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Influence of Fractional Reduction Ratio Material Deformation During Extrusion: A FEM and Experimental Analysis

[1]Gundu, D.T.; [2]Ibrahim, J.S.; [3]Wuese, A.F.

[123]Joseph Sarwuan Tarka University, Makurdi, Nigeria

ABSTRACT

This study investigates the effects of fractional reduction ratio on material deformation during the extrusion process using finite element method (FEM) simulations and experimental validation. The maximum principal stress variation, displacement distribution, strain behavior, and extrusion pressure for different fractional reduction ratios were studied. FEM simulations showed increase in effective stress with increase in fractional reduction ratio. From results fractional reduction ratio of 0.38 resulted in maximum stress of 7.0 MPa, and minimum principal stress, -74.6 MPa. At a ratio of 0.52, the maximum stress rose to 10.3 MPa, while the minimum principal stress was -65.5 MPa. At 0.79, the maximum principal stress reached 77 MPa, with a minimum of -113 MPa, reflecting significant deformation and increased resistance to material flow. The displacement patterns indicated a smooth material flow at 0.38, with a maximum displacement of 40.9 mm. However, higher reduction ratios led to more pronounced displacement gradients, with 0.79 showing a maximum displacement of 104 mm. The strain distribution showed increasing strain values with higher reduction ratios, with the highest strain observed at 0.79, reaching 8.5 in experiments and 9.5 in simulations along the Y-axis. Experimental strain distributions at 0.79 showed a maximum of 8.75 and a minimum of -0.5 in the Y-axis. The maximum extrusion pressure increased with fractional reduction ratio, from 0.172 KN/mm² at 0.38 to 0.674 KN/mm² at 0.79. The temperature distribution also showed an increase with higher reduction ratios, peaking at 48.2°C at a reduction ratio of 0.79. The FEM results were in good agreement with the experimental data, particularly in stress and strain distribution, although FEM values were slightly higher, likely due to simplifying assumptions such as uniform material properties. These findings highlight the importance of controlling the reduction ratio to balance material flow, minimize defects, and optimize the extrusion process.

Keywords: Fractional reduction ratio, strain distribution, extrusion pressure, material deformation and Finite Element Method (FEM).

INTRODUCTION

Cold direct extrusion has over the years remained a crucial manufacturing process widely used in the production of complex cross-sectional shapes from metals and their alloys. Unlike the hot extrusion process where materials are worked at elevated temperatures, cold extrusion is performed at or near room temperature (Rakshith and Seenuvasaperumal, 2021). This offers several advantages, including enhanced mechanical properties, superior surface finish, and tighter dimensional tolerances. However, challenges such as higher required extrusion pressures and increased risk of defects due to material work hardening are associated with this extrusion method.

The use of lead alloys particularly in the context of cold extrusion is due to their unique properties. Lead's softness and malleability make it suitable for various applications, from radiation shielding to battery

components (Garcia et al, 2016). Lead alloys, due to their specific characteristics, are used in applications where their density and corrosion resistance provide distinct advantages.

The finite element method (FEM) is a computational tool used to model and simulate the behavior of materials under various conditions. FEM allows researchers to predict the flow of the material, distribution of stresses and strains, and potential defect formation. In metal forming processes, finite element method is beneficial due to its ability to handle complex geometries and material behaviors (Chen et al., 2021). FEM can be used to simulate the flow of lead alloys through dies of various shapes and sizes, predicting how the material will behave under different extrusion conditions. This includes understanding how factors like die design, extrusion speed, and material properties influence the final product. FEM simulations can identify potential issues before they occur in real-world experiments, such as regions of high stress that could lead to cracking or areas where material flow may be insufficient resulting in voids or other defects (Wang et al., 2018). When potential issues are identified in the simulation phase, manufacturers can refine their processes to achieve higher quality and more consistent results.

By integrating laboratory data with simulation results, researchers can develop a comprehensive understanding of the extrusion process and identify optimal conditions for producing high-quality extruded products. Optimization of cold direct extrusion process for lead alloys remains a challenge since traditional methods rely heavily on empirical data and experimentation. The application of FEM provides theoretical framework that complements experimental approaches which are time-consuming and resource intensive. Furthermore, FEM offers a more efficient path to process optimization.

Raj and Jain (2018) conducted a study on the effect of process parameters on tool wear during the cold extrusion of copper alloys. Their findings indicated that a reduction in extrusion speed could decrease the rate of tool degradation, thus extending tool life. They utilized FEM to simulate the thermal and mechanical stresses on the tool surfaces, which is particularly important in the context of lead alloys, where wear can be more pronounced due to the softer nature of the material.

In another Study by Chen et al., (2019) the impact of die geometry on the material flow during the extrusion of lead alloys was investigated. Their findings showed that optimizing die design could significantly reduce material waste and improve product quality. The research focused on the relationship between die angle and material flow, showing that a specific die design reduced friction and resulted in smoother surface finishes. This study is relevant to the current work, as it underscores the importance of die design but does not incorporate the simulation of energy consumption, a key aspect of the current study.

Xu et al., (2020) conducted a comprehensive study on the cold extrusion of lead-free alloys using FEM simulations. They examined the effects of extrusion parameters like billet temperature and die geometry on the material flow and process efficiency. The results showed that optimizing extrusion parameters leads to significant reduction in power consumption. Although their focus was on lead-free alloys, their work provides valuable insights into the energy-saving potential of process optimization, which the current study extends to include lead alloys, a material with different extrusion challenges.

Gupta et al., (2021) examined the use of FEM to optimize the extrusion of zinc alloys, with a particular focus on energy efficiency and material flow. They observed that adjusting the extrusion pressure and speed improved both the quality of the extruded product and the overall energy consumption. Their study used FEM to predict pressure distribution and material flow, similar to the methodology applied in the current study. However, lead alloys present distinct challenges, such as their increased tendency to stick to the die and higher friction, which requires tailored solutions that are explored in the present research.

While several studies have focused on the optimization of extrusion processes for various alloys using FEM, there remains a lack of comprehensive research specifically addressing the cold direct extrusion of lead alloys. Most existing studies have concentrated on materials like aluminum, copper, and zinc, which exhibit different physical and thermal properties from lead alloys. Lead alloys present unique challenges such as higher viscosity and increased die wear, which need to be accounted for in process simulations. Additionally, the majority of studies have not simultaneously optimized for energy consumption, material flow, and tool wear, as this research intends to do. Therefore, this study aims to fill this gap by applying FEM to optimize the cold direct extrusion process for lead alloys, focusing on reducing energy

consumption, improving material flow, and extending tool life under practical, industrial conditions. Furthermore, the application of FEM in optimizing cold direct extrusion processes bridges the gap between theoretical modeling and practical experimentation thereby unlocking new possibilities for efficient and effective production of lead alloy components. By addressing these gaps, this research will contribute to the development of more efficient, cost-effective, and sustainable extrusion practices for lead alloys, with potential applications in various industries.

METHODOLOGY

The materials used in this study are lead alloy (Pb-Sn alloy), tool steel and DEFORM 3D.

The billets were obtained from automobile battery grids. Sand casting method was used to cast molten lead alloy into rods. Cooled rods were machined to 25.4 mm diameter and 25.4 mm length specimen. Each specimen was split in halves and surfaces smoothened.

Extrusion dies of fractional reduction ratios 0.79, 0.6, 0.52 and 0.38 (that is, extrude diameters 11.5, 16, 17.5 and 20.0 mm) with entrant angle 180^{o} and bearing length 1mm were used for the extrusion process. The billet was loaded into rig and placed under the ELE compact-1500 compressive testing machine and compressed (Gundu *et al.*,2014). The maximum extrusion load (P_{max}) was recorded for each extrusion.

RESULTS

Results for mechanical properties at (a) 0.79 (b) 0.6 (c) 0.52 and (d) 0.38 Fractional reduction ratio.

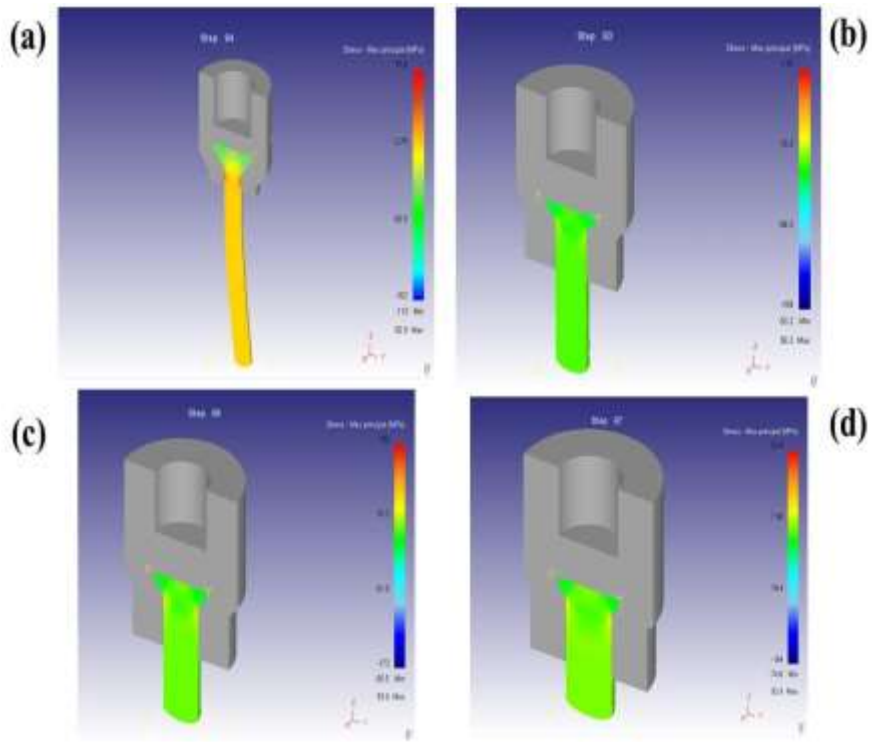

Figure 1: Stress distribution of the lead billet

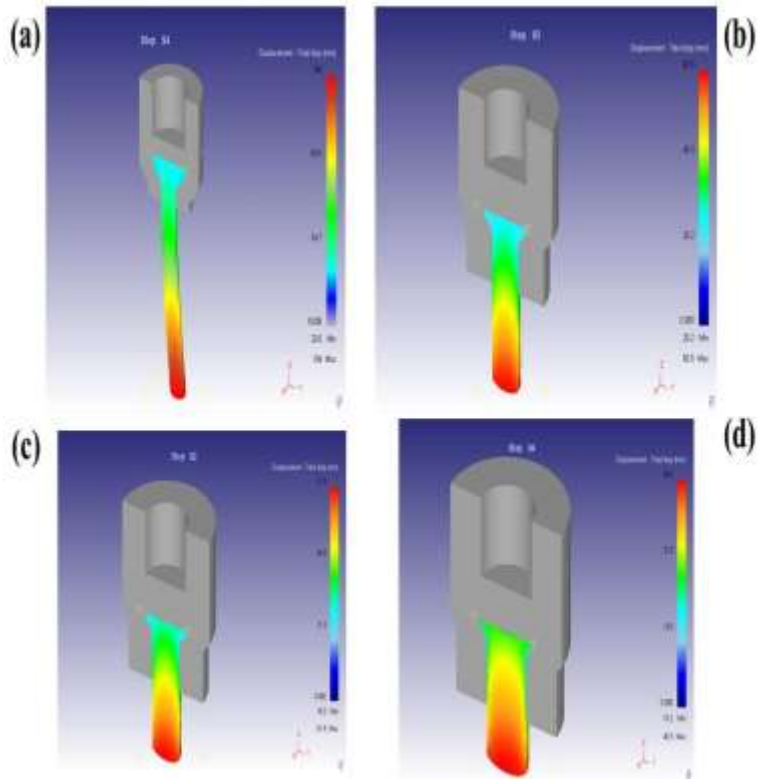

Figure 2: Displacement distribution of billets

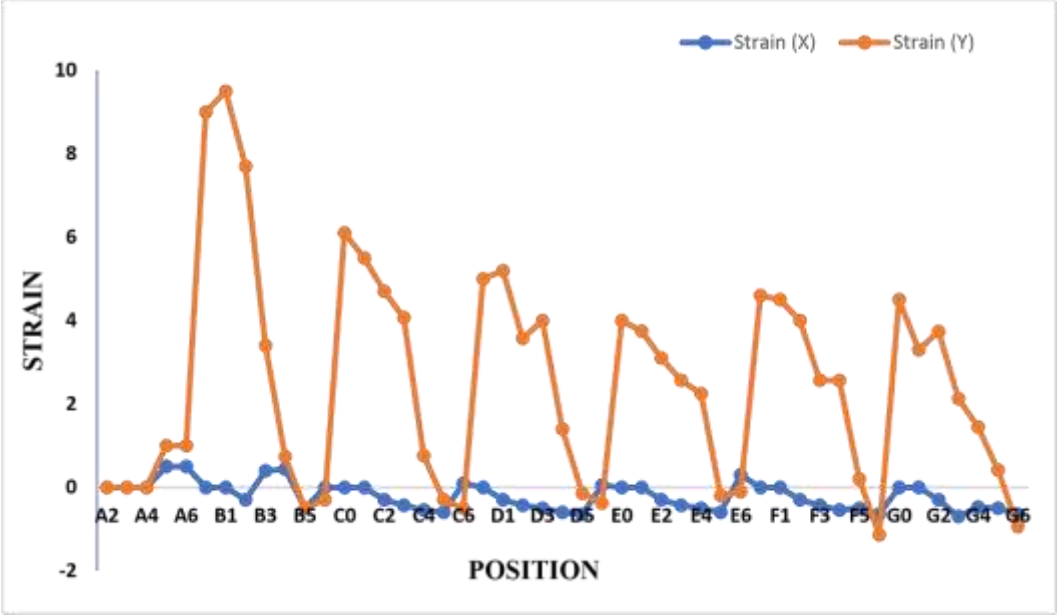

Figure 3: Simulation Strain Distribution for 0.79 Fractional Reduction Ratio

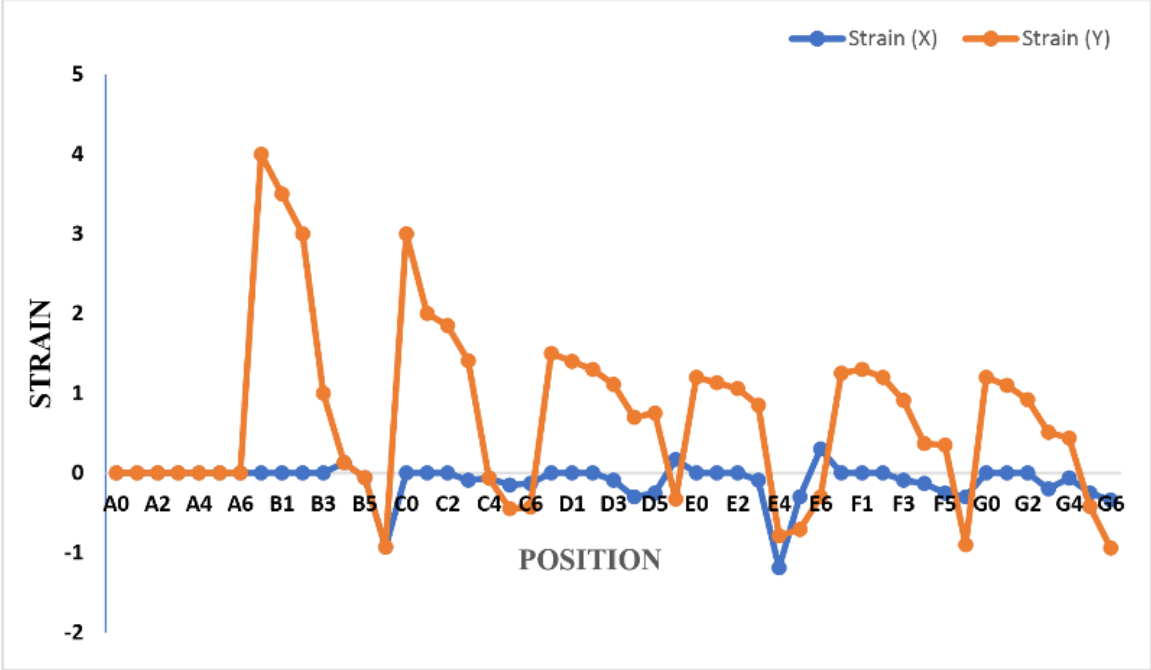

Figure 4: Simulation Strain Distribution for 0.6 Fractional Reduction Ratio

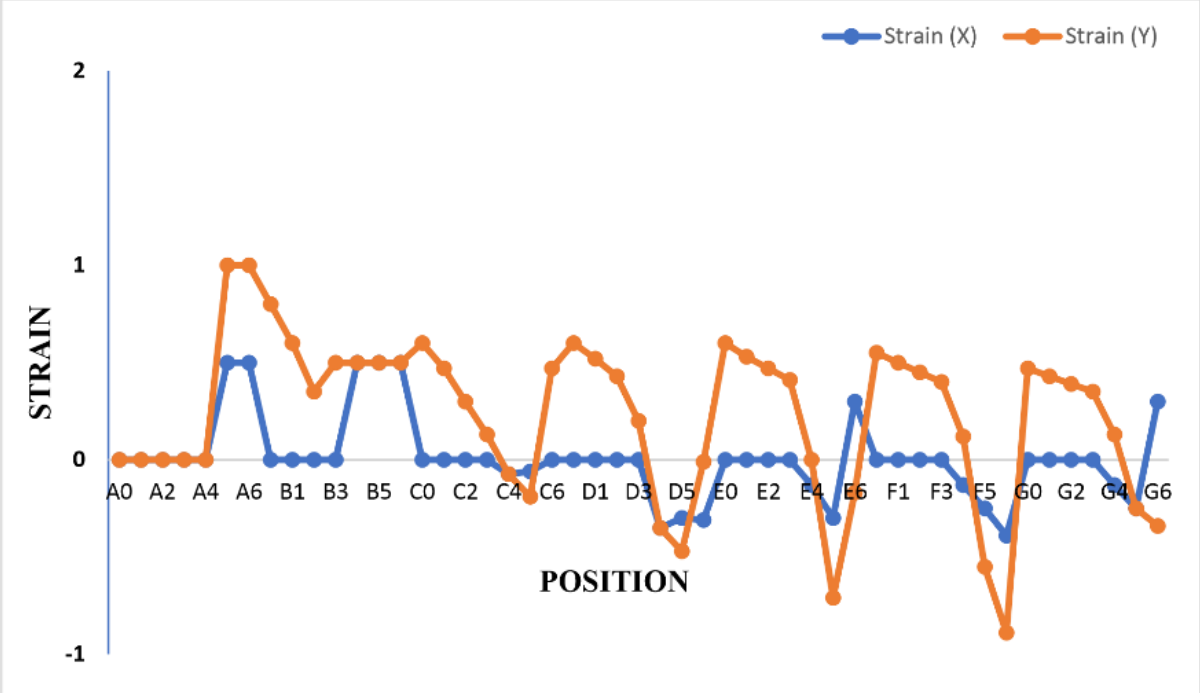

Figure 5: Simulation Strain Distribution for 0.52 Fractional Reduction Ratio

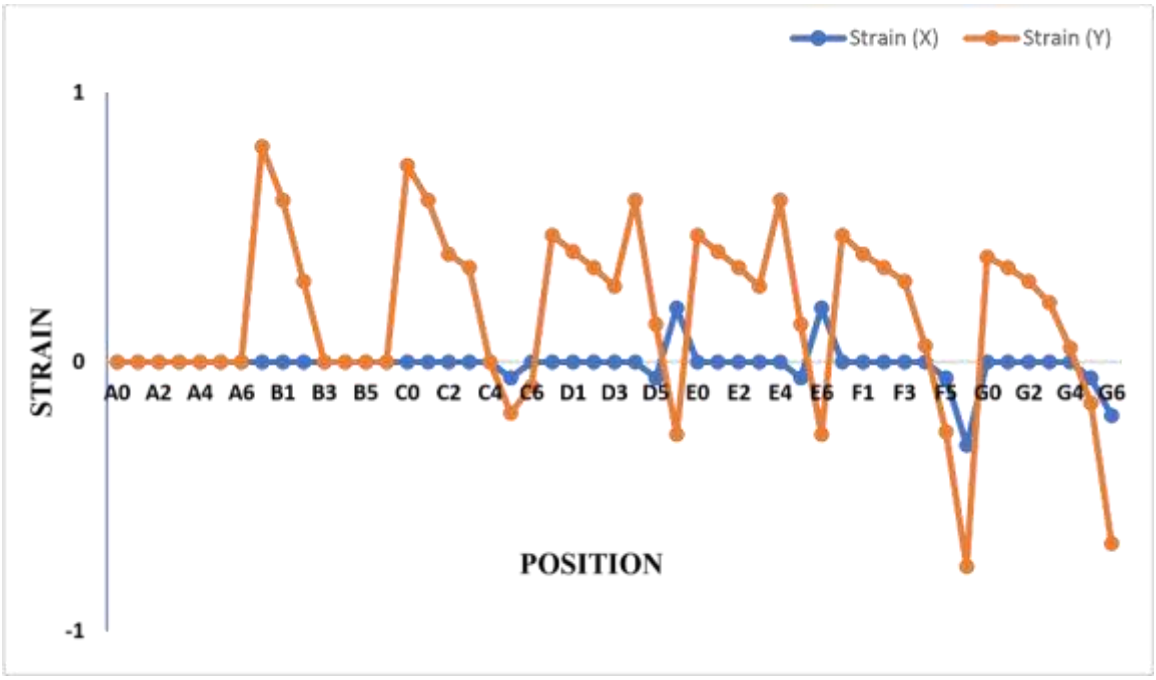

Figure 6: Simulation Strain Distribution for 0.38 Fractional Reduction Ratio

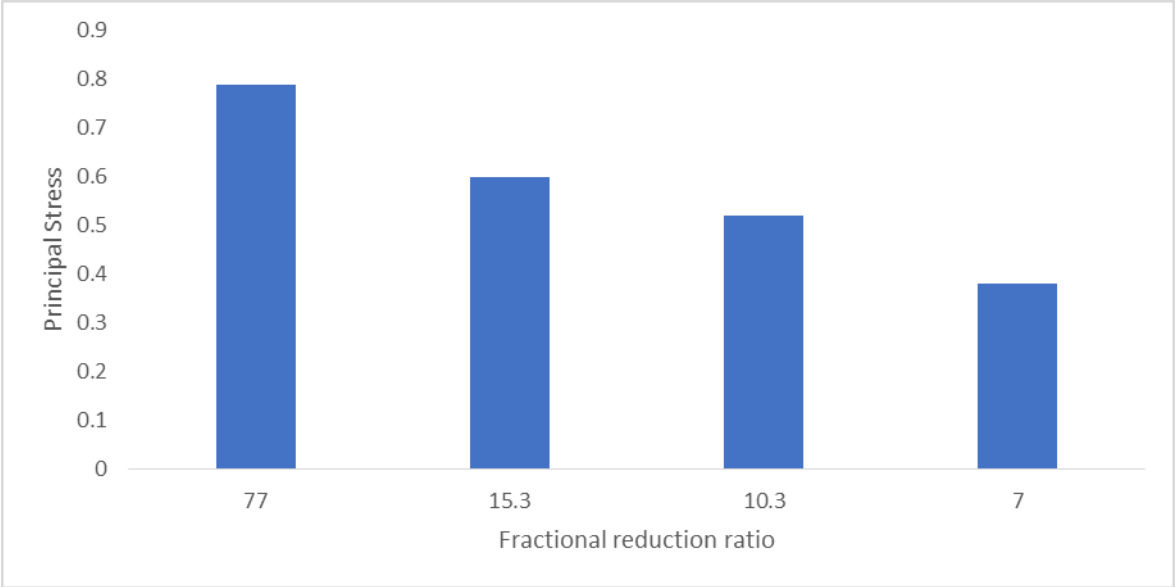

Figure 7: Variation of Maximum Simulated Principal Stress with Fractional Reduction

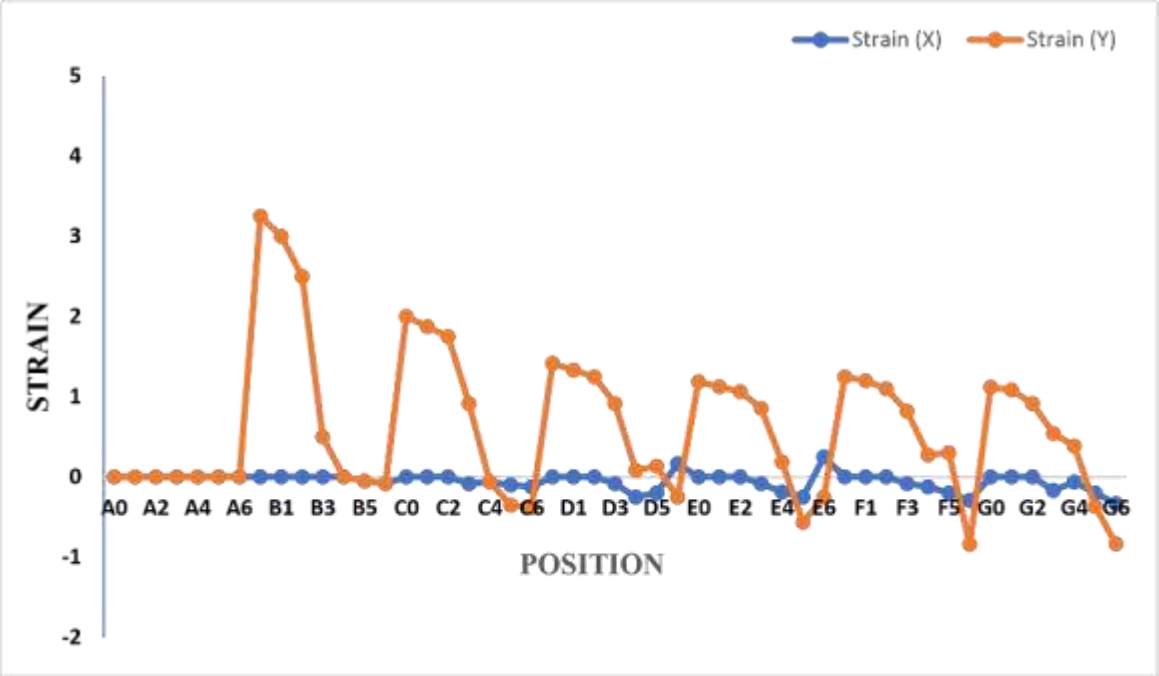

Figure 8: Strain Distribution for 0.6 Fractional Reduction Ratio

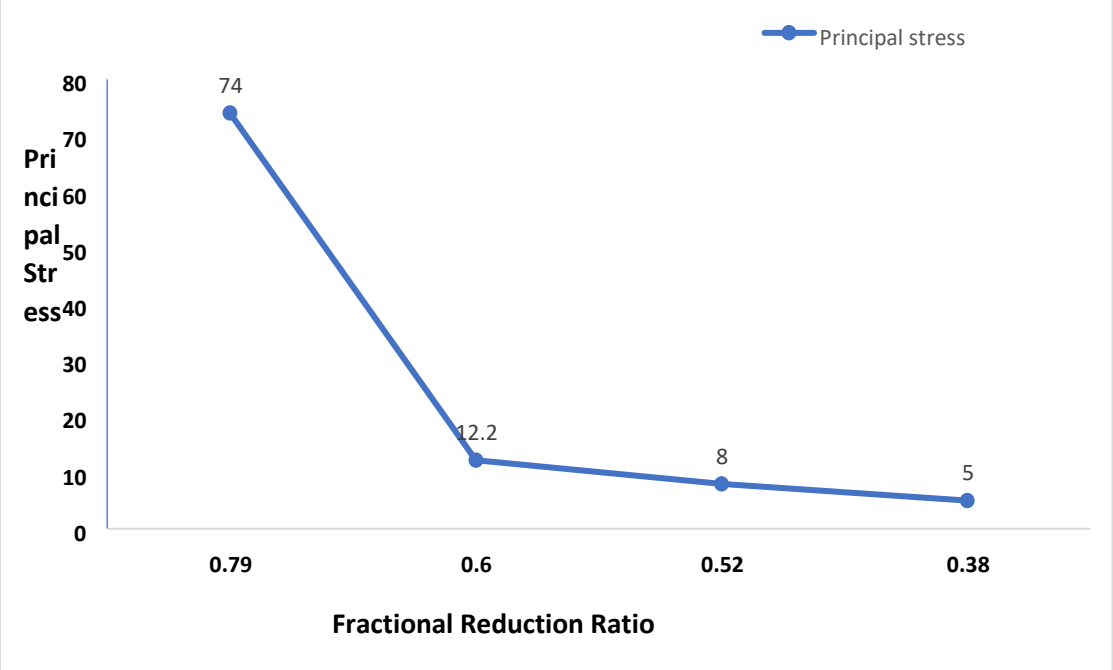

Figure 9: Variation of Maximum Extrusion Pressure with Fractional Reduction Ratio

DISCUSSION

Effect of Fractional Reduction Ratio on principal stress of billets

The results for maximum principal stress variation for different fractional reduction ratio for FEM simulation are shown in Figure 1-2. The stress distribution within the billet plays a very crucial role in understanding the material deformation during the extrusion process (Francy et al., 2018). FEM simulations showed that as fractional reduction ratio increased, the magnitude of the effective stress

increased. At fractional reduction of 0.38, the maximum stress is 7.0 MPa while the minimum principal stress is -74.6 MPa. At fractional reduction of 0.52, the maximum stress is 10.3 MPa while the minimum principal stress is -65.5 MPa. At fractional reduction of 0.6, maximum stress was 15.3 MPa and the minimum principal stress was -53.2 MPa. At the fractional reduction of 0.79, the maximum stress is 77 MPa while the minimum stress is -113MPa. It was observed that as the fractional reduction ratios increased, the magnitude of effective stress increased. Furthermore, at 0.38m fractional reduction ratio, a more uniformly distributed stress was seen throughout the billet with minimal concentration around the die entrant. This behaviour suggests that lower fractional reduction ratios result in less aggressive deformation thereby allowing materials to flow more evenly through the die (Dorin, 2018).

There was increase in stress concentration near the die entry and along the edges as the fractional reduction ratio increased. This showed high-stress areas around regions were billet experience most intense deformation. This aligns with the theory that higher reductions lead to greater resistance to material flow (Tiernan et al., 2005). Furthermore, the maximum principal stress is induced at the point where the billet has just emerged from the die. However, the principal stress is found to fluctuate without any specific pattern though it ranges from 56.3 MPa to 93.6 MPa over the fractional reduction ratio of $0.79 \geq r \geq 0.38$. The reaction of the billet with the container and die due to this high compressive stress implies that this reduction ratio is effective in reducing the cracking of the billet material during primary breakdown from the billet (Sathishkumar et al. 2017).

The displacement distribution in the billet showed different patterns in the displacement behaviour at fractional reduction ratios of 0.38, 0.52, 0.6 and 0.78. At Fractional reduction ratio of 0.38, the distribution was relatively smooth and uniform with a maximum displacement of 40.9mm. The material flow was consistent showing the material experience less resistance during extrusion process. This suggests that lower reduction ratios lead to less aggressive deformation thereby allowing the billet to maintain even displacement (Zhang, et al., 2007). At 0.52 fractional reduction ratio, the displacement increased with maximum displacement reaching 51.9mm. Here, more displacement gradients were observed along the die entrance and the billet surface. The overall flow of deformation remained controlled. However, at 0.6 fractional reduction ratio, the displacement distribution became more uneven with maximum displacement of 60.5mm. This can be attributed to more material flow particularly near the outer edges of the billet where resistance to extrusion is higher (Jaramillo, 2018). At 0.79 fractional reduction ratio, the displacement reached a maximum of 104mm. the displacement pattern showed increased lateral movement of material, deviating further from the extrusion axis. This suggests that at very high reduction ratios, the material is subjected to excessive deformation forces, flow instability and defects in the extruded billet.

Furthermore, the result showed that the minimum displacement at the fractional reduction of 0.79 was 20.6mm, at fractional reduction of 0.6, minimum displacement was 20.2mm, at fractional reduction of 0.52, minimum displacement was 19.0mm, and at fractional reduction of 0.38, minimum displacement was 15.2mm. This result showed the need to carefully balance the reduction ratios so as to ensure smooth material flow while minimizing the risk of failure or defects during extrusion.

The stress distribution obtained from the simulation showed a concentration of stress around the entrant angle for all fractional reduction ratios employed. The peak stress was recorded at 77MPa while the peak extrusion pressure obtained during the experimental procedure was 74 MPa. This peak was both obtained at fractional reduction ratios of 0.79. The result showed good agreement with both having similar trend. The strain measurement revealed non-uniform deformation with the highest strain for simulation localized at 0.79 fractional reduction ratio. Similar trend is seen in the experimental strain distribution with 0.79 fractional reduction ratio having the highest strain value of 8.5. The strain distribution predicted by FEM corresponds well with experimental findings especially in areas of with fractional reduction ratios of 0.52 and 0.38.

Effect of Variation of Fractional Ratio on strain distribution of billets

The result for experimental strain distribution and maximum extrusion pressure variations for different fractional reduction ratio is shown in Figures 3-8. FEM simulations showed varied strain distribution at different fractional reduction ratios explored in this study. The result obtained from the strain distribution

of the billet at various fractional reduction ratio showed that for fraction reduction of 0.79, the maximum strain value in the X-axis is 5 while that of the Y-axis is 9.5. However, the minimum strain value for X-axis and Y-axis are -0.30 and -0.30 respectively. At 0.6 fractional reduction ratio, the maximum strain value in the X-axis is 0.30 while that of the Y-axis is 3.5. However, the minimum strain value for X-axis and Y-axis are -0.06 and -0.17 respectively. At 0.52 fractional reduction ratio, the distribution showed a peak value of 0.50 at the X- axis, and a relatively higher strain with a peak of 0.80 along the Y-axis. The increase in the material strain distribution along the Y-axis suggests the material experiences greater deformation along this axis as the reduction ratio decreases (Zhang et al., 2004). Similarly, at 0.38 reduction ratio, the maximum strain along the Y-axis reaches 0.73 while the X-axis is -0.31respectively. This shows a more uniform strain distribution suggesting a smoother material flow during the extrusion process.

The X-axis show strains of relatively moderate values. At 0.79 fractional reduction ratio, the Y-axis shows a peak strain of 2.4 while the X-axis and Z-axis reaches 2.11 and 2.59 respectively. The strain increases with increase in fractional reduction ratios highlighting the relationship between fractional reduction ratio and the extent of material deformation (Jaramillo, 2018).

The results from the experimental strain distribution at different fractional reduction ratios shows close relationship with the simulated data. The results showed that maximum strain in the X-axis for fractional reduction factor of 0.79 is 0.55 while the minimum strain in the X-axis is -0.667. Furthermore, the result shows that the maximum strain and minimum strain in the Y-axis are 8.75 and -0.5. Similarly, the result showed that maximum strain in the X-axis for fractional reduction factor of 0.69 is 0.333 while the minimum strain in the X-axis is -0.83. The result showed that the maximum and minimum strain in the Y-axis is 3.25 and -0.55 respectively. Furthermore, the result showed that maximum strain in the X-axis for fractional reduction factor of 0.52 is 0.292, while the minimum strain in the X-axis is 0.291. The result further shows that the maximum and minimum strain in the Y-axis is 0.75 and -0.542 respectively. Furthermore, the result shows that maximum strain in the X-axis for fractional reduction factor of 0.38 is 0.167 while the minimum strain in the X-axis is -0.208. The result shows that the maximum and minimum strain in the Y-axis is 0.75 and -0.375. The experimental strain distribution was in agreement with FEM predictions however, FEM predictions were higher in values when compared to experimental values. This can be attributed to several factors such as the assumption of uniform material properties and negligence of frictional forces at die interface (Dorin, 2018).

The relationship between die fractional reduction ratios and stress-strain distribution shows insights into the effect of extrusion on the mechanical behavior of billet (Gundu et al., 2014). The result obtained shows fractional reduction ratios affects the stress distribution of billet. Increase in stress values were observed with increase in fractional reduction ratios. This can be attributed to the need for greater deformation pressures and loading at higher fractional reduction ratios which enhances the internal resistance of the material. Furthermore, as the fractional reduction ratios increased, high-stress areas tended to shift deeper into the material (Figure 18) indicating the material experienced varying degrees of resistance to deformation during the extrusion process (Dorin, 2018). The strain distribution also showed relationship with changes in fractional reduction ratios.

Effect of Variation of Temperature on Fractional Reduction Ration

The results for simulated temperature distribution of lead billet are shown in Figure 2. The FEM simulation showed that the maximum temperature of the extruded billet at the fractional reduction of 0.38 was 33.1 ^{o}C, at fractional reduction of 0.52, the maximum temperature was 36.5 ^{o}C, at fractional reduction of 0.6, the maximum temperature was 37.3 ^{o}C, and at 0.79 was 48.2 ^{o}C. This result shows a linear pattern trend which denotes that at a higher fractional reduction ratio, higher extruded billet temperature was observed. Furthermore, the temperature within the billet rises near the die entrance. These findings are similar to that obtained by Ajiboye and Adeyemi (2007) who noted that the increased heat generation at higher reduction ratios is due to greater deformation energy and frictional forces which enhances material flow.

Effect of Variation of Maximum Extrusion Pressure on Fractional Reduction Ratio

The result for maximum extrusion pressure variations with fractional reduction ratio is shown in Figures 9. The maximum extrusion pressure exerted during the extrusion process was measured across different fractional reduction ratios. This was done to evaluate the influence of die geometry and material behavior. The results obtained showed as fractional reduction ratio increased, the maximum extrusion pressure increased. At 0.38 fractional reduction ratio a max pressure of 0.172KN/mm^2 was exerted. Furthermore at 0.52, 0.6 and 0.79 fractional reduction ratios, a maximum pressure of 0.249, 0.338 and 0.674 KN/mm^2 was exerted respectively. This phenomenon can be attributed decreased in cross-sectional area of die thereby requiring higher pressing force/pressure to push the material through the die (Gundu et al., 2014). Furthermore, the introduction of strain hardening and frictional forces as a result of the interaction between the billet and the die wall increases the strength of the material during deformation. This frictional resistance tends to increase with increase in fractional reduction ratio thereby increasing the need for higher pressures for extrusion (Wuese, 2006).

CONCLUSION

The results of this study demonstrate a clear relationship between fractional reduction ratios and the stress-strain behavior of billets during extrusion. As the fractional reduction ratio increases, there is a corresponding increase in both principal stress and strain, with higher concentrations of stress at the die entry and billet edges. Lower reduction ratios result in more uniform stress and strain distributions, promoting smoother material flow with less risk of cracking. However, higher reduction ratios lead to greater material resistance, uneven displacement, and potential deformation instability, which may compromise the quality of the extruded billet. The findings emphasize the need for careful selection of fractional reduction ratios to balance effective material flow and minimize the risk of defects, such as cracking or excessive deformation, in the final extruded product. These insights are crucial for optimizing extrusion processes and improving the mechanical properties of the final billet.

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