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Introduction

1.1 Background and Importance of Inclusion Control in Steels

Steel remains the backbone of modern industry, widely used across sectors such as construction, transportation, energy, and advanced manufacturing [1]. As performance requirements grow ever more stringent—demanding higher strength, improved ductility, enhanced fatigue resistance, and exceptional reliability—the role of microscopic features within the steel matrix has become increasingly critical. Among these microstructural features, non-metallic inclusions represent both a persistent challenge and a potential opportunity in tailoring material properties.

1.1.1 The Ubiquity of Inclusions in Steel

Non-metallic inclusions are inevitably introduced during steelmaking through deoxidation reactions, slag–metal interactions, refractory erosion, and alloying element additions. Even in highly controlled environments, completely eliminating inclusions is thermodynamically and practically impossible [2]. Thus, the challenge lies not in elimination but in control—managing the size, morphology, chemical composition, and spatial distribution of inclusions to minimize harmful effects while exploiting potential benefits.

In aluminum-killed steels (AK steels), where aluminum is used as a strong deoxidizer, inclusions are predominantly composed of aluminum oxide (Al_2O_3), often accompanied by spinel-type compounds or complex oxysulfides [3]. These inclusions can agglomerate, grow and float, or they can be entrapped during solidification, forming defects that impair the final product's mechanical integrity.

1.1.2 From Detrimental to Functional: A Shift in Perspective

Historically, inclusions have been viewed strictly as impurities—undesirable remnants of processing that must be removed to the greatest extent possible. This view dominated the development of clean steel technology, which emphasizes inclusion removal via secondary metallurgy techniques such as argon stirring, vacuum degassing, and flux refining [4]. The resulting steels exhibit lower inclusion counts and better macroscopic cleanliness.

However, more recent research has uncovered a functional role for fine, well-dispersed inclusions, especially in promoting desirable transformations during solidification and cooling [5]. This has led to the concept of oxide metallurgy, where inclusion engineering is deliberately employed to control phase nucleation and grain refinement. For instance, finely dispersed oxide inclusions can serve as nucleation sites for intragranular ferrite (IGF), enhancing the toughness and weldability of high-strength steels [6].

This paradigm shift—from exclusion to inclusion design—has dramatically expanded the metallurgist's toolbox, opening new pathways for microstructure control and property optimization.

1.1.3 Why AK Steels Deserve Special Attention

AK steels represent a major category of commercial steel products, widely used in applications requiring excellent surface quality, deep drawability, or high resistance to aging. Examples include automobile panels, white goods, pipelines, and structural components. However, AK steels are particularly prone to the formation of hard, angular Al_2O_3 inclusions, which tend to be small but stubbornly persistent [7, 8].

These inclusions present several challenges:

- **Poor deformability**: Angular inclusions cannot elongate plastically during hot rolling or forging, causing microcracks or delamination.
- **Tool wear**: Al_2O_3 inclusions are abrasive and accelerate die and mold wear during downstream processing.
- **Fatigue crack initiation**: Inclusions act as stress concentrators and preferential crack initiation sites, especially under cyclic loading.

Because Al_2O_3 inclusions form early in the steelmaking process and have high melting points, their removal via conventional flotation is difficult without stirring or other dynamic means [9]. Thus, controlling inclusions in non-stirred aluminum-killed steel melts presents a distinct scientific and engineering problem.

1.1.4 Strategic Importance of Inclusion Control

Efficient control over inclusions provides multiple advantages:

- **Improved mechanical properties**: Better toughness, fatigue resistance, and ductility.
- **Enhanced processability**: Smoother surface finish, lower die wear, improved weldability.
- **Greater consistency and reliability**: Fewer defects and a narrower range of property variation across batches.
- **Alignment with clean steel standards**: Meeting high-end application requirements (e.g., aerospace, nuclear, automotive).

In a broader industrial context, mastering inclusion control contributes to process optimization, cost reduction, and sustainability. Reducing the reliance on intensive secondary metallurgy, while still achieving functional cleanliness, allows for more energy-efficient and environmentally friendly production routes.

Moreover, as advanced steel grades become more complex—often involving microalloying, thermomechanical processing, and precise heat treatments—the microstructural role of inclusions becomes even more intertwined with the final properties [10]. Inclusion control thus lies at the intersection of fundamental research, process engineering, and performance design.

1.1.5 Challenges in Non-stirred Systems

Most inclusion refinement techniques rely on melt stirring or flotation during secondary metallurgy. However, many steel production scenarios—such as small-batch casting, thin slab casting, or in situ alloy additions—lack stirring, either due to design constraints or cost considerations. In these cases, inclusions can aggregate, sediment, or remain trapped, leading to defects or inhomogeneities in the solidified steel [11].

Studying inclusion control under non-stirring conditions is thus both technically challenging and highly relevant. It requires a deep understanding of:

- Nucleation and growth kinetics of oxide inclusions;
- Thermodynamic stability and interfacial behavior;
- Agglomeration and collision mechanisms;
- Interactions with fluid flow and the solidification front.

The lack of turbulence significantly alters inclusion dynamics compared to conventional ladle metallurgy, making predictive modeling and control even more complex.

1.2 Types and Origins of Non-metallic Inclusions

A systematic understanding of the types and origins of non-metallic inclusions is essential for addressing inclusion control in steels. This section examines inclusions from the perspectives of their formation origin, chemical nature, and typical manifestations in aluminum-deoxidized steel systems, thereby establishing a conceptual foundation for subsequent discussions on inclusion evolution and control mechanisms.

1.2.1 Fundamental Distinction Between Endogenous and Exogenous Inclusions

Non-metallic inclusions in steel are generally classified into two broad categories based on their formation mechanisms and origins: endogenous inclusions and exogenous inclusions.

Endogenous inclusions are generated internally within the molten steel as a result of chemical reactions among dissolved elements or between dissolved elements and gases. Their formation is closely associated with steel composition, deoxidation practice, temperature, and thermodynamic equilibrium conditions [12]. Because they originate within the melt, endogenous inclusions are typically very fine at the moment of nucleation and are characterized by high number densities. Their subsequent evolution is governed by kinetic processes such as diffusion, collision, agglomeration, and flotation [13].

Exogenous inclusions, by contrast, originate outside the steel melt and are introduced through external sources, including slag entrainment, refractory erosion, tundish flux contamination, and reactions between molten steel and casting or nozzle materials. These inclusions often enter the melt with an already appreciable size, exhibit irregular morphologies, and possess complex and heterogeneous chemical compositions. Their sporadic and unpredictable nature makes them particularly difficult to control [14].

In industrial practice, inclusions observed in solidified steel rarely fall strictly into one category. Instead, the final inclusion population often reflects a complex superposition of endogenous formation, exogenous introduction, and subsequent interactions between the two. This complexity complicates both the identification of inclusion origins and the development of effective control strategies.

1.2.2 Typical Endogenous Inclusions in Aluminum-deoxidized Steels

In aluminum-deoxidized steels, endogenous inclusions arise primarily from the strong chemical affinity between aluminum and dissolved oxygen. Due to the extremely high thermodynamic driving force for the Al–O reaction, deoxidation occurs almost instantaneously after aluminum addition.

The most representative endogenous inclusions are Al_2O_3. Al_2O_3 possesses a very high melting point and exhibits poor deformability relative to the steel matrix. Consequently, these inclusions commonly appear in angular, platelet-like, or clustered forms. Because of their rapid formation and high initial number density, Al_2O_3 particles are particularly prone to collision and agglomeration in the molten steel, leading to the development of large inclusion clusters [15].

In addition to single-phase Al_2O_3 inclusions, several other types of endogenous inclusions are frequently observed in AK steels:

- **Complex oxides**, such as Al_2O_3–MnO or Al_2O_3–SiO_2, whose formation depends on the contents of Mn and Si and the sequence of deoxidation reactions;
- **Oxide–sulfide composite inclusions**, typically Al_2O_3–MnS, formed when sulfides precipitate heterogeneously on pre-existing oxide surfaces during solidification or cooling;
- **Nitride-containing inclusions**, such as AlN or mixed oxynitrides, which may form under high nitrogen levels or specific cooling conditions.

These inclusions are not static entities. Instead, their composition, morphology, and interfacial characteristics evolve continuously in response to changes in temperature and melt chemistry, reflecting the integrated history of the metallurgical process.

1.2.3 Inclusion Formation and Evolution During the Deoxidation Process

From a mechanistic viewpoint, the formation of endogenous inclusions during deoxidation can be divided into three stages: nucleation, growth, and subsequent evolution.

In the initial stage, extremely high local supersaturation levels following aluminum addition favor the formation of a large number of nanoscale oxide nuclei, either through homogeneous nucleation or quasi-homogeneous mechanisms. At this stage, inclusions are very small but exceptionally numerous.

As deoxidation proceeds, these fine particles undergo collision and agglomeration driven by Brownian motion, differential settling, and interfacial forces, particularly under quiescent or weakly convective melt conditions. In aluminum-deoxidized steels, this agglomeration tendency is especially pronounced and constitutes a major challenge for inclusion control [16].

In the later stages, inclusions may further react with other dissolved elements in the steel. Oxide surfaces frequently act as preferential nucleation sites for sulfides or nitrides, leading to the formation of composite inclusions with modified interfacial properties and mechanical behavior [17].

1.2.4 Sources and Characteristics of Exogenous Inclusions

Exogenous inclusions originate primarily from non-ideal interactions between molten steel and its surrounding environment during melting, refining, and casting. Common sources include [12, 18]:

- Mechanical entrainment of furnace slag or tundish slag;
- Chemical or mechanical erosion of refractory linings;
- Entrainment of mold or tundish flux during continuous casting;
- Reaction products formed between molten steel and nozzle or ladle materials.

These inclusions are typically characterized by relatively large sizes, irregular morphologies, and complex chemical compositions. Because their formation is not governed by the internal chemical equilibrium of the steel melt, conventional compositional control and deoxidation strategies are often ineffective in mitigating their occurrence.

Even when present in small numbers, exogenous inclusions can act as critical defects in high-quality steels, frequently dominating failure behavior. Their control, therefore, remains a central concern in industrial steelmaking practice.

1.2.5 Coupling and Transformation Between Endogenous and Exogenous Inclusions

It is important to recognize that endogenous and exogenous inclusions do not exist independently in real steel systems. Once introduced into the melt, exogenous inclusions often serve as heterogeneous substrates for the precipitation of endogenous oxides or sulfides, resulting in the formation of large, complex composite inclusions [2].

Conversely, endogenous inclusions that undergo extensive agglomeration may exhibit characteristics similar to those of exogenous inclusions in terms of size and harmfulness. This coupling and mutual transformation blur the distinction between inclusion categories and significantly complicate the analysis of inclusion evolution paths [19].

Understanding this interplay between endogenous and exogenous inclusions is therefore essential for developing realistic models of inclusion behavior and for designing effective inclusion control strategies, particularly under conditions where melt stirring and flotation are limited.

1.3 Classification and Characterization Methods

A rigorous classification and characterization framework is indispensable for understanding the role of non-metallic inclusions in steels. Because inclusions differ widely in composition, morphology, size, and spatial distribution, no single criterion is sufficient to capture their metallurgical significance. This section reviews the principal classification schemes and analytical techniques used in inclusion research and industrial practice, with particular emphasis on their applicability and inherent limitations.

1.3.1 Classification Based on Chemical Composition

One of the most fundamental approaches to inclusion classification is based on chemical composition. According to this scheme, non-metallic inclusions in steels are commonly grouped into oxides, sulfides, nitrides, and composite inclusions.

Oxide inclusions constitute the dominant category in aluminum-deoxidized steels. Typical examples include Al_2O_3, Al_2O_3–SiO_2, and Al_2O_3–MnO systems. Their chemical stability, high melting points, and interfacial characteristics strongly influence their evolution and interaction with the steel matrix [20].

Sulfide inclusions, most commonly MnS, generally precipitate during solidification as the solubility of sulfur decreases. Unlike oxides, sulfides often exhibit better plastic deformability and tend to elongate along the rolling direction during hot working, giving rise to stringer-type morphologies [21].

Nitride inclusions, such as TiN or AlN, form under conditions of high nitrogen activity and strong nitride-forming elements. These inclusions are typically hard and brittle, and their formation is highly sensitive to temperature and cooling rate [22].

Composite inclusions consist of two or more distinct phases, such as oxide–sulfide or oxide–nitride combinations. These inclusions are particularly important in oxide metallurgy, as their complex interfacial structures often exhibit enhanced potency for heterogeneous phase nucleation [23].

While composition-based classification provides valuable thermodynamic insight, it does not fully capture the mechanical or functional effects of inclusions, which are also strongly governed by size, morphology, and distribution.

1.3.2 Classification Based on Morphology and Size

Inclusions may also be classified according to their morphology and size, parameters that are directly linked to their impact on mechanical properties and processing behavior.

Morphologically, inclusions are often described as [24]:

- **Isolated, equiaxed particles**, typically associated with fine endogenous oxides;
- **Elongated or stringer-like inclusions**, commonly sulfides formed during solidification and deformation;
- **Clusters or aggregates**, resulting from collision and agglomeration of fine particles;
- **Irregular, angular inclusions**, frequently indicative of exogenous origin.

From a size perspective, inclusions are often divided into fine (submicron to a few micrometers) and coarse (tens of micrometers or larger) categories. Coarse inclusions are generally considered detrimental, acting as preferential sites for crack initiation and propagation. In contrast, fine and uniformly dispersed inclusions may exert beneficial effects, particularly in promoting grain refinement or intragranular phase nucleation [25].

It is increasingly recognized that inclusion size alone is not a sufficient descriptor. Rather, the combined effects of size, number density, and spatial distribution determine the overall metallurgical response.

1.3.3 Quantitative and Qualitative Characterization Techniques

A wide range of experimental techniques has been developed to characterize inclusions in steels. Among these, scanning electron microscopy coupled with energy dispersive X-ray spectroscopy (SEM–EDS) remains the most widely used tool for routine inclusion analysis, offering a balance between spatial resolution, compositional information, and practical accessibility.

For more precise compositional analysis and elemental mapping, electron probe microanalysis (EPMA) is often employed. EPMA provides superior quantitative accuracy, particularly for complex or multiphase inclusions, albeit at the cost of longer analysis times.

Advanced techniques, such as automated inclusion analysis systems [26], enable statistical evaluation of inclusion populations by analyzing large areas and generating size distributions, number densities, and compositional classifications. These methods are particularly valuable for identifying rare but critical large inclusions.

However, it should be noted that most characterization techniques are inherently two-dimensional, relying on polished cross sections. As a result, three-dimensional inclusion morphology and spatial connectivity are often underestimated or misrepresented, introducing uncertainty into quantitative assessments.

1.3.4 Standardized Inclusion Rating Methods

To ensure consistency in quality control and facilitate communication between producers and end users, several standardized inclusion rating methods have been established. Among the most widely used are ASTM E45 [27] and JIS G0555 [28], which classify inclusions based on morphology and severity levels.

These standards typically categorize inclusions into types such as A (sulfides), B (alumina), C (silicates), and D (globular oxides), with ratings assigned according to inclusion length or area fraction observed in metallographic sections.

While such standards are effective for routine inspection and acceptance testing, they were primarily developed from a defect-elimination perspective. Consequently, they tend to emphasize coarse and elongated inclusions while offering limited sensitivity to fine, dispersed inclusions that may play a functional role in microstructure control.

1.3.5 Limitations of Conventional Classification Approaches

Despite their widespread use, conventional classification and characterization methods suffer from several intrinsic limitations. First, they often treat inclusions solely as defects, without considering their potential functional contributions. Second, static classification schemes fail to capture the dynamic nature of inclusion evolution during processing and solidification.

Moreover, standardized rating systems are generally insensitive to nanoscale inclusions and inclusion–matrix interfacial characteristics, both of which are central to modern oxide metallurgy concepts. As a result, steels with markedly different microstructural behaviors may receive similar inclusion ratings under existing standards.

These limitations highlight the need for more physically informed classification frameworks that integrate thermodynamics, kinetics, and interfacial science. Such frameworks are particularly important for understanding inclusion behavior under non-stirred conditions, where traditional assumptions regarding flotation and removal no longer apply.

1.4 The Concept of Oxide Metallurgy

The concept of oxide metallurgy represents a fundamental rethinking of the role of non-metallic inclusions in steels. Rather than treating inclusions solely as unavoidable defects to be eliminated, oxide metallurgy proposes that inclusions can be deliberately engineered and utilized as active microstructural constituents. This section introduces the historical background, conceptual framework, and metallurgical implications of oxide metallurgy, with particular emphasis on aluminum-deoxidized steel systems.

1.4.1 Historical Background and Emergence of Oxide Metallurgy

The traditional philosophy of steelmaking has long been dominated by the pursuit of cleanliness. Advances in secondary metallurgy, such as vacuum degassing [29], argon stirring [30], and refined slag practices [31], have enabled significant reductions in total oxygen and inclusion content, leading to substantial improvements in mechanical performance and reliability.

However, as steel grades evolved toward higher strength and toughness requirements, it became increasingly apparent that ultra-clean steels did not always exhibit optimal microstructural characteristics. In particular, excessive removal of inclusions was found to limit the availability of heterogeneous nucleation sites during solidification and solid-state phase transformations.

Against this backdrop, the concept of oxide metallurgy emerged as a response to the limitations of the clean steel paradigm. Rather than aiming for the minimum possible inclusion content, oxide metallurgy emphasizes the controlled formation, modification, and stabilization of fine oxide inclusions to achieve specific microstructural objectives.

1.4.2 Fundamental Principles of Oxide Metallurgy

At its core, oxide metallurgy is founded on the recognition that inclusions are governed by the same thermodynamic and kinetic principles as other microstructural features. By tailoring steel composition and processing conditions, it is possible to influence the nucleation behavior, growth kinetics, and interfacial characteristics of oxide particles.

Three fundamental principles underlie oxide metallurgy. First, inclusions should be thermodynamically stable under processing and service conditions, preventing undesirable phase transformations or coarsening [32]. Second, inclusions should be sufficiently fine and uniformly dispersed to avoid acting as stress concentrators [33]. Third, inclusions should possess favorable interfacial relationships with the surrounding matrix, enabling them to interact constructively with phase transformations or dislocation processes [34].

In aluminum-deoxidized steels, these principles are particularly relevant due to the inherent tendency of Al_2O_3 to form large, angular clusters. Oxide metallurgy seeks to mitigate these drawbacks by modifying inclusion chemistry or by promoting composite inclusion structures that exhibit improved interfacial behavior.

1.4.3 Oxide Metallurgy Versus Conventional Clean Steel Concepts

Although oxide metallurgy and clean steel technology share certain objectives, such as improved mechanical properties and reliability, their underlying philosophies differ fundamentally.

Clean steel technology prioritizes the elimination of inclusions, relying on flotation, absorption into slag, and physical removal during refining. Success is typically measured by reduced total oxygen content or lower inclusion counts [35].

Oxide metallurgy, in contrast, prioritizes inclusion functionality rather than inclusion absence. In this framework, the effectiveness of inclusions is evaluated in terms of their ability to influence microstructure, such as promoting grain refinement or facilitating intragranular phase nucleation.

These differing perspectives lead to distinct process strategies. Whereas clean steel practices emphasize stirring and flotation, oxide metallurgy often relies on compositional design and controlled precipitation, particularly under conditions where stirring is limited or undesirable.

1.4.4 Metallurgical Significance of Fine and Dispersed Oxide Inclusions

Fine and uniformly dispersed oxide inclusions can exert profound effects on steel microstructure. By acting as heterogeneous nucleation sites during solidification, such inclusions can refine as-cast grain structures and reduce segregation [36–38].

More importantly, during solid-state transformations, oxide inclusions can facilitate intragranular nucleation of ferrite or other phases, effectively subdividing prior austenite grains [16, 39, 40]. This leads to a reduction in effective grain size and an enhancement of toughness without sacrificing strength.

The efficacy of oxide inclusions in these roles depends strongly on their size, number density, and interfacial energy with the matrix. Excessively large inclusions remain harmful, while excessively small or sparse inclusions may be ineffective. Oxide metallurgy thus seeks an optimal balance rather than an extreme condition.

1.4.5 Scope and Limitations of Oxide Metallurgy in Aluminum-deoxidized Steels

Despite its promise, oxide metallurgy faces inherent challenges in aluminum-deoxidized steels. The strong affinity between aluminum and oxygen favors the rapid formation of Al_2O_3, often leading to uncontrolled nucleation and agglomeration.

Achieving the controlled dispersion of fine oxides in such systems requires careful consideration of thermodynamic stability, kinetic constraints, and process sequence. Furthermore, the absence of melt stirring in certain production routes limits the effectiveness of traditional inclusion modification techniques.

These challenges underscore the need for a deeper mechanistic understanding of inclusion formation and evolution, particularly under non-stirred conditions. Addressing these issues is a central theme of this book and forms the basis for the detailed discussions presented in the subsequent chapters.

1.5 IGF Nucleation and Role of Inclusions

IGF formation represents one of the most significant microstructural phenomena exploited in modern oxide metallurgy. Unlike grain-boundary ferrite, which nucleates at prior austenite grain boundaries, IGF forms within the austenite grains and plays a critical role in refining the effective grain size and enhancing mechanical performance. This section examines the conditions for IGF formation and elucidates the role of non-metallic inclusions as heterogeneous nucleation sites.

1.5.1 Formation Conditions and Metallurgical Significance of IGF

The formation of IGF requires a combination of thermodynamic driving force and suitable nucleation sites within the austenite grains. From a thermodynamic perspective, sufficient undercooling below the equilibrium transformation temperature is necessary to provide the driving force for ferrite nucleation [41]. However, thermodynamics alone is insufficient to explain the preferential formation of IGF.

The metallurgical significance of IGF lies in its ability to subdivide prior austenite grains internally. By forming ferrite plates or laths within the grain interior, IGF effectively reduces the mean free path for crack propagation and suppresses cleavage fracture [42]. As a result, steels containing a high fraction of IGF often exhibit superior toughness and resistance to brittle fracture.

1.5.2 Heterogeneous Nucleation of IGF on Inclusions

Non-metallic inclusions serve as the primary heterogeneous nucleation sites for IGF. The effectiveness of an inclusion as a nucleation substrate is governed by the classical criteria for heterogeneous nucleation, including low interfacial energy between the inclusion and ferrite, favorable crystallographic relationships, and chemical stability at transformation temperatures.

Inclusions that exhibit good lattice matching with ferrite can significantly reduce the nucleation energy barrier, thereby promoting ferrite formation within the austenite grains [43, 44]. In contrast, inclusions with poor interfacial compatibility may remain inert or even suppress intragranular nucleation.

In aluminum-deoxidized steels, the inherent interfacial characteristics of Al_2O_3 with ferrite are generally unfavorable. Consequently, unmodified Al_2O_3 inclusions often exhibit limited nucleation potency unless their surface chemistry or structure is altered through interaction with other elements.

1.5.3 Influence of Inclusion Size, Distribution, and Chemistry

The nucleation potency of inclusions is strongly dependent on their size and spatial distribution. Inclusions that are too small may be ineffective due to insufficient reduction of the nucleation barrier, while excessively large inclusions tend to act as stress concentrators and degrade mechanical properties [45].

An optimal inclusion size range is therefore required to maximize nucleation efficiency while minimizing detrimental effects. In addition, a uniform spatial distribution of inclusions within the austenite grains is essential to ensure widespread IGF formation.

Inclusion chemistry further influences nucleation behavior by determining interfacial energy and chemical stability. Composite inclusions, such as oxide–sulfide systems, often exhibit enhanced nucleation potency compared with single-phase oxides, as their complex interfaces provide multiple favorable nucleation sites [23].

1.5.4 Comparative Nucleation Potency of Different Inclusion Types

Extensive experimental studies have compared the nucleation activity of different inclusion types. Titanium nitrides (TiN) are widely recognized as highly potent nucleation sites due to their favorable lattice correspondence with ferrite [44, 46]. Oxide inclusions, including Al_2O_3-based particles, generally exhibit lower potency unless modified or combined with other phases.

Composite inclusions, particularly those consisting of an oxide core with a sulfide shell, have been shown to exhibit superior nucleation behavior. In such systems, the oxide provides chemical stability, while the sulfide layer improves interfacial compatibility with ferrite.

These findings highlight that inclusion effectiveness cannot be assessed solely based on composition; rather, the interfacial structure and multiphase nature of inclusions play decisive roles.

1.5.5 Literature Perspectives and Remaining Controversies

Although the role of inclusions in IGF nucleation is widely accepted, several unresolved issues remain. One ongoing debate concerns the relative importance of crystallographic matching versus chemical effects in determining nucleation potency. Another concerns the extent to which inclusion-induced local chemical gradients contribute to ferrite nucleation.

Moreover, most existing studies have been conducted under conditions involving melt stirring or intensive secondary metallurgy. The applicability of these conclusions to non-stirred systems remains uncertain. Understanding IGF nucleation under such conditions requires renewed investigation of inclusion formation and evolution mechanisms, particularly in aluminum-deoxidized steels.

1.6 Scientific and Technological Challenges

Despite decades of intensive research and significant advances in steelmaking technology, effective control of non-metallic inclusions remains one of the most challenging problems in physical metallurgy. These challenges arise not only from the inherent complexity of inclusion formation and evolution but also from practical constraints imposed by industrial processing routes. This section outlines the principal scientific and technological challenges that motivate the investigations presented in this book.

1.6.1 Difficulty in Controlling Inclusion Size and Spatial Distribution

One of the central challenges in inclusion control lies in simultaneously regulating inclusion size, number density, and spatial distribution. Thermodynamics dictates which inclusion phases are stable, but it does not uniquely determine their final size or dispersion state. These characteristics are governed largely by kinetic processes, including nucleation rate, growth kinetics, collision frequency, and agglomeration behavior [47].

In aluminum-deoxidized steels, the strong driving force for Al–O reactions leads to rapid and extensive nucleation of Al_2O_3 particles. While this favors the formation of fine inclusions initially, it also increases the likelihood of particle collision and agglomeration, ultimately producing large and harmful inclusion clusters. Preventing this transition from fine dispersion to coarse aggregation remains a fundamental challenge.

1.6.2 Agglomeration and Flotation Limitations Under Non-stirred Conditions

Most conventional inclusion refinement strategies rely heavily on melt stirring, whether through argon bubbling, electromagnetic stirring, or ladle circulation. Stirring enhances inclusion collision, promotes flotation, and facilitates inclusion removal by slag absorption [48].

However, in non-stirred or weakly stirred systems—such as small-scale melts, thin slab casting, or certain in situ alloying processes—these mechanisms are significantly suppressed. Under such conditions, inclusions may remain suspended in the melt, undergo uncontrolled agglomeration, or become entrapped by the advancing solidification front.

The lack of forced convection fundamentally alters inclusion dynamics, rendering many established assumptions invalid. Understanding and controlling inclusion behavior in non-stirred systems therefore requires a re-examination of inclusion kinetics under near-quiescent conditions.

1.6.3 Thermodynamic and Kinetic Uncertainties in Inclusion Evolution

Inclusion evolution is governed by a complex interplay between thermodynamics and kinetics. While thermodynamic calculations can predict stable inclusion phases under equilibrium conditions, real steelmaking processes are inherently non-equilibrium.

Transient temperature gradients, local composition fluctuations, and time-dependent reactions introduce significant uncertainty into inclusion evolution pathways. Moreover, the interfacial energies governing nucleation and growth are often poorly constrained, particularly for complex or composite inclusions.

These uncertainties limit the predictive capability of existing models and complicate efforts to design inclusion populations with targeted characteristics.

1.6.4 Limitations of Current Characterization and Monitoring Techniques

Another major challenge arises from the lack of effective in situ or real-time monitoring tools for inclusion behavior. Most inclusion characterization techniques rely on post-solidification analysis, providing only a static snapshot of a highly dynamic process.

As a result, critical information regarding inclusion nucleation, growth, collision, and transformation during melting and solidification is lost. This disconnect between process dynamics and final microstructure hinders the development of feedback-controlled inclusion engineering strategies.

1.6.5 Integration of Fundamental Understanding with Industrial Constraints

Finally, any scientifically sound inclusion control strategy must contend with practical industrial constraints, including cost, productivity, equipment availability, and process robustness. Techniques that are effective in laboratory-scale experiments may be impractical or uneconomical at industrial scale.

Balancing fundamental insight with industrial feasibility remains a central challenge. Addressing this challenge requires not only improved mechanistic understanding but also the development of simplified, scalable approaches that can be readily implemented in real production environments.

1.7 Industrial Relevance and Application Scenarios

The significance of inclusion control extends far beyond academic interest and directly impacts the performance, reliability, and economic viability of steel products. In industrial practice, even minor deviations in inclusion characteristics can lead to severe quality issues or catastrophic failures. This section discusses the relevance of inclusion control in major application fields and highlights the practical constraints faced by industry.

1.7.1 Inclusion Control Requirements in Major Steel Products

Different categories of steel impose distinct requirements on inclusion characteristics. In **automotive steels**, particularly those used for exposed panels and deep-drawing applications, stringent control of inclusion size and morphology is essential to ensure surface quality and formability. Hard and angular inclusions, such as Al_2O_3 clusters, can initiate surface defects and reduce stamping performance [49, 50].

In **pipeline steels**, inclusion control is critical for ensuring resistance to fatigue, hydrogen-induced cracking, and brittle fracture. Large or elongated inclusions act as stress concentrators under cyclic loading and may serve as initiation sites for crack propagation, especially in sour service environments [51, 52].

Bearing and tool steels represent some of the most demanding applications with respect to cleanliness. Even a single large inclusion can drastically reduce fatigue life. For these steels, the tolerance for exogenous inclusions is extremely low, and inclusion populations must be tightly controlled in both size and distribution.

1.7.2 Industrial Defects Associated with Inadequate Inclusion Control

Inadequate inclusion control manifests in a variety of industrial defects. During continuous casting, Al_2O_3 inclusions are a major cause of nozzle clogging [53, 54], leading to unstable casting conditions and productivity losses. In rolled products, inclusion clusters may result in surface slivers, laminations, or internal cracks [55].

From a service perspective, inclusions frequently act as preferential sites for crack initiation under tensile, fatigue, or impact loading [56–58]. Numerous industrial failure analyses have traced premature fracture back to the presence of coarse or clustered inclusions, underscoring their critical role in determining component reliability.

1.7.3 Economic and Process Constraints in Industrial Steelmaking

While advanced secondary metallurgy techniques can significantly reduce inclusion content, their implementation is constrained by economic and operational considerations. Intensive stirring, prolonged refining times, and complex slag practices increase production costs and energy consumption.

Moreover, not all production routes are compatible with such interventions. Compact furnaces, thin slab casting lines, and specialty alloy production often operate under conditions where extensive stirring is impractical or undesirable. In these cases, reliance on traditional inclusion removal strategies may be insufficient.

1.7.4 Inclusion Control in the Context of Green and Low-carbon Metallurgy

The ongoing transition toward green and low-carbon steelmaking introduces additional challenges for inclusion control. Efforts to reduce energy input, shorten process chains, and minimize slag generation may limit the effectiveness of conventional inclusion removal methods.

At the same time, reduced process flexibility places greater emphasis on intrinsic inclusion control through composition design and controlled precipitation. Developing inclusion engineering strategies that are compatible with low-carbon production routes is therefore becoming increasingly important.

1.7.5 Need for Robust and Scalable Inclusion Engineering Strategies

The industrial scenarios discussed above highlight the need for inclusion control approaches that are not only scientifically sound but also robust, cost-effective, and scalable. Strategies that rely on minimal external intervention and are effective under non-stirred or weakly stirred conditions are particularly attractive.

Such approaches require a deep understanding of inclusion formation mechanisms and evolution pathways, as well as their interactions with solidification and phase transformation processes. Addressing these requirements forms a central motivation for the research presented in this book.

1.8 Objectives and Structure of This Book

The preceding sections have highlighted both the scientific complexity and the industrial importance of non-metallic inclusion control in aluminum-deoxidized steels. Despite substantial progress in clean steel technology and oxide metallurgy, significant gaps remain in our understanding of inclusion behavior, particularly under conditions where conventional stirring and flotation mechanisms are limited. This book is motivated by the need to address these gaps in a systematic and mechanistic manner.

1.8.1 Core Scientific Question

The central scientific question addressed in this book can be stated as follows:

How can effective control of non-metallic inclusions be achieved in aluminum-deoxidized steel systems without relying on strong external interventions such as melt stirring or intensive secondary metallurgy?

This question reflects both a fundamental scientific challenge and a practical engineering constraint. It recognizes that inclusions are an inevitable consequence of steelmaking and seeks to shift the focus from removal to control, modification, and functional utilization.

1.8.2 Research Scope and Conceptual Framework

To address this question, the book adopts a framework that integrates thermodynamics, kinetics, and interfacial science. Inclusion formation is examined as a dynamic process involving nucleation, growth, agglomeration, and transformation, rather than as a static defect population.

Special emphasis is placed on aluminum-deoxidized systems, where the strong affinity between aluminum and oxygen creates unique challenges and opportunities for inclusion engineering. The role of inclusions as functional microstructural elements, particularly in promoting IGF formation, is examined in detail.

1.8.3 Structure and Organization of the Book

The book is organized to guide the reader from fundamental principles to practical implications. Early chapters introduce the thermodynamic and kinetic foundations of inclusion formation and evolution. Subsequent chapters focus on experimental observations, analytical techniques, and modeling approaches used to investigate inclusion behavior.

Later chapters explore strategies for inclusion control under non-stirred or weakly stirred conditions, drawing on both laboratory studies and industrial case analyses.

The final chapters discuss the broader implications of inclusion engineering for advanced steel design and future steelmaking technologies.

1.8.4 Intended Audience

This book is intended for researchers and engineers engaged in physical metallurgy, steelmaking, and materials design, as well as graduate students seeking a deeper understanding of inclusion phenomena. A basic familiarity with metallurgical thermodynamics and microstructural analysis is assumed, but the book is structured to progressively build the necessary concepts.

By bridging fundamental theory and industrial practice, the book aims to serve as both a reference for specialists and a guide for practitioners facing real-world inclusion control challenges.

1.8.5 Methodological and Interdisciplinary Perspective

Finally, this book emphasizes the importance of an interdisciplinary approach to inclusion control. Advances in experimental characterization, computational modeling, and data-driven analysis are integrated to provide a comprehensive understanding of inclusion behavior.

By combining metallurgical theory with modern analytical and computational tools, the book seeks to establish a coherent and forward-looking framework for inclusion engineering in aluminum-deoxidized steels.

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