# A Review on ANSYS-Based Thermal Simulation Techniques for Metal Casting Optimization

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***Abstract*—Metal casting remains a critical manufacturing process for producing complex and high-performance metallic components used across automotive, aerospace, power generation, and industrial machinery sectors. However, achieving defect-free castings continues to be challenging due to the influence of thermal gradients, solidification behaviour, gating and riser design, cooling strategies, and mold material selection. Recent advancements in computational simulation, particularly using ANSYS, have enabled highly accurate prediction and analysis of temperature distribution, heat transfer patterns, solidification time, porosity formation, residual stresses, and microstructural development. This review synthesizes findings from multiple studies conducted between 2016 and 2024, highlighting the role of ANSYS-based thermal simulation in optimizing casting processes. The literature demonstrates that simulation-assisted design significantly reduces shrinkage defects, improves directional solidification, increases yield, enhances dimensional accuracy, and minimizes costly trial-and-error experimentation. Key contributions across studies include adaptive meshing for increased precision, integration of artificial intelligence for defect prediction, incorporation of digital twin frameworks for real-time monitoring, and advanced modeling of complex alloys such as aluminum, copper, and magnesium. The review concludes that computational thermal analysis is essential for modern foundry development and Industry 4.0-based smart manufacturing, and identifies future opportunities involving hybrid AM-casting systems, machine learning-enhanced prediction models, and improved material property databases.**

***Index Terms*—Thermal analysis, Metal casting, Solidification modeling, Heat transfer simulation, Finite element analysis (FEA)**

## I. INTRODUCTION

Metal casting is an important manufacturing process in industries such as automotive, aerospace, construction, and heavy engineering. Process casting involves pouring molten metal into a cavity and allowing it to solidify isothermal solidifications to achieve a metal shape. The major characteristic of a good casting is internal soundness, and this is affected mainly by the thermal behavior of the casting during solidification. The casting's microstructure and final shape's accuracy is also a product of this thermal behavior, and even the mechanical properties of the casting are affected as well. While internal defects such as shrinkage porosity, hot tears, and nonuniform grain structure are caused by excessive temperature gradients, temperature gradients are also necessary to control. Many foundries have, and to a certain extent still, rely heavily on empirical methods, based mainly on trial and error, to optimize their castings in regards to control parameters such as cooling conditions, and placement and shape of risers, as well as the material composition of the molds. The equilibrium and steady state thermal conditions are fundamental to empirical control procedures. Advances in engineering simulation tools, such as ANSYS, have been able to reliably predict transfer functions in thermal control systems, have improved designs to a level where physical trials are no longer necessary.

## II. LITERATURE REVIEW

Zhang and Li (2016) performed a thermo-mechanical finite element simulation using ANSYS software in order to investigate the evolution of residual stresses and the temperature differentials that occur as an aluminum alloy casting cools. The authors included temperature-dependent thermal properties in the simulation and employed a transient heat flux model that accurately predicted the formation of thermal hotspots. The results of the simulation showed a strong correlation between the peak temperature areas and areas of volumetric contraction. The authors underscored the importance of implementing thermal control methods, and evidenced the validation of the simulation results through the utilization of thermocouples. The authors concluded that needed improvements to the dimensional accuracy and internal integrity of the casted parts can be obtained through the use of an engineered gating system and stratagems that control cooling rate.

Using ANSYS Workbench, Kumar and Srinivasan (2017) performed a transient thermal analysis of a casting of steel in order to discern the effect of the mold material and thickness of the different sections on the cooling rate. The authors used silica sand, zircon sand, and ceramic molds and analyzed the effect of the different molds on the rate of heat on the solidification of the casting and the thermal conductivity of the solidified casting. The results showed that the ceramic molds produced a more even temperature distribution and also decreased the formation of thermal hotspots. The authors emphasized that the use of computer simulations to predict the results of a solidification process in a mold decreased the number of physical trials needed, therefore, reducing the time and expenses associated with the process of casting and solidification of a material.

Using ANSYS Fluent, Patel and Deshmukh (2018) predicted the casting of fluid plus heat transfer behaviour in complexly gated cast iron components. The study assessed the time taken for molten metal to fill the cavity, turbulence generated, and heat losses in runner channels. The authors concluded that the flow turbulence resulted in uniform temperature distribution and early solidification, causing misruns. The study improved flow and lowered porosity by redesigning the shape of runners and strategic placement of risers. The simulation results were validated by foundry casting trials which corroborated the credibility of CAE in productivity enhancement in foundries.

Sharma and Gupta (2018) explored the influence of casting thickness variations on thermal gradients using ANSYS transient analysis. Their study concluded that thickness transitions create localized heat retention zones that delay solidification and contribute to shrinkage cavity formation. Analytical comparison with the Chvorinov rule confirmed simulation accuracy. Recommendations included uniform wall thickness and cooling channel placement near heavy sections. The research highlighted the importance of simulation in early design evaluation to reduce costly defects.

Reddy et al. (2019) applied ANSYS APDL to predict temperature-dependent solidification behaviour in aluminum–silicon alloy automotive components, focusing on thermal gradients and their influence on residual stresses. They developed a coupled thermal–structural finite element model that incorporated latent heat of solidification, temperature-dependent material properties, and convection boundary conditions to accurately simulate cooling patterns. Their simulation detected significant stress accumulation in areas of geometric discontinuity such as fillets and junctions, confirming that nonuniform cooling promotes micro-crack development. The study demonstrated the utility of multiphysics modeling in forecasting failure-prone zones and guiding preventive design strategies. Experimental validation using microstructure hardness distribution and residual stress measurement confirmed strong agreement with simulation outcomes, emphasizing ANSYS as a reliable tool for industrial casting optimization.

Singh and Agarwal (2019) conducted a comparative investigation between experimental measurements and numerical thermal simulations in ANSYS for sand-cast aluminum wheel components. Thermocouples were embedded strategically at multiple mold locations to record real-time temperature variations throughout the casting solidification cycle. These readings were compared with transient temperature plots generated from finite element modeling. The study reported close correlation between measured and simulated cooling curves, validating the accuracy of simulation settings and interface heat transfer coefficients. Their research highlighted that precise characterization of mold–metal contact plays a critical role in improving prediction accuracy. The authors concluded that thermal simulation significantly reduces dependence on traditional trial-and-error casting practices and supports defect minimization in automotive foundry production.

Rahman and Ali (2020) explored the influence of forced cooling and external thermal control strategies on solidification characteristics of aluminum castings using ANSYS transient thermal simulation. The study introduced water-based cooling channels strategically placed around the mold surface to analyze heat extraction efficiency. Simulation outcomes indicated a reduction in total solidification time by nearly 24%, enabling improved directional solidification from the extremities towards the riser, thus reducing shrinkage cavity formation. Shrinkage defects near the riser–mold interface were particularly minimized due to controlled thermal gradients. Industrial-scale experiments supported these findings, validating simulation accuracy. Their research demonstrated the potential of integrating active cooling systems for productivity enhancement and energy-efficient casting operations.

Verma and Tiwari (2020) conducted thermal simulations of copper alloy castings using ANSYS Workbench to optimize riser placement and improve casting yield. Their research analyzed the impact of riser positioning, size variation, and thermal conductivity on temperature distribution and cooling behaviour. Simulation results revealed that improper riser location leads to isolated thermal hot spots, creating shrinkage porosity and increasing rejection rates. After redesign, which included relocating risers closer to thick sections and increasing efficiency of feeding paths, casting yield improved by approximately 11% while defect density reduced significantly. The authors concluded that computer-aided optimization is essential for cost-effective casting system design, especially for expensive alloy components.

Das and Mukherjee (2020) examined the influence of ceramic and graphite mold coatings on heat transfer characteristics during casting solidification through ANSYS thermal simulations. They evaluated thermal gradients and surface temperature variations using coatings with different conductivities. The findings demonstrated that high-conductivity coatings enhance heat removal, accelerate cooling rates, and reduce thermal fatigue effects on mold surfaces. Graphite coatings proved beneficial for improving surface finish and dimensional precision due to smoother thermal transitions. The research emphasized the importance of selecting appropriate coatings to ensure better solidification control and reduce defect accumulation. Their work highlighted ANSYS simulation as a valuable tool for optimizing coating materials before large-scale industrial implementation.

Mishra and Chatterjee (2021) developed a comprehensive ANSYS-based solidification model for magnesium alloys characterized by complex shrinkage behaviour and sensitivity to thermal gradients. Their study focused on predicting internal porosity and grain structure based on mold temperature and cooling channel design. The model successfully demonstrated that strategically placed cooling channels promote directional solidification, reducing porosity by nearly 18% and producing more homogeneous grain distribution. The study integrated metallographic examination and density analysis for validation, showing close agreement with predicted outcomes. Their research provided new insight into thermally controlled casting design, particularly for lightweight automotive and aerospace components where defect tolerance is minimal.

Prakash and Jain (2021) introduced an innovative hybrid modelling framework that integrates neural network algorithms with ANSYS thermal simulation outputs for enhanced defect prediction in metal castings. The research utilized machine learning classification techniques to analyze simulation-generated temperature profiles and correlate them with defect probability. The hybrid system significantly reduced simulation time by eliminating unnecessary iterations and improved prediction accuracy for complex geometries. Their findings demonstrated that artificial intelligence models can identify subtle temperature fluctuations linked to early defect indicators. The authors emphasized the future potential of combining ANSYS simulation and AI-driven optimization, particularly for smart foundry systems and real-time process control.

Banerjee et al. (2021) conducted thermal distribution analysis in investment casting applications using ANSYS to evaluate shell thickness effects on cooling patterns and microstructure refinement. Their work showed that shell layers with higher thermal resistance slow down heat extraction, resulting in extended solidification time and coarser grain structure. Conversely, optimized shell thickness improved directional solidification and mechanical properties. Simulation results were validated using thermal imaging and metallographic samples. The study emphasized the importance of shell design in achieving superior casting quality and minimizing warpage in precision components.

Thomas and Wilson (2022) investigated heat transfer patterns and cooling cycle efficiency in die-cast aluminum components using ANSYS Fluent. Their simulation included detailed modeling of internal cooling channels, spray cooling, and transient temperature evolutions in multi-cavity molds. The results demonstrated that cooling channel geometry optimization leads to reduced production cycle time and higher thermal uniformity, decreasing thermal fatigue and mold wear. They highlighted that effective heat removal directly enhances dimensional accuracy and surface finish quality. Industrial testing confirmed productivity gains and defect reduction, establishing simulation as a key tool for die casting process automation.

Pandey and Sahu (2022) focused on the role of latent heat treatment in thermal simulation and investigated phase change modeling accuracy during solidification of ferrous castings. Their findings indicated that ignoring latent heat leads to underestimated solidification times and inaccurate prediction of critical hot spots. By incorporating detailed thermodynamic phase transformation data into ANSYS, simulation results closely matched experimental solidification measurements. They concluded that precise latent heat modelling is essential for predicting shrinkage risks and optimizing gating system design. Their study highlighted the need for improved material property databases to strengthen casting simulation accuracy.

Gautam and Bansal (2022) performed a three-dimensional simulation of solidification behaviour in sand-cast turbine components using ANSYS Workbench. The research examined temperature gradients across varying section thicknesses and correlated solidification cooling rates with tensile strength outcomes. Higher cooling rates produced finer grains and improved strength, whereas low cooling zones near heavy sections exhibited porosity. The study confirmed a strong correlation between thermal gradients and mechanical performance. Recommendations included optimized riser positioning and controlled cooling environments to enhance uniformity. Their findings supported simulation as a critical tool for improving casting performance in high-temperature turbine applications.

Joshi and Kulkarni (2023) demonstrated the critical role of adaptive meshing techniques in improving simulation quality and computational efficiency in thermal analysis of complex metal castings. Their study systematically compared uniform meshing and adaptive meshing within the ANSYS environment, particularly focusing on castings with varying wall thicknesses and intricate gating networks. Results indicated that adaptive meshing provided significantly greater accuracy in capturing steep temperature gradients and identifying hot spots without demanding excessive computational effort. Mesh refinement in localized zones—especially around sharp corners, fillet intersections, and feeding junctions—allowed for precise prediction of shrinkage-prone regions. The researchers emphasized that uniform meshing often leads to inaccurate thermal predictions and unnecessary computational burden. Their study concluded that adaptive meshing offers an optimal balance between simulation speed and precision, making it highly suitable for industrial environments where rapid design iterations and defect prediction are essential for competitive manufacturing.

Ali and Hassan (2023) investigated the impact of squeeze pressure on heat transfer efficiency and defect control in squeeze casting processes using transient thermal simulation in ANSYS. Their research aimed to understand how varying pressure levels influence solidification behaviour, temperature distribution, and microstructural quality. The simulation results revealed that increased applied pressure improved contact heat transfer between molten metal and die surfaces, promoting uniform cooling and suppressing localized hot spots. This led to a significant reduction in shrinkage porosity and enhanced overall casting density. To validate the numerical model, physical squeeze casting experiments were conducted, and microstructural analysis showed refined grain structures with improved mechanical properties. Their findings reinforced the importance of pressure optimization for defect-free casting production. The authors concluded that simulation-driven process control significantly enhances repeatability, reduces material wastage, and supports quality improvement in high-performance casting industries such as aerospace and automotive manufacturing.

Mehta and Chauhan (2023) conducted an in-depth study on optimizing cooling line placement within die-casting molds using ANSYS thermal simulations to reduce thermal fatigue and prevent premature mold failure. Their work evaluated numerous cooling channel layouts and geometrical variations to determine the most effective designs for uniform thermal regulation. Simulation results demonstrated that strategically positioned cooling lines significantly minimized peak temperature zones and reduced large thermal gradients responsible for crack initiation and die erosion. The optimized configuration extended mold service life and reduced downtime due to repair or replacement. Additionally, the authors highlighted the economic benefits associated with simulation-led experimental planning, reducing the need for costly trial-and-error approaches. They emphasized that integrating predictive modeling with industrial mold design processes enhances performance reliability and supports preventive maintenance strategies. Their findings are particularly relevant for mass-production environments where consistent quality and long tooling lifespan are essential.

Bose and Kumar (2024) analyzed the thermal behaviour and solidification characteristics in hybrid additive manufacturing (AM) and casting processes by using a coupled ANSYS modeling framework. Their research explored the combined influence of layered additive deposition and conventional mold-based casting, focusing on heat transfer paths, fusion integrity, and structural uniformity in the final product. The simulation demonstrated that the thermal gradients between deposited layers and cast metal significantly affect bonding performance, stress distribution, and grain refinement. Their study provided crucial insights into process parameter optimization for hybrid systems, which are gaining attention due to their ability to manufacture complex geometries with reduced material wastage. The authors emphasized that accurate thermal prediction is essential to avoid defects such as interlayer cracking and porosity. Their work contributes to emerging research trends in digital manufacturing and advanced casting technologies.

Fernandes et al. (2024) developed an advanced digital twin-based thermal monitoring and simulation framework that integrates real-time temperature sensor data with ANSYS predictive modeling for metal casting processes. Their research aimed to enhance intelligent process automation by enabling dynamic control of thermal behaviour during solidification. The system continuously collected live temperature data from multiple mold locations and synchronized it with simulation forecasts to detect process deviations early. Based on prediction outcomes, automated adjustments were applied to cooling rates, gating configurations, and pouring conditions, preventing defect formation proactively rather than reactively. The authors concluded that digital twin technology improves process transparency, reduces variability, and supports adaptive manufacturing environments. Their work demonstrated the future potential of connecting physical foundry operations with virtual simulation models for smart factory implementation and Industry 4.0 transformation.

## III. CONCLUSION

The collective body of research reviewed demonstrates the transformative role of ANSYS-based thermal simulation in enhancing the accuracy, efficiency, and reliability of metal casting processes across various alloys, casting methods, and industrial applications. The studies consistently reveal that temperature gradients, solidification behaviour, and heat transfer characteristics critically influence casting quality, affecting defect formation, microstructural evolution, residual stresses, and overall mechanical performance. ANSYS simulations enable precise visualization and control of thermal profiles, reducing dependence on costly trial-and-error manufacturing practices and supporting evidence-based design optimization. Across the reviewed literature, key contributions include optimization of gating and riser systems, adaptive meshing for accuracy enhancement, integration of machine learning models for intelligent defect prediction, application of forced cooling and pressure-based heat transfer improvements, and implementation of digital twin frameworks for real-time process adaptation. The findings collectively confirm that simulation-assisted casting design significantly improves yield, reduces porosity and shrinkage defects, shortens production cycles, and enhances dimensional accuracy and surface finish. Furthermore, coupling thermal simulation with experimental validation ensures model credibility, enabling predictive maintenance and reducing material waste. Emerging advancements such as hybrid AM-casting simulation, AI-assisted computation, and smart manufacturing integration highlight the future direction of research.

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