Journal Homepage: - www.journalijar.com

INTERNATIONAL JOURNAL OF ADVANCED RESEARCH (IJAR)

ISSN NO. 2320-5407

Article DOI: 10.21474/IJAR01/20099
DOI URL: http://dx.doi.org/10.21474/IJAR01/20099

RESEARCH ARTICLE

COMPUTATIONAL ANALYSIS OF FLUID-STRUCTURE INTERACTION AND HEAT TRANSFER IN EXTRUSION PROCESSES

Kcavyan Agarwal and Pinal Rana
Dhirubhai Ambani International School.

……………………………………………………………………………………………………....

Manuscript Info

Manuscript History
Received: 20 October 2024
Final Accepted: 23 November 2024
Published: December 2024

Abstract

The extrusion process is integral to manufacturing, enabling the production of continuous profiles with precise cross-sections for various industries, including automotive, construction, and aerospace. This study focuses on the computational analysis of material flow and heat transfer during the extrusion of an L-type section under steady-state conditions. Finite element analysis is used to model the extrusion process.The research evaluates the impact of key parameters such as container temperature, ram velocity, and friction coefficients on the billet's thermal profile and exit temperature. The study incorporates non-Newtonian flow dynamics, and thermal coupling to provide comprehensive insights into optimizing process efficiency, die design, and material flow uniformity. The results demonstrate the critical role of thermal and frictional parameters in enhancing extrusion quality and preventing material defects.

……………………………………………………………………………………………………....

Introduction:-

Metal extrusion is a widely used manufacturing process that involves shaping a metal billet into a desired profile by forcing it through a die under high pressure. This technique is essential in producing components for various industries, including construction, automotive, and aerospace, where precision and material performance are critical. The extrusion process operates under high temperatures and plastic deformation, necessitating a deep understanding of the interactions between thermal, structural, and fluid dynamics phenomena to optimize product quality and operational efficiency.

A few researchers have worked on modelling the extrusion process to evaluate temperature at different controlling parameters. Zhang et al. worked on Heat transfer modeling of the friction extrusion process [1].The study presents an experimentally validated thermal model for predicting the temperature field in the extrusion process, focusing on heat transfer phenomena and utilizing aluminum alloy 6061. Tibbetts et al. present a methodology for real-time process control of extrusion, involving the development of a thermo-mechanical model, parameter identification, and open-loop control strategies to optimize production efficiency and product quality [2]. Mishin et al.developed a finite-element model to simulate the thermo-mechanical behavior of 6061 aluminum alloy during friction stir welding (FSW). The research identified that FSW-induced deformation occurs in two stages: the stirring action of the rotating tool probe and a secondary deformation in the near-surface area by the shoulder edge post-tool passage. Both stages were found to contribute comparably to temperature and strain, with the secondary deformation primarily affecting the near-surface layer [3]. Liu et al. investigation examined the flow and friction behaviors of 6061 aluminum alloy sheets at elevated temperatures to form a B-pillar through hot stamping. The study developed

Corresponding Author:- Kcavyan Agarwal
Address:- Dhirubhai Ambani International School.

modified Arrhenius and Cowper–Symonds models based on hot tensile tests conducted at temperatures ranging from 350°C to 500°C and strain rates between 0.01 and 1 s^{-1}. The research also measured coefficients of friction at temperatures between 300°C and 500°C, providing insights into the material's behavior under these conditions [4]. Bala et al. described the thermal analysis of friction stir welded aluminum alloy AA 6061, utilizing high-speed steel tools with tapered profiles, both threaded and unthreaded. The study investigated process parameters and their effects on thermal analysis, calculating the heat transfer model and temperature evolution during FSW. Theoretical values of heat rate and peak temperatures were evaluated and compared with practical analysis values based on ANSYS simulations [5].

During extrusion, internal friction within the billet generates heat, making it essential to use thermal and fluid dynamics analysis to accurately model material flow and temperature distribution. Computational fluid dynamics (CFD) effectively simulates these conditions, treating metals as high-viscosity non-Newtonian fluids. Integrating thermal and structural analysis enables engineers to predict key parameters such as velocity profiles, and heat transfer effects, leading to enhanced process control and die design improvements.

This study aims to build on existing benchmarks and computational methodologies to model metal extrusion processes using advanced finite element methods. By simulating steady-state extrusion conditions, the research integrates non-Newtonian flow behavior, heat transfer, and structural stresses to evaluate process performance and validate experimental findings. The results offer valuable insights into optimizing die designs and operational parameters for a variety of metal extrusion applications.

Modeling approach

The extrusion process involves shaping a billet into the desired profile by forcing it through a die under high pressure and elevated temperatures. During this process, the billet's internal friction generates heat, and the thermal interactions between the billet, die, and environment significantly influence the quality of the final product. Accurately predicting temperature distributions and heat fluxes is essential for optimizing the process and preventing issues such as thermal fatigue or uneven material flow. This study addresses the thermal modeling of extrusion, focusing on coupling heat transfer with structural and fluid dynamics to simulate real-world scenarios.

Model Physics

The thermal model considers both conduction and convection mechanisms to simulate heat transfer within the billet and die. The process involves:

- Conduction: Heat conduction occurs due to temperature gradients in the billet and die materials, modeled using Fourier’s law.
- Convection: Convection at the billet-die interface and the outer surfaces exposed to ambient air is included using appropriate heat transfer coefficients.
- Volumetric Heat Generation: Viscous dissipation resulting from billet deformation acts as a heatsource.

This model couples heat transfer with fluid flow and structural deformations to reflect the dynamic nature of the process.

Model Geometry

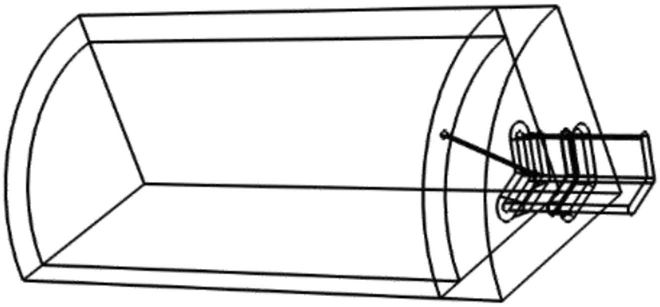

Figure 1:- Model geometry.

The figure represents a schematic diagram of the extrusion process, a commonly used manufacturing technique for producing continuous profiles. In the present study V-type section is extruded using the process and aim of this study is to evaluate exit billet temperature at different extrusion conditions such as container temperature, ram velocity, and friction conditions.

Assumptions

To simplify the thermal analysis, the following assumptions are made:

1. Steady-State Conditions: The thermal model assumes a constant billet velocity and steady-state thermal profiles.
2. Homogeneous Material Properties: Thermal properties such as conductivityand heat capacity are considered constant for the billet and die materials.
3. Negligible Radiation: Heat transfer via radiation is deemed negligible due to the relatively small temperature gradients and confined environment.
4. Incompressible Flow: The billet material is treated as an incompressible non-Newtonian fluid.
5. Constant Boundary Temperatures: The die and ram maintain constant temperatures during the process.

Governing Equations

The thermal behavior is governed by the heat conduction equation which is as follows:

$$\rho C_p \frac{\partial T}{\partial t} + \Delta\,(-K\nabla T) = Q,$$

where, ρ density of the material, C_p specific heat of the material, K is the thermal conductivity, and Qis the volumetric heat generation term due to viscous dissipation and friction given by:

$$Q = Q_{viscous} + Q_{friction}\ ,$$

where,

$$Q_{viscous} = \gamma(\nabla v : \nabla v)$$

Where, γ is the dynamic viscosity of the material, ∇v velocity gradient tensor.

$$Q_{friction} = \mu\, v_{slip}$$

Where μ is shear stress at the billet-die interface, v_{slip} slip velocity, which is the relative velocity between the billet surface and the die wall.

Boundary Conditions

The thermal model employs the following boundary conditions:

1. The billet enters the die at a fixed initial temperature.
2. A constant temperature is maintained on the die's surfaces.
3. Heat loss to the environment is modeled using:

   where h is the convective heat transfer coefficient, and T_∞ is the ambient temperature.
4. Symmetry boundary conditions are applied along the planes of symmetry to reduce computational complexity.

Computational Method

The computational method for analyzing the extrusion process employs advanced FEA to simulate the coupled interactions of heat transfer and fluid flow under steady-state conditions. The process begins with detailed mesh generation, focusing on high-resolution meshes near critical areas like the billet-die interface to capture steep thermal gradients and stress concentrations. Adaptive meshing techniques refine these regions further, ensuring accuracy. The analysis integrates thermal behavior, treating heat conduction within the billet and die using Fourier's law while including convection at exposed surfaces and volumetric heat generation from material deformation and friction. Fluid flow is modeled by treating the billet as a high-viscosity, non-Newtonian fluid, with slip boundary conditions applied at the billet-die interface. The simulation is conducted sequentially, first solving thermal and fluid equations to determine temperature and velocity fields. Stationary solvers ensure steady-state conditions, while iterative solvers handle the complexity of coupled systems, ensuring convergence. Realistic boundary conditions are applied, including fixed inlet velocity, slip interfaces, and constant die and container temperatures, with convective heat loss modeled using specific coefficients. Post-processing involves analyzing temperature fields and velocity profiles, with visualization tools like streamline and slice plots highlighting critical insights. This computational approach provides a comprehensive and efficient framework for optimizing extrusion processes and enhancing design and operational control while minimizing defects.

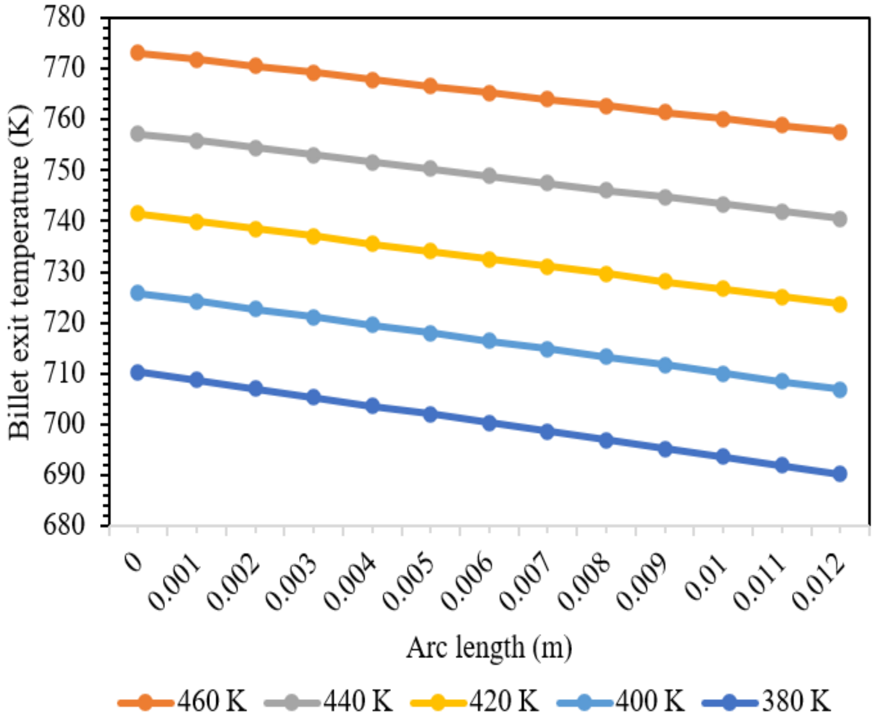

Figure 2:- Variation in temperature at billet exit with arc length at different values of container temperatures.

The thermal model is solved using a finite element approach with the following steps:

1. Mesh Generation: A fine mesh is created near the billet-die interface to capture steep thermal gradients.
2. Coupled Analysis: The thermal equations are solved in conjunction with fluid flow and structural equations using an iterative solver.
3. Boundary Layer Refinement: Adaptive meshing techniques refine the mesh near-critical regions such as the die exit and contact surfaces.
4. Solver Settings: A stationary solver is used for steady-state conditions, while time-stepping is disabled for thermal equilibrium analysis.

The integration of these methods ensures the accurate prediction of temperature fields, facilitating insights into process optimization and design improvements.

Results and Discussion:-

In this section results obtained from the model are discussed to identify the optimum processing conditions for extrusion which can be used to produce defect-free ingots.

Figure 2 illustrates the variation in exit billet temperature along the arc length atthe exit of the container for differentcontainer temperatures (460°C, 440°C, 420°C, 400°C, and 380°C). All curves show a linear decline in temperature along the billet length, attributed to heat transfer from the billet to the container and cooling effects during extrusion. Higher container temperatures (e.g., 460°C) result in uniformly higher exit billet temperatures, while lower container temperatures (e.g., 380°C) lead to steeper temperature drops along the length. The temperature gradient is less pronounced at higher container temperatures, ensuring better uniformity, whereas lower container temperatures exhibit sharper gradients, potentially causing flow inconsistencies or material defects. These results underscore the critical role of container temperature in achieving uniform billet temperatures, optimizing material flow, and preventing defects, making it essential to carefully regulate container temperatures during extrusion.

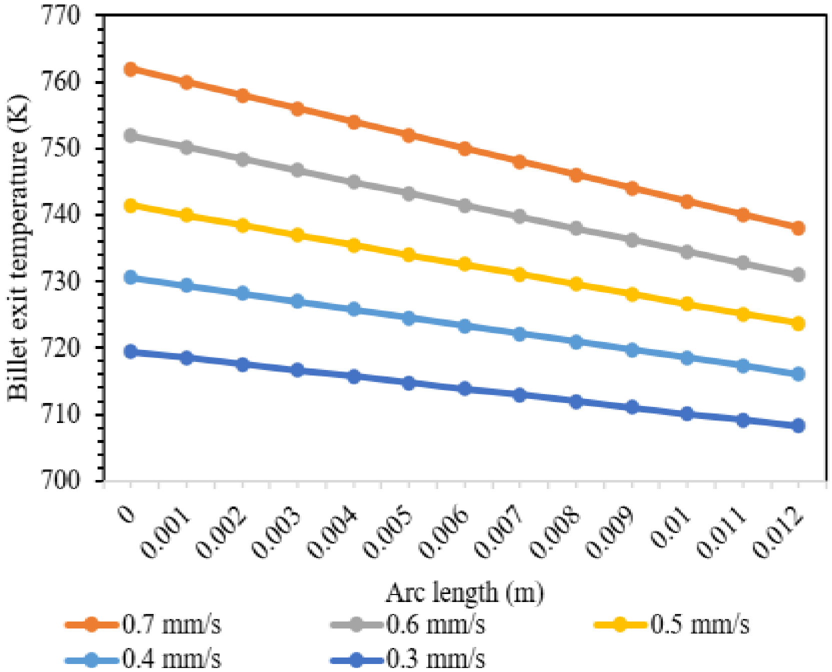

Figure 3:- Variation in temperature at billet exit with arc length at different values of ram velocities.

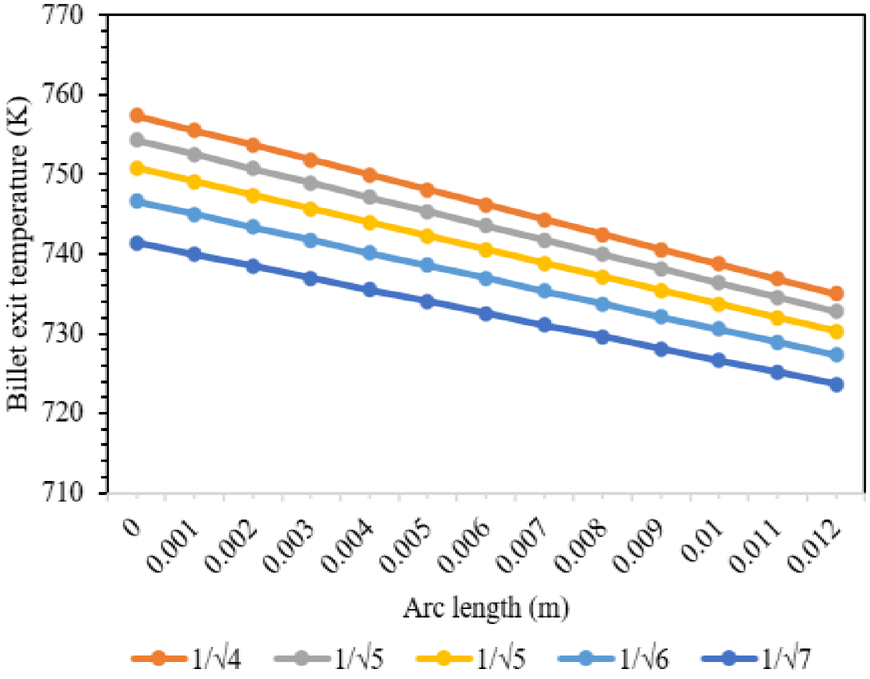

Figure 4:- Variation in temperature at billet exit with arc length at different values of coefficient of friction.

Figure 3 illustrates the variation in exit billet temperature along the arc length for different ram velocities (0.3 mm/s, 0.4 mm/s, 0.5 mm/s, 0.6 mm/s, and 0.7 mm/s) during the extrusion process. A general trend observed is that the exit billet temperature decreases linearly along the arc length for all ram velocities, with higher ram velocities consistently leading to higher exit temperatures across the billet. This is because higher ram velocities generate greater frictional heat and plastic deformation energy, contributing to increased temperatures. Conversely, lower ram velocities produce less heat, resulting in lower billet temperatures. The slope of the temperature decline along the arc length becomes steeper at lower ram velocities, indicating a more significant cooling effect along the length due to prolonged contact with the container and surrounding cooling mechanisms. This behavior highlights the critical impact of ram velocity on the thermal profile of the billet, with higher velocities ensuring a more uniform and higher temperature profile, which can influence material flow and extrusion quality. These findings underscore the need for optimizing ram velocity to balance heat generation and uniformity for effective extrusion process control.

Figure 4 demonstrates the variation in exit billet temperature along the arc length for different friction coefficients ($1/\sqrt{3}$, $1/\sqrt{4}$, $1/\sqrt{5}$, $1/\sqrt{6}$, and $1/\sqrt{7}$) during the extrusion process. A consistent trend observed across all friction coefficients is a linear decline in temperature along the arc length, with higher friction coefficients leading to higher exit billet temperatures throughout. This behavior can be attributed to the fact that greater friction at the billet-container interface generates more heat due to increased resistance to material flow, resulting in elevated billet temperatures. Conversely, lower friction coefficients produce less heat, leading to lower overall billet temperatures. The temperature gradient(slope) along the arc length remains relatively consistent for all friction coefficients, indicating a uniform cooling effect along the billet length. However, the starting temperatures at thebeginning of the billet increase progressively with the friction coefficient. These findings highlight the significant influence of the friction coefficient on the thermal profile of the billet, emphasizing that higher friction coefficients increase heat generation, which can enhance billet plasticity but may also risk overheating. Optimizing the friction coefficient is crucial to achieving the desired thermal conditions for effective material flow and maintaining extrusion quality.

Conclusion:-

This research highlights the importance of computational modeling in understanding and optimizing the extrusion process. The findings demonstrate that higher container temperatures lead to uniform billet temperature profiles, minimizing defects and enhancing material flow consistency.Increased ram velocities generate higher temperatures due to frictional heat and plastic deformation, ensuring better material flow but requiring careful control to avoid overheating.Higher friction coefficients increase billet temperature due to greater resistance at the billet-container interface, improving plasticity but potentially risking material overheating.The integration of thermal, fluid, and structural analysis provides valuable insights into process control and die design, aiding in the development of more efficient and reliable extrusion processes. Future work may explore transient conditions, material property variations, and multi-scale modeling approaches to further refine these findings and expand their applicability to complex extrusion scenarios.

Acknowledgement:-

We sincerely thank Dhirubhai Ambani International School for its support and encouragement throughout this journey. The author extends special appreciation to Mr. Hansraj Singh for his guidance in mathematics, which played a pivotal role in establishing the foundation and progression of this research paper. We are truly grateful for the inspiration and support provided.

References:-

[1] Zhang, H., Li, X., Tang, W., Deng, X., Reynolds, A.P. and Sutton, M.A., 2015. Heat transfer modeling of the friction extrusion process. Journal of Materials Processing Technology, 221, pp.21-30.

[2] Tibbetts, B.R. and Wen, J.T.Y., 1998. Extrusion process control: Modeling, identification, and optimization. IEEE transactions on control systems technology, 6(2), pp.134-145.

[3] Mishin, V., Shishov, I., Kalinenko, A., Vysotskii, I., Zuiko, I., Malopheyev, S., Mironov, S. and Kaibyshev, R., 2022. Numerical simulation of the thermo-mechanical behavior of 6061 aluminum alloy during friction-stir welding. Journal of Manufacturing and Materials Processing, 6(4), p.68.

[4] Liu, Y., Zhu, Z., Wang, Z., Zhu, B., Wang, Y. and Zhang, Y., 2018. Flow and friction behaviors of 6061 aluminum alloy at elevated temperatures and hot stamping of a B-pillar. The International Journal of Advanced Manufacturing Technology, 96, pp.4063-4083.

[5] Bala Chennaiah, M., Sreenivasulu, A. and Ravi Kumar, K., 2021. Influence of Tool Profiles on Heat Transfer Analysis in Al-6061 Alloy Using Friction Stir Welding. Trends in Manufacturing and Engineering Management: Select Proceedings of ICMechD 2019, pp.545-553.