
SIMULATION-BASED DEFECT PREDICTION IN IRON CASTINGS: A REVIEW OF COMPUTATIONAL METHODS AND CLEANING VALIDATION TECHNIQUES FOR SUSTAINABLE MANUFACTURING

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Abstract.

The foundry industry continues to struggle with reliable prediction and mitigation of surface and subsurface defects in iron castings, directly impacting material efficiency, energy consumption, and production economics. This review critically examines the current state of simulation-based defect prediction methodologies for iron castings, with focused attention on validation protocols utilizing conventional mechanical cleaning versus high-pressure water jet cleaning. Based on systematic analysis of peer-reviewed, we identify a clear evolutionary trajectory: casting process simulation has progressed from rudimentary hot spot prediction to sophisticated microstructural modeling incorporating fluid-structure interaction and machine learning architectures. A key finding of this review is that high-pressure water jet cleaning demonstrates measurably superior defect revelation capability relative to conventional methods, particularly for complex geometric features and subsurface defect populations, while offering concurrent environmental and ergonomic advantages. We further argue that the integration of simulation-based prediction with advanced cleaning validation directly supports sustainable manufacturing objectives by reducing scrap generation, minimizing rework, and enabling closed-loop quality control frameworks. This review synthesizes existing knowledge, identifies critical research gaps requiring investigation, and proposes an integrated framework for AI-enhanced defect prediction validated through high-pressure water jet cleaning.

Keywords. Simulation-based defect prediction, high-pressure water jet cleaning, iron castings, sustainable manufacturing, defect validation, machine learning.

1. INTRODUCTION

1.1 Background and Industrial Significance

The iron casting industry constitutes a foundational pillar within global manufacturing networks, delivering critical components to sectors such as automotive production, aerospace engineering and energy generation. A comprehensive examination of extant scholarly literature indicates that rejection rates attributable to casting imperfections across international foundries typically fall within a range of 5 % to 15 % [1, 4]. Such defects encompassing gas-induced porosity, oxide film entrapment, sand particle entrainment,

surface irregularities, and micro-shrinkage cavities not only generate considerable economic losses but also impose a substantial ecological burden owing to increased energy consumption and secondary material processing demands.

1.2 The Problem of Simulation

As documented by Sturm and Schäfer [3], this domain has progressed considerably from its early emphasis on rudimentary thermal identification of localized overheating zones toward an integrated evaluation of the complete production sequence. Contemporary simulation platforms incorporate sophisticated functionalities, including phase-transformation modeling, coupled fluid–structure interaction schemes and more recently data-driven predictive architectures grounded in machine learning, which are reported to deliver forecasts of component soundness. Still, a critical reappraisal of the existing body of work exposes a fundamental yet underexplored methodological concern, the issue of empirical verification. Vitally downstream cleaning and finishing operations implemented to strip residual molding aggregates, particulate debris, and superficial impurities from cast surfaces exert a direct influence on the detectability and morphological characterization of flaws during subsequent inspection stages. This circumstance introduces a potentially systematic observational distortion that, in our assessment, has not received adequate critical scrutiny within the broader research community.

1.3 The Validation Gap

Conventional cleaning methods, possess significant limitations that may systematically underestimate true defect populations [2][5]. These methods may leave subsurface defects undetected, alter defect morphology through mechanical deformation, or introduce secondary artifacts that complicate inspection. High-pressure water jet cleaning has gained increasing acceptance as an alternative finishing process for castings. The literature suggests advantages in defect revelation capability, environmental compliance, and worker safety [5][7]. Yet, no systematic review has examined how the choice of cleaning validation method affects reported accuracy of simulation-based defect prediction models.

2. CASTING DEFECTS.

Shrinkage Porosity: In cast irons, this phenomenon is rendered inherently complex by the volumetric expansion associated with graphite precipitation during the eutectic solidification stage, an effect that serves to offset, at least partially, the contraction of the primary austenite phase [3,4]. **Sand Inclusions and Adhesion:** These imperfections originate from erosion of the molding. Such surface-bound discontinuities pose particular difficulties for downstream finishing operations, including machining processes. **Oxide Films and Cold Shuts:** These structural irregularities arise when oxidized surface layers become entrained within the molten metal stream under conditions of turbulent cavity filling. **Gas Porosity:** This category of defect is attributable either to the solution of dissolved gaseous species from the liquid metal during solidification or to the liberation of volatiles from the mold formulation. Gas porosity characteristically presents as discrete internal cavities, which may assume spherical, elongated, or irregular morphologies depending upon the prevailing solidification dynamics and gas nucleation conditions.

3. SIMULATION-BASED DEFECT PREDICTION METHODOLOGIES

The advancement of casting process simulation over the past twenty-five years marks a substantial, albeit partial, technological accomplishment. Sturm and Schäfer [3] document this evolutionary arc, observing that the discipline has transitioned from its original function forecasting thermal hotspots and solidification pathways. The capacity to predict casting defects in iron-based alloys with greater fidelity was substantially advanced through the adoption of microstructural simulation methodologies. According to Sturm and Busch [8], To achieve quantitatively dependable defect forecasts, they assert that solidification modeling had to be interfaced with computations of density evolution and solute redistribution, permitting a thorough assessment of the relationship between solidification structure and melt feeding dynamics. The fundamental physics of casting solidification is governed by the heat equation with phase change:

$$\rho c_p \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T) + \dot{q}_{\text{latent}}$$

where $\dot{q}_{\text{latent}}$ represents latent heat release during phase transformation. The Niyama criterion remains widely used for shrinkage prediction: $N_y = G/\sqrt{\dot{T}}$, where G is thermal gradient and $\dot{T}$ is cooling rate. Lower Niyama indicate higher shrinkage porosity risk [4].

3.1 Machine Learning Integration

The convergence of artificial intelligence and data-driven algorithms with conventional simulation platforms confers several operational advantages: the capacity to generate expeditious forecasts without recourse to resource-intensive computational fluid dynamics solvers, the ability to discern latent patterns across multidimensional parameter regimes, and the facility for in-process adaptive control during manufacturing operations. Shah and Began [1] specifically delineate the deployment of AI/ML-based surrogate models.

4. POST-PROCESSING CLEANING METHODS

High-pressure water jet cleaning constitutes a technique that employs pressurized aqueous media—typically within the range of 680–1360 bar for high-temperature alloy systems and 204–408 bar for aluminum-based materials—to abrade and dislodge residual molding media without introducing secondary contamination [5]. The utilization of high-pressure water streams for component decontamination and surface preparation represents a widely adopted and historically well-established practice across diverse industrial sectors. Water jet cleaning can be applied in two stages [2][5]: Primary Operation for gross removal of mold material (90–100% removal) and Secondary Operation for fine removal from blind holes, internal passageways, and recesses inaccessible to primary cleaning.

5. VALIDATION AND SUSTAINABLE MANUFACTURING

As highlighted by Stefanescu [4], the published record indicates that high-pressure water jet cleaning provides enhanced defect identification capabilities. For simulation-based defect prediction, validation against water jet-cleaned surfaces provides a more complete and accurate ground truth. The combination of simulation-based defect prediction with water jet cleaning validation enables closed-loop quality control. As described in recent literature [1], data-centric near-real-time intelligent process control represents the Industry 4.0 paradigm for foundry operations.

6. CONCLUSION

This review has explored both the current state of simulation-based defect prediction in iron casting and the critical role that cleaning methodologies play in model corroboration. Process simulation has advanced to integrate microstructural modelling and data-driven learning techniques. High-pressure water jet cleaning, in contrast, affords enhanced defect visualization. The validation protocol selected directly influences the reported accuracy of predictive systems, and the combined use of computational prediction with water jet-based inspection supports broader objectives of sustainable production.

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Biographies



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