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POROSITY, DEFECT CONNECTIVITY AND TIGHTNESS IN Al-Si-Cu alloys PRODUCED BY HPDC: FOCUSED SYSTEMATIC REVIEW AND LEAKAGE RISK FRAMEWORK

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Summary

High Pressure Die Casting (HPDC) of Al-Si-Cu alloys is widely used in the production of critical industrial components that require high tightness. However, the formation of porosity resulting from the entrapment of gases and contraction during solidification compromises the functional reliability of these parts. This focused systematic review integrates porosity formation mechanisms, process parameters, and their impacts on tightness performance, based on a structured search in the Web of Science, which resulted in a final portfolio of 12 articles selected by explicit eligibility criteria and comparative analysis. The results demonstrate that the volumetric fraction of porosity, alone, is not sufficient to predict functional failures, with connectivity, percolation, nature of defects and proximity to the surface being the most relevant factors for the risk of leakage. The most used characterization methods - metallography, X-ray radiography and micro-computed tomography (micro-CT) - and the main functional tests, with emphasis on the helium leak test and air decay test, are also critically discussed. Finally, a conceptual framework of industrial applicability is proposed that integrates process parameters, morphology and connectivity of defects, detection methods and functional validation of tightness, contributing to technical decision making in HPDC components subjected to severe sealing requirements.

Keywords: HPDC. Porosity. Tightness. Al-Si-Cu alloys. Risk of leakage.

1 Introduction

The aluminum alloys of the Al-Si-Cu system are widely used in the manufacture of high-liability industrial components, especially in the automotive, hydraulic and brake system sectors, due to the combination of low density, good mechanical strength, high fluidity and excellent filling capacity for complex geometries. Among the alloys most used in this context are A380, ADC12 and AlSi9Cu3, often processed by High Pressure Die Casting (HPDC), a

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technology that enables high productivity, dimensional repeatability and good surface finish (NIU et al., 2000; ADAMANE et al., 2015; LORDAN et al., 2022).

Despite these technological advantages, the HPDC process has a high susceptibility to the formation of internal defects, especially porosity associated with gas entrapment during mold filling and volumetric contraction during solidification. In critical applications, these defects compromise not only mechanical properties and structural integrity, but also tightness, understood as the functional ability to prevent the formation of continuous leakage paths between a pressurized region and the outer surface of the component (CAO et al., 2020; NOURIAN-AVVAL; FATEMI, 2020; SOARES et al., 2023).

The specialized literature presents a vast scientific production on porosity formation mechanisms, influence of process parameters, vacuum systems, mold design and metallurgical control. However, such studies are often conducted in a fragmented manner, with a strong emphasis on quantification or mitigation of porosity, but with less integration between defect morphology, three-dimensional connectivity and functional performance of tightness. As a result, the transition between the metallurgical defect and the functional failure is still treated in an insufficiently systematized way (LORDAN et al., 2022; NOURIAN-AVVAL; FATEMI, 2020).

Given this scenario, a functionally oriented approach is necessary, capable of critically consolidating the available evidence and organizing knowledge in a way that is applicable to the industrial environment. The present article responds to this need by structuring a systematic review focused on HPDC, Al-Si-Cu alloys, porosity, and tightness, culminating in the proposition of an integrated framework for leak risk assessment, understood here as a conceptual synthesis derived from convergent evidence, and not as a model empirically validated by the study itself.

2 Research problem and objective

Despite the advancement of the literature on porosity formation and mitigation in HPDC, there is still a lack of syntheses that integrate, in a functionally oriented way, process parameters, defect morphology and connectivity, and tightness performance in Al-Si-Cu alloys.

Thus, this study aims to critically consolidate the state of the art on the mechanisms of porosity formation, process control strategies and their impacts on the tightness of Al-Si-Cu alloys produced by HPDC, proposing an integrated framework for leak risk assessment.

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To operationalize this objective, the review was guided by the following research questions:

(i) Which process parameters in HPDC most influence the formation and morphology of porosity in Al-Si-Cu alloys?;

(ii) To what extent do connectivity and the location of defects, and not just their volumetric fraction, control the risk of leakage?;

(iii) Which characterization and functional testing methods are most suitable to correlate porosity and tightness in an industrial context?

3 Theoretical foundation

3.1 HPDC and Al-Si-Cu alloys in critical applications

The HPDC process consists of rapid filling of the mold cavity under high pressure, followed by solidification under mechanical load. This route is particularly attractive for the production of components with complex geometries, relatively thin walls and strict dimensional requirements. In Al-Si-Cu alloys, this process is widely used in housings, hydraulic bodies, automotive components, and parts subjected to mechanical and sealing stresses (NIU et al., 2000; LORDAN et al., 2022).

However, the fast-fill dynamics itself, associated with the flow turbulence and the short thermal solidification time, makes the process sensitive to the formation of internal defects. This condition explains why the discussion about quality in HPDC cannot be restricted to productivity and geometric repeatability; It must necessarily include analysis of the internal integrity and functional behavior of the component in service.

3.2 Porosity formation and influence of process parameters

Porosity in HPDC-produced parts can be broadly classified into gas porosity and shrinkage porosity. The first is associated with air entrapment during filling, the presence of dissolved gases, and the decomposition of lubricants; the second results from volumetric contraction in poorly fed regions during solidification (NIU et al., 2000; NOURIAN-AVVAL; FATEMI, 2020). In HPDC, gaseous porosity tends to assume greater relevance, since the high injection speeds favor turbulent flow and air incorporation.

The literature converges by indicating that variables such as the speed of the first and second injection phases, transition position between phases, intensification pressure, liquid

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metal temperature, and mold temperature directly influence the formation, distribution, and morphology of pores. Excessive speeds can amplify turbulence and gas trapping; insufficient speeds can promote incomplete filling or premature solidification. On the other hand, the intensification pressure tends to contribute more strongly to the reduction of porosity by shrinkage than to the elimination of trapped gases (ADAMANE et al., 2015; LI et al., 2023; ZHANG et al., 2024).

In addition to pores, recent studies reinforce the importance of bifilms, that is, folds of surface oxides incorporated into the liquid metal during flow. These defects act as non-adhered internal surfaces and can favor pore nucleation, preferential growth of discontinuities, and the formation of internal trajectories that are more susceptible to percolation, with a direct impact on seal integrity (CAO et al., 2020).

3.3 Use of vacuum, mold design and tightness

Among the strategies for mitigating gaseous porosity, the use of vacuum stands out as one of the most effective. The final portfolio studies converge in showing that vacuum-assisted HPDC reduces the amount of air in the mold cavity, decreases the volumetric porosity fraction, and improves mechanical properties and functional reliability. However, the effectiveness of this strategy depends on the vacuum level achieved, the synchronism with the injection cycle and the adequate design of the mold ventilation and sealing systems (NIU et al., 2000; SZALVA; ORBULOV, 2019; SOARES et al., 2023).

The design of the mold also exerts a decisive influence. Poorly dimensioned feed channels, attacks, vents, and overflows can lead to recirculation zones, air trait, and unfavorable defect distribution. In the opposite direction, a more progressive and targeted filling contributes to reducing turbulence, expelling oxidized metal, and minimizing the formation of critical pores near the surface (ZHOU et al., 2014; LORDAN et al., 2022).

From a functional point of view, tightness does not simply depend on the presence of pores, but on the existence of continuous leakage paths. Thus, the connectivity of the defects, their internal percolation and their proximity to the pressurized surface become more relevant than the mere global volumetric fraction. This understanding represents the conceptual basis of the present work and guides the critical interpretation of the results of the review (CAO et al., 2020; NOURIAN-AVVAL; FATEMI, 2020; SOARES et al., 2023).

4 Methodology

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The research was conducted through a focused systematic review of the literature, structured from the procedure proposed by Medeiros et al. (2015), based on adaptation of the ProKnow-C method, and interpreted in the light of the typology of focused systematic review discussed by Grant and Booth (2009). The methodological strategy was organized to ensure traceability, reproducibility, and coherence between the research problem, the descriptors used, and the final portfolio selected, without claiming quantitative exhaustiveness typical of classic systematic reviews with a broad scope.

The bibliographic search was carried out on January 10, 2026 in the Web of Science - Main Collection database, selected for its relevance and scope in the areas of Engineering, Materials Science and Manufacturing. The title, abstract and keywords fields were searched based on the following expression: ("high pressure die casting" OR HPDC OR "pressure die casting" OR "vacuum die casting") AND (porosity OR "gas porosity" OR "shrinkage porosity" OR "gas entrapment") AND ("Al-Si-Cu" OR A380 OR ADC12 OR "AlSi9Cu3") AND ("leak tightness" OR "pressure tight" OR leakage OR "leak test").

Table 1 - Summary of the selection stages of the bibliographic portfolio

Step/Filter	Criterion applied	Records
Initial search	Structured search in the Web of Science with the four thematic groups: process, defect, material and functional requirement.	186
Filter 1	Main time frame from 2015 to 2026, English language and documentary type article/review. Two previous classical studies were maintained for conceptual and historical-causal relevance.	142
Filter 2	Preliminary screening by thematic descriptors in the titles, excluding studies without simultaneous adherence to process, material, and defects.	38
Filter 3	Analytical reading of the titles to verify adherence to the scope HPDC + Al-Si-Cu + porosity + functional requirement, excluding thematic duplications and lateral studies.	21
Filter 4	Reading of the abstracts and confirmation of the direct relationship with porosity, process parameters, characterization and/or tightness, followed by final consensual checking of the portfolio.	12

Source: prepared by the author based on the methodological strategy of this review.

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Although the main time frame favored publications between 2015 and 2026, two previous studies were maintained due to their classic character in explaining the mechanisms of porosity formation and the role of process design in HPDC: Niu et al. (2000) and Zhou et al. (2014). This decision was made due to conceptual relevance, and not due to temporal proximity, since both support the causal basis used in the subsequent discussion.

Generative AI tools were used exclusively as operational support in the initial organization of the retrieved records, in the standardization of bibliographic fields, and in the preliminary signaling of recurring terms. No eligibility decisions, interpretive reading, critical synthesis, or substantive scientific writing have been delegated to AI. All methodologically critical decisions were made by the authors, in accordance with the principle of full human supervision and subject to the journal's editorial policy.

The final portfolio of 12 articles reflects an intentional restriction of the inclusion criteria to studies that simultaneously correlate the HPDC process, Al-Si-Cu family alloys, porosity, and functional tightness requirements. It is, therefore, a focused or thematic systematic review, whose objective is to critically integrate convergent evidence in a specific technical niche, rather than to produce extensive coverage of all related literature.

4.1 Eligibility criteria, extraction and analysis

Although the main time frame favored publications between 2015 and 2026, two previous studies were maintained due to their classic character in explaining the mechanisms of porosity formation and the role of process design in HPDC: Niu et al. (2000) and Zhou et al. (2014).

Generative AI tools were used exclusively as operational support in the preliminary stages of organization and initial screening of records, without generating scientific text, without interpreting the results, and without automating inclusion or exclusion decisions. All critical eligibility decisions were conducted by the authors, through technical judgment and analytical reading of the abstracts.

The final portfolio consisted of 12 studies, including experimental and review articles, all related to the behavior of aluminum alloys processed by HPDC. Investigations on A380, ADC12 and AlSi9Cu3 predominate, as well as studies exploring the effects of injection speed, intensifying pressure, vacuum use, microstructure and defect connectivity on mechanical properties and functional integrity. For analytical purposes, the studies were classified

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according to their adherence to tightness at three levels: direct evidence, when the work includes a leak test or explicit functional discussion; strong indirect evidence, when the architecture of the defects is correlated with the probability of percolation; and mechanistic evidence of support, when the study causally subsidizes the formation or mitigation of defects.

5 Results and discussion

5.1 Characterization of the final portfolio

From the methodological point of view, there was a predominance of experimental studies supported by real casting by HPDC or vacuum die casting, combined with metallographic characterization techniques and non-destructive methods. In a smaller number, there are revisions aimed at consolidating the state of the art. This configuration reinforces that the field has good maturity in terms of investigating the mechanisms of defect formation, but there is still a lack of studies that quantitatively close the link between three-dimensional morphology of defects and effective leakage rate.

The comparative analysis of the portfolio shows a high presence of terms related to process, porosity, vacuum, A380 and mechanical properties. On the other hand, there is less explicit centrality of descriptors associated with leak, leak test and leak tightness, which reinforces the hypothesis that the literature still deals insufficiently integrated with the transition between metallurgical defect and functional failure. Relevant heterogeneities are also observed regarding the alloy analyzed, geometry of the part, experimental scale, characterization method and presence or absence of direct functional validation, which recommends caution in the face of excessive generalizations.

Table 2 - Final bibliographic portfolio and thematic contribution of the selected studies

Author/Year	Study focus	League/Context	Contribution, functional adherence and level of evidence
Niu et al. (2000)	Vacuum-assisted HPDC	Aluminum Alloys in HPDC	Classic base on reducing gaseous porosity and improving internal quality. Strong indirect evidence for tightness, as it relates vacuum and internal integrity.
Zhou et al. (2014)	Process design and forced mixing in R-HPDC	A380	Discusses process design, flow, and internal integrity. Supporting mechanistic evidence,

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Author/Year	Study focus	League/Context	Contribution, functional adherence and level of evidence
			with relevance to critical defect zones.
Adamane et al. (2015)	Review of injection parameters, porosity and mechanical properties	High Pressure Al-Si	Synthesizes the effect of operating parameters on defect formation. Supporting mechanistic evidence, without direct functional validation.
Medeiros et al. (2015)	Systematic review method and bibliometrics	Methodological procedure	It methodologically supports the search and filtering of this review; it is not part of the empirical basis of tightness.
Szalva and Orbulov (2019)	Effect of vacuum on mechanical properties	AlSi9Cu3(Fe)	It reinforces the role of vacuum in defect reduction and reliability. Strong indirect evidence for functional performance.
Cao et al. (2020)	Pore, stress concentration and mechanical damage in vacuum die casting	Vacuum Cast Alloys	It supports the interpretation of the role of pores and bifilms in functional criticality. Strong indirect evidence, oriented to the architecture of the damage.
Nourian-Avval and Fatemi (2020)	Comparison between metallography, radiography and micro-CT	Al melted under high pressure	It underlies the discussion on 3D connectivity and sensing capability. Strong indirect evidence for leak paths, although no leak test.
Lordan et al. (2022)	HPDC Advancements Review	State of the art of the process	It offers a broad view of technological advances and process limitations. Mechanistic evidence of technological support and contextualization.
Soares et al. (2023)	Characterization of vacuum-injected alloys and the effect of T6	Vacuum-assisted HPDC	It relates internal quality, vacuum and component reliability. Strong indirect evidence, with conceptual proximity to watertightness.
Li et al. (2023)	Effect of process parameters and wall thickness	A380	It reinforces the influence of operational parameters on microstructure and porosity. Supporting mechanistic evidence.
Zhang et al. (2024)	High-speed transition position and porosity	Al-Si-Mn-Mg for giga casting	Updates the discussion on fine control of filling and defects. Supporting

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Author/Year	Study focus	League/Context	Contribution, functional adherence and level of evidence
			mechanistic evidence, with a validity domain distinct from giga casting.
Grant and Booth (2009)	Types of revisions	Review methodology	It supports the characterization of the methodological design as a focused systematic review; it is not part of the empirical basis of tightness.

Source: prepared by the author.

From the methodological point of view, there was a predominance of experimental studies supported by real casting by HPDC or vacuum die casting, combined with metallographic characterization techniques and non-destructive methods. In a smaller number, there are revisions aimed at consolidating the state of the art. This configuration reinforces that the field has good maturity in terms of investigating defect formation mechanisms, but still lacks syntheses functionally oriented to tightness.

The thematic recurrence analysis shows a high presence of terms related to process, porosity, vacuum, A380 and mechanical properties. On the other hand, there is less explicit centrality of descriptors associated with leak, leak test and leak tightness, which reinforces the hypothesis that the literature still treats the transition between metallurgical defect and functional failure in an insufficiently integrated way.

5.2 Integrated synthesis between process, defect, connectivity and tightness

Table 3 - Integrated synthesis: process x defects x connectivity x detection x functional implication

Process element	Predominant type of defect	Connectivity / nature of evidence	More adherent method of evaluation	Functional implication
High injection speed and turbulent filling	Gaseous porosity and incorporation of bifilms	It can favor interconnected paths; evidence predominantly inferred from the architecture of the defects and the physics of the flow.	micro-CT for connectivity; Helium Leak Test for microleaks	Increases the risk of leakage even with low overall porosity.
Insufficient or poorly synchronized intensifying pressure	Porosity due to shrinkage and localized defects	It tends to generate less critical defects when isolated, but	Metallography, radiography and	It compromises local integrity and can reduce

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Process element	Predominant type of defect	Connectivity / nature of evidence	More adherent method of evaluation	Functional implication
		relevant in areas close to the surface; indirect evidence.	correlation with functional assay	the functional safety margin.
Absence or low vacuum efficiency	Elevation of the gaseous porosity fraction	Increases the probability of interconnection between defects; Strong indirect evidence in studies with vacuum die casting.	Comparison between radiography, micro-CT and leak tests	Reduces reliability in pressurized components.
Improper channel design, attacks, and overflows	Air trapping and defect concentration in critical regions	Connectivity may become regionally high; evidence inferred by simulation and spatial distribution of defects.	Filling Simulation + Micro-CT + Radiography	Generates preferred points of failure and leakage.
Defects near the pressurized surface	Functional percolation microchannels	The proximity to the surface enhances the effect of connectivity; Here the functional grip is the most direct.	Helium leak test and air decay test	It is the most critical scenario for loss of tightness.

In summary, the portfolio studies converge by demonstrating that process variables such as vacuum use, flow control and mold design are more relevant for tightness than the simple reduction of the total pore volume. Even so, the strength of the evidence is not homogeneous: it is more robust when there is associated 3D characterization and functional testing, moderate when the interpretation stems from the architecture of the defects, and more incipient when the inference is based only on mechanistic foundations.

Table 3 shows that the relationship between porosity and tightness is not linear or dependent exclusively on the volumetric fraction of defects. Isolated gaseous porosity, typically spherical and disconnected, may have limited functional impact. In contrast, defects associated with bifilms and interconnected networks have high criticality, as they favor continuous leakage trajectories.

As summarized in Figure 1, the functional criticality of porosity does not result only from its presence, but from the combination of connectivity, percolation, and proximity to the surface, which defines the possibility of forming continuous leakage paths. In this sense, the

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framework should be read as an analytical framework for industrial prioritization, and not as a closed universal criterion.

In summary, the portfolio studies converge by demonstrating that process variables such as vacuum use, flow control and mold design are more relevant for tightness than the simple reduction of the total pore volume. This finding reinforces the need for an integrated approach between process, characterization and functional validation.

6 Conceptual framework and industrial application

The proposed framework converges with studies that associate process and porosity, but advances by shifting the analytical focus from the isolated volumetric fraction to the causal chain that links defect formation, connectivity/percolation, and failure in tightness tests. In other words, porosity is no longer treated only as a metallurgical imperfection and is interpreted as a functional risk variable. Its validity domain, however, remains centered on HPDC components of Al-Si-Cu alloys and should not be automatically extrapolated to other die casting routes, other alloys, or scenarios such as giga casting without specific validation.

In an industrial environment, the framework can be operationalized through a sequence of technical decisions:

(i) Definition and control of critical HPDC parameters, with emphasis on injection speed, phase transition, intensification pressure and vacuum level;

(ii) Selection of critical samples for internal characterization by radiography and/or micro-CT;

(iii) Preliminary quantification of operational descriptors, such as density of subsurface defects, critical distance to the pressurized surface and extension of interconnected networks;

(iv) Correlation between morphology/connectivity and results of functional tests, such as helium or air decay;

(v) Construction of risk matrices by part family, allowing you to prioritize regions, geometries and process windows most susceptible to leak failures.

Figure 1 - Conceptual framework for leak risk assessment in HPDC components, integrating process parameters, defect formation, connectivity/percolation, detection methods and functional validation

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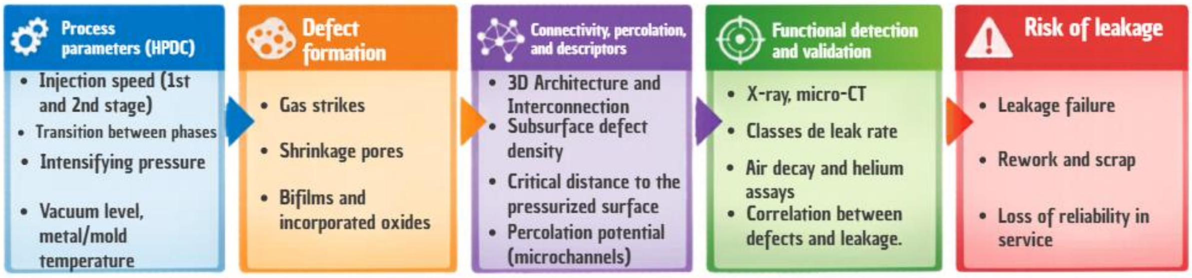

This operationalization is particularly useful in brake components, hydraulics, and high-liability automotive parts, where requirements for zero leakage and high service reliability impose a direct connection between metallurgical engineering, process engineering, and functional validation. As a future agenda, studies that correlate micro-CT and leak rate, predictive models by part family, and cross-validation between filling simulation, defect architecture, and functional testing stand out.

6.1 Limitations of the study

The focused systematic review demonstrated that porosity control in Al-Si-Cu alloys produced by HPDC remains a central theme for obtaining components with high functional integrity. The analyzed portfolio shows that porosity, whether of gaseous origin or by shrinkage, continues to be one of the main limiting factors for the reliability of parts submitted to pressurization, although the strength of the evidence varies according to the type of characterization and the presence of functional validation.

The results reinforce that the simple reduction of the volumetric fraction of porosity does not guarantee tightness. Functional criticality depends mainly on the connectivity of the defects, their percolation capacity, their nature, and their proximity to the pressurized surface. From this perspective, the integration between three-dimensional characterization methods and functional tests becomes indispensable for the robust assessment of the risk of leakage.

The proposed conceptual framework offers an interpretative framework based on the critical consolidation of the literature, contributing to bring metallurgical control closer to the functional requirements of sealing. Its main advance is to transform the porosity analysis into a causal reasoning that connects process parameters, defect architecture, detection methods and functional failure, respecting, however, the validity domain of the corpus analyzed.

As future perspectives, the following stand out: the development and validation of operational connectivity metrics applicable to the industrial routine; the quantitative correlation between vacuum level, three-dimensional architecture of the defects, critical distance to the

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surface and risk of leakage; and the integration between filling/solidification simulation, micro-computed tomography and functional tightness tests. These advancements can extend the predictive capability of die casting engineering, bringing metallurgical control closer to zero-leakage functional requirements.

7 Conclusions

The systematic review showed that porosity control in Al-Si-Cu alloys produced by HPDC remains a central theme for obtaining components with high functional integrity. The analyzed portfolio shows that porosity, whether of gaseous origin or by retraction, continues to be one of the main limiting factors for the reliability of parts submitted to pressurization.

The results reinforce that the simple reduction of the volumetric fraction of porosity does not guarantee tightness. Functional criticality depends mainly on the connectivity of the defects, their percolation capacity and their proximity to the pressurized surface. From this perspective, the integration between three-dimensional characterization methods and functional tests becomes indispensable for the robust assessment of the risk of leakage.

The proposed conceptual framework offers an interpretative framework based on the critical consolidation of the literature, contributing to bring metallurgical control closer to the functional requirements of sealing. Its main advance is to transform porosity analysis into causal reasoning, which connects process parameters, defect architecture, detection methods and functional failure.

As future perspectives, the following stand out: the development of operational connectivity metrics applicable to the industrial routine; the quantitative correlation between vacuum level, three-dimensional architecture of defects and risk of leakage; and the integration between filling/solidification simulation, micro-computed tomography and functional tightness tests. These advancements can extend the predictive capability of die casting engineering, bringing metallurgical control closer to zero-leakage functional requirements.

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