

Experimental and numerical prediction of extrusion load at different lubricating conditions of aluminium 6063 alloy in backward cup extrusion

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ABSTRACT

In the present research work using a backward cup extrusion (BCE) die profile, different lubricating conditions on aluminum alloy AA6063 have been experimentally and numerically investigated to predict the extrusion load. It was obvious that due to an increase in applications of the extrusion process, many researchers have worked on the extrusion process using different methods to achieve their aims. This experiment was conducted with three different lubricants namely: Castor oil, Palm Oil and tropical coconut oil; as well as without lubricants. Different lubricating conditions were employed of varying strain rates ranges from $1.5 \times 10^{-3} \text{s}^{-1}$, $2.0 \times 10^{-3} \text{s}^{-1}$, $2.5 \times 10^{-3} \text{s}^{-1}$, and $3.0 \times 10^{-3} \text{s}^{-1}$; Numerical analysis and simulation for dry and lubricated conditions during extrusion load were also performed using DEFORM 3D software. The results show that prediction extrusion load increases with increasing strain rates. The maximum extrusion load was found to be higher for extrusion without lubricants. In all cases of strain rate, palm oil showed a lower extrusion load compared to the other lubricants. Castor oil indicated the highest extrusion load when the experiment is carried out using lubrication. There was a consistent agreement between the result gotten from the experiment and simulation result of the extrusion load-strike curve.

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1. Introduction

In the press design, the most important parameter that affects the final integrity and the structure of the final product is the extrusion load (i.e. deformation load). The structure evolution and the strain hardening of the extrudate are because of the amount of deformation load generated from the extrusion parameters and die shape (Flitta et al., 2007; Libura & Zasadziński, 1992; Solomon & Solomon, 2010). Therefore, in recent times, many extrusion parameters have been investigated to minimize the forces involved during metal deformation and flow process (Jolgaf et al., 2008; Oyinbo et al., 2015).

Several materials like metals, metallic alloys, composite materials, concrete, foodstuff, and polymers were successfully extruded by the backward extrusion process. The number of industrial applications for extrusion has been growing worldwide in the field of aerospace, automobile, transport or construction (DaChang et al., 2001).

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DaChang et al. (2001) in their conclusion on the investigation of various sizes of aluminium billet showed that extrusion pressure decreases significantly when the cup external diameter is larger than the inner diameter of the rod and zero reduction rate at the compression zone was observed, and the distortion band resulted from the deformation zone (DaChang et al., 2001). Although in metal forming, the enhancement of surface texture control and plasticity are best achieved by equal speed rolling (ESR) and differential speed rolling techniques (DSR) (Gong et al., 2014; Gong et al., 2009; Gong et al., 2010). A similar investigation was also carried out by Bashir et al., (2017) in inspecting for backward cup extrusion the parametric effects such as temperature, time, billet radius and punch displacement on aluminium billet. They observed that temperature increases with an increase in the percentage area reduction and extrusion pressure increase with increasing billet length. However, it was concluded that the following factors affect the extrusion load; the extrusion speed, initial billet temperature, frictional effect at the die interface, extrusion ratio and billet flow stress. It was also noticed by Ajiboye & Adeyemi (2008) that increasing frictional energy at the deformation zone is because of increasing punch size which brings about the increase in the deformation load. The conclusion of Udomphol, (2007) during his investigation shows that as temperature increases, extrusion load also increases for a given extrusion load. Sathishkumar et al., (2017) studied the effect of the extrusion ratio of Silicon Carbide reinforced aluminium matrix composite on the plastic strain of billet temperatures using Finite element analysis (FEA) during the hot extrusion process. It was discovered that as the extrusion ratio increases, the strain rate and plastic strain also increases.

The effects of various lubricating conditions were investigated by Ikumapayi et al., (2019) on aluminum AA6063 alloy during the backward cup extrusion process to determine the temperature distribution during deformation. Different lubricants were used at different strain rates. The result of their finding was also compared with numerical analysis which shows that during deformation, the increasing strain rates increase the temperature both at the lower die and punch interface. Also, when tropical coconut oil was used as the lubricating oil at a higher strain rate, the highest temperature was recorded as compared with other lubricants. Uyyuru and Valberg, (2006) use finite element analysis (FEA) and physical modeling to examine aluminium alloy slug using the backward cup extrusion process. The material flow was studied using circular shape or on-tube-like intrinsic material. It was inferred from their result that along with the cup length the surface extension varies considerably with the punch head. At the top of the cup, the extension was higher than that of the base. Ajiboye and Oyinbo, (2014) numerically simulated extrusion of various shapes ranging from simple to advanced polygons using Deform 3D, a solid CAD model from a round billet. Dry and lubricated conditions were observed to determine the extrusion load. It was discovered that predictive loads for simple shapes are lower than that of advanced polygons and there was a significant reduction in the extrusion load during lubricating conditions.

Abrinia and Gharibi (2008) use an upper bound model (UBM) and finite element method (FEM) in their research to analyse thin-walled cans during the backward extrusion process. Their result shows that consistent and smaller can wall thickness can be achieved by using the appropriate punch head profile. Shear extrusion process was used to study aluminium alloy AA6063 in order to determine the forming load using variables such as die diameter, punch land and lubricants by Ojo et al., (2015). They found out that a punch with small punch land and with large diameter is best for material forming during shear backward cup extrusion. Also, the effects of various lubricants were also examined to determine the stress distribution and extrusion load during deformation. Palm oil shows minimum load during the process. Ajiboye et al., (2014) investigated the effects of environmentally friendly lubricants on aluminium alloy AA6063 to improve its mechanical properties during equal channel angular extrusion (ECAE). It was observed that the maximum ductility and ultimate tensile strengths with the least extrusion pressure were obtained when palm oil lubricant was used. Palm and olive oil yields the least deformation load than others, Furthermore, greater hardness and higher homogeneity were observed within the rod at the tensile strain side than the compressive side.

The focus of this investigation is to determine the extrusion load for the aluminum alloy AA6063 using an unconventional backward extrusion process (i.e. backward cup extrusion, BCE) at different lubricating conditions that allows considerably increased strength because of grain size reduction. Semi-products of complex shapes are often produced using this alloy by a known industrial forming process which is hot extrusion, the underlying conventional approach. Surface quality and predefined strength is the aim to be achieved at minimum cost while processing the material. At elevated temperature, the extrusion process is performed, and additional heat treatments further adjust the properties of the final material (Bauser et al., 2006). In contrary to conventional hot extrusion, this research work investigates how different lubricants at a temperature below recrystallization temperature can be used to predict extrusion load by increased strain hardening and grain refinement. The plastic deformation process during cold extrusion for technical-economic evaluation of materials can be found in (Herold et al., 2018) and the isothermal extrusion using the surface formation of the extrudate and flow pattern of material methods (Peng & Sheppard, 2004).

2. Materials, methods and model development

2.1 Extrusion material and lubricants selection

Aluminium alloy AA6063 is the workpiece material used in this investigation with the chemical composition and properties outlined in Tables 1 and 2 (Groover, 2004). The material was first machined into cylindrical billets and then annealed using the electrical furnace at 410°C temperature this is because the aluminium was received as cast, soaked for forty-five minutes after which it was allowed to cool down gradually until it was room temperature. This will allow uniform temperature distribution within the workpiece and grain refinement. The equipment used was

- i. Vernier caliper's
- ii. Two Thermocouple (type k)
- iii. Hydraulic press
- iv. Temperature meter

The test was performed on a 600kN Avery-Denison universal hydraulic testing machine. Various extrusion parameters have been worked on in the past different researchers as reflected in the introduction of this work. In this research work, the authors predicted experimentally the extrusion load for aluminium alloy AA6063 using an unconventional backward cup extrusion (BCE) process with the following objectives.

- i. Predicting the distribution of extrusion Load in backward cup extrusion using aluminium AA6063 alloy
- ii. Investigating the effects of the lubricant on the distribution of extrusion load during backward cup extrusion using aluminium AA6063 alloy AA6063
- iii. Comparing both the experimental and numerical simulation results.

Castor oil, Palm Oil and tropical coconut oil were locally sourced and used for this experiment as lubricants. The lubricants were selected based on the following criteria; workpiece cooling effects, tool wear, pick up minimization on tools, favorable wetting characteristics, low procurement cost and non-toxicity, surface finish control, and deformation load reduction. The performance of these lubricants is due to their viscous properties over a wide temperature range.

Table 1
Aluminum 6063 alloy chemical composition

Alloying Element (wt%)	Fe	Si	Cu	Mn	Mg	Sn	Pb	Zn	Ti	Al
AA6063	0.251	0.518	0.007	0.006	0.521	0.007	0.000	0.10	0.013	98.62

Table 2

Aluminium AA6063 alloy Properties

THERMAL	
Thermal Conductivity (w/m-k)	218
Thermal Expansion ($10^{-6}/^{\circ}\text{C}$)	23.4
MECHANICAL	
Tensile Strength (MPa)	90.0
Elastic Modulus (GPa)	70.0– 80.0
Poisson's Ratio	0.330
Density ($\times 1000\text{kg/m}^3$)	2.70
Fatigue Strength (MPa)	55.0
Shear Strength (MPa)	69.0
Hardness (HB500)	25.0
Yield Strength (MPa)	48.0

2.2 The extrusion punch and rig design

The design of extrusion rig, punch, the lower die, thermocouple and other accessories used in carrying out this research work depends considerably on the choice of material, tooling, and equipment used in the task execution (Akhtar & Arif, 2010; Kostic & Reifschneider, 2006).

2.3 The punch designs

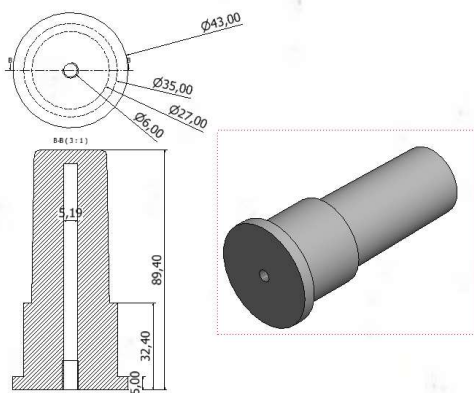
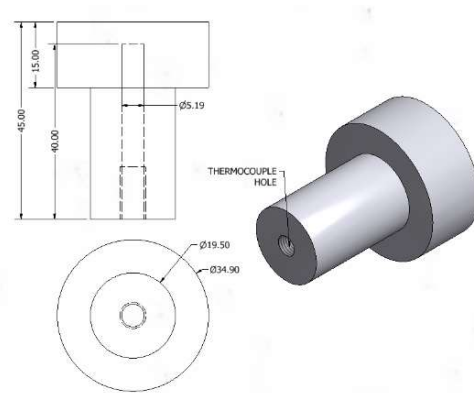
The punch has a diameter of 27mm as shown in figure 1. And to accommodate the thermocouple, a drilled hole is located at the backside. The thermocouple is inserted into this hole for temperature measurement during the experiment. Three guide pins as shown in figure 5 were attached to the punch to centrally control the position of the punch when placed on top of the workpiece.

2.4 The lower die

Fig. 2 shows the construction of the lower die. To effectively measure the temperature of the billet base, a thermocouple was inserted into the drilled hole on the lower die with a 5mm allowance, this is to prevent the flow of lubricant during the extrusion process.

2.5 The extrusion rig

Fig. 3 and Fig. 4 show the design of the extrusion rig used for all extrusion tests. This rig was used to extrude aluminium AA6063 alloy billets to a reduced rate in the area of 0.6. The billet is of 34.8 mm diameter and 25 mm in height.

**Fig. 1.** The Punch**Fig. 2.** The Lower Die

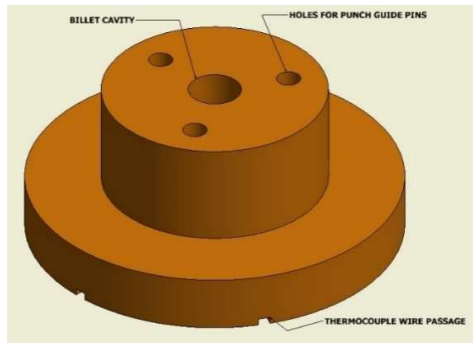


Fig. 3. Extrusion Rig

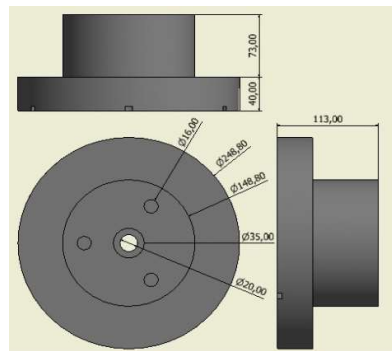


Fig. 4. Extrusion Rig Orthographic views

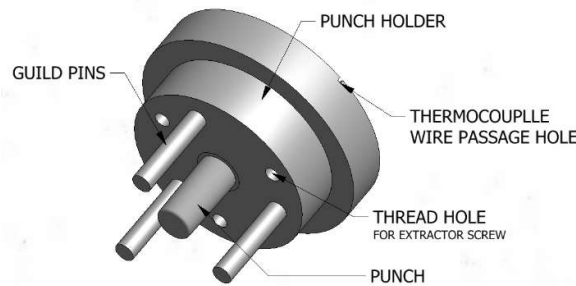


Fig. 5. Punch Assembly

2.6 Determination of extrusion force

Table 3

Simulation parameters

PARAMETERS	Max. Displacement	Ram Speed	Strain Rate	Temperature
INPUTS	20 mm	0.075 mm/s	$0.003s^{-1}$	30^0

The finite element analysis model was used in the prediction of extrusion force that is sufficient to extrude aluminium AA6063 alloy using Deform 3D software. The input parameters for the simulation are outlined in Table 3 and the result obtained in Fig. 6.

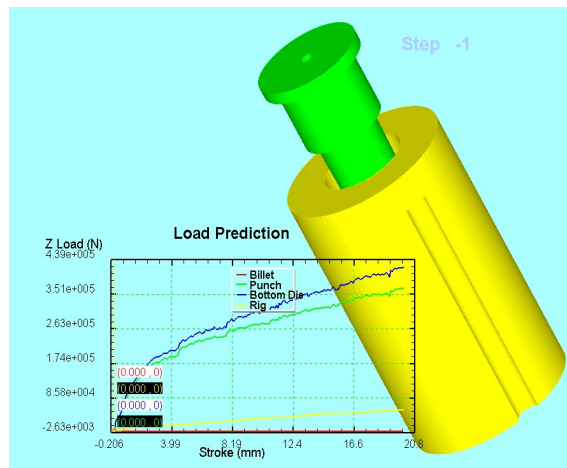


Fig. 6. Result of the simulation from Deform 3D postprocessor to determine the extrusion load

2.7 Determination of shell diameter

Failure criteria were used to determine the diameter of the shell rig. The shell failure criteria are based on the theory and principle of elasticity. At the extreme end of the container, the three guide pins are inserted at equidistance to the shell diameter. The drilled holes reduce the possibility of the rig wall. At the tensile yield point, failure occurs according to the four failure theories shown in Eq. (1-4); Eq. (1) shows the theory of maximum principal stress, Eq. (2) is the theory of maximum shear stress, Eq. (3) and Eq. (4) are the maximum principal strain and the maximum distortion energy theory respectively, where; Internal Pressure, p_i is 390 MPa from simulation; Yield Stress, σ_{yp} for aluminium alloy is 48 MPa; Poisson ratio, ν is 0.33 for aluminium, Internal diameter, d_i is 35mm, and outer to internal diameter ratio r , k is d_o/d_i . When all the values for the parameters are substituted into Eqs. (1-4), the failure theories, 109 mm was obtained for the maximum diameter and the displacement of the guide pin holes from the centre is 62 mm

$$k = \sqrt{\frac{1 + p_i/\sigma_{yp}}{1 - p_i/\sigma_{yp}}} \quad (1)$$

$$k = \sqrt{\frac{1}{1 - 2(p_i/\sigma_{yp})}} \quad (2)$$

$$k = \sqrt{\frac{1}{1 - 2(p_i/\sigma_{yp})}} \quad (3)$$

$$k = \sqrt{\frac{1}{1 - \sqrt{3}(p_i/\sigma_{yp})}} \quad (4)$$

2.8 Temperature measurement and heat treatment of extrusion toolings.

MASTECH MY64, temperature digital multimeter and type K thermocouple were used in the experiment for the measurement of temperature. Heat treatment was performed during the extrusion process on the tools to prolong the tool life and to be able to withstand high pressure. To change the microstructure of the tool to obtain metallurgical characteristics and optimum desirable properties, heat treatment was performed on the lower die and the punch. Carburising box at a temperature of 910°C was used to case-hardening the lower die and the punch and then soaked for half an hour at this temperature. Engine oil (SAE) was used to quench the tools and then tempered at a temperature of 200°C so that the induced residual stresses can be reduced, and the tempering took an hour. The wear resistance of the tools and the carbon content were increased by case hardening, this correlates with the research performed by Onuh et al., (2003). Heat treatment was also performed on the cylinder at a temperature of 910°C, soaked and quenched in water for an hour to attained uniform grain refinement because of uniform temperature distribution.

3. Experimentation

Fig. 7 below shows the experimental setup, a 3D model. The experiments were conducted in 16 trials with 4 experiments conducted for each lubricant and it was performed at room temperature. Thermocouple inserted into the drilled holes located at the punch and the lower die was used to obtain the temperature reading. The billet, rig walls, punch, and the lower die were lubricated during the experiment to reduce the deformation force with different lubricants and at 4 different strain rates. The experiment was performed on a 600KN universal testing machine extrusion press known as Danison

Hydraulic press. The thin metal layers left after each extrusion test were removed by cleaning the assembly after each test. Fig. 8 shows the experimental setup snapshot.

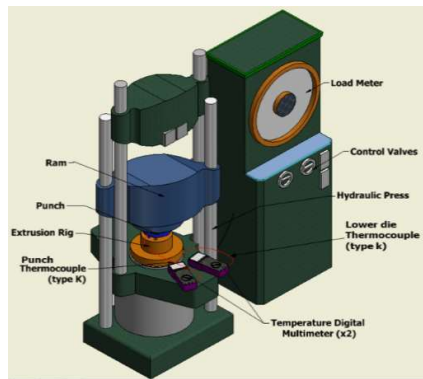


Fig. 7. 3D Model of the Set-up



Fig. 8. Snapshot of the Setup

4. Results and discussions

The results gotten from the experiments performed at different lubricants using Universal Hydraulic Press and at varying velocities are plotted to predict the effects of lubricating conditions on extrusion load during backward cup extrusion of aluminium AA6063 alloy. A combination of parameters in the selection of optimum tools for backward cup extrusion of aluminium alloy AA6063 gives the lowest stress and extrusion load. The parameters of the experiment are shown in Table 4. The billet and the extrudate products for both wet and dry lubricating conditions are shown in figure 9(A-C). The extrudate cup with lubrication has a better surface finish, minimum surface cracking, and dark coloration compared to the products produced during dry conditions (without lubrication).

Table 4

Experimental parameters

EXP NO.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
STRAIN RATE(10^{-3})	1.5	2.0	2.5	3.0	1.5	2.0	2.5	3.0	1.5	2.0	2.5	3.0	1.5	2.0	2.5	3.0
LUBRICANT	Nil(Dry)				Palm Oil				Tropical Coconut Oil				Castor Oil			

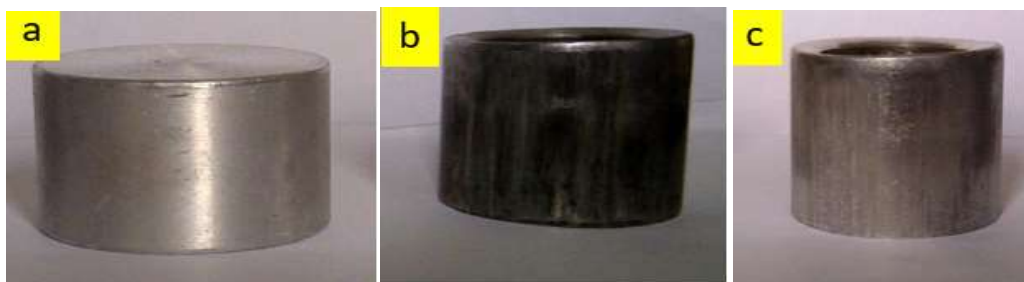


Fig. 9. Billet and the Extrudates (A) BILLET (B) Lubricated (C) Without Lubricants)

4.1 Extrusion load – stroke curves

The extrusion loads versus punch displacements or stroke curves for the aluminium alloy AA6063 in backward cup extrusion at room temperature comparing the curves at different strain rates for the different lubricants. Fig. 10 shows the graph of extrusion load versus stroke without lubrication and Fig. 11 shows using palm oil, tropical coconut oil, and castor oil as a lubricant at different strain rates. The graph shows the extrusion load increases as the strain rate increases. Also, the graph shows a decrease in

extrusion load as the strain rate reduces from $1.5 \times 10^{-3} \text{ s}^{-1}$ to $3.0 \times 10^{-3} \text{ s}^{-1}$. The extrusion load – stroke curve with a $3.0 \times 10^{-3} \text{ s}^{-1}$ strain rate from the graph shows the highest extrusion load. This indicates that at a higher strain rate, the punch load increases. Figs. 12-13 present the extrusion load using palm oil, tropical coconut oil, and castor oil as a lubricant with different strains. The extrusion load – stroke curve using different lubricants also shows a decrease in extrusion load as the strain rate reduces from $3.0 \times 10^{-3} \text{ s}^{-1}$ to $1.5 \times 10^{-3} \text{ s}^{-1}$. The extrusion load – stroke curve with a $3.0 \times 10^{-3} \text{ s}^{-1}$ strain rate from the graph shows the highest extrusion load. This indicates that at the higher strain rate the punch load increases. The extrusion load against the stroke curves showing the effect of different lubricants used in the study at a constant $1.5 \times 10^{-3} \text{ s}^{-1}$ strain rate as shown in Fig. 14. The graph indicates that as the extrusion load is highest without lubrication, this means that the extrusion load decreases when the experiment is carried out using lubricants. Palm oil as lubricants shows the lowest extrusion load followed by tropical coconut oil. Castor oil showed the highest extrusion load as lubricant. Fig. 15 to Fig. 17 show the extrusion load–stroke curves with different lubricant at strain rates of $2.0 \times 10^{-3} \text{ s}^{-1}$, $2.5 \times 10^{-3} \text{ s}^{-1}$ and $3.0 \times 10^{-3} \text{ s}^{-1}$. Similarly, palm oil as lubricants shows the lowest extrusion load followed by tropical coconut oil at all cases of the strain rate.

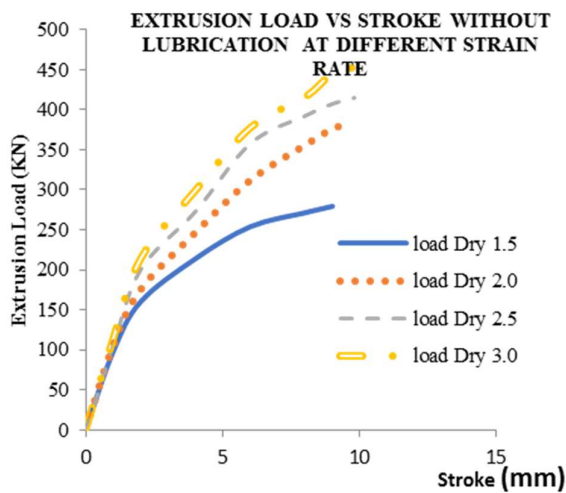


Fig. 10. Extrusion Load Vs Stroke without Lubrication at Different Strain

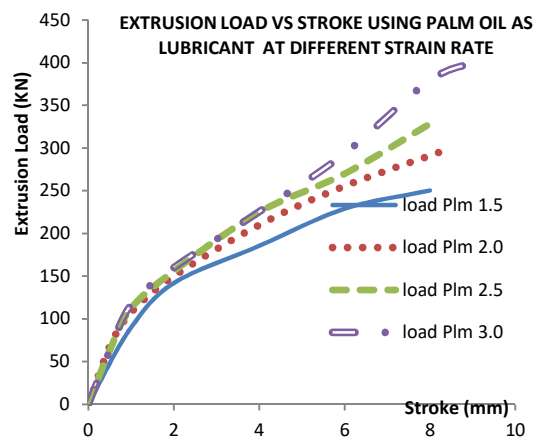


Fig. 11. Extrusion Load Vs Stroke Using Palm Oil as Lubricant at different Strain Rate

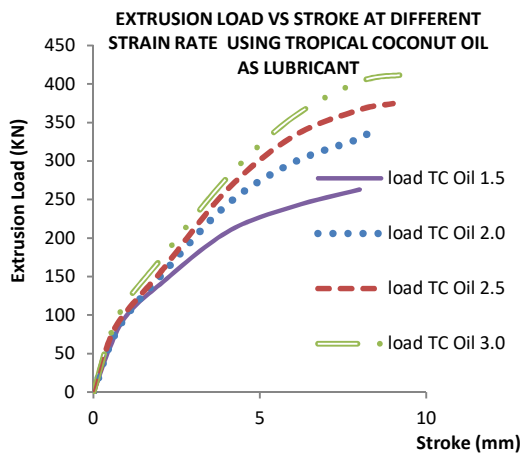


Fig. 12. Extrusion Load Vs Stroke at different Strain Rates Using Tropical Coconut Oil as Lubricant

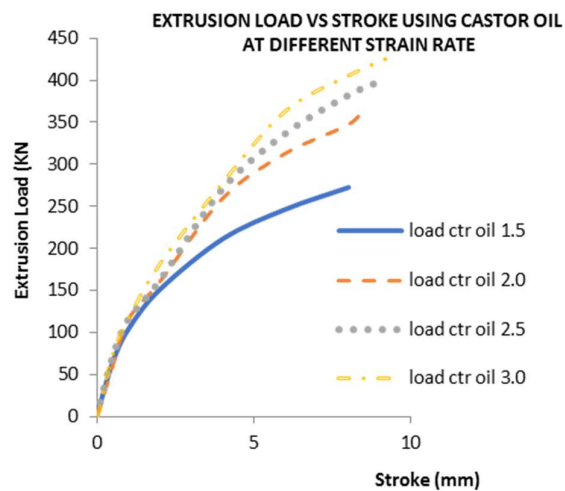


Fig. 13. Extrusion Load Vs Stroke at different Strain Rates Using Castor Oil as Lubricant

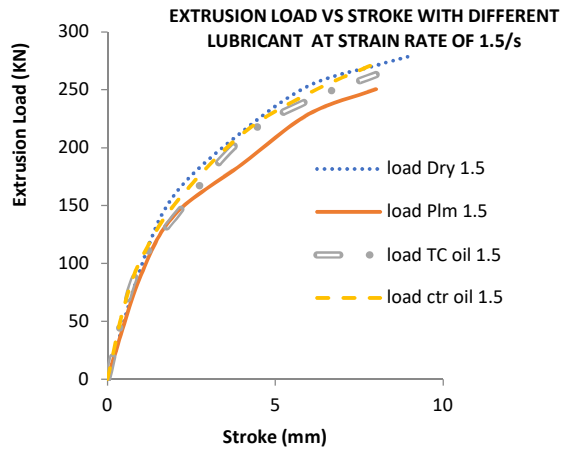


Fig. 14. Extrusion Load Vs Stroke with different Lubricant at Strain Rate of $1.5 \times 10^{-3}/s$

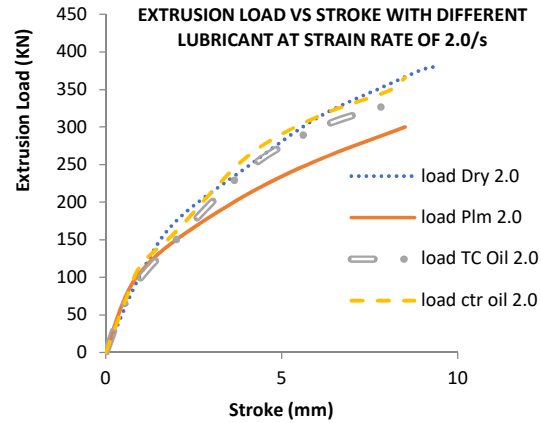


Fig. 15. Extrusion Load Vs Stroke with different Lubricant at Strain Rate of $2.0 \times 10^{-3}/s$

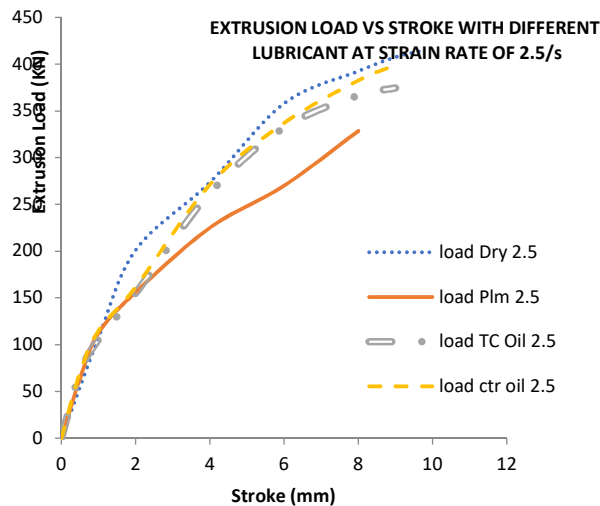


Fig. 16. Extrusion Load Vs Stroke with different Lubricant at Strain Rate of $2.5 \times 10^{-3}/s$

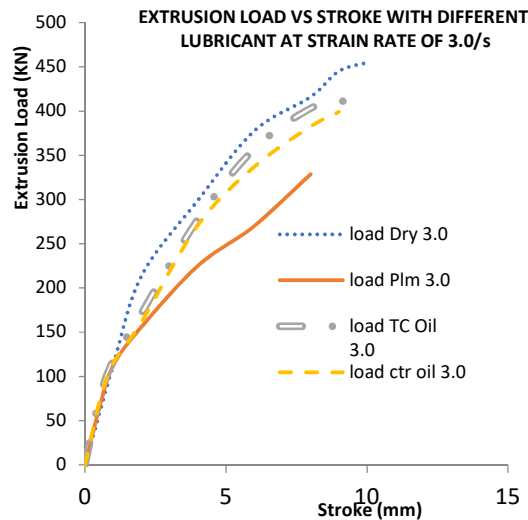


Fig. 17. Extrusion Load Vs Stroke with different Lubricant at Strain Rate of $3.0 \times 10^{-3}/s$

4.2 Comparison of FEA simulation result and experimental result

Finite element analysis was performed using DEFORM 3D software to determine the actual extrusion parameters and die geometry. The result of the simulation of the extruded profile was comparable to the experimental shape as foretold by Li et al., (2004). The input parameters for the simulation are outlined in Table 5. The result gotten from the experiment, as shown above, is compared with the result of FEA simulation at $2.0 \times 10^{-3}s^{-1}$ and $2.5 \times 10^{-3}s^{-1}$ Strain rate. Fig. 18 and Fig. 19 shows the deformation load-stroke. A close relationship was revealed from the result gotten from the experiment and that of the simulation at both strain rate.

Table 5

Parameters used in the Simulation

Parameters	Friction	Maximum. Displacement	Strain Rate	Ram Speed	Temp.
Case 1	0.47	10 mm	0.0025s^{-1}	0.0625 mm/s	30°
Case 2	0.47	10 mm	0.0020s^{-1}	0.0500 mm/s	30°

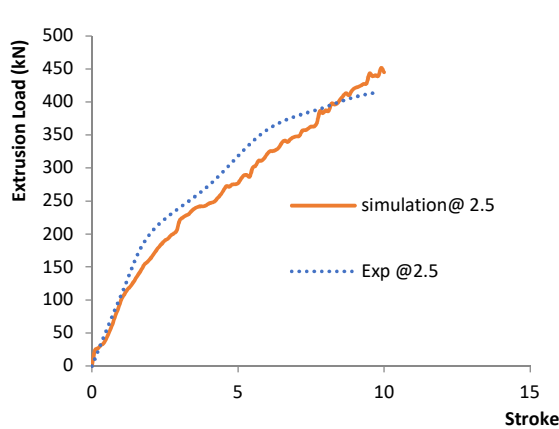


Fig. 18. Extrusion Load Vs Stroke Simulation and Experimental at Strain Rate of $2.0 \times 10^{-3}/\text{s}$

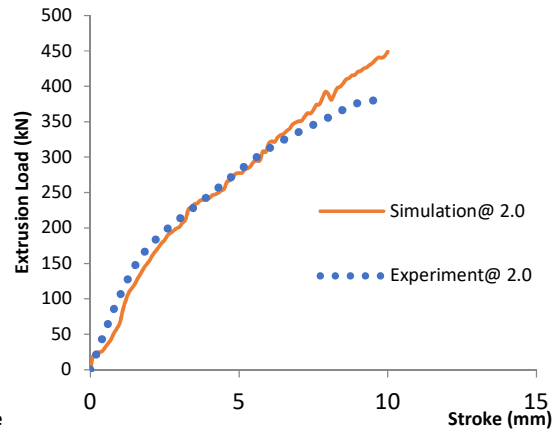


Fig. 19. Extrusion Load Vs Stroke Simulation and Experimental at Strain Rate of $2.5 \times 10^{-3}/\text{s}$

5. Conclusion

The experimental and numerical investigation was successfully performed to predict the extrusion load of aluminium AA6063 alloy at different lubricating conditions (i.e. palm oil, castor oil, and tropical coconut oil as lubricants) during the backward cup extrusion process. The determination of plastic deformation has been achieved through various methods, especially through backward cup extrusion processes. The material flow behaviour can be described by the mechanics of plasticity when using the desired geometry. Dry and lubricating conditions were used in the experiment at room temperature. In the case of wet conditions, $1.5 \times 10^{-3}\text{s}^{-1}$, $2.0 \times 10^{-3}\text{s}^{-1}$, $2.5 \times 10^{-3}\text{s}^{-1}$ and $3.0 \times 10^{-3}\text{s}^{-1}$ was used as strain rates. The following conclusions based on the analysis and the discussion of the results gotten from the research performed were made:

As the strain rates increases, the extrusion load increase. The maximum extrusion pressure was found to be higher for extrusion without lubricants. In all cases of strain rate, palm oil showed a lower extrusion load compared to the other lubricants. Castor oil indicated the highest extrusion load when the experiment is carried out using lubrication.

Finite element analysis was performed using DEFORM 3D software to determine the actual extrusion parameters and die geometry. The result of the simulation of the extruded profile was compared with the actual experimental shape during the process of extrusion. The extrusion load is higher at a higher strain rate. There was a consistent agreement between the result gotten from the experiment and simulation result of the extrusion load-strike curve.

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