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FINITE ELEMENT MODELING OF STRESS BEHAVIOR IN COLD FORGING PROCESSES UTILIZING PALM KERNEL OIL AS A BIO-LUBRICANT

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Abstract: Mineral oils have traditionally been used in most metal-forming lubricants. Vegetable oils, such as palm kernel oil (PKO), may serve as a non-toxic and biodegradable alternative. This study investigates the potential of PKO as a bio-lubricant in metal forming processes using the finite element method. The research focuses on stress-strain characteristics of workpieces lubricated with PKO to evaluate its effectiveness as an environmentally friendly option. The finite element model accurately simulates the mechanical behaviour, highlighting PKO's role in reducing friction, enhancing formability, and minimizing tool wear. A comparison with conventional metal forming oils, using aluminium (AA1100) as a specimen, demonstrates the significant advantages of PKO in promoting process efficiency and sustainability. These findings emphasize the relationship between friction and stress, particularly in low-deformation regions like the dead meal zone.

Keywords: palm kernel oil; Tribology: Metal forming; Finite element method (FEM); Coulomb-Tresca friction.

1. INTRODUCTION

Optimizing mass production while reducing energy usage is achievable through computer-based closed forging process simulation, benefiting the steel manufacturing industry. DEFORM-3D, a popular finite element program, handles complex issues like heat dispersion and deformation [1]. In the automotive sector, 1000 series aluminium blanks are widely used for lightweight components [2]. Unlike conventional steels, aluminium’s unique material and tribological properties affect metal forming quality and tool wear [3]. To develop a reliable sheet forming simulation, the coefficient of friction (COF) must be established using real tribological data. Initially, the Coulomb friction model was used in finite element (FE) analyses, assuming a constant COF [4]. However, this model doesn't account for COF fluctuations under varying contact conditions, prompting advanced friction models for closed forging. Local tribology changes due to tool shape, pressure, and surface deformation.

Research shows that factors like contact pressures, lubricants, velocities, temperatures, and surface topographies influence COF. Hazra et al. [5] studied cold forming of AA-6111-T4 and AA-5754-O aluminium alloys, finding that temperature increases during forming affect lubrication and aluminium’s formability. Sabet et al. [6] examined tribology in deep drawing, emphasizing the role of lubricants and surface treatments in improving efficiency and quality.

To improve friction models, Ma et al. [7] developed a load-dependent friction model, considering plastic contact behaviour, showing that surface topography impacts COF more at low contact pressures. Karupannasamy et al. [8] included local friction in their multi-scale contact model, showing rougher tool surfaces result in higher COF.

Vegetable oils, due to their amphiphilic properties, are excellent lubricants [9-12], forming effective

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surface films. However, their cold flow characteristics and thermo-oxidative stability are limitations [15]. This study aims to demonstrate the use of PKO as a bio-lubricant in forging, comparing hydraulic press forces with finite element analysis results.

2. MATERIALS AND METHODS

2.1. Physicochemical properties of samples lubricants

The sample lubricant in this work and their main properties are listed in Table 1. This study evaluated the fatty acid content of Palm kernel oil (PKO) derived from fatty acid palm oil using the ASTMD1983-90 method, which employs differential scanning calorimetry (DSC). PKO contains a high saturation of C12:0 fatty acids; this substance is accompanied by massive volumes of other short and medium chain acids (C8:0, C10:0, and C14:0), but only limited portions of C16:0 and C18 fatty acids (C18:0, C18:1, C18:2). PKO is also more saturated than palm oil; the saturated fatty acid concentration of PKO is often around 80%, whereas in palm oil it is only about 50%.

Table 1. Sample lubricant properties.

Lubricants	CMFO	PKO	Test Method
Density (kg/m^3) @ 25°C	0.900	0.887	ASTM D1298-85(90)
Viscosity (mm^2/s) @ 40°C and 100°C	107.71 and 11.2	35.36 and 11.24	ASTMD-445/ISO 3104
Viscosity Index (VI)	88	329	ASTM D2270
Fourball weld point (kg)	260	110	ASTM 2270
Pour point (°C)	-24.0	15.17	ASTM D97-93
Melting point (°C)	-	18.30	ASTM D217
Worked Penetration Range, (25°C)	265 -295	85 -115	
Flash Point (°C)	236	>225	ASTM D93

2.2 Metal forming test

The experiment employed 35×15×4.5 mm (Height: width: thickness) commercially available pure aluminium and subjected it to compression resulting in about 100% distortion at ambient temperature. An experimental setup and a schematic depiction of the workpiece set in the forging test are shown in Figure 1. Two identical billets were stacked and combined into a single billet unit. At one side of the contact surface of the coupled billets, a plastic flow was seen.

Table 2. Experimental material and condition.

Properties	Value
Workpiece	A1100
Hardness (Hv)	Before annealing = 134.8, after annealing = 52.6
Tooling Material	SKD-11
Workpiece size (mm)	35×15×4.5 (H×W×T)
Reduction in height (s)	3.0, 3.7, 4.2, 4.5 and 4.9
Lubrication quantity (mg)	10
Compression speed (mm/s)	1
Temperature (°C)	24-26

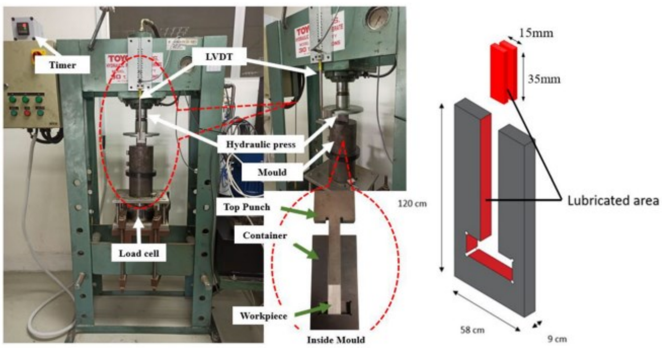


Figure 1. Experiment set up for metal forming process.

3. FINITE ELEMENT METHOD

The material characteristics of an aluminium alloy 1100 workpiece are determined by correlating the actual stress and true strain data on the Instron 5982 universal testing machine using the finite element method (FEM). Figure 2 displays the findings of the three samples obtained from the tensile tests conducted for this investigation.

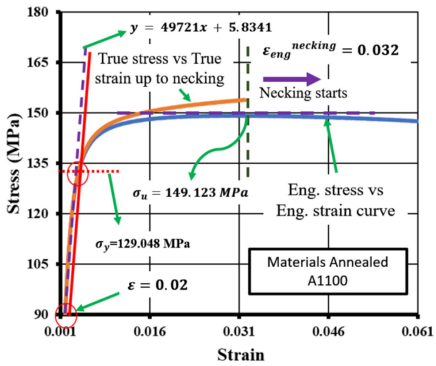


Figure 2. Tensile test analysis for A1100.

3.1. Mesh Sensitivity test

The choice of mesh size in finite element analysis (FEA) involves balancing computational resources and accuracy. Mesh size directly affects simulation results—finer meshes improve accuracy but demand more computational power, while coarser meshes may simplify computation but risk reduced accuracy. Mesh size must be sufficient to capture physical behaviour; too coarse may miss key geometrical details, while too fine increases time without added accuracy. The closed forging sample test for different meshes is shown in Figure 3. To maintain precision, mesh size variation is kept below 1%, as shown in Figure 4(a), where stress distribution accuracy remains consistent between mesh sizes 55,000 and 60,000. Figure 4(b) confirms that more meshes don't significantly change the results.

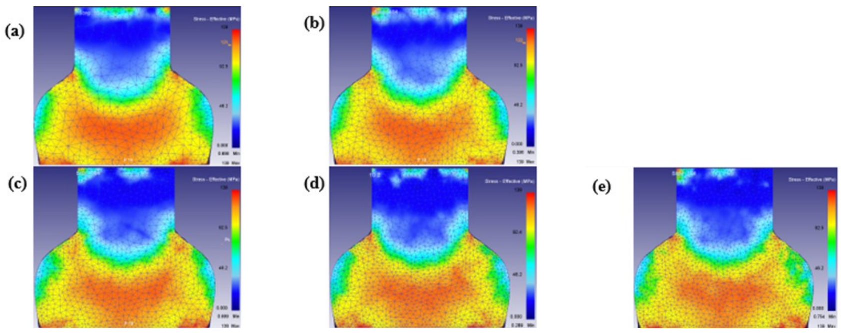
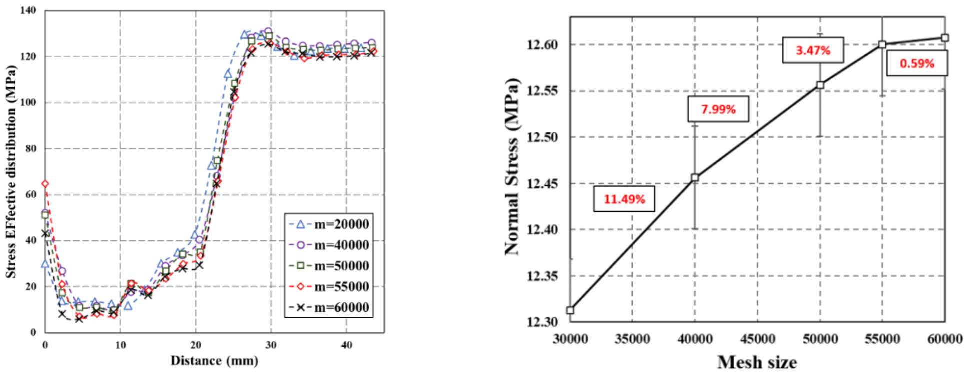


Figure 3. Closed forging model of mesh sensitivity for (a) Mesh=30000, (b) Mesh=40000, (c) Mesh=50000, (d) Mesh=55000 and (d) Mesh=60000.



(a) (b)

Figure 4. The analysis of meshing for (a) Stress effective distribution and (b) Normal Stress.

3.2. Validation and analysis of FEM

Zhang and Ou (2016) addressed how the precision of the finite element model results in a nearly constant inner diameter of the sample for e<0.005, with just a little variance in the friction condition. The discrepancies between the experiment findings and the calibrated curves that were fitted were calculated. Changes in the workpiece's width are negligible for a minor drop in height due to tiny changes in μ or m. The investigation's conclusions showed that, save from a few minor errors totalling less than 0.5%, the experimental results were exactly in line with one calibration curve. The validation graph from the experimental testing is compared to the simulation data's deformation. Unlike the ring compression test, where the friction can be simply characterised as a single friction behaviour, it seems that the friction acts differently depending on the die stroke that is being squeezed [4]. An average of m=0.46/μ=0.18 indicates very high friction due to an absence of lubrication (NA-O). In comparison to NA-O, the results also showed that, during the cold forging test, palm kernel oil (average of m=0.42/μ=0.17) and commercial metal forming oil (average of m=0.42/μ=0.17) had the lowest average amounts of friction. PKO having a propensity for friction to grow at compression ratios of 40% to 50%. After going through the process of validation, it has come to the conclusion that the development of friction during a closed forging test may be summed up as shown in Figure 5.

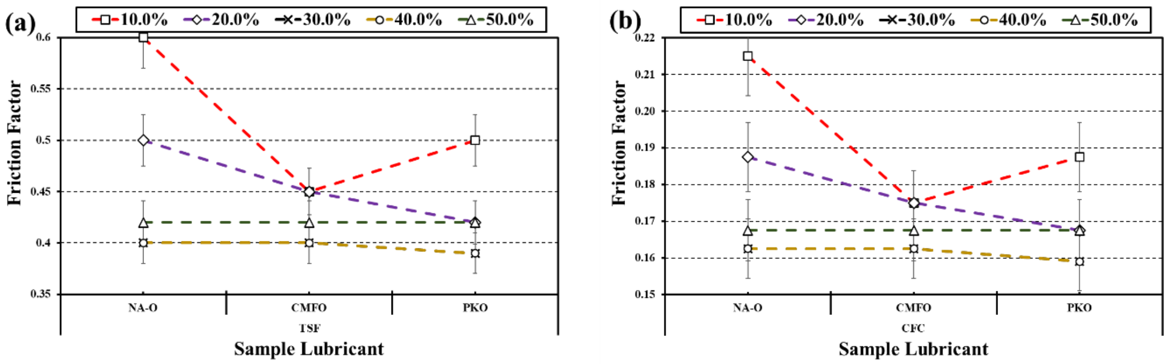


Figure 5. Summary of friction behaviour for each component of the sample test following FEM validation for (a) TSF and (b) CFC.

3.3. Stress-strain effective of workpiece sample

Figure 6 demonstrates the experimental parameters, in which the workpiece was subjected to a compressing deformation of ~40%. At three different stages of the validation procedure, the sample lubricant was exposed to friction levels given by the values m=0.39/μ=0.159 (PKO), and m=0.40/μ=0.1625 (CMFO and NA-O) respectively. It is apparent that the low friction has a lower relative stress at below 3mm displacement after reaching the steady state, and the stress effective has been seen getting higher as displacement is above 11mm. The trend for the stress effective on L2 and L3 area is starting to shift, with the exception of the L1 region, where the stress effective has shown an almost precision value for all of the sample friction. At location L2, the stress effective exhibits a higher value as friction increases before reaching the steady state, which is around 8.5mm.

On the other hand, in contrast to the pattern that was seen before, the stress effective at area L3 shows a decreasing pattern when the friction increases after 11.2mm of displacement and continues upward. This might be because to low deformation at the end of the region, also known as the dead meal zone on the side, which results in a lower stress effective, as illustrated in Figure 7 (a), (b), and (c). Throughout the validation procedure for each sample lubrication test, Figure 7 depicts the final phase of the stress contour analysis done on the sample workpieces for the 2 types of fiction analysis that mostly occur in the compression test. All sample lubricant has the same value of friction that is m=0.42/μ=0.1675 (PKO, CMFO and NA-O). It would seem that the area of L1 and L3 has achieved a steady level of stress effective where the value is consistent for both sample friction, which is due to the fact that the majority of the region is now subject to a very high stress. However, the region at L2 exhibits a tendency of increasing friction leading to higher stress at displacements of less than 10mm, and then the stress reaches the steady state level where both samples have a precise value.

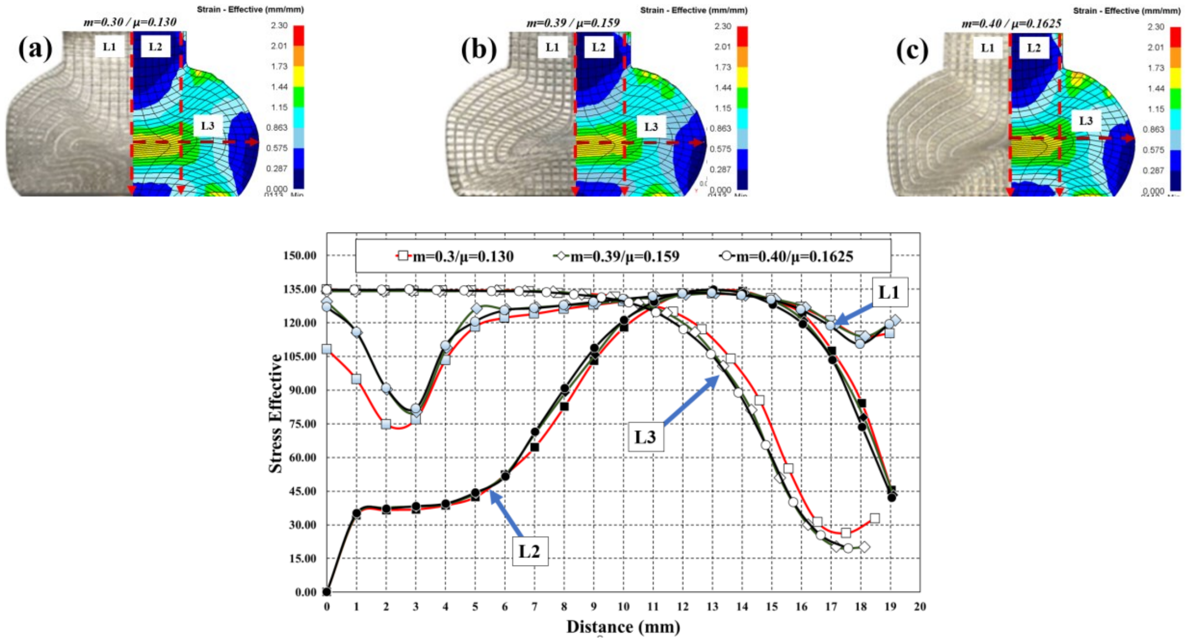


Figure 6. Stress effective at 40% deformation of sample workpiece for (a) m=0.30/μ=0.130, (b) m=0.39/μ=0.159 (PKO), and (c) m=0.40/μ=0.1625 (CMFO and NA-O) respectively.

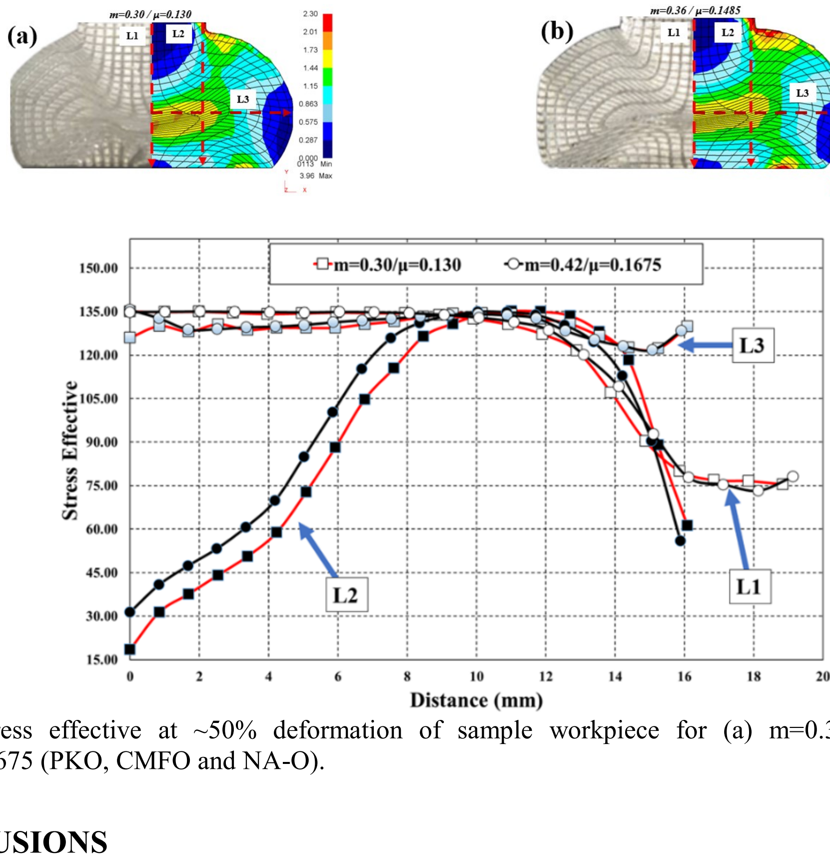


Figure 7. Stress effective at ~50% deformation of sample workpiece for (a) m=0.30/μ=0.130 and (b) m=0.42/μ=0.1675 (PKO, CMFO and NA-O).

4. CONCLUSIONS

Using the finite element method enabled observation of both friction during compression and stress-strain behaviours during deformation. The closed forging process (CFP) was used to study the lubricant's behaviour under various forging processes. The findings suggest that friction changes with die stroke compression, unlike in the open forging test, where friction is described by a single behaviour. Results show NA-O (m=0.6; μ=0.215) has higher friction compared to PKO (m=0.42; μ=0.17) and CMFO (m=0.42; μ=0.17) in cold forging. friction and displacement significantly affect stress distribution during compression. Stress behaviour varies by region: L1 remains consistent, L2 increases with friction until steady state, and L3 decreases beyond 11.2mm displacement. These findings emphasize the link between friction and stress, especially in low-deformation areas like the dead meal zone. The steady-state stress values for all lubricants confirm friction's consistent impact, especially at higher displacement levels.

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