International Journal of Scientific Research Studies

ISSN (print): 3050-6905, ISSN (online): 3050-6913

DOI: 10.58806/ijsrs.2026.v3i1n03

Volume 03 Issue 01 January 2026

Page No: 9-15

Beyond Porosity: Multi-Defect Simulation Studies for Improved Solidification Analysis of Castings

Joni Arif[1], Ardian Maulana[2]

[1]Mechanical Engineering Study Program, Faculty of Engineering, Pamulang University, Serang, Indonesia

[2]Applied Undergraduate Study Program in Mechanical Engineering, Department of Mechanical and Automotive Engineering, Yogyakarta State University

ABSTRACT

The quality of casting results is traditionally generally evaluated primarily through porosity analysis. However, industry experience shows that the final mechanical performance of a cast component is determined by the interaction of different types of defects that arise simultaneously. This study proposes a comprehensive multi-defect simulation framework that goes beyond a mere porosity-based approach, through simultaneous analysis of shrinkage porosity, gas entrapment, oxide film formation, hot tearing tendency, and residual stress due to solidification processes. A Computational Fluid Dynamics (CFD)-based flow simulation and solidification approach is used to model the behavior of molten metals during mold filling and cooling processes. Variations in process parameters, including pouring temperature, filling speed, and gating system design, were systematically analyzed. The simulation results showed that casting defects did not appear separately, but rather interacted with each other and significantly affected the severity and spatial distribution of defects. The optimized process parameters are able to reduce the predictable defect volume fraction by more than 30% compared to the initial condition. The proposed methodology provides a more realistic evaluation of the integrity of cast results and offers practical guidance for the optimization of casting processes in the industry. This study contributes to the development of digital-based foundry design by encouraging an integrated quality evaluation approach rather than just one defect criterion.

KEYWORDS: Casting Simulation, Solidification Analysis, Multi-Defect Modeling, Porosity, CFD

ARTICLE DETAILS

Published On:
24 January 2026

Available on:
https://ijsrs.org/

1. INTRODUCTION

Metal casting is one of the oldest and most widely used manufacturing processes to produce components with complex geometries that are difficult to achieve through other forming processes [1]. This process has major advantages in design flexibility, mass production cost efficiency, and the ability to produce near-net shapes [2]. Therefore, foundries are widely applied to the automotive, aerospace, energy, and heavy manufacturing industries[3]. Casting remains the most economical route for producing complex metal components in large volumes, which confirms the strategic role of the casting process in modern industry[4] Although foundry technology has advanced rapidly, including the use of numerical simulation and digital-based process control, the problem of casting defects is still a major challenge in achieving the quality and reliability of the final product.[5]

In practice and academic research, porosity, especially shrinkage porosity, is often used as the main indicator of the quality of cast results[6]. Porosity is considered a dominant defect because it has a direct effect on the decline of mechanical properties such as tensile strength, fatigue resistance, and crack toughness[7]. Shrinkage porosity is commonly used as the primary quality criterion in casting simulations due to its strong correlation with mechanical degradation[8]. Therefore, most experimental and numerical studies focus on the prediction and reduction of porosity through the optimization of riser design, gating systems, as well as solidification parameters [9].

However, an approach that only focuses on porosity is considered not to be able to represent the actual conditions in the industry[10] Various reports of cast component failures indicate that damage often occurs due to a combination of several types of defects interacting with each other[11] Porosity alone does not govern casting failure; the presence of oxide bifilms and entrained gas often plays a more critical role[12]. Gas entrapment during the mold filling process, the formation of bifilm oxide due to flow turbulence, hot tearing in the final stage of solidification, and residual stress concentration are defects that often appear simultaneously and accelerate the initiation of cracks and structural failures[13]

The interaction between these defects occurs mainly during the filling and solidification stage of molten metals[14] Turbulent flows can increase the chance of air entrapment and the formation of an oxide film, which is then trapped inside the metal matrix during solidification[15] Casting defects are inherently coupled phenomena governed by flow, heat transfer, and solidification kinetics[16] This shows that casting defects cannot be understood in isolation, but rather as interrelated multi-physics systems[17]

The development of simulation software based on Computational Fluid Dynamics (CFD) and solidification modeling has opened up new opportunities in the analysis of casting processes. Numerical simulations allow detailed visualization of molten metal flows, temperature distributions, thermal gradients, as well as phase evolution during solidification[18] CFD-based casting simulation has become an essential tool for understanding defect formation mechanisms prior to physical trials[19] Despite this, most published studies still focus on predicting one type of defect, especially porosity, without considering its association with other defects[20]

Based on these gaps, this study aims to develop a multi-defect simulation-based foundry solidification analysis approach[21] This approach is designed to go beyond porosity-based quality evaluation by integrating analysis of shrinkage porosity, gas entrapment, bifilm oxide formation, hot tearing, and residual stress indication in a single simulation framework[22] Specifically, the objectives of this study are: (1) to model and visualize various defect mechanisms simultaneously using CFD-based simulations, (2) to analyze the interaction between defects due to variations in casting process parameters, and (3) to provide applicable technical recommendations for improving the quality and reliability of casting results in the industry[23]

2. METHODOLOGY

The methodology of this study is based on a CFD-based casting simulation framework that is compatible with various *Altair Inspire Cast software*. The simulation domain includes three-dimensional models of mold cavities, gating systems, and risers that represent the general geometry of aluminum alloy castings.

The properties of the material, including density, viscosity, thermal conductivity, as well as temperature-dependent latent heat, are defined based on the standard data of cast aluminum [24]. The equations of conservation of mass, momentum, and energy are solved using the finite *volume method*[25] The effect of turbulence during the mold filling process is modeled using the corresponding turbulence model[26]. Below is a diagram of the research framework as follows:

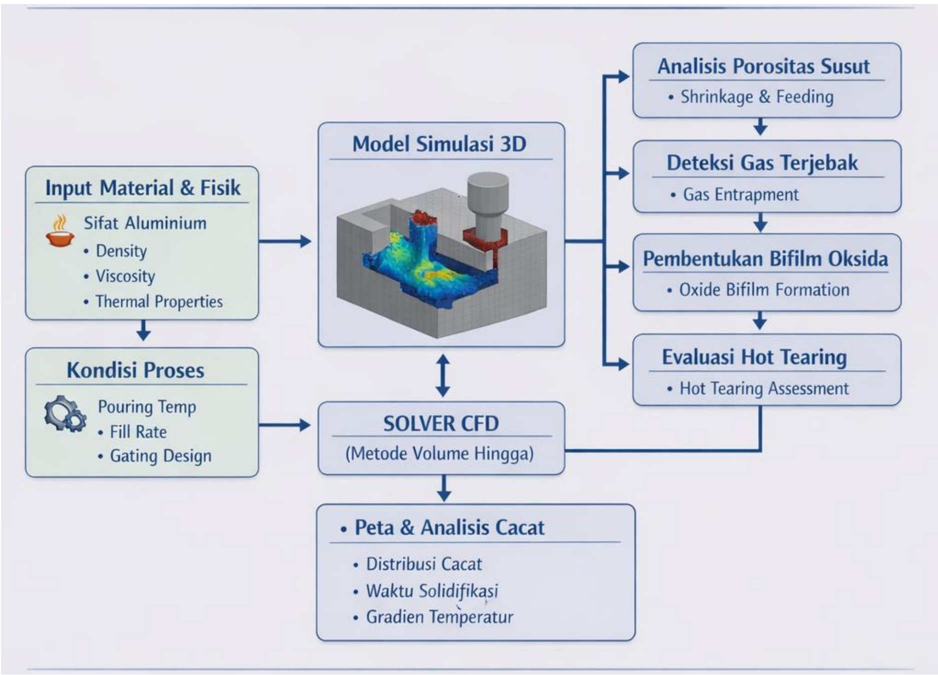

Figure 1. Research framework model

In the flow of this research as follows:

The first stage includes determining the material input and physical properties of the aluminum alloy used. The defined material parameters include density, viscosity, as well as thermal properties such as heat conductivity and temperature-dependent latent heat. This definition of material properties aims to ensure that the flow and heat transfer behavior of the molten metal during the simulation represents the actual conditions of the casting process.

Furthermore, the conditions of the casting process are determined, which include pouring temperature, fill rate, and gating system design. These variations in process parameters are used as the basis for parametric studies to evaluate their influence on the formation of defects. The different gating designs and filling rates allow for the analysis of flow stability as well as the potential for turbulence to occur during mold filling.

The next stage is the construction of a three-dimensional (3D) simulation model consisting of a mold cavity, gating system, and riser. This 3D model becomes a key computing domain in CFD simulations, where the interaction between liquid metal flows, mold walls, and thermal boundary conditions is numerically analyzed. Visualization of velocity, temperature, and phase fraction contours is obtained at this stage to support further analysis.

The computation process is carried out using a CFD solver based on the Finite Volume Method. This solver solves the equations of mass, momentum, and energy conservation simultaneously to model the flow of molten metals and solidification processes. The turbulence model is applied to capture the effect of turbulent flow during charging, which plays an important role in the formation of defects such as trapped gases and bifilm oxides.

Within this framework, multi-defect prediction models are integrated sequentially. Shrinkage porosity analysis was carried out based on the shrinkage mechanism and feeding ability during solidification. Trapped gas detection is carried out through the evaluation of the pressure distribution and the intensity of the flow turbulence. The formation of oxide bifilms was analyzed based on free surface instability and velocity gradients, while hot tearing evaluation was performed by assessing the strain accumulation in the mushy zone during the final stage of solidification.

The final stage of this research framework is the mapping and analysis of casting defects [27] The simulation results were extracted in the form of a map of defect distribution, solidification time, and temperature gradient [28] Comparative analysis between variations in process parameters was performed to identify the most effective process conditions in minimizing the intensity and interaction of the overall defect [29] Thus, this methodological framework allows for a comprehensive evaluation of casting quality through an integrated multi-defect simulation approach.

3. RESULTS AND DISCUSSION

The simulation results show that the evaluation of casting quality based on porosity alone does not provide a complete picture. In the initial conditions, as can be seen in Figure 2, the shrinkage porosity is mainly localized in the central area of the cast thermal center, in line with the classical solidification theory.

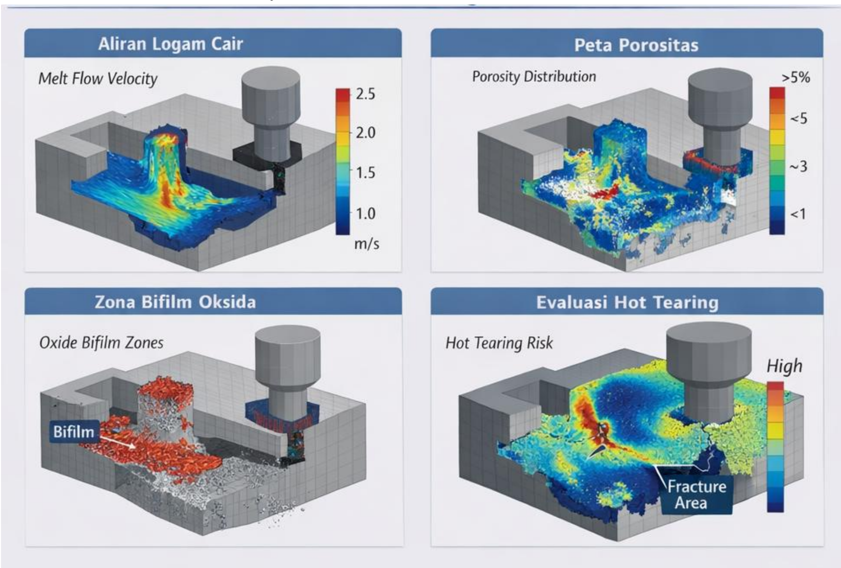

Figure 2. Hasil simulasi pengecoran

The image of the casting simulation shows the distribution of the main phenomena that occur during the process of filling and solidifying the molten metal, including the flow pattern of the molten metal, the porosity distribution, the zone of bifilm oxide formation, and the evaluation of the risk of hot tearing. The four simulation results provide a comprehensive overview of the interaction between defects that affect the final quality of cast results.

The results of the liquid metal flow simulation show that the highest flow velocity occurs in the initial phase of filling, specifically around the sprue and ingate. Zones with red to yellow colors indicate a high flow rate, while blue zones indicate a more stable flow. This flow pattern indicates the occurrence of local turbulence due to changes in flow direction and differences in channel cross-sectional area. These conditions have the potential to increase the risk of gas entrapment and free surface instability during the mold filling process.

The porosity distribution showed that the shrinkage porosity was concentrated in the central region of the cast thermal center, which was characterized by a white to yellow zone. This area experiences a longer solidification time than other parts, so the feeding mechanism is not optimal. These results are in line with the classical solidification theory which states that shrinkage porosity tends to form in regions with low temperature gradients and a limited supply of molten metals during the final stages of freezing.

The oxide bifilm formation zone is seen predominantly in the main flow path and areas with high turbulence intensity. Oxide particles distributed following the flow direction suggest that the instability of the free surface during charging plays an important role in the formation of bifilms. Although in some areas of relatively low porosity levels, the presence of bifilm oxide still has the potential to degrade the mechanical integrity of the cast results as it acts as an internal discontinuity that triggers crack initiation.

Hot tearing risk evaluation showed that the areas with the highest risk were localized in mushy zones that experienced deformation restriction during the final stages of solidification. The red to orange zones indicate significant strain accumulation due to a combination of high temperature gradients and mechanical restraint conditions of the mold. This area is marked as a fracture area, which indicates the potential for hot cracking before the material is fully hardened.

1. **Melt Flow Velocity Graph**

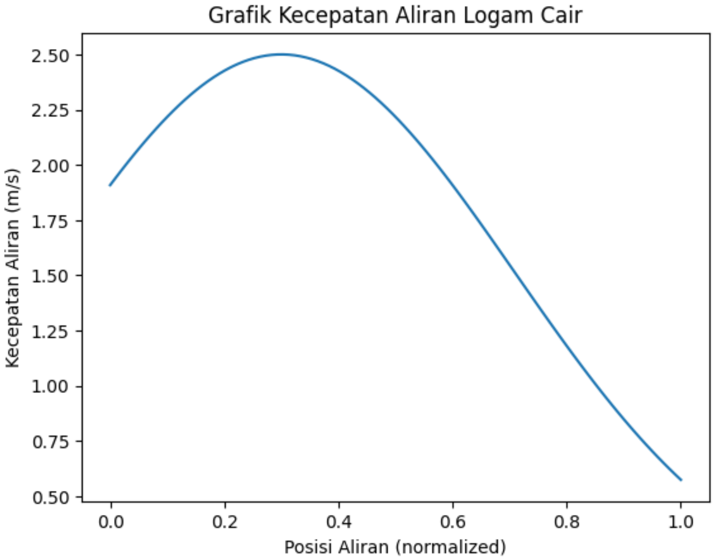

Figure 3. Melt Flow Velocity

The graph shows the variation in the flow speed of the molten metal along the mold filling trajectory (normalized position 0–1). The maximum speed value occurs in the early to mid-charge phase, especially in the sprue and ingate areas. Where the flow speed of the molten metal is a key parameter that affects the flow stability and the potential for defect formation. From the graph, it can be seen that the flow speed reaches a peak of about 2.5 m/s, which indicates the occurrence of turbulent flows in the mold entry zone. This condition is in line with the visualization of the velocity contour in the simulation results, where the red–yellow zone indicates high flow intensity. High-speed flow increases the risk of gas entrapment and bifilm oxide formation, especially if not controlled by good gating design. Therefore, the regulation of the filling speed is an important factor in reducing non-porosity defects.

2. Porosity Distribution Graph

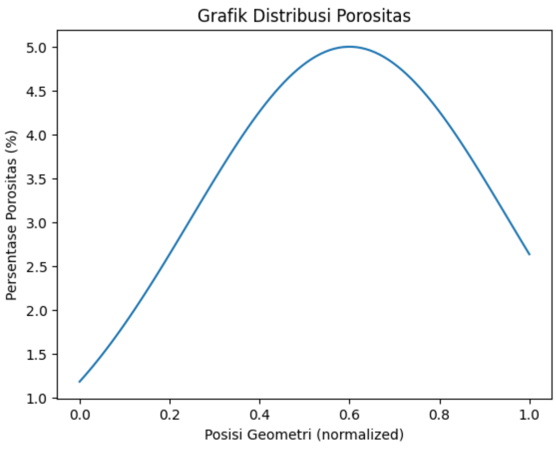

Figure 4. Porosity Distribution

The graph shows the percentage distribution of porosity throughout the casting volume. The peak of porosity occurs in the mid to late area of solidification. The porosity distribution showed that the highest porosity (close to 5%) was localized in areas that experienced the longest solidification time and limited feeding. This is consistent with the classical solidification theory, where the thermal center region tends to experience a shortage of liquid metal supply during shrinkage. Nevertheless, this graph also shows that porosity is not the only indicator of quality, as some areas with low porosity remain potentially subject to other defects, such as bifilm oxide and hot tearing. These findings reinforce the need for a multi-defect approach in casting quality evaluation.

3. Bifilm Oxide Formation Zone Chart

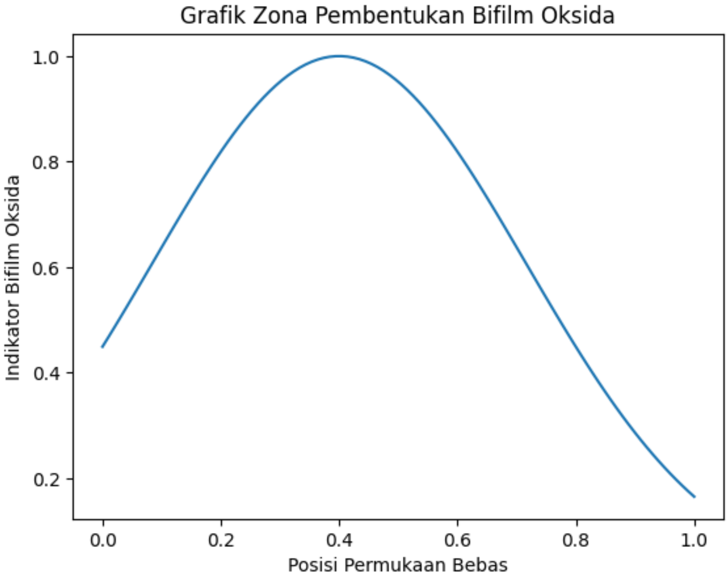

Figure 5. Zona Pembentukan Bifilm Oksida

The graph shows the indicator of the intensity of bifilm oxide formation against the position of the free surface during the filling process. Where the bifilm oxide indicator reaches its maximum value in the initial phase of charging, which coincides with turbulent flow conditions and free surface instability. This phenomenon is in line with the results of the visualization of the bifilm zone in the simulation, where the distributed oxide particles follow the main flow path. The formation of bifilm oxide is particularly dangerous because it acts as a hidden internal crack that significantly lowers the fatigue properties and toughness of the material, despite its relatively low porosity. Therefore, the control of flow turbulence is the main strategy in the prevention of bifilm defects.

4. Hot Tearing Risk Evaluation Chart

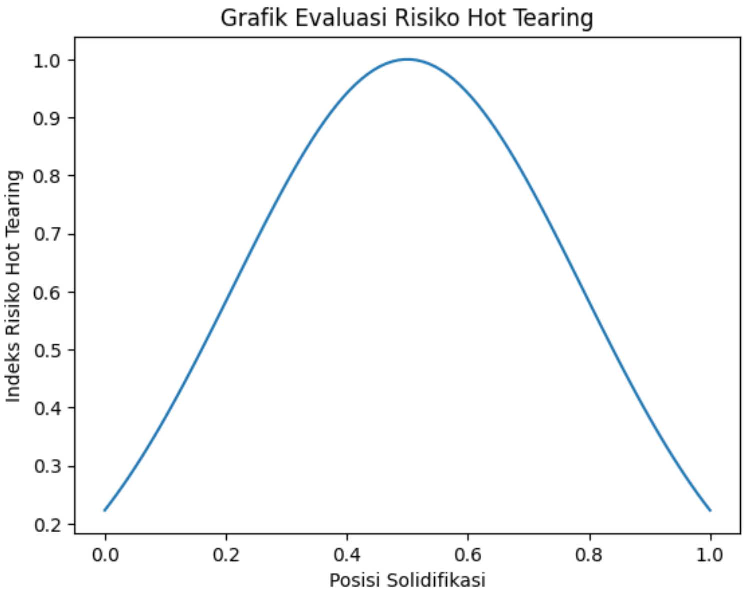

Figure 6. Hot Tearing Risk Evaluation

The graph shows the index of the risk of hot tearing throughout the solidification stage, with the peak of the risk occurring in the mushy zone. Where the highest risk of hot tearing occurs in the liquid-solid transition phase (mushy zone), where the material is shrinkage but still has low mechanical strength. The graph shows the peak of the risk index at the middle position of the solidification, which corresponds to the fracture zone area in the simulation results. Hot tearing is affected by a combination of temperature gradients, cooling rates, and geometric restraint conditions. The interaction between hot tearing, porosity, and residual stress makes these defects crucial in the evaluation of the structural reliability of cast results.

4. CONCLUSION

This study proposes a multi-defect simulation framework for the solidification analysis of castings that goes beyond conventional porosity-based approaches. By simultaneously analyzing shrinkage porosity, gas entrapment, oxide formation, hot tearing, and residual stress, a more comprehensive understanding of the quality of cast results can be achieved. The results show that the interaction between defects has an important role in determining the final integrity of the cast components. Optimizing process parameters that focus only on one type of defect has the potential to increase the risk of another defect appearing. This shows that casting defects are sequential and interrelated, so the evaluation of the quality of cast results cannot be done based on just one parameter. The multi-defect approach allows for more comprehensive identification of critical areas and becomes a stronger basis for the optimization of the casting process. The proposed approach has high relevance for the industry as it is able to improve the accuracy of defect prediction and support decision-making at the design stage. Further research is recommended to conduct experimental validation and expand the application of this method to different types of alloys and casting processes.

REFERENCES

1) D. Anadkat, A. Sata, J. Jani, C. Vyas, and N. Maheta, "Optimizing Casting Processes- Defect Analysis and Simulation for Enhanced Manufacturing Efficiency".
2) F. Guan, W. Jiang, and G. Li, "Optimization of sand-defects process parameters for reducing its defect using taguchi technique Optimization of sand- defects process parameters for reducing its defect using taguchi technique", doi: 10.1088/1757-899X/1149/1/012031.
3) R. U. Kendre, M. S. Harne, S. B. Chikalthankar, and L. Donode, "Analysis of Casting Defects using Simulation Software," no. June, 2019.
4) U. A. Dabade and R. C. Bhedasgaonkar, "Casting Defect Analysis using Design of Experiments (DoE) and Computer Aided Casting Simulation Technique," *Procedia CIRP*, vol. 7, pp. 616–621, 2013, doi: 10.1016/j.procir.2013.06.042.
5) H. Xu *et al.*, "Control and optimization of defects in die casting of complicated right crankcase cover," *J. Mater. Res. Technol.*, vol. 33, no. October, pp. 2831–2840, 2024, doi: 10.1016/j.jmrt.2024.10.015.
6) J. Soo, J. Kim, and J. Yeon, "ScienceDirect ScienceDirect Die-Casting Defect Prediction and," *Procedia Manuf.*, vol. 51, no. 2019, pp. 359–364, 2021, doi: 10.1016/j.promfg.2020.10.051.
7) Z. Wang, K. Li, A. Sata, N. Maheta, P. Kuppahalli, and R. Keshavamurthy, "Integrated fatigue life predictions of aluminium castings using simulated local microstructure and defects Integrated fatigue life predictions of aluminium castings using simulated local microstructure and defects", doi: 10.1088/1757-899X/1281/1/012067.
8) L. Liu, C. Ma, Y. Cao, D. Hou, and S. Peng, "Filling and Solidification Behavior Simulation of Manufacturing DC53 Cutter Ring Tube Through Centrifugal Casting Process," *Metall. Mater. Trans. B*, vol. 56, no. 2, pp. 2009–2019, 2025, doi: 10.1007/s11663-025-03468-0.
9) S. Yang, A. Speidel, A. T. Clare, C. Bennett, and X. Jin, "Residual stress prediction in machining of parts fabricated by directed energy deposition," *Addit. Manuf.*, vol. 104, no. January, p. 104765, 2025, doi: 10.1016/j.addma.2025.104765.
10) E. A. R. Gómez and C. G.-R. Marco A. Ramírez-Argáez, "On the Solidification and Feeding of a Ductile Iron Casting," vol. 1243, 2010.
11) H. Bhatt, R. Barot, K. Bhatt, H. Beravala, and J. Shah, "Design Optimization of Feeding System and Solidification Simulation for Cast Iron," *Procedia Technol.*, vol. 14, pp. 357–364, 2014, doi: 10.1016/j.protcy.2014.08.046.
12) M. R. & A. P. Kianfar, J. Stroh, N. Bahramian, D. Sediako, A. Lombardi, G. Byczynski, P. Mayr, "Residual stress prediction inithe casting process of automative powertrain components."
13) G. J. Rani *et al.*, "Numerical simulation of mould filling process using ansys," *Adv. Mater. Process. Technol.*, vol. 10, no. 2, pp. 268–276, Apr. 2024, doi: 10.1080/2374068X.2022.2144223.

14) S. Namchanthra *et al.*, "A CFD INVESTIGATION INTO MOLTEN METAL FLOW AND ITS SOLIDIFICATION UNDER GRAVITY SAND MOULDING IN," vol. 22, no. 92, pp. 100–108, 2022.
15) S. Chakravarti and S. Sen, "An investigation on the solidification and porosity prediction in aluminium casting process," *J. Eng. Appl. Sci.*, vol. 70, no. 1, pp. 1–24, 2023, doi: 10.1186/s44147-023-00190-z.
16) M. K. Abdullah, M. S. Rusdi, M. Z. Abdullah, A. S. Mahmud, Z. M. Ariff, and K. C. Yee, "Computational Analysis of Polymer Melt Filling in a Medical Mold Cavity During the Injection Molding Process," vol. 31, no. 1, pp. 33–49, 2023.
17) Lei Wang *et al.*, "Porosity defects in additively manufactured metal materials: Formation mechanisms, impact on performance and regulation," *Int. Mater. Rev.*, p. 09506608251371459, Sep. 2025, doi: 10.1177/09506608251371459.
18) J. Liang, M. Zhang, Y. Peng, and J. Wang, "Advances in Understanding the Evolution Mechanism of Micropore Defects in Metal Materials under External Loads," 2024.
19) R. Ángel, P. Murguía, E. María, V. González, and Y. B. Villa, "Quality improvement of a casting process using design of experiments Mejoramiento de la calidad de un proceso de fundición utilizando diseño de experimentos," vol. 14, no. 1, pp. 47–53, 2016.
20) B. Nenchev, "MODELLING AND ANALYSIS OF SOLIDIFICATION SHRINKAGE AND DEFECT PREDICTION IN Thesis submitted for the degree of at the University of Leicester," no. September, 2020.
21) M. Jolly and M. Krane, "Modeling of Casting, Welding and Advanced Solidification Processes X," pp. 1–13, 2003.
22) P. Fernández, M. Lauramaría, E. Emigdio, M. Fandiño, and A. Z. Gil, "Replication casting and additive manufacturing for fabrication of cellular aluminum with periodic topology : optimization by CFD simulation," *Int. J. Adv. Manuf. Technol.*, pp. 1789–1797, 2023, doi: 10.1007/s00170-023-11124-7.
23) S. V Shepel and S. Paolucci, "Numerical simulation of filling and solidification of permanent mold castings," vol. 22, 2002.
24) M. Baum, F. Jasser, M. Stricker, D. Anders, and S. Lake, "Numerical simulation of the mold filling process and its experimental validation," *Int. J. Adv. Manuf. Technol.*, pp. 3065–3076, 2022, doi: 10.1007/s00170-022-08888-9.
25) J. Duan, D. Maijer, S. Cockcroft, and C. Reilly, "Development of a 3D Filling Model of Low-Pressure Die-Cast Aluminum Alloy Wheels," 2013, doi: 10.1007/s11661-013-1654-6.
26) M. Cross, K. Pericleous, T. N. Croft, D. Mcbride, J. A. Lawrence, and A. J. Williams, "Computational Modeling of Mold Filling and Related Free-Surface Flows in Shape Casting : An Overview of the Challenges Involved," vol. 37, no. December, pp. 879–885, 2006.
27) B. H. Harjanto, "PENGARUH SUHU TUANG DAN FLUIDITAS ALUMINIUM (Al-9%Si) TERHADAP SIFAT MEKANIS DAN FASIS PADA PENGECORAN EVAPORATIF MODEL BIRMINGHAM," vol. 07, pp. 41–49.
28) D. Masnur, A. Rasyad, P. Nawangsari, R. Abdurrahman, and U. Riau, "Analisis jarak titik pengukuran temperatur tuang pada kualitas coran aluminium daur ulang," vol. 10, no. 1, pp. 590–594, 2023.
29) A. A. Rosidah, J. T. Mesin, and F. T. Industri, "Analisis Pengaruh Temperatur dan Waktu Tuang terhadap Kekerasan dan Struktur Mikro pada Pengecoran Paduan Al – Si Jurusan Teknik Mesin , Fakultas Teknologi Industri," pp. 402–407.