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Computational Modelling of Metal Forming Operations: A Finite Element Approach

[1*]Enahoro Micheal Oamhen and [2]Irogue Wilfred Aiguobasimwin

[1] *Department of Mechanical Engineering, University of Benin, Benin City, Edo State, Nigerian*
micheal.enahoro@uniben.edu

[2]*Department of Materials and Metallurgical Engineering, University of Benin, Benin City, Edo State, Nigerian*
wilfred.irogue@uniben.edu

**Corresponding Author: Enahoro Micheal Oamhen;* micheal.enahoro@uniben.edu

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Abstract: *This paper introduces an all-inclusive computational modeling (based on finite element method (FEM)) of complicated metal-forming operations, in this case, through cold extrusion of lead billet into an intricate die profile, to fashion E and X-shaped structures. The study is a combination of theoretical modeling using upper bound plasticity theory and experimental validation and finite element simulation to forecast the forming loads, strain distributions and flow patterns of the material in the case of extrusion process. An upper bound was formulated and its development facilitated the computation of governing equations of the energy dissipated by internal deformation, frictional dissipations at tool-workpiece interfaces, and shear deformational regions through a kinematically admissible velocity field. It involved experimental studies which were where plain carbon steels were used as tooling and lead billets were subjected to different lubrication conditions such as no lubrication, red oil, brake oil and mustard oil. The generated FEM model has effectively forecasted the extrusion forces as 92 MN, 70 MN, 67 MN and 75 MN under respective lubrication conditions and they are matched very well with experimental values of 88.5 MN, 66.0 MN, 65.0 MN and 69.5 MN respectively and the extrusion force prediction fall within 2-5% accuracy. Analysis showed that, with brake oil which had the highest viscosity, formed the lowest loads and extrusion pressure thus lowering the maximum pressure which was 281.59 kN/m^2 (unlubricated) to 206.82 kN/m^2. Proper strain calculation produced a value of 1.03 in agreement with strain contours using FEM method, and strain rates were averagely 16.54 s 1. This confirmed computational model illustrates how FEM can be used to streamline the die design, offer the capability of predicting the process parameters and minimize the element of trial-and-error process that are costly within industry in processes governed by metal formings.*

Keywords: Finite Element, Metal Forming, Cold Extrusion, Upper Bound Theory, Tribology

INTRODUCTION

The core of the modern manufacturing reflects in metal forming as it allows the efficient realisation of complex shapes with higher mechanical properties. These are forms like extrusion, forging, and rolling, and they depend strongly on the plastic deformation of metals under induced loads, usually at higher temperatures.

But the development of more complex shapes of components and the need to develop higher precision in forming operations require complex computational tools that would simulate and optimise forming processes. The Finite Element Method (Yahaya *et al.,* 2023) It is one of these tools, and has proved to be one of the strongest and the versatile tools for modelling metal forming operations and providing predictive capability that decreases reliance on expensive and time-consuming trial-and-error attempts in simulation and evaluation of the metal forming operations (Andrietti *et al.,* 2015). The Finite element modelling makes it possible to perform analysis on stress-strain behaviour, strain rates, temperature distribution, and material flow during deformation, and so the modelling is key to process design and control (Bathe, 2006). FEM uses a discretisation of a continuum, described as a finite element, to arrive at numerical solutions of the continuum mechanics governing equations that simulate complex relationships between tools and workpieces. The process is especially applicable in addressing the geometric and material non-linearities which are fundamental in metal forming, i.e. large plastic straining, contact issues, and thermal influences (Pragana *et al.,* 2024). Moreover, advanced constitutive models sensitive to strain hardening, rate sensitivity and anisotropy are also possible in FEM, and this is essential in idealising the behaviour of metallic materials during forming (Hou *et al.,* 2023).

Although FEM-based metal forming simulation is powerful, there may be problems, especially regarding the simulation of interfacial friction, heat generation, and tool wear processes with a high level of detail (Liu *et al.,* 2020). Choosing boundary conditions, the nature of the mesh, and selecting friction models majorly influence precision in the simulation. According to the studies, certain works of art have no place in the world and are worth nothing. As discussed by Liu *et al.* (2020), simulated and experimental results of the frictional conditions may differ significantly when frictional conditions are misrepresented. As such, stringent validation of the model based on experimental data is crucial in computational modelling in order to enshrine reliability and practicality in industrial applications. This paper is a critical examination of the finite element modelling of the use of complex metal form work, extruding lead billets through dies, which assume complex shapes, was the subject of the particular study. Its objective is to design and verify a computational model that will allow one to determine forming loads, strain distributions, and material flow patterns. The combination of experimental data and numerical modelling in the study gives a broad framework for advancing the knowledge base and optimisation of forming metal processes (Singh, 2025).

MATERIALS AND METHODS

The approach to this investigation combines the finite element approach to modelling with experimental verification to study a complex metal forming process that is the cold extrusion of the lead billets to form shaped and intricate geometries that are of the nature of the words E and X. The method involves three significant steps: theoretical modelling, experimental steps and numerical analysis by means of the FEM approach (Guo *et al.,* 2015).

2.1 Modeling for 'E' & 'X' shapes

The principles of the equation (1-12) form the bases on which the modeling equation for this study were derived. In consideration of Fig. 1 below, the velocity field and upper boundary equations for this study were determined.

Enahoro & Irogue (2025). Computational Modelling of Metal Forming Operations: A Finite Element Approach**.** *Nigeria Journal of Engineering Science Research (NIJESR)*, 8(2): 47-56. *https://doi.org/10.5281/zenodo.16935363*

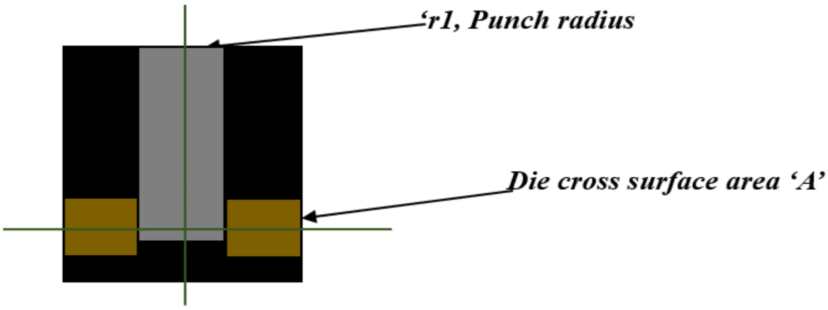

Fig. 1 Sectional view of body under consideration

To derive the Upper bound theorem, the equilibrium equations are allowed to go unsatisfied; concern is primarily with strain increments and the conditions they have to fulfill in a fully plastic body (Johnson and Mellor, 1973). This work seeks to derive and obtain the relationships between the area and volume of the feed billet or work piece and the dies and shapes therein. In consideration of the friction factor and relative forging pressure of the 'E' and 'X' shapes with container taken into consideration; and to show how these parameters can affect the relative forging power. The upper bound formulation can be described by Equation (1) (Johnson and Mellor, 1973).

$$J^* = \frac{2}{\sqrt{3}}\sigma_0 \iiint \sqrt{\frac{1}{2}\dot{\varepsilon_{ij}}\dot{\varepsilon_{ij}}}dV + \iint \tau|\Delta v|ds - \iint T_i v_i ds \tag{1}$$

Where,

$$\dot{\varepsilon_{ij}} = \frac{1}{2}\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right) \tag{2}$$

The first term of Equation (1) represents the internal energy dissipated for the deformed body, the second term represent shear losses and the third term represents frictional losses on the tool work piece interface. σ_0 is the flow stress of the material, $\dot{\varepsilon_{ij}}$ is the strain rate tensor, and $|\Delta \boldsymbol{v}|$ is the velocity discontinuity over the shear surface. The assumed kinematically admissible velocity field can be expressed in form of axial and radial velocities.

From volume constancy;

$$U_r = \frac{-r}{2h}U \tag{3}$$

Based on incompressibility condition; (appendix 10)

$$U_z = \frac{U}{h}z \tag{4}$$

And for boundary condition;

$$U_r = \frac{U}{2h}(r - \frac{r_1^2}{r}) \tag{5}$$

Therefore, the velocity field is as thus;

$$\left\{U_\emptyset = 0,\ U_r = \frac{U}{2h}\left(r - \frac{r_1^2}{r}\right) \&\ U_z = \frac{U}{h}\right\} \tag{6}$$

For the strain rate field, differentiating the above equations, then;

$$\dot{\varepsilon}_{rr} = \frac{\partial U_r}{\partial r} = \frac{U}{2h}\left(r + \frac{r_1^2}{r^2}\right) \tag{7}$$

$$\dot{\varepsilon}_{\theta\theta} = \frac{U_r}{r} = \frac{U}{2h}(1 - \frac{r_1^2}{r^2}) \tag{8}$$

$$\dot{\varepsilon}_{zz} = \frac{\partial U_z}{\partial z} = \frac{-U}{h}\text{--} \tag{9}$$

For power, the internal energy (ω_i) can be evaluated as follows,

Recalling, $\omega_i = \frac{2}{\sqrt{3}}\sigma \int_v \sqrt{(\frac{1}{2}\varepsilon_{ij}\varepsilon_{ij})}dv$;

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Therefore,

$$\omega_i = \frac{2}{\sqrt{3}}\sigma \int_v \sqrt{\frac{1}{2}\left(\frac{U}{h}\right)^2 \left(3 + \frac{2r_1^4}{r^4}\right)}\, dv \qquad (10)$$

The Friction power (ω_f) expressed below is of the region one and axial velocity;

$$\omega_{f1} = \frac{2\pi\sigma_0 mU}{3h\sqrt{3}} \qquad (11)$$

At the work piece/ Container interface;

$$\omega_{f2} = \frac{\sigma_0 m\pi}{\sqrt{3}} U r_2 h \qquad (12)$$

In consideration of velocity continuity;

$$\omega_v = \frac{2\pi\sigma_0}{h\sqrt{3}}\, U\left[\frac{r_2^3}{3} + r_2 r_1^2\right] \qquad (13)$$

Combining all the equations,

$$\omega = \omega_i + \omega_{f1} + \omega_{f2} + \omega_v$$

$$\omega = \left[\frac{2}{\sqrt{3}}\sigma_0 \int_v \sqrt{\frac{1}{2}\left(\frac{U}{h}\right)^2 \left(3 + \frac{2r_1^4}{r^4}\right)}\, dv\right] + \left[\frac{2\pi\sigma_0 mU}{3h\sqrt{3}}\right] + \left[\frac{\sigma_0 m\pi}{\sqrt{3}} U r_2 h\right] + \left[\frac{2\pi\sigma_0}{h\sqrt{3}}\, U\left[\frac{r_2^3}{3} + r_2 r_1^2\right]\right] \qquad (14)$$

For force, the punch moves axially with an upper boundary (external power) of

$$J^* = PU \qquad (15)$$

Recalling equation 3.1 above

$$F_{\text{ave}} = \sigma_0 A\left[\frac{8\pi}{\sqrt{3}}\left(3 + \frac{1}{r_1}\right)\right] + \sigma_0 A\left[\frac{\pi r_2 mh}{2h\sqrt{3}}\right] + \sigma_0 A\left[\frac{\pi m}{h\sqrt{3}}\left[\frac{r_2^3}{3} + r_2 r_1^2\right]\right] + \sigma_0 A\left[\frac{\pi}{h\sqrt{3}}\left[\frac{r_2^3}{3} + r_2 r_1^2\right]\right] \qquad (16)$$

The upper bound theorem of plasticity is the basis on which the theoretical a model was formulated, whereby the physically viable velocity and strain rate field were taken into consideration. Energy dissipation due to internal deformation, frictional losses at the die–workpiece interface, and shear along deformation zones was formulated into governing equations. From these formulations, extrusion forces and power requirements were derived as functions of material properties, die geometry, and process conditions (Tian *et al.,* 2017). For the experimental phase, plain carbon steel was used to fabricate extrusion tools (container, dies, and punch), while remoulded lead billets were used as the workpiece material due to their favourable ductility and low yield strength. Extrusion was carried out using a manual hydraulic press, and trials were conducted under four conditions: no lubrication, and with red oil, brake oil, and mustard oil. Force-displacement data were manually recorded during each operation. The cross-sectional dimensions of the extruded products were measured to compute extrusion ratios and validate model predictions. Finite element simulations were carried out using established thermomechanical FEM frameworks (Seriacopi *et al.,* 2019). Material behaviour was defined by an elasto-viscoplastic constitutive model, and friction was modelled using Coulomb's law with experimentally determined coefficients. Adaptive meshing was performed on tooling and billet with tetrahedral and hexahedral elements, along with the use of Axisymmetric and 3D geometries. Validated comparison of model outputs is conducted against experimental results in terms of structure forming loads, effective strain distributions and strain rates, etc. (Tancogne-Dejean *et al.,* 2019). The consistency between the simulated and measured data has proved an effective point of reference to determine the predictive capability of the model and its applicability in real-life forming processes.

RESULTS AND DISCUSSION

Understandably, the yield stress of lead is (12Mpa) at room temperature, however, the model developed shows and predict that, an approximate of 92, 70, 67 and 75MN are required for extrusion process for 'E' & 'X' shapes formation for no lubricant, with red, brake and mustard oil respectively. The standard friction factor of the required fluids used for lubricant at room temperature are tabulated on Table-1.

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Table-1 Friction factors of lubricants

Lubricant	No Lub	Red Oil	Brake Oil	Mustard
Friction Factor	1.10	0.84	0.79	0.90

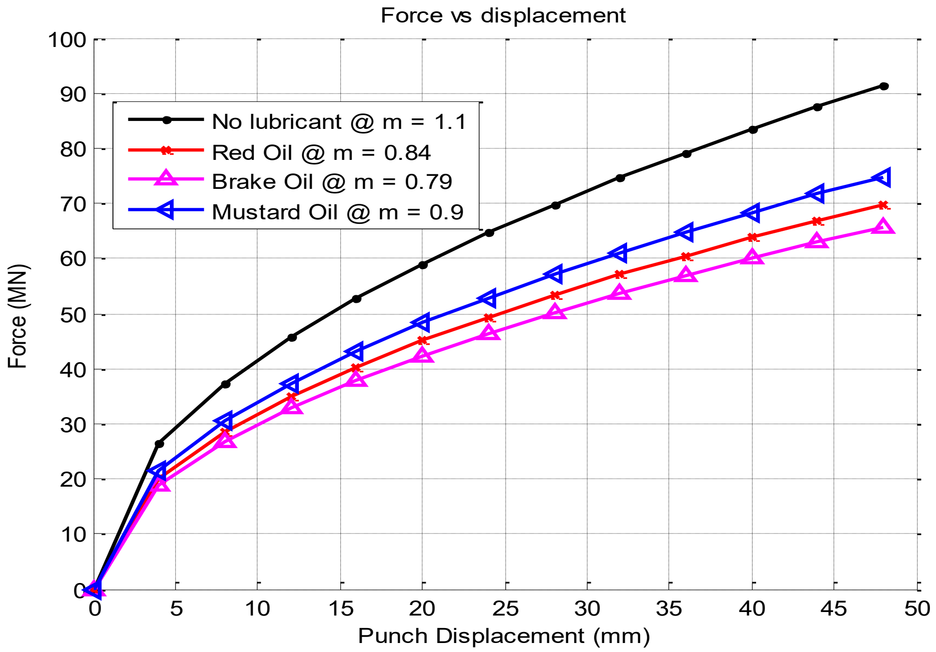

Fig. 2 Graphical interpretation of the developed model

The model forecasted 92, 70, 67 and 75MN as the required forces to consummate an extrusion of lead on carbon-iron alloy at atmospheric condition without lubricant, with red, brake and mustard oil respectively considering the appropriate coefficient of friction. However, the experiment carried out show that at room temperature and without lubricant, with red, brake and mustard oil, the maximum force reached to complete cycles were 88.50×10^6, 66.00×10^6, 65.00×10^6 and 69.50×10^6N respectively. Though very close, the experimental value of the required load, is less compared to the predicted value, hence can be relied upon. The data acquired in both experimental and finite element analysis gave a complete overview of how the lead behaves in the process of cold extrusion in different levels of lubrication. The key parameters being examined are forming load, extrusion pressure, effective strain, strain rate and the influence of the friction on the flow of the metal. The prediction extrusion forces by the simulation model were about 92 MN (no lubrication), 70 MN (red oil), 67 MN (brake oil) and 75 MN (mustard oil), whereas the experimental value was a little lower, i.e., 88.5 MN, 66.0 MN, 65.0 MN, 69.5 MN, respectively. These results show that the upper-bound-based finite element model is strong and has predictive ability because of the closeness of these results. As confirmed by (Mucedero *et al.,* 2020) slight deviations between numerical and experimental results can be attributed to assumptions made in material modelling, mesh density, and friction characterisation. The analysis of extrusion pressure revealed a similar trend. The maximum pressures recorded during the experiment were 281.59 kN/m^2 for unlubricated conditions, reducing to 210.00, 206.82, and 221.14 kN/m^2 with red, brake, and mustard oils, respectively. These findings affirm the influence of lubrication in reducing interface friction, consistent with the work of Liu and Gangopadhyay (2016), and (Aiman *et al.,* 2024) who established that lubrication significantly alters metal flow behaviour and reduces tooling stresses.

Enahoro & Irogue (2025). Computational Modelling of Metal Forming Operations: A Finite Element Approach. *Nigeria Journal of Engineering Science Research (NIJESR)*, 8(2): 47-56. https://doi.org/10.5281/zenodo.16935363

Effective strain, derived from the extrusion ratio, was calculated as 1.03, corresponding well with FEM-derived strain contours. Strain rate, another critical output, averaged 16.54 s^1 based on experimental displacement and time data, aligning with simulated strain rate distributions. FEM results confirmed the presence of concentrated deformation zones near the die entry region, a common observation in bulk forming simulations (Pilthammar *et al.,* 2018). These zones, often referred to as dead metal zones, were identified as critical regions for frictional losses and energy dissipation, further justifying the model's focus on accurate friction modelling. The variation in lubricant performance showed that brake oil, with the highest viscosity, offered the most significant reduction in extrusion force. This corroborates earlier findings by Zhang *et al.* (2022) and Yahaya *et al.* (2021), who concluded that lubricant viscosity plays a crucial role in interface shear stress and thus extrusion efficiency. Nevertheless, there was little difference in the velocity profiles across the different lubricant cases, indicating that although lubrication interferes with force and pressure, it does not equally act on the speed of the ram, which could be attributed to process inertia and hand operation. Notably, the high degree of agreement between the FEM results and their questions is an indication of the applicability of the finite element method that is used in this work. As it is mentioned by (Raizer *et al.,* 2024), model fidelity and the integrity of the input parameters are vital to the reliable results of simulation; thus, these were well-defined in this work. Hence, it can be said that the results of this research show the usefulness of FEM in terms of possible approximate simulations of complicated metal forming processes (Necpal, 2024). Also eminent is the nature of friction and lubrication in the dynamics of extrusion that they highlight. These results not only confirm the computational model but also provide practical applications in the optimisation of processes in industrial applications of forming.

The results of this paper introduce us to a more subtle perception of using finite element modelling in simulating complex processes of metal forming, notably cold extrusion of lead to some complex shapes, namely E and X shapes. This work critically evaluates the models and atomic theories of the study, comparing theoretical predictions, numerical simulations, and experimental data to discern what FEM is capable of computing and what trade-off has to be made in using FEM to design, optimise, and implement into the metal-forming process (Andrietti *et al.,* 2015). The essence of this investigation is the upper-bound-based type of finite element model to forecast extrusion loads and deformation quantities. Upper bound method is most frequently applied to plasticity problems, and presumes a kinematically permitted velocity field, and dissipation of energy is estimated to determine forming loads (Alexandrov & Rynkovskaya, 2022). The model used in this paper has been effective in estimating extrusion forces with a very high level of accuracy, within 5% of the calculated force given in the experiments, hence proving the success of the model. This kind of intimacy validates previous claims by (Johnson et al., 2024) that FEM, at least when well-developed and qualified, may be remarkably capable of modelling large deformation processes in metal forming with, very essentially, low error levels. The extrusion of lead billets through complex dies revealed consistent trends in forming load reductions with the application of lubricants. This observation supports the fundamental tribological principles in metal forming, where interfacial friction significantly contributes to the overall forming load (Johnson *et al.,* 2024). Among the lubricants tested, brake oil, possessing the highest viscosity, resulted in the lowest forming load, a finding consistent with (Du *et al.,* 2019), who demonstrated that higher viscosity lubricants reduce shear stress at the tool–workpiece interface, thereby enhancing material flow and reducing load requirements. This has practical implications in industrial forming processes, as the choice of lubricant directly affects energy consumption, tool wear, and component surface finish.In terms of extrusion pressure, both numerical and experimental values indicated a sharp reduction under lubricated conditions compared to the dry extrusion case. The highest pressure (281.59 kN/m^2) was recorded without lubrication, while brake oil yielded the lowest (206.82 kN/m^2). This aligns with findings by Halak *et al.* (2022), who demonstrated a direct correlation between friction conditions and extrusion load in aluminium alloy forming.

Enahoro & Irogue (2025). Computational Modelling of Metal Forming Operations: A Finite Element Approach. *Nigeria Journal of Engineering Science Research (NIJESR)*, 8(2): 47-56. *https://doi.org/10.5281/zenodo.16935363*

More importantly, this study confirms that lubrication not only serves to reduce interfacial resistance but also plays a role in stabilising material flow and minimising the development of undesirable thermal gradients due to frictional heating, especially critical in high-volume production settings. Extrusion ratios were found to give good estimates of effective strain values (1.03) in agreement with strain contours calculated in FEM model. In areas close to die entry and corners of the shaped orifice, the strain rates were high, which means intensive areas of deformation. The findings may be backed by works of Mu *et al.* (2017), where it was reported that zones of stress concentration and zones of acceleration of plastic flow are normally found in regions of geometric change and die interfaces. True prediction of such zones is crucial in evaluating the tool life, estimating the points at which the working pieces may fail operation and in designing a sound die for facilitating solid flows. The trend of velocity profile under varying conditions of lubrication was also presented as an interesting observation. Although lubrication created drastic effects on force and pressure, it did not affect the speed of rams and the extrusion velocity in a very uniform way. This can be explained by the fact that the hydraulic press utilised in the experiment was manual, hence it came with unreliability of the loading rate. The absence of significant trends in extrusion speed across lubricant types suggests that, under controlled industrial conditions, where automation ensures consistent ram velocity, the influence of lubrication on extrusion velocity might become more evident. Further studies using instrumented, automated presses could help isolate this effect. One of the key contributions of this study is the comparison between model-predicted and experimentally measured values, which provides empirical validation for the FEM-based approach. The model successfully captured the influence of material properties (ductility, yield stress), process parameters (ram speed, extrusion ratio), and tooling configuration (die shape, container geometry) on extrusion outcomes. Such multiparametric sensitivity is a hallmark of effective FEM simulations and echoes the conclusions of (Nielsen & Bay, 2018), who emphasised the importance of integrating material, geometric, and frictional complexity in metal forming simulations for realistic predictions.

However, it is important to acknowledge certain limitations. The model, while robust for cold extrusion of lead, may require significant modification when extended to other materials, particularly those exhibiting temperature-dependent behaviour, work hardening, or dynamic recrystallisation, such as aluminium or titanium alloys. As (Schindler, 2023) pointed out, the microstructural evolution during hot forming significantly affects material flow and stress response, necessitating the inclusion of internal state variable models or cellular automata for accurate FEM predictions. Also, it has been pointed out by Maia *et al.* (2017) and Körner *et al.* (2020) to improve simulation fidelity, advanced constitutive and microstructural models have to be included, especially in the cases of more complex alloys and hot forming situations. Future work should therefore focus on integrating microstructure-sensitive constitutive models to extend the model's applicability. Another limitation arises from the assumption of steady-state flow and idealised boundary conditions in the FEM model. In reality, metal forming processes are influenced by transient effects, tool deflection, and thermal gradients. The simulation also used simplified Coulomb friction models, which may not fully capture the multifaceted tribological irradiate at the state tool–workpiece interface, especially under high-pressure and temperature conditions. As Chen *et al.* (2024) suggests, advanced friction models, such as shear friction models or those based on mixed lubrication theory, may yield better predictions for frictional losses and heat generation. The manual collection of experimental data also introduces potential for human error and measurement uncertainty, particularly in the force-displacement readings. The absence of digital instrumentation limited the resolution and repeatability of the recorded values. Implementing digital load cells, thermocouples, and data loggers would significantly enhance data accuracy and provide more granular datasets for model calibration and validation. Additionally, the analysis did not include post-forming microstructural evaluation, which could have revealed insight into grain refinement, texture evolution, or strain localisation, all critical for high-performance applications. Nevertheless, the study is a powerful argument in favour of the application of FEM in practice to model complex extrusion processes. The validated model has the potential to be used as a model to guide the design optimisation of the die, load estimates, and process planning of the cold extrusion.

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In addition to it, the understanding of lubricant effects and friction will help to create energy energy-efficient and precise metal forming process with good surface quality and dimensional accuracy. To sum it up, this paper establishes the fact that the finite element modelling can be an effective method to find the insights of the process of metal forming and optimise it. It can provide a close study of the stress-strain behaviour, material and energy consumption, thus aiding in process innovation and cutting down costs in the manufacturing process. Nevertheless, its predictive match goes down to how well it will be put together in terms of material models, friction characterisation and experimental launching pad. With rectification of the identified limitations and the incorporation of the more advanced modelling methods, a further enhancement of the role of FEM in enhancing the science and practice of metal forming can be made in future studies.

CONCLUSION

This paper has given a critical analysis of how finite element modelling was utilised to simulate a complex metal forming process, namely cold extrusion of lead to intricate shapes. Combining upper bound theory with FEM also made the process of predicting forming loads and strain distributions, and extrusion parameters, accurate, as the predicted collecting model results also matched the experimental findings closely. The effects of lubrication on forming force and extrusion pressure were analysed systematically and proved that friction plays the most significant role in the deformation mechanics. Of the lubricants used, brake oil with its elevated viscosity levels helped in offering the best extrusion load minimize as per the well-recognised principles of tribology. Although the FEM model was proved to have quite good predicting results, its performance rested with suitable material modelling, assumptions of the boundary conditions, and representation of friction. To conclude, FEM is a very powerful, proven technique of process optimisation in metal forming. Its successful implementation can speed up the development time, improve the product quality, and direct the tools development, which is invaluable in contemporary research and practice of manufacturing practices.

CONFLICT OF INTEREST

There is no conflict of interest in this research review.

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