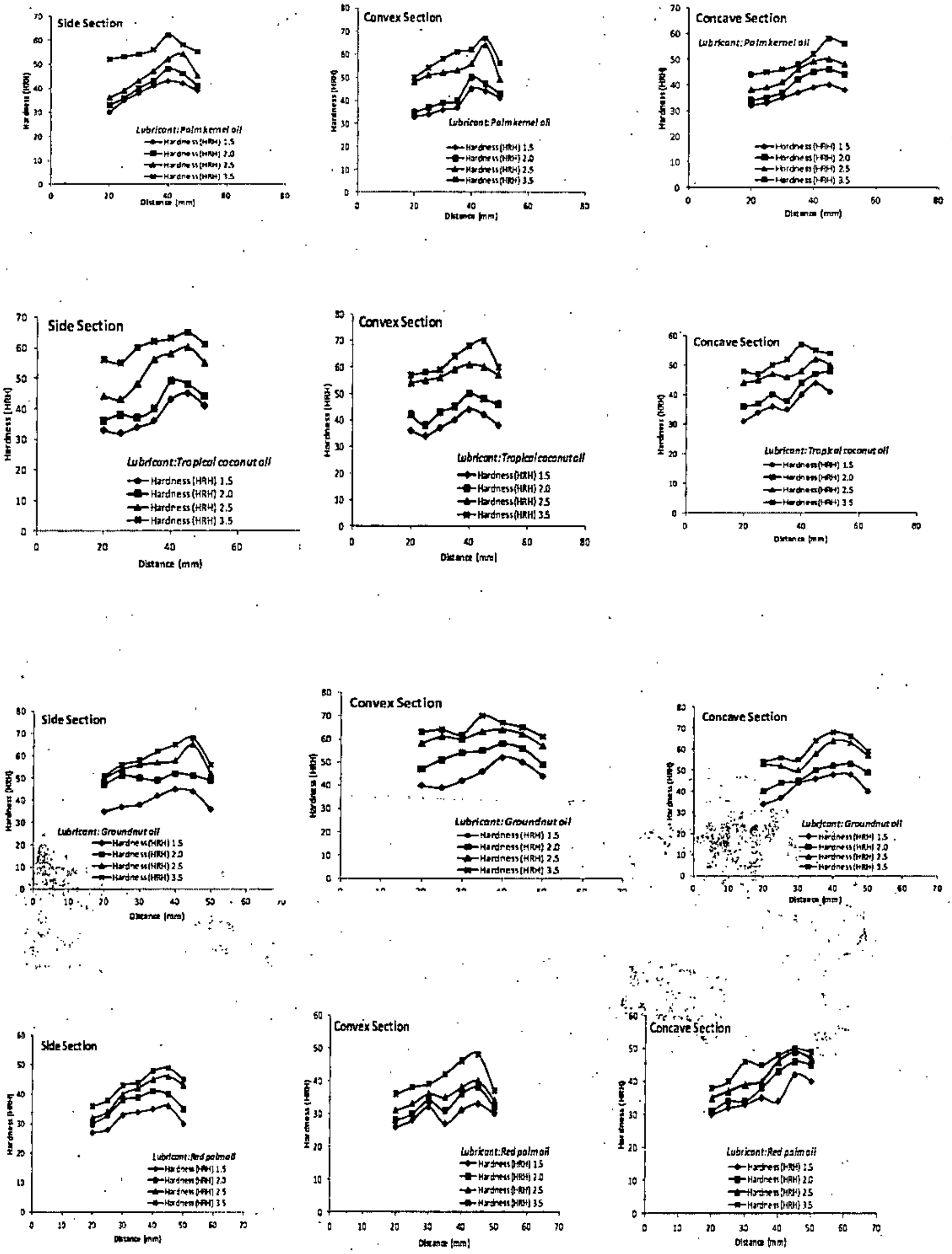

Figure 14. Variation of surface hardness due varying strain rates and lubricant

Figure 14 shows the hardness variation from the rear to the leading edge of the extrudate at different strain rates of 1.5 x 10^{-3}/s, 2.0 x 10^{-3}/s, 2.5 x 10^{-3}/s and 3.5 x 10^{-3}/s with different lubricants. The measurement was taken at three locations namely side, concave and convex sections. Also, the measurement commenced at the rear end (punch/billet interface) to the leading edge (free end). For all the lubricants, the hardness gradually increases from the rear end to a maximum at a common distance of about 40 mm, which is about 10 mm to the free end of the product after which there is a gradual decline in hardness values to the end. The point of maximum hardness lies at the center of the deformation zone. Though the rear end has not pass through the deformation zone, it nonetheless affected by the impact of the strain impacted at the deformation zone. This is consistent with continuum mechanics theory as deformation varies from point to point which account for increasing hardness value at the approach of deformation zone. Considering the effect of lubricants used, though palm oil gives the least load, the hardness plots fell within narrow bond with increasing strain rate at side, convex and concave sections showing greatest homogeneity of the particles. For all the lubricants and sections, increasing strain rate leads to increasing hardness values. Specimens extruded with palm oil shows the least hardness value, followed by that extruded with palm kernel oil, then tropical coconut oil and groundnut oil showing the highest.

Future works will explore used vegetable oils as possible lubricants in metal forming operations.

CONCLUSION

Seven environmentally benign lubricants were tested using double cup extrusion test for annealed and non-annealed specimens and equal channel angular extrusion. The effect of strain rate on the strength coefficient and strain hardening exponent were also investigated. The following conclusions may be drawn.

i. Some vegetable-based oils, such as groundnut oil, that performed creditably well in conventional metal forming processes fail badly under severe plastic deformation condition.
ii. For the annealed specimens, it was seen that the cup height ratio for Soya oil the least; followed by sesame oil, then palm kernel, coconut oil, mustard oil while palm oil has the highest cup to height ratio showing poor lubricity.
iii. However, when these oils were used for non-annealed specimen, palm oil gives the best lubricity, followed by palm kernel oil, then soya oil, sesame oil while mustard and coconut were the worst of the six oils under severe deformation conditions.
iv. The current experiment based on equal channel angular extrusion, selects red palm oil as the best lubricant, followed by palm kernel oil, then tropical coconut oil with groundnut oil the worst of the four oils tested. A physical inspection of the products formed showed that a much finer surface finish of the extruded material formed with a low strain rate and good lubrication than with a higher strain rate and relatively poor lubricity. This shows that with good lubrication, a good surface finish of the product is guaranteed.

v. Strength coefficient increases with increasing strain rate while the strain hardening exponent decreases with increasing strain rate.

vi. For all the lubricants and sections, increasing strain rate leads to increasing hardness values. Specimens extruded with palm oil shows the least hardness value, followed by that extruded with palm kernel oil, then tropical coconut oil and groundnut oil showing the highest.

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