

Review

Effect of Niobium-Containing Metallic Powders on Microstructural Evolution, Mechanical Performance, and Corrosion Resistance: A Critical Review and Research Perspective

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Abstract

Metallic powder systems containing niobium play a key role in the development of advanced materials for structural, biomedical, energy, and surface-engineering applications. The incorporation of niobium into metallic powders influences particle behavior during processing, phase stability, microstructural evolution, and the resulting mechanical and corrosion properties of consolidated materials. This review examines the scientific and technological advances related to niobium-containing metallic powders, covering powder production routes, particle characterization methods, processing techniques, and performance evaluation. Publications on powder metallurgy, additive manufacturing, thermal processing, surface modification, and corrosion-resistant materials were analyzed to identify relationships among powder characteristics, processing conditions, and material performance. The available evidence indicates that niobium contributes to grain refinement, precipitation control, microstructural stabilization, improved resistance to wear, and localized corrosion. The element also expands the applicability of metallic powders in functional coatings, biomaterials, engineered surfaces, and components manufactured from particulate feedstocks. Current challenges involve powder homogeneity, process reproducibility, economic considerations, and the prediction of long-term service behavior. The analysis highlights niobium's contribution to the design of high-performance metallic powder systems and identifies research directions for developing materials with enhanced reliability and industrial applicability.

Keywords: niobium-containing powders; metallic powder systems; powder processing; particle characterization; powder metallurgy; microstructural evolution



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1. Introduction

Metallic powder systems have become increasingly important in modern manufacturing because they enable the production of components with controlled composition, tailored microstructures, and near-net-shape geometries. Powder-based technologies are currently employed in powder metallurgy, additive manufacturing, thermal spraying, and advanced coating processes, offering opportunities to improve material utilization and enhance engineering performance [1–3]. The continuous expansion of these technologies has spurred significant research to elucidate the relationships among powder characteristics, processing conditions, microstructural evolution, and final material properties [4].

Particle-related parameters, including particle size distribution, morphology, apparent density, and flowability, strongly influence the performance of powder-derived materials. These characteristics affect powder handling, packing behavior, layer deposition, densification kinetics, and defect formation during manufacturing operations [5,6]. Consequently, particle engineering and powder characterization have become essential components of modern powder technology, particularly in applications requiring high dimensional accuracy and reproducible performance.

Among the alloying elements used in advanced metallic materials, niobium has attracted increasing attention for its effects on phase stability, precipitation behavior, grain refinement, and corrosion resistance [7]. In recent years, the growing availability of niobium-containing powders and the development of advanced processing technologies have expanded the potential application of niobium in powder-derived materials [8]. Furthermore, niobium-containing systems have been investigated in fields ranging from additive manufacturing to biomedical engineering, where enhanced microstructural stability and long-term reliability are frequently required [9,10]. The broad scientific relationships connecting powder production, characterization, processing routes, microstructural evolution, corrosion performance, sustainability, and engineering applications are illustrated in Figure 1.

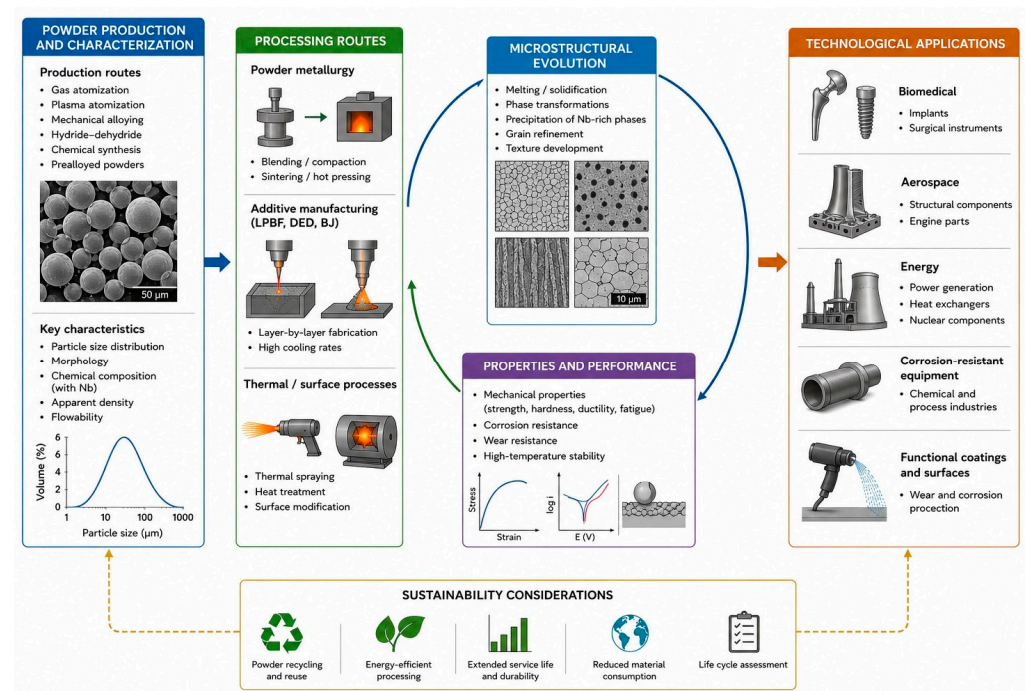


Figure 1. Schematic representation of the processing–microstructure–property relationships governing the behavior and technological applications of niobium-containing metallic powder systems.

To clarify how micrograph selection supports the discussion and maintains reader engagement, selected illustrative micrographs were incorporated into the figures as representative examples of particle morphology, microstructural evolution, and phase-related features reported for metallic powders and niobium-containing powder systems [11–40].

These images support the concepts discussed in the literature, including powder production, particle characterization, and microstructural development [11–40], facilitating the interpretation of complex processing and microstructural phenomena. Research activities conducted at UNIFEI over the last decade provided representative optical and SEM observations incorporated exclusively as illustrative material to facilitate the interpretation of particle morphology, microstructural evolution, and phase-related phenomena discussed in the cited literature.

Metallographic specimens associated with these investigations were prepared using conventional grinding and polishing procedures followed by alloy-specific chemical etching to reveal characteristic microstructural features. Optical characterization was performed using an Olympus BX53M microscope (Olympus Corporation/Evident Corporation, Tokyo, Japan), while higher-magnification observations were obtained with a TESCAN VEGA 3 scanning electron microscope, operating primarily in secondary-electron imaging mode. Typical SEM operating conditions involved accelerating voltages between 5 and 20 kV and working distances between 8 and 15 mm, selected according to particle size, surface morphology, and microstructural scale. The illustrative microstructural images presented throughout this review are intended exclusively as qualitative material to support the interpretation of mechanisms discussed in the cited literature. They should not be interpreted as quantitative datasets for direct comparison among studies to prevent misinterpretation of research findings.

The increasing adoption of advanced powder-processing technologies has intensified interest in niobium-containing metallic powders, as these materials often undergo complex thermal histories during manufacturing [41,42]. Processes such as laser powder bed fusion, directed energy deposition, and advanced sintering involve rapid heating and cooling cycles, steep thermal gradients, and non-equilibrium solidification conditions that can significantly alter phase formation and microstructural stability [3,7,43–53]. Under these conditions, the material’s response depends not only on alloy composition but also on particle characteristics, powder homogeneity, and processing parameters. For niobium-containing systems, these interactions are particularly important because niobium influences diffusion behavior, phase stability, and precipitation phenomena, all of which contribute to the final mechanical and corrosion performance of powder-derived components [31–40,54–60].

Although substantial progress has been made in the study of niobium-containing materials, the available literature remains dispersed across several research domains, including powder metallurgy, additive manufacturing, biomaterials, corrosion science, and surface engineering. Consequently, information concerning powder production, particle characterization, processing routes, microstructural evolution, and engineering performance is often fragmented across specialized disciplines. An integrated assessment is therefore necessary to establish broader scientific connections and identify future research directions relevant to powder technology.

The influence of powder characteristics on processing behavior and final material performance is summarized in Table 1. These parameters constitute the foundation of powder engineering and directly affect densification, microstructural evolution, and engineering reliability.

Table 1. Principal powder characteristics and their influence on processing and performance in metallic powder systems.

Powder Characteristic	Influence on Processing	Influence on Final Properties
Particle size distribution	Packing efficiency and densification	Microstructural uniformity
Particle morphology	Flowability and powder spreading	Defect susceptibility
Surface condition	Particle interaction and oxidation behavior	Corrosion performance
Apparent density	Powder-bed stability	Consolidation efficiency
Chemical homogeneity	Phase formation and diffusion behavior	Mechanical and functional properties

The objective of this review is to provide a comprehensive assessment of niobium-containing metallic powder systems, with emphasis on powder production, particle characterization, processing routes, microstructural evolution, corrosion behavior, sustainability

aspects, and industrial applications. Attention is given to the mechanisms through which niobium influences powder-derived materials and to the opportunities that may support future developments in particulate material engineering.

2. Review Methodology

2.1. Literature Search and Classification

The methodology adopted in this review was designed to identify, classify, and critically evaluate publications addressing niobium-containing metallic powder systems. Particular attention was given to studies examining relationships among powder characteristics, processing conditions, microstructural evolution, corrosion behavior, and engineering performance in powder-derived materials. The objective of the methodological framework was to organize the available literature into coherent thematic categories and facilitate a comparative assessment of the principal scientific developments reported in the field [1–6].

The literature survey was conducted using peer-reviewed journal articles, review papers, conference proceedings, books, and technical reports addressing metallic powders, powder metallurgy, additive manufacturing, particle characterization, niobium-containing alloys, corrosion behavior, and advanced engineering applications. Attention was given to publications describing powder-related phenomena, processing–microstructure relationships, and performance evaluation of powder-derived materials [5–10]. The methodological sequence adopted for literature identification, thematic classification, critical evaluation, and synthesis is presented in Figure 2.

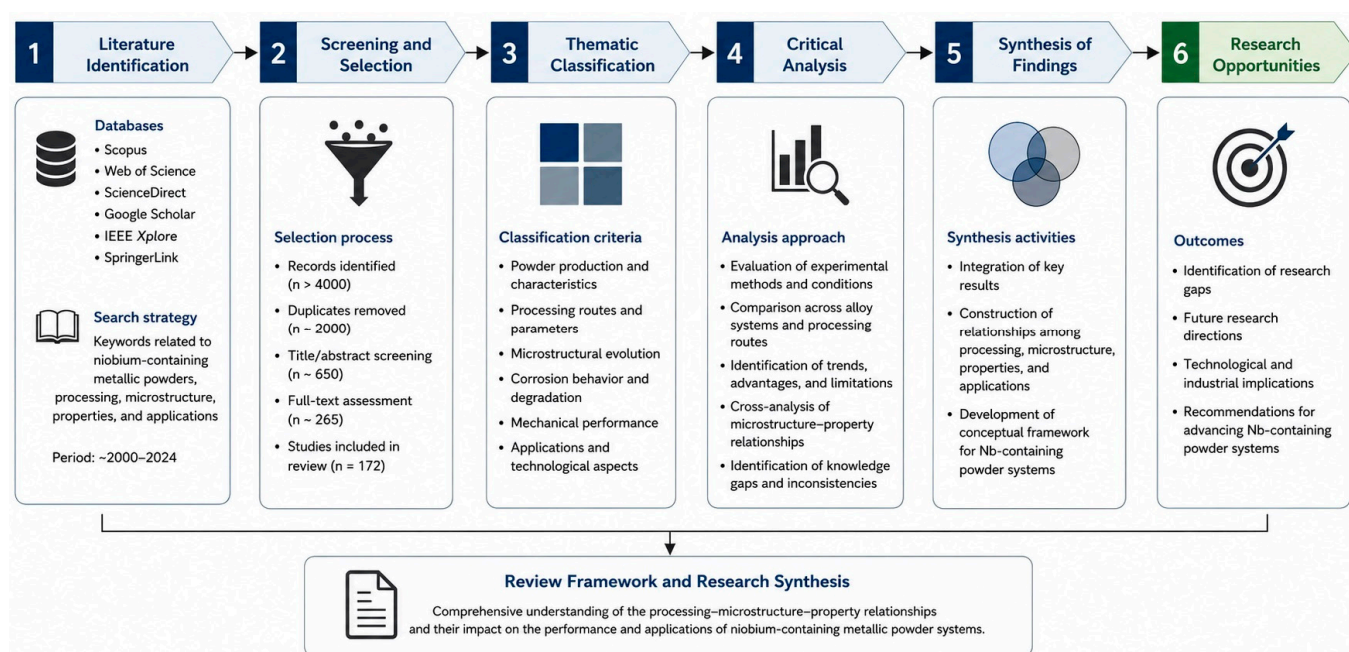


Figure 2. Methodological workflow adopted for the development of this review, including literature identification, screening, thematic classification, critical analysis, and synthesis of research opportunities.

Following identification and screening, the selected publications were classified by their primary scientific focus, enabling systematic comparison of studies on powder production, characterization methods, processing technologies, microstructural evolution, corrosion performance, sustainability, and industrial implementation. This classification framework facilitated identification of convergent findings, knowledge gaps, and emerging research directions reported in the literature [3–10]. This approach facilitated the evalua-

tion of relationships among powder characteristics, processing conditions, microstructural evolution, and engineering performance [3,5–8].

To facilitate a systematic evaluation of the literature, the collected studies were organized into thematic categories according to their primary scientific focus. The classification framework adopted in this review is presented in Table 2.

Table 2. Thematic classification was adopted to organize the literature database used in this review.

Thematic Area	Principal Topics Evaluated
Metallic powder systems	Powder production, morphology, particle size distribution
Particle characterization	Flowability, apparent density, powder quality
Niobium-containing powders	Alloy design, powder composition, functional properties
Processing routes	Powder metallurgy, additive manufacturing, thermal spraying
Microstructural evolution	Phase transformations, precipitation, grain refinement
Corrosion behavior	Passivation, localized corrosion, and electrochemical performance
Sustainability and applications	Recycling, industrial implementation, resource efficiency

The review emphasizes studies that provide detailed information concerning powder characteristics and their influence on processing and performance. Preference was given to publications presenting quantitative analyses, reproducible methodologies, and clear descriptions of powder-processing conditions. Recent studies published during the last decade were prioritized, while classical references were retained when necessary to establish the theoretical foundations of powder metallurgy, particle characterization, corrosion science, and phase-transformation behavior [1–6].

A critical-analysis approach was adopted throughout the review rather than a simple descriptive compilation of published information. The selected literature was evaluated to identify convergent findings, unresolved scientific questions, technological limitations, and future research opportunities. Emphasis was placed on understanding the role of niobium in modifying the behavior of metallic powder systems and on identifying knowledge gaps relevant to the future development of powder-based technologies [7–10].

The resulting framework provides the basis for the subsequent sections of this review, which examine fundamental aspects of metallic powder systems, the characteristics of niobium-containing powders, processing routes, microstructural evolution, corrosion performance, sustainability considerations, and emerging research directions in powder technology.

Rather than functioning solely as a descriptive survey, the review methodology was structured to support critical comparison among studies and to identify factors responsible for differences in reported processing–microstructure–performance relationships across niobium-containing powder systems [7–10].

2.2. Bibliometric Overview of the Reviewed Literature

In addition to the thematic classification adopted in this review, a qualitative bibliometric assessment was conducted to examine the temporal evolution of the scientific literature on niobium-containing metallic powder systems. The objective was not to conduct a formal bibliometric study but rather to identify the principal research trends represented within the body of literature analyzed in this review.

The reviewed publications indicate a progressive expansion of research activity in this field over the last two decades. Early investigations were primarily focused on powder metallurgy fundamentals, powder production technologies, particle characterization methods, and the influence of alloying elements on phase stability and processing behavior [1–10]. As powder-based manufacturing technologies evolved, research efforts increasingly addressed

microstructural development, phase transformations, and the relationships between processing parameters and material performance [11–25].

A significant increase in scientific interest is evident during the period of rapid development of additive manufacturing technologies and advanced powder-processing routes. During this stage, studies expanded beyond conventional powder metallurgy to emphasize process optimization, thermal history effects, corrosion performance, and application-specific alloy development [26–50]. More recently, the literature has increasingly incorporated computational thermodynamics, CALPHAD-based methodologies, sustainability considerations, powder recycling strategies, and data-driven approaches for materials design and process optimization [51–80].

The evolution of the principal research topics represented in the reviewed literature is summarized in Table 3. The observed progression demonstrates how the field has evolved from traditional powder-processing investigations toward integrated studies combining powder engineering, advanced manufacturing, microstructural design, corrosion science, sustainability assessment, and computational materials development.

Table 3. Qualitative evolution of research topics represented in the literature reviewed for niobium-containing metallic powder systems.

Publication Period	Predominant Research Topics
Before 2005	Powder metallurgy fundamentals, powder production, particle characterization
2005–2015	Alloy development, phase stability, powder-processing optimization
2015–2020	Additive manufacturing, microstructural evolution, corrosion behavior
2020–Present	Sustainability, computational materials design, CALPHAD, machine learning, multifunctional materials

The bibliometric trends identified in the reviewed literature suggest that future research will increasingly focus on integrated processing–microstructure–performance relationships supported by computational modeling, advanced characterization techniques, and sustainability-oriented manufacturing strategies. This evolution reflects the growing complexity of powder-based technologies and the increasing demand for materials capable of simultaneously meeting mechanical, corrosion, environmental, and industrial performance requirements.

Although the present assessment is qualitative, the observed evolution of research topics clearly indicates increasing convergence among powder engineering, advanced manufacturing, corrosion science, computational materials design, and sustainability. This multidisciplinary trend provides the foundation for the thematic organization adopted throughout the present review.

3. Fundamentals of Metallic Powder Systems

Metallic powder systems constitute the foundation of numerous manufacturing technologies, including powder metallurgy, additive manufacturing, thermal spraying, and metal injection molding. The performance of powder-derived materials is strongly influenced by powder characteristics established during production, such as particle size distribution, morphology, internal defects, chemical composition, and surface condition [11–13]. Consequently, understanding the fundamental aspects of powder generation and characterization is essential for the development of advanced metallic materials.

Several production routes are currently employed to manufacture metallic powders. Among them, gas atomization, water atomization, plasma atomization, and mechanical comminution are the most widely used industrial techniques. Each route produces powders with distinct particle morphologies, size distributions, and surface characteristics,

which directly influence subsequent processing stages [14,15]. Production routes capable of generating fine or ultrafine powders have attracted increasing attention because reduced particle size may improve sintering kinetics, increase available surface area, and facilitate the manufacture of functional materials. However, very small particles may also introduce challenges related to flowability, agglomeration, powder handling, and oxidation susceptibility during processing [14,15,24].

The growing adoption of powder-based manufacturing technologies has increased the demand for powders exhibiting high reproducibility and controlled particle characteristics. In additive-manufacturing applications, particle morphology and particle-size distribution significantly affect powder spreading, layer uniformity, and process stability [16,17]. The principal powder-production routes and their influence on particle characteristics and manufacturing applications are summarized in Figure 3.

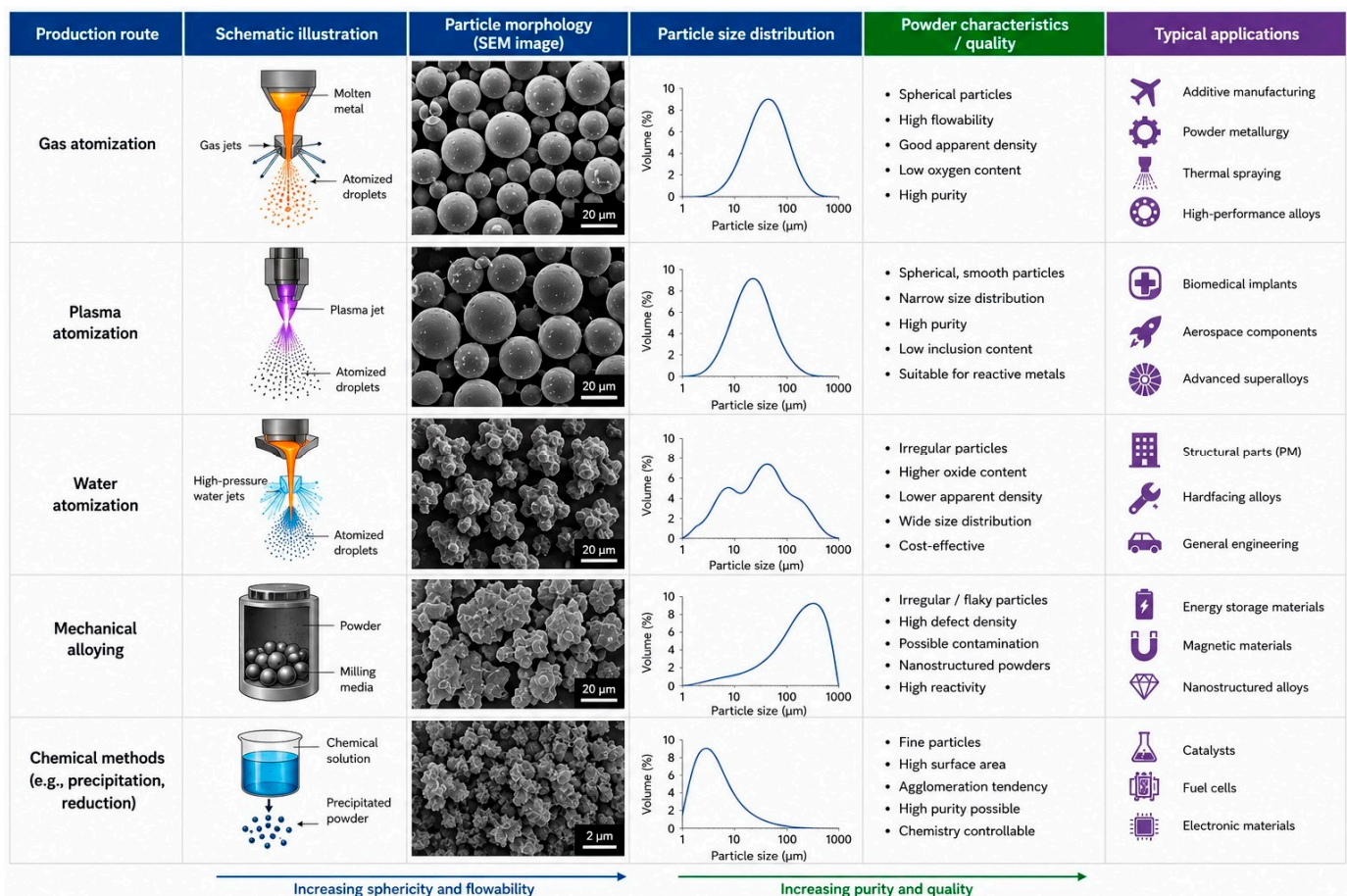


Figure 3. Principal production routes for metallic powders and their influence on particle morphology, particle size distribution, powder quality, and manufacturing applications. Chemical-reduction techniques are commonly associated with the production of relatively fine or ultrafine powders compared with conventional atomization routes [14,15,24].

Particle morphology is one of the most important parameters affecting powder behavior. Spherical particles exhibit superior flowability and packing characteristics when compared with irregular particles, making them particularly attractive for additive manufacturing applications [18,19]. However, irregular particles may be advantageous in certain powder metallurgy operations where mechanical interlocking contributes to green strength and compaction behavior. The influence of particle morphology, therefore, depends on both the manufacturing route and the intended engineering application.

In addition to morphology, particle size distribution plays a critical role in powder performance. Narrow particle size distributions may improve process consistency by reducing variations in powder packing behavior, layer thickness, and local powder-bed density during manufacturing operations [5,20,21]. More uniform particle populations tend to promote reproducible powder spreading, more homogeneous energy absorption, and reduced variability in densification behavior, particularly in powder-bed-based manufacturing processes [5,18,21]. In contrast, broader particle size distributions may enhance packing density by allowing smaller particles to occupy interparticle voids. However, excessive particle-size variation may reduce powder-flow consistency and process reproducibility [20,21]. Consequently, the optimization of particle size distribution is frequently employed to improve powder-bed quality, densification efficiency, and final component integrity [5,20,21].

The desirable particle size distribution depends on the manufacturing route. Additive manufacturing processes often benefit from controlled particle-size ranges that promote uniform layer deposition and stable powder flow. In contrast, certain powder metallurgy applications may tolerate broader distributions when increased packing efficiency is required [18,20,21].

The reuse and recycling of metallic powders have become increasingly important topics in powder technology. Repeated processing cycles may alter particle morphology, surface chemistry, oxygen content, and flowability characteristics, potentially affecting manufacturing consistency and final material properties [22,23]. As a result, continuous powder characterization has become an essential requirement for ensuring process reliability and maintaining quality standards in advanced manufacturing environments.

The principal production routes for metallic powders differ in particle morphology, powder quality, and industrial applicability. These characteristics are summarized in Table 4.

Table 4. Principal metallic powder production routes and their typical characteristics.

Production Route	Typical Particle Morphology	Main Advantages	Typical Applications
Gas atomization	Spherical	High flowability and purity	Additive manufacturing
Water atomization	Irregular to semi-spherical	Lower production cost	Powder metallurgy
Plasma atomization	Highly spherical	Excellent powder quality	Aerospace and biomedical applications
Mechanical milling	Irregular	Alloying flexibility	Composite and experimental powders
Chemical reduction	Fine to ultrafine particles, commonly exhibiting particle sizes below those typically produced by atomization routes	Controlled composition	Functional materials

The term fine particles used in Table 4 refers to powder populations generated by chemical reduction routes that frequently exhibit particle sizes significantly smaller than those produced by conventional atomization techniques. The exact particle-size range depends on precursor chemistry, reduction conditions, particle-growth mechanisms, and subsequent powder processing steps. Consequently, the designation should be interpreted as a relative classification rather than a fixed particle-size threshold [14,15,24].

Recent advances in powder characterization techniques have enabled a more comprehensive evaluation of powder behavior prior to processing. Modern approaches integrate particle-size analysis, flowability measurements, density evaluation, image analysis, and surface characterization to establish relationships between powder properties and manufacturing performance [24]. These developments contribute to improved process control and support the production of components with higher quality and reliability.

Metallic powder systems exhibit behavior that results from the combined effects of particle characteristics, processing conditions, and application-specific requirements.

Consequently, powder production and characterization are not merely preliminary manufacturing steps but key factors governing densification, microstructural evolution, and final component performance. These aspects are particularly relevant when evaluating the role of niobium in powder-derived materials, as discussed in the following section [25].

4. Niobium-Containing Metallic Powders

Niobium has attracted considerable interest in materials engineering because of its ability to modify phase stability, precipitation behavior, grain growth, and diffusion-controlled transformations. These characteristics have promoted the incorporation of niobium into a wide range of metallic systems intended for structural, functional, biomedical, and surface-engineering applications [26–28]. In powder-based technologies, the addition of niobium offers opportunities to tailor microstructural evolution during consolidation and thermal processing, contributing to the development of materials with enhanced performance and reliability.

The increasing availability of high-quality metallic powders has facilitated the development of niobium-containing systems produced via powder metallurgy and additive manufacturing. The use of niobium as an alloying element has been associated with improvements in strength, thermal stability, and corrosion resistance, depending on alloy composition and processing conditions [29,30]. In addition, niobium may influence phase formation and transformation mechanisms, which are particularly important in powder-derived materials subjected to rapid thermal cycles and non-equilibrium solidification conditions.

Among the most widely investigated systems are titanium-based alloys containing niobium. These materials have received significant attention because niobium serves as a strong β -phase stabilizer and may enhance mechanical compatibility and corrosion resistance in biomedical applications [31–35]. The principal mechanisms by which niobium influences phase stability, grain refinement, precipitation behavior, and engineering performance are schematically illustrated in Figure 4.

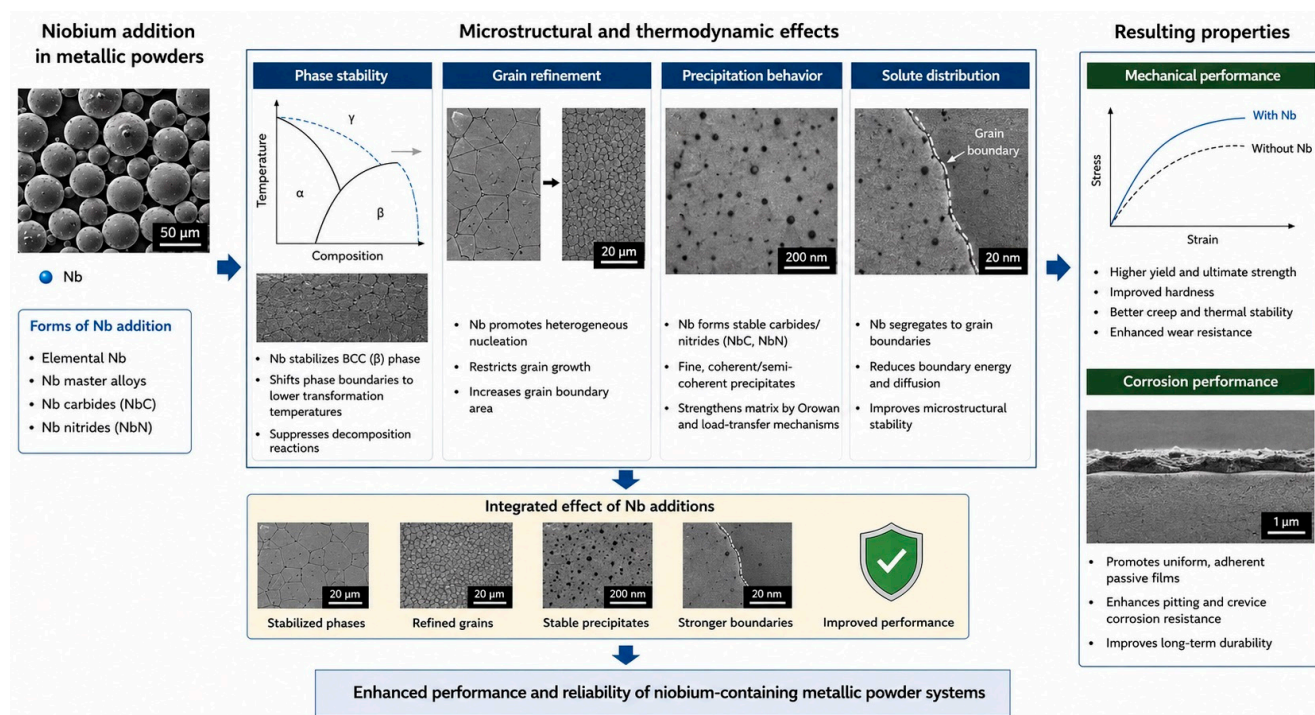


Figure 4. Mechanistic framework illustrating the influence of niobium additions on phase stability, grain refinement, precipitation behavior, and the resulting mechanical and corrosion performance of metallic powder systems.

In addition to titanium-based alloys, niobium has been incorporated into nickel-containing systems and shape-memory materials. The presence of niobium may modify transformation behavior, precipitation kinetics, and microstructural stability, thereby influencing the functional response of these materials [30,31]. Such effects are particularly relevant in powder-derived alloys where thermal processing conditions can strongly affect phase evolution and the resulting engineering properties.

Recent developments have also expanded the application of niobium to advanced alloy concepts, including refractory alloys and multi-principal-element systems. In these materials, niobium frequently contributes to phase stabilization and high-temperature performance, making it attractive for demanding engineering environments [36–40]. The increasing interest in these systems reflects the broader trend toward designing materials capable of operating under severe thermal and mechanical conditions.

The engineering relevance of niobium-containing powder systems originates from the diversity of alloy families in which niobium is employed. Titanium-based powders, Fe-containing systems, NiTiNb alloys, and refractory compositions each utilize niobium for distinct performance objectives, including biomechanical compatibility, thermal stability, transformation control, and high-temperature performance [26–40]. Because the underlying metallurgical mechanisms differ between alloy systems, a detailed discussion of phase stability, precipitation behavior, diffusion phenomena, and grain-refinement mechanisms is presented separately in Section 6.

The effects of niobium additions vary with alloy family, niobium content, and processing route. For this reason, direct comparisons among material systems should be made with caution, as equivalent niobium contents can yield substantially different performance outcomes depending on the intended application [26–40]. In titanium-based systems, niobium is associated with β -phase stabilization and reduced elastic modulus. In contrast, in iron-containing alloys, it is commonly related to carbide or carbonitride precipitation and grain-boundary pinning [26,31,33,36,37]. In nickel- and NiTi-based systems, niobium may modify transformation behavior, precipitation kinetics, and corrosion response [30,32]. These differences are summarized in Table 5, which compares representative niobium-containing powder systems according to composition range, processing route, microstructural effect, and performance outcome.

Table 5. Representative effects of niobium additions in metallic powder systems are reported in the literature.

Material System	Nb Content	Processing Route	Principal Microstructural Effect	Performance Improvement	Ref.
Ti–Nb	10–35 wt.%	Powder metallurgy	β -phase stabilization and reduced elastic modulus	Improved biomechanical compatibility	[26,31,33]
Ti–Nb	15–40 wt.%	Additive manufacturing	Grain refinement and phase stabilization	Enhanced mechanical reliability	[31,33]
NiTiNb	3–10 wt.%	Powder metallurgy	Modification of transformation temperatures	Improved shape-memory response	[30,32]
Fe–Nb	0.1–1.0 wt.%	Conventional powder metallurgy	NbC precipitation and grain-boundary pinning	Increased strength and thermal stability	[36,37]
Ni–Nb	1–10 wt.%	Powder processing and coating technologies	Suppression of undesirable phase transformations	Improved corrosion resistance	[29,30]
Refractory Nb alloys	Variable	Additive manufacturing	High-temperature phase stabilization	Improved thermal performance	[38–40]

Although the beneficial effects of niobium additions are widely recognized, the magnitude of the reported improvements varies according to alloy composition, niobium concentration, powder characteristics, and processing route. Representative quantitative

trends extracted from the literature are summarized in Table 6. The reported ranges should be interpreted as indicative values because processing conditions, thermal history, and characterization methodologies differ among investigations [26–40].

Table 6. Representative quantitative effects of niobium additions reported for metallic powder systems.

Material System	Typical Nb Content	Principal Effect	Representative Improvement	Ref.
Ti–Nb alloys	10–40 wt. %	β -phase stabilization	Elastic modulus reduction of 20–40% compared with conventional Ti alloys	[26,31,33]
Ti–Nb alloys	15–40 wt. %	Grain refinement and phase stabilization	Improved strength-to-modulus ratio and enhanced biomechanical compatibility	[31,33–35]
Fe–Nb systems	0.1–1.0 wt. %	NbC/Nb (C, N) precipitation	Yield-strength increases typically reported between 10–30% depending on processing conditions	[36,37]
NiTiNb alloys	3–10 wt. %	Transformation control	Reported improvements include enhanced transformation stability, reduced degradation of cyclic functional response, and improved reproducibility of transformation temperatures	[30,32]
Ni–Nb systems	1–10 wt. %	Phase stabilization and microstructural homogenization	The literature commonly reports reductions in corrosion current density and increases in passive film stability; however, the magnitude of these improvements remains strongly dependent on alloy composition and processing route	[29,30]
Refractory Nb-containing alloys	Variable	High-temperature phase stabilization	Enhanced thermal stability and improved elevated-temperature performance	[38–40]

Although the quantitative values reported in the literature vary significantly according to alloy composition, powder characteristics, and processing route, several trends can be identified. In Ti–Nb alloys, increasing niobium concentration is generally associated with a progressive reduction in elastic modulus due to β -phase stabilization—studies involving compositions between approximately 10 and 40 wt. % Nb frequently report elastic modulus values substantially lower than those measured in conventional $\alpha + \beta$ titanium alloys used for biomedical applications [26,31,33].

In Fe-based systems, beneficial effects are commonly observed at considerably lower niobium concentrations, often below 1 wt. %. Under appropriate processing conditions, niobium promotes precipitation strengthening by forming Nb-rich carbides and carbonitrides, resulting in measurable increases in yield strength and resistance to grain coarsening [36,37]. In contrast, NiTiNb alloys exhibit property modifications that are more closely related to changes in transformation behavior than to conventional strengthening mechanisms, reflecting the influence of niobium on phase stability and transformation kinetics [30,32].

Collectively, the reported findings demonstrate that quantitative assessment of niobium effects requires simultaneous consideration of composition, processing route, and microstructure. To facilitate comparison among studies, a consolidated summary of representative variations in properties reported in the literature is presented in Figure 5.

Figure 5 highlights the distinct quantitative responses observed in different alloy systems. The magnitude of the property changes depends not only on niobium concentration but also on processing conditions and resulting microstructural features. The figure therefore should not be interpreted as a universal predictive model but rather as a comparative synthesis of representative trends reported in the literature. The observed variability reinforces the importance of evaluating niobium effects within specific processing–microstructure–property contexts.

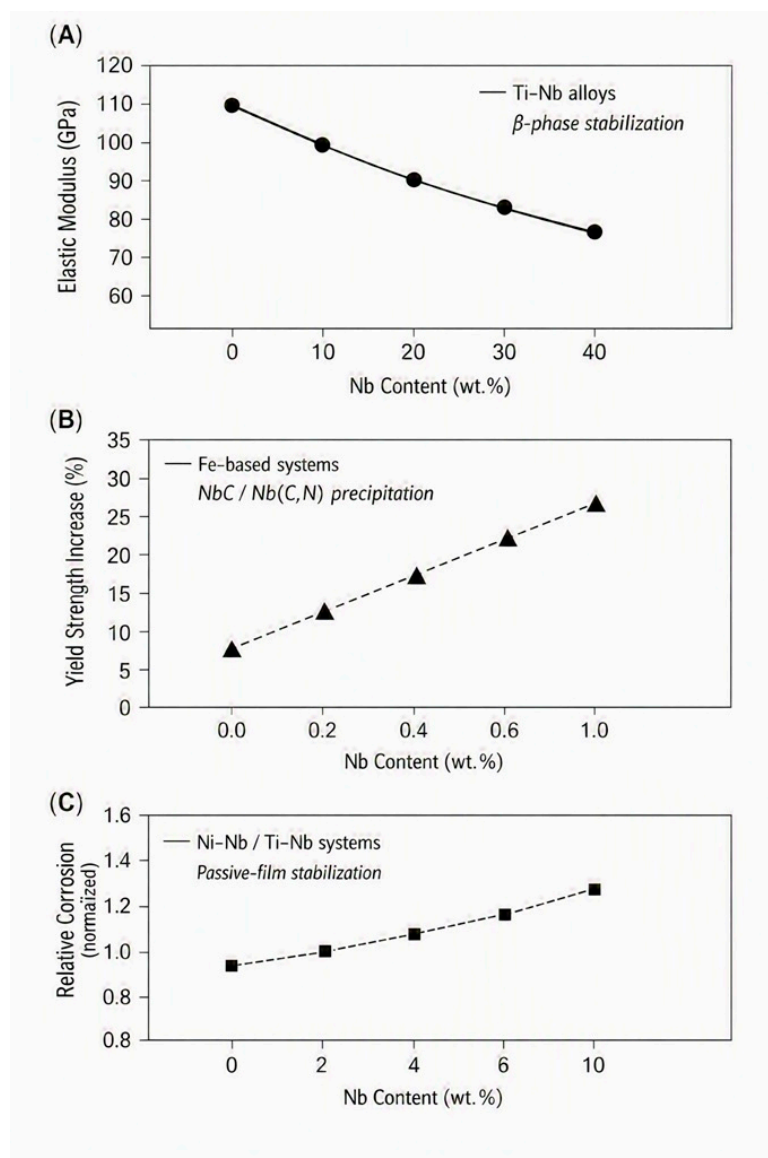


Figure 5. Literature-derived schematic representation of representative trends relating niobium content to selected properties reported for powder-derived metallic alloys: (A) influence of niobium content on elastic modulus and β -phase stabilization in Ti-Nb alloys; (B) influence of niobium additions on yield strength increase through NbC/Nb(C,N) precipitation in Fe-based systems; (C) influence of niobium content on relative corrosion resistance through passive-film stabilization in Ni-Nb/Ti-Nb systems. The curves are intended exclusively for comparative interpretation and do not represent a unified experimental dataset.

Reported improvements associated with niobium additions vary among alloy systems and processing routes [26,31,33,36–40]. While Ti-Nb alloys are primarily investigated for reductions in elastic modulus and improvements in biocompatibility [26,31,33], Fe-Nb systems are more commonly associated with precipitation strengthening and grain-boundary pinning [36,37], whereas Ni-Nb and NiTiNb systems have been linked to transformation control, surface stability, and corrosion-related benefits [29,30,32]. These differences indicate that the contribution of niobium should be interpreted in the context of the specific alloy system, processing route, and target application rather than as a universally transferable effect [31–40].

The behavior of niobium-containing powder systems cannot be generalized across different alloy families. While Ti-Nb alloys are primarily associated with β -phase stabilization and biomedical performance, Fe-Nb systems often derive their benefits from precipitation-

assisted grain refinement, and refractory Nb-containing alloys are commonly investigated for thermal stability at elevated temperatures [31–40]. These differences emphasize that the contribution of niobium must be evaluated within the context of each alloy system, processing route, and intended application.

The next section examines the principal processing routes employed in metallic powder systems, emphasizing the relationships among powder characteristics, consolidation mechanisms, thermal history, and material behavior in niobium-containing alloys.

Despite the growing number of studies on niobium-containing powder systems, quantitative comparisons remain challenging because different investigations employ distinct alloy compositions, processing routes, characterization methodologies, and performance metrics. Consequently, apparent discrepancies among reported values should be interpreted in light of differences in thermal history, consolidation mechanisms, and microstructural condition rather than solely in terms of niobium concentration.

5. Processing Routes

The performance of metallic powder systems is strongly dependent on the processing route employed during consolidation and manufacturing. Although powder characteristics establish the initial conditions for processing, the thermal and mechanical history imposed during manufacturing determines phase evolution, defect formation, densification behavior, and final material performance [41,42]. Consequently, the selection and optimization of processing routes represent critical stages in the development of niobium-containing metallic powder systems.

Powder metallurgy remains one of the most widely used technologies for consolidating metallic powders. This route typically involves powder preparation, compaction, and sintering, allowing for the production of components with controlled composition and low material waste [41]. The effectiveness of powder metallurgy processing depends on powder characteristics, compaction conditions, diffusion mechanisms, and thermal treatment parameters, all of which influence densification and microstructural development [42].

The rapid expansion of additive manufacturing has significantly increased the importance of powder-based processing technologies. Additive manufacturing enables the fabrication of complex geometries while maintaining a high degree of material utilization efficiency [43,44]. Figure 6 provides a generalized overview of the processing–microstructure–property relationships governing powder-derived materials. Rather than illustrating every individual manufacturing route discussed in this section, the figure summarizes the fundamental interactions among consolidation mechanisms, thermal history, microstructural development, and engineering performance that are common to several powder-processing technologies [41–50].

Among additive-manufacturing technologies, laser powder bed fusion has emerged as one of the most important methods for producing high-performance metallic components. In this process, thin layers of powder are selectively melted using a focused laser beam, generating highly localized thermal gradients and rapid cooling rates [3,43–45]. These conditions frequently result in non-equilibrium microstructures and complex phase-transformation phenomena, which are particularly relevant in niobium-containing alloys due to their sensitivity to thermal history and diffusion-controlled processes.

Thermal spraying represents another important processing route for metallic powders. Unlike powder metallurgy and additive manufacturing, thermal-spray technologies are primarily employed to produce coatings rather than fully consolidated components [47,48]. In these processes, powder particles are heated and accelerated toward a substrate, forming protective or functional surface layers that improve wear resistance, corrosion resistance, thermal insulation, and surface durability.

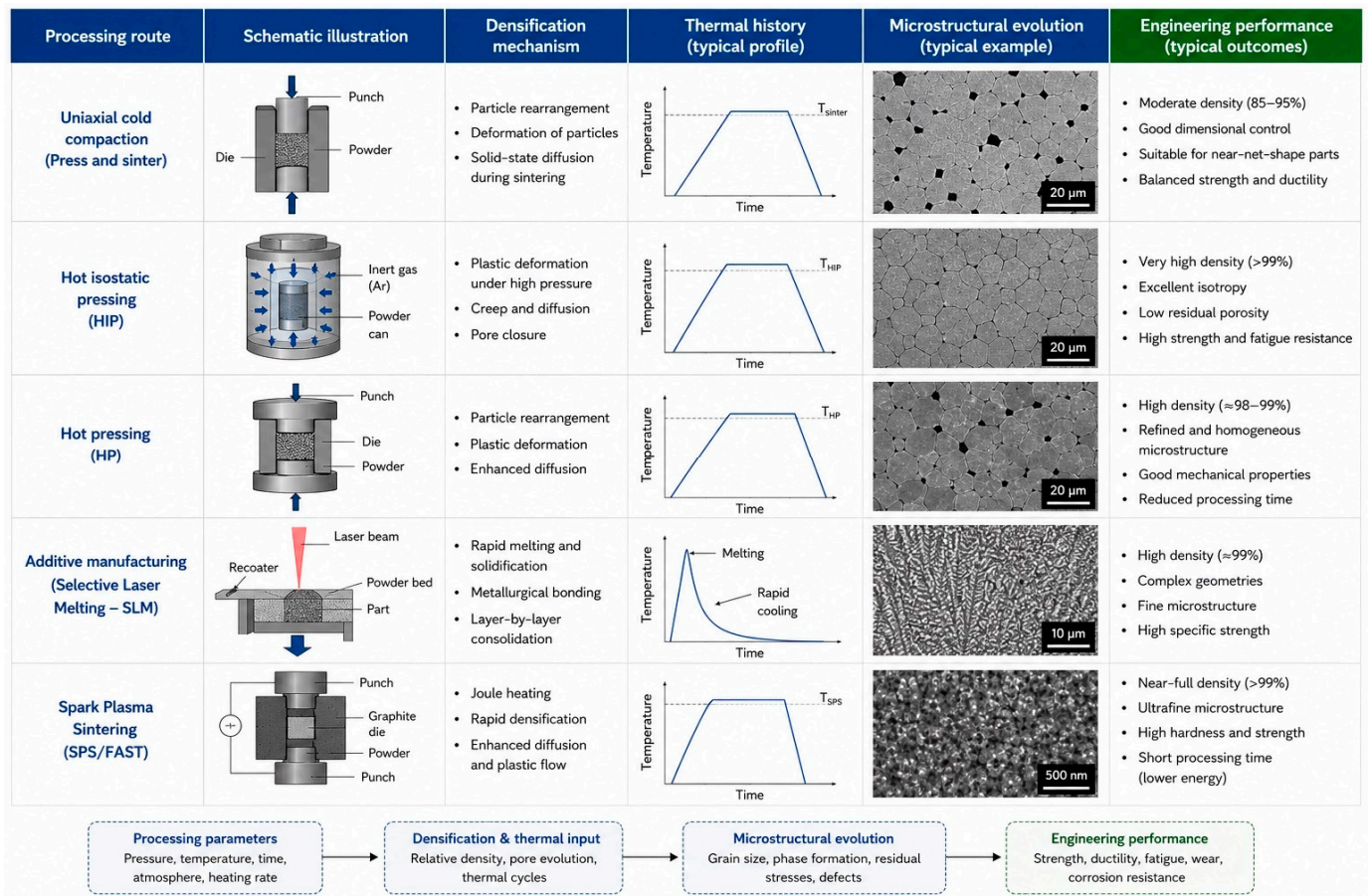


Figure 6. Conceptual representation of the principal processing pathways used in metallic powder systems and their influence on consolidation behavior, thermal history, microstructural evolution, and subsequent engineering performance. The figure is intended to illustrate generalized processing–microstructure–property relationships and does not represent all individual manufacturing technologies discussed in this section.

It should be noted that some processing routes discussed in this section, including thermal spraying and electrodeposition, do not primarily rely on bulk densification mechanisms, as in conventional powder metallurgy. Instead, these technologies are generally employed for surface engineering and coating applications.

Electrodeposition and powder-assisted electrochemical processing routes have also been investigated to incorporate metallic particles into coatings and composite surface layers. These approaches provide opportunities for tailoring surface composition and microstructure through the controlled incorporation of metallic powders and reinforcing phases [49]. Such strategies have become increasingly attractive for applications involving corrosion protection and surface engineering.

The principal processing routes currently employed for metallic powder systems, along with their associated characteristics, are summarized in Table 7.

Recent developments have increasingly focused on hybrid processing routes that combine multiple manufacturing technologies to leverage the advantages of each [50]. These approaches seek to improve microstructural control, reduce defect formation, and enhance material performance by integrating powder-based manufacturing with complementary processing techniques. Such developments are particularly relevant for niobium-containing metallic powders, where processing history strongly influences phase stability and microstructural evolution.

Table 7. Principal processing routes employed for metallic powder systems and their main characteristics.

Processing Route	Consolidation Mechanism	Principal Advantage	Typical Application
Powder metallurgy	Solid-state sintering	Material efficiency	Structural components
Laser powder bed fusion	Localized melting and solidification	Complex geometries	Additive manufacturing
Directed energy deposition	Simultaneous powder feeding and melting	Component repair and fabrication	Aerospace and energy sectors
Thermal spraying	Particle deposition on substrates	Surface modification	Protective coatings
Electrodeposition	Electrochemical incorporation	Surface engineering	Corrosion-resistant coatings
Hybrid processing	Combined manufacturing approaches	Property optimization	Advanced engineering applications

The literature consistently shows that processing routes directly influence the evolution of metallic powder systems. Powder characteristics, thermal history, and consolidation mechanisms collectively determine phase formation, defect distribution, densification efficiency, and the resulting engineering properties. Therefore, interpretation of the behavior of niobium-containing powder systems requires simultaneous consideration of alloy chemistry and processing history, particularly when comparing results obtained using different manufacturing technologies [41–50].

6. Microstructural Evolution and Phase Stability

The present section focuses exclusively on the metallurgical mechanisms responsible for the behavior of niobium-containing powder systems. To avoid overlap with Sections 4 and 7, the discussion focuses on phase transformations, diffusion phenomena, precipitation reactions, grain-structure evolution, and thermodynamic stability. At the same time, application-specific performance and corrosion behavior are discussed separately in subsequent sections [51–60].

Mechanistic Role of Niobium in Different Alloy Systems

Although niobium is frequently associated with grain refinement, phase stabilization, and improved corrosion performance, the mechanisms underlying these effects differ substantially across alloy systems. This distinction is particularly important when interpreting the literature because apparently conflicting results often originate from fundamentally different metallurgical responses.

In Ti–Nb alloys, niobium functions predominantly as a β -stabilizing element. Increasing niobium content promotes the retention of β -phase structures and suppresses phase transformations that would otherwise increase elastic modulus. Consequently, improvements reported for biomedical alloys are commonly attributed to phase stability and mechanical compatibility rather than to conventional precipitation-strengthening mechanisms [26,31,33].

In Fe-based alloys, niobium exerts its principal influence through precipitation reactions involving NbC and Nb(C, N) particles. These precipitates restrict grain growth during thermal processing and may contribute to precipitation strengthening. However, the effectiveness of this mechanism depends strongly on processing temperature, holding time, and interstitial element content [36,37].

For NiTiNb alloys, niobium additions are frequently associated with changes in transformation behavior and microstructural stability. The formation of Nb-rich phases and modification of transformation kinetics may influence shape-memory response, thermal hysteresis, and functional reliability. Therefore, the performance of these systems cannot be explained solely by conventional strengthening approaches [30,32].

The distinct metallurgical roles of niobium across different alloy families explain why the magnitude of reported improvements frequently varies among studies and highlight the importance of evaluating processing–microstructure–performance relationships within each material system.

Microstructural evolution is one of the key factors governing the performance of metallic powder systems. Regardless of the manufacturing route employed, the final properties of powder-derived materials are determined by the interaction among phase transformations, diffusion mechanisms, precipitation phenomena, grain-structure development, and defect formation during processing [51]. Consequently, understanding the mechanisms responsible for microstructural evolution is essential for optimizing the performance of niobium-containing metallic powder systems.

The thermal history imposed during powder processing directly influences phase formation and stability. Processes involving melting and solidification, such as laser powder bed fusion and directed energy deposition, frequently generate non-equilibrium microstructures characterized by high cooling rates and steep thermal gradients [52,53]. In contrast, solid-state consolidation routes, including conventional powder metallurgy, promote diffusion-controlled transformations and progressive microstructural homogenization [51]. These differences demonstrate the strong relationship between processing routes and microstructural development.

Diffusion phenomena play a fundamental role in powder-derived materials, as they govern densification, phase redistribution, chemical homogenization, and precipitation behavior [51,53]. During thermal processing, diffusion mechanisms determine the stability of existing phases and influence the formation of new microstructural constituents. The effectiveness of these processes depends on both alloy chemistry and the thermal conditions imposed during manufacturing.

The influence of niobium on microstructural evolution depends on the thermodynamic and kinetic characteristics of each alloy system and cannot be interpreted as a universal strengthening mechanism. In titanium-based alloys, niobium acts primarily as a β -phase stabilizer, decreasing the driving force for α -phase formation and promoting the retention of metastable or stable β microstructures after processing. This effect is particularly important in powder-derived Ti–Nb alloys because phase constitution strongly influences elastic modulus, mechanical compatibility, and corrosion behavior in biomedical applications [26,31,33].

In iron-based alloys, the role of niobium is fundamentally different. Small additions of niobium promote the formation of Nb-rich carbides and carbonitrides during thermal processing. These precipitates restrict grain-boundary motion via pinning and strengthen the material by hindering dislocation motion. Consequently, the magnitude of the strengthening effect depends not only on the niobium concentration but also on the availability of carbon and nitrogen, precipitation kinetics, and thermal history [36,37].

In NiTiNb and related nickel-containing systems, niobium may modify transformation behavior by influencing phase stability and precipitate formation. Such effects can alter transformation temperatures, thermal hysteresis, and microstructural stability, thereby affecting the reproducibility of functional properties and long-term performance [30,32]. The available evidence demonstrates that the microstructural contribution of niobium is highly system-dependent and should be interpreted within the context of alloy chemistry, processing route, and resulting phase constitution rather than solely in terms of composition.

The influence of niobium on mechanical performance is associated with the microstructural mechanisms discussed above. In powder-derived metallic systems, improvements in yield strength, hardness, and wear resistance are frequently attributed to grain refinement, precipitation strengthening, and enhanced phase stability [26,31,33,36,37,58]. The

interactions among processing routes, thermal history, diffusion phenomena, phase transformations, and engineering properties are summarized in Figure 7.

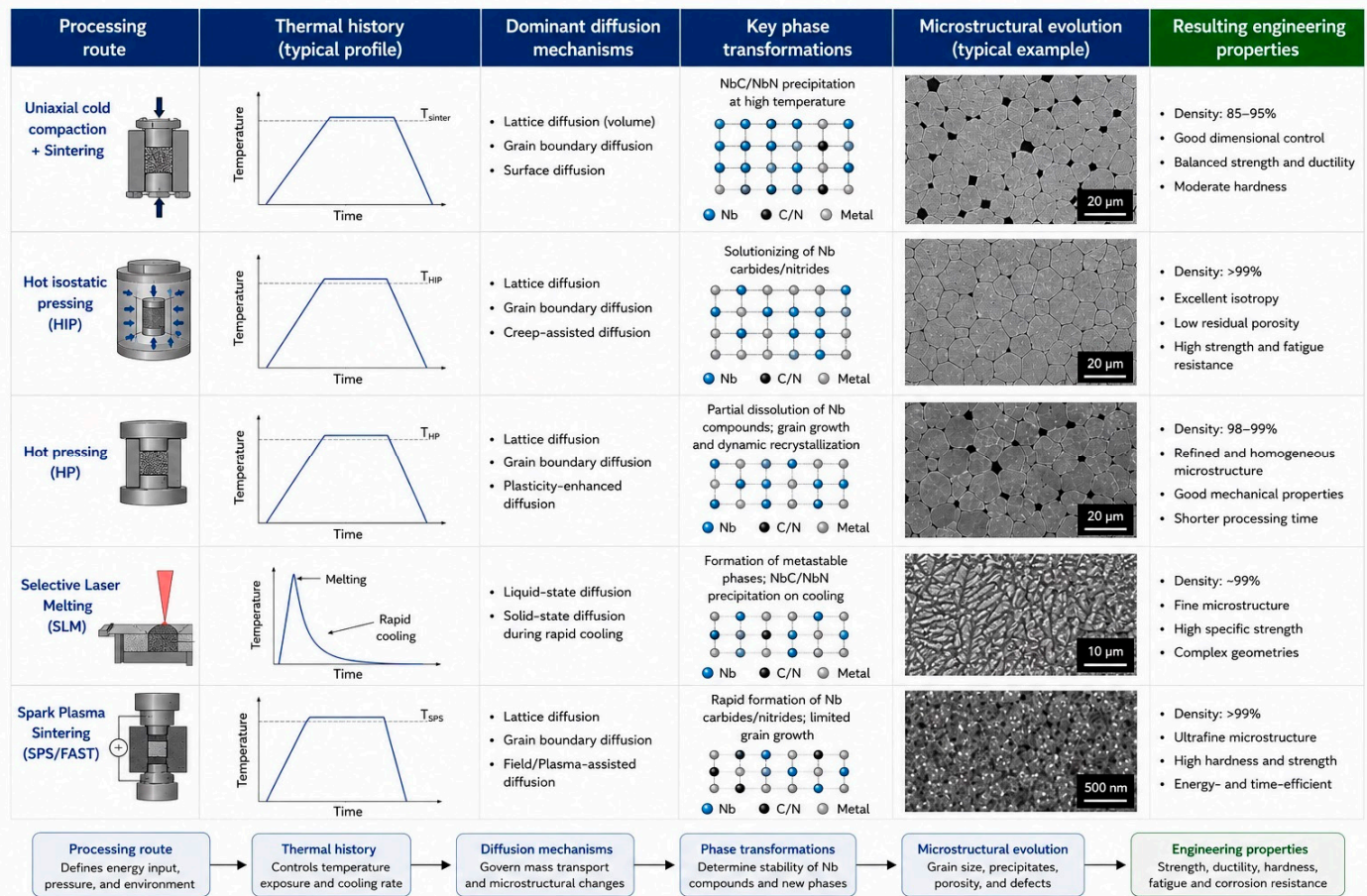


Figure 7. Relationship between processing route, thermal history, diffusion mechanisms, phase transformations, microstructural evolution, and resulting engineering properties in niobium-containing metallic powder systems.

The formation of Nb-rich carbides and carbonitrides may restrict grain-boundary mobility and function as effective obstacles to dislocation motion [55–58], whereas β -phase stabilization in Ti–Nb alloys contributes to improved combinations of strength and elastic modulus [26,31,33]. However, the magnitude of these improvements varies across studies because mechanical performance depends not only on niobium concentration but also on powder characteristics, consolidation efficiency, porosity, and thermal history [21,24,41–45]. Consequently, comparisons between different investigations should consider processing route and resulting microstructure rather than alloy composition alone [53–57].

The metallurgical role of niobium varies significantly across alloy systems, influencing microstructure and properties through different mechanisms. The representative images presented in Figure 8 provide visual support for these mechanisms and concepts. While Ti–Nb alloys derive their properties primarily from β -phase stabilization, Fe–Nb systems are more commonly influenced by precipitation-assisted grain refinement through the formation of Nb-rich carbides and carbonitrides. In NiTiNb alloys, niobium may alter transformation behavior through its effect on phase stability and Nb-rich constituent formation [26,30–33,36,37]. Understanding these microstructural mechanisms is essential for predicting alloy behavior.

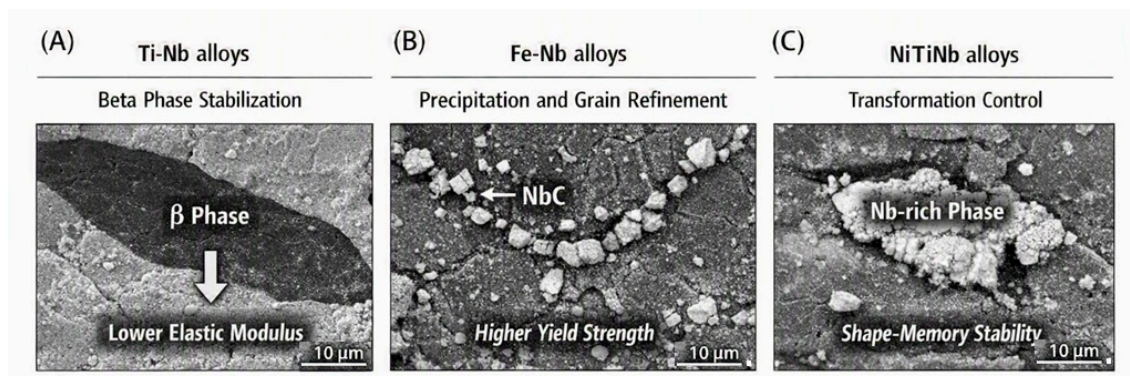


Figure 8. Representative microstructural features associated with niobium additions in different powder-derived metallic systems. (A) β -phase stabilization in Ti–Nb alloys; (B) grain-boundary pinning by NbC/Nb(C, N) precipitates in Fe–Nb systems; and (C) formation of Nb-rich constituents affecting transformation behavior in NiTiNb alloys. These images help elucidate how niobium influences microstructure in each alloy system.

The representative microstructural features shown in Figure 8 indicate that a single metallurgical mechanism cannot fully capture the influence of niobium. Instead, niobium acts through different thermodynamic and kinetic pathways depending on the alloy system. In Ti–Nb alloys, the predominant effect is the stabilization of the β phase, which contributes to a lower elastic modulus and improved biomechanical compatibility [26,31,33]. In Fe-based systems, niobium additions frequently promote precipitation of NbC and Nb(C, N), restricting grain growth during thermal processing and increasing resistance to plastic deformation through precipitation strengthening mechanisms [36,37].

The behavior of NiTiNb alloys differs from that observed in both Ti–Nb and Fe–Nb systems. In these materials, niobium influences phase-transformation behavior and stability through the formation of Nb-rich constituents and changes in transformation kinetics [30,32]. Consequently, property improvements reported for NiTiNb alloys are commonly attributed to functional stability and transformation reproducibility rather than to conventional strengthening mechanisms.

The system-dependent responses illustrated in Figure 8 help explain the quantitative trends presented in Figure 5 and the processing-dependent microstructural responses summarized in Figure 7. Taken together, these findings reinforce the need to evaluate niobium-containing powder systems within a processing–microstructure–performance framework rather than assuming a universally transferable effect of niobium additions [26,30–37].

Although grain refinement is frequently reported in niobium-containing powder systems, the magnitude of this effect varies among studies. Differences in cooling rate, powder particle size distribution, consolidation route, and alloy chemistry often produce distinct microstructural responses, even when similar niobium concentrations are employed [31,33,36,37]. For example, additive manufacturing processes may generate significant grain refinement due to rapid solidification. In contrast, conventional powder metallurgy routes frequently rely on precipitation-assisted grain-boundary pinning during sintering and subsequent thermal treatments. These observations indicate that microstructural refinement should not be interpreted as an intrinsic consequence of niobium addition alone but rather as the result of interactions among composition, processing history, and thermodynamic stability.

Grain refinement is frequently cited as one of the most beneficial microstructural effects of niobium additions. Fine-grained microstructures provide improved mechanical performance, enhanced microstructural stability, and more uniform phase distributions [31,33,36,37]. In powder systems, grain refinement may result from the com-

combined effects of rapid solidification, restricted grain growth, and precipitation-assisted stabilization mechanisms.

Precipitation phenomena play a decisive role in the behavior of niobium-containing alloys; however, the nature of the precipitates formed depends strongly on alloy chemistry and thermal history [54–58]. In Fe-based systems, niobium commonly participates in the formation of NbC and Nb(C, N) precipitates during thermal processing. These particles can restrict grain-boundary migration through pinning mechanisms and contribute to precipitation strengthening by acting as obstacles to dislocation motion [55–58]. The effectiveness of this mechanism depends on precipitate size, distribution, volume fraction, and stability during thermal exposure.

In Ti–Nb alloys, the influence of niobium on precipitation behavior is generally associated with suppression of undesirable phase transformations and stabilization of β -phase structures rather than extensive carbide precipitation [26,31,33]. Depending on composition and processing conditions, niobium may alter the formation of metastable phases and influence phase balance, thereby affecting elastic modulus, mechanical compatibility, and microstructural stability [26,31,33].

In NiTiNb systems, niobium additions may promote the formation of Nb-rich constituents that influence transformation kinetics and phase stability. These microstructural features affect transformation temperatures, thermal hysteresis, and functional reliability, demonstrating that precipitation-related effects in shape-memory alloys differ substantially from those observed in conventional structural alloys [30,32].

Because niobium influences different precipitation reactions depending on the alloy family, precipitation strengthening should not be regarded as a universal consequence of niobium addition. Instead, the resulting microstructural response reflects the interaction among alloy composition, diffusion behavior, thermodynamic stability, and processing history. This distinction helps explain part of the variability observed among studies investigating different niobium-containing powder systems [26,30–33,54–58].

The increasing availability of computational thermodynamics tools has significantly improved the understanding of phase stability in metallic systems. CALPHAD-based approaches and related thermodynamic models enable the prediction of phase equilibria, precipitation behavior, and transformation sequences under different processing conditions [58,59]. These methodologies have become valuable tools for the design and optimization of powder-derived alloys because they provide insights that are difficult to obtain exclusively through experimental investigations.

The combined effects of niobium on phase stability, grain growth, precipitation behavior, and diffusion processes influence the mechanical response of powder-derived materials. Representative relationships between microstructural evolution and mechanical performance reported for niobium-containing metallic powder systems are summarized in Table 8.

Recent investigations have increasingly combined experimental characterization with thermodynamic modeling to establish relationships among processing parameters, precipitation behavior, phase stability, and engineering performance [57–60]. Such approaches are particularly valuable for niobium-containing alloys because precipitation kinetics, phase constitution, and microstructural stability frequently depend on subtle interactions among alloy chemistry, diffusion phenomena, and thermal history [54–60]. Such approaches contribute to a more comprehensive understanding of powder-derived materials and facilitate the development of alloys with tailored microstructures and predictable behavior.

Microstructural evolution and phase stability result from the interaction among powder characteristics, processing parameters, diffusion phenomena, and alloy chemistry. In niobium-containing systems, these variables govern grain refinement, precipitation be-

havior, phase transformations, and microstructural stability, influencing both mechanical performance and corrosion resistance. Understanding these relationships is essential for establishing reliable processing–microstructure–property correlations in powder-derived materials [51–60].

Table 8. Representative relationships between microstructural evolution and engineering performance in niobium-containing metallic powder systems.

Phenomenon	Principal Mechanism	Typical Effect on Microstructure	Engineering Consequence	Ref.
β -phase stabilization	Solute partitioning	Increased β -phase fraction	Reduced elastic modulus	[26,31,33]
Grain refinement	NbC/Nb (C, N) precipitation	Restricted grain growth	Increased strength	[36,37]
Phase stabilization	Reduced transformation kinetics	Enhanced thermal stability	Improved service reliability	[31,33,38–40]
Precipitation strengthening	Formation of NbC, Nb(C, N), or Nb-rich precipitates depending on alloy chemistry and thermal history	Obstacle to dislocation motion	Increased resistance to dislocation motion, improved strength, and enhanced microstructural stability	[55–58]
Chemical homogenization	Diffusion-assisted redistribution	Reduced segregation	Improved corrosion behavior	[58–60]

7. Corrosion Behavior and Surface Performance

Corrosion resistance is a critical performance parameter for metallic materials produced via powder-based technologies, as the electrochemical behavior of these systems is strongly influenced by microstructural characteristics developed during processing. Factors such as porosity, phase distribution, grain structure, chemical homogeneity, and defect population directly affect passive-film formation and corrosion susceptibility [61–63]. Consequently, understanding the relationship between powder processing and corrosion performance is essential for the development of durable engineering materials.

Although corrosion behavior is strongly influenced by microstructural condition, the objective of this section is not to revisit the metallurgical mechanisms previously discussed in Section 6. Instead, emphasis is placed on how microstructural features generated during powder processing affect passive-film stability, localized corrosion susceptibility, and long-term electrochemical performance [61–70].

The corrosion behavior of powder-derived materials differs from that of conventionally processed alloys because powder processing may introduce unique microstructural features. Residual porosity, incomplete particle bonding, local compositional variations, and non-equilibrium phase distributions can modify electrochemical activity and influence degradation mechanisms [64–66]. As a result, corrosion assessment has become an increasingly critical component of material qualification in powder metallurgy and additive manufacturing.

Microstructural evolution plays a leading role in determining corrosion performance. Grain refinement, phase stability, and microstructural homogeneity influence passive film formation and the material's resistance to localized attack [61,63]. The relationships linking processing history, microstructural condition, passive-film stability, and corrosion behavior are summarized in Figure 9. The figure provides a simplified representation of the principal pathways through which powder-processing routes influence electrochemical performance and long-term surface durability in metallic powder systems [61–70].

Localized corrosion represents one of the principal degradation mechanisms affecting metallic materials exposed to aggressive environments. Pitting corrosion, crevice corrosion, and galvanic interactions frequently initiate at microstructural discontinuities, compositional heterogeneities, or surface defects [61,62]. In powder-derived materials, such

features may originate from processing conditions and consolidation history, highlighting the importance of process optimization for corrosion control.

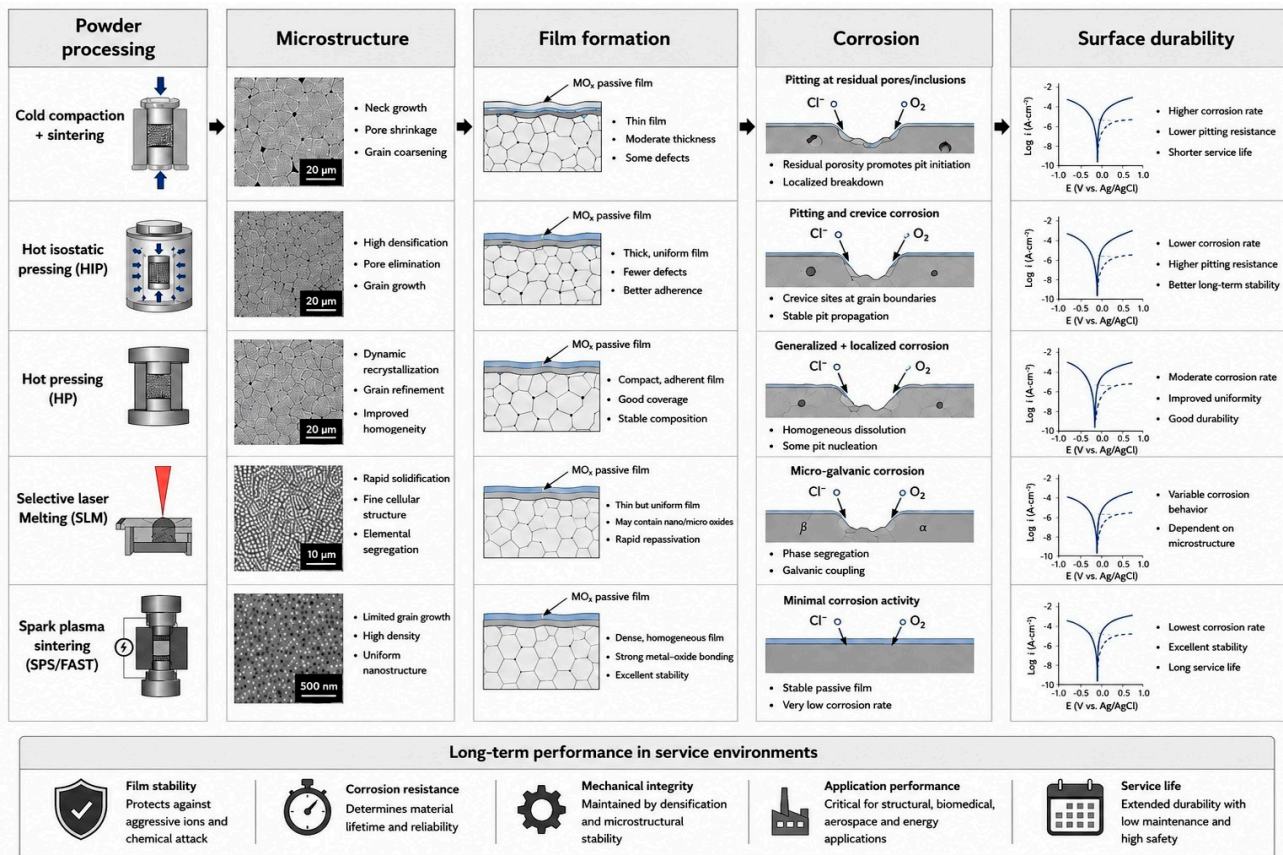


Figure 9. Schematic representation of the relationships among powder processing, microstructural condition, passive-film stability, corrosion mechanisms, and surface durability in metallic powder systems. The polarization curves shown in the Surface durability column are qualitative representations of electrochemical behavior ($\log i$ vs. E), where E denotes the electrode potential (V vs. Ag/AgCl) and $\log i$ denotes the logarithm of the current density ($A \cdot cm^{-2}$). The solid line represents the electrochemical response associated with the illustrated condition, whereas the dashed line represents a comparatively less favorable corrosion response for reference. Lower current densities and broader passive regions are associated with improved corrosion resistance, enhanced passive-film stability, and longer service life.

The incorporation of niobium may influence corrosion behavior by affecting passive-film stability, electrochemical homogeneity, and susceptibility to localized corrosion mechanisms. The metallurgical origins of phase stabilization, grain refinement, and precipitation behavior were previously discussed in Section 6, as their influence on corrosion performance is primarily indirect and mediated by microstructural development [54–70].

Several studies have reported improved corrosion performance in niobium-containing systems, particularly when niobium additions promote phase stability, chemical homogenization, and passive-film integrity [68–70]. Nevertheless, improvements are not universally observed because processing-induced porosity, segregation phenomena, cooling-rate effects, and secondary-phase formation may significantly influence electrochemical behavior [64–67]. Therefore, corrosion performance should be interpreted as the result of the combined effects of alloy chemistry, microstructural conditions, and manufacturing history rather than as an intrinsic result of niobium addition alone [61–70]. These effects are especially relevant for biomedical, energy-related, and corrosion-resistant engineering applications.

The increasing use of additive manufacturing has intensified research concerning corrosion in powder-derived alloys. Rapid solidification and repeated thermal cycling frequently generate microstructures that differ from those produced by conventional manufacturing routes [64–67]. Consequently, corrosion performance must be evaluated considering both the characteristics of the powder feedstock and the processing conditions used during component fabrication.

The influence of niobium on corrosion behavior remains a subject of ongoing investigation because reported results depend strongly on alloy composition and microstructural condition. In several stainless-steel and titanium-based systems, improvements in corrosion resistance have been associated with enhanced passive-film stability and reduced electrochemical heterogeneity resulting from favorable microstructural conditions [68–70]. The microstructural mechanisms responsible for these conditions are discussed separately in Section 6 to avoid repetition and to emphasize the distinction between metallurgical evolution and corrosion response. However, the literature also indicates that the beneficial effects of niobium may be diminished when processing-induced porosity, segregation, or secondary-phase formation introduces preferential sites for localized corrosion initiation [64–67]. These findings highlight the importance of considering both alloy chemistry and processing history when evaluating the corrosion performance of niobium-containing powder-derived materials.

Factors Influencing Corrosion Performance

Although numerous investigations have reported beneficial effects associated with niobium additions, direct comparison among studies remains challenging because corrosion behavior depends on the combined effects of alloy composition, processing route, microstructural condition, and testing methodology rather than on chemical composition alone [61–67]. Previous studies on powder metallurgy and additive manufacturing have demonstrated that similar nominal alloy compositions may exhibit substantially different electrochemical responses when distinct processing histories generate different defect populations and phase distributions [64–67].

One major source of variability is residual porosity generated during powder consolidation. As discussed in Section 5 and schematically illustrated in Figure 6, different manufacturing routes impose distinct densification mechanisms, thermal cycles, and solidification conditions [41–50]. Consequently, powder metallurgy, laser powder bed fusion, and directed energy deposition may produce significantly different pore populations and defect distributions. Because pores may act as preferential sites for electrolyte accumulation and localized electrochemical attack, the beneficial effects associated with niobium additions can be partially masked when residual porosity remains significant [64–67,70].

Microstructural homogeneity is another important factor contributing to discrepancies among published results. The processing–microstructure relationships summarized in Figure 6 demonstrate that diffusion behavior, phase evolution, and chemical redistribution are directly affected by thermal history and consolidation conditions [51–60]. Several studies have linked improved corrosion performance to enhanced phase stability and reduced segregation, whereas microstructures containing chemical heterogeneities often exhibit increased susceptibility to localized corrosion processes [57,64–70].

Additional variability may arise from precipitation phenomena and secondary-phase formation. As summarized in Table 8, niobium may influence precipitation behavior, phase stability, grain refinement, and diffusion-controlled transformations through different metallurgical mechanisms depending on the alloy family [26,31,33,54–58]. However, precipitates beneficial for mechanical strengthening are not necessarily advantageous for corrosion resistance. Depending on their morphology, distribution, and electrochemical

characteristics, secondary phases may induce localized galvanic interactions that modify passive-film stability and corrosion behavior [61–67].

Differences in corrosion-testing methodologies further complicate comparison among studies. Electrolyte composition, chloride concentration, solution pH, temperature, exposure time, and electrochemical testing procedures may influence the measured corrosion response [61–63]. Consequently, apparent disagreement among reported results often reflects variations in experimental conditions rather than contradictory conclusions regarding the fundamental role of niobium in corrosion performance [64–67].

The factors discussed above demonstrate that the corrosion mechanisms summarized in Table 9 should be interpreted within a broader processing–microstructure–performance framework. The contribution of niobium cannot be isolated from the effects of porosity, segregation, phase stability, precipitation behavior, and processing history. This interpretation also helps explain why the representative quantitative trends presented previously in Table 6 and Figure 5 do not necessarily exhibit the same magnitude of improvement across different alloy systems and manufacturing routes [31–40,54–70].

Table 9. Principal sources of variability responsible for discrepancies reported in corrosion studies of niobium-containing powder-derived alloys.

Source of variability	Microstructural Consequence	Possible Effect on Corrosion Behavior	Representative References
Residual porosity	Localized electrolyte retention	Increased susceptibility to pitting and crevice corrosion	[64–67,70]
Chemical segregation	Electrochemical heterogeneity	Localized corrosion initiation	[57,64–70]
Secondary phases	Galvanic microcells	Variable passive-film stability	[61–67]
Cooling rate	Different phase fractions	Modified corrosion response	[51–57]
Heat treatment	Changes in precipitate population and homogenization	Distinct corrosion behavior	[53,57–60]
Testing methodology	Different electrochemical conditions	Limited quantitative comparability	[61–67]

The information summarized in Table 9 indicates that many of the differences reported in the literature cannot be attributed exclusively to niobium concentration. Instead, corrosion performance emerges from interactions among processing conditions, the resulting microstructural characteristics, and experimental evaluation procedures. Therefore, interpretation of corrosion data should consider the combined influence of these variables to establish reliable processing–microstructure–performance relationships in niobium-containing powder systems [51–70].

Corrosion behavior in powder-derived metallic materials arises from the combined influence of alloy chemistry, microstructural development, passive-film stability, and defects generated during powder processing and consolidation. Uniform corrosion is associated with the alloy’s intrinsic electrochemical characteristics. In contrast, localized degradation mechanisms such as pitting, crevice corrosion, and galvanic attack are strongly influenced by porosity, compositional heterogeneities, secondary phases, and microstructural discontinuities introduced during manufacturing [61–67]. Table 10 summarizes the principal relationships between corrosion mechanisms and their underlying microstructural factors. The literature consistently shows that improvements in corrosion resistance depend not only on alloy selection but also on the ability of processing routes to promote chemical homogeneity, microstructural stability, and controlled defect populations throughout the material [64–70].

Table 10. Principal corrosion mechanisms and microstructural factors influencing corrosion behavior in metallic powder systems.

Corrosion Mechanism	Dominant Microstructural Factor	Typical Consequence
Uniform corrosion	General surface reactivity	Material loss
Pitting corrosion	Local heterogeneities and inclusions	Localized attack
Crevice corrosion	Restricted electrolyte access	Accelerated degradation
Galvanic corrosion	Phase and compositional differences	Selective dissolution
Intergranular corrosion	Grain-boundary instability	Loss of structural integrity

The information presented in Table 10 demonstrates that corrosion behavior is strongly dependent on microstructural integrity and phase stability. Processing routes that minimize porosity, segregation, and unstable phase formation exhibit superior resistance to localized degradation mechanisms. Consequently, corrosion performance should be evaluated as a direct consequence of the interaction between processing history and microstructural development rather than as an isolated material property.

Surface engineering approaches have increasingly been employed to improve the corrosion resistance of powder-derived materials. Coatings, surface modifications, and compositional adjustments are frequently used to enhance passive-film stability and mitigate degradation under aggressive environmental conditions [67,69]. Such strategies are particularly attractive because they enable performance improvements without substantial modifications to the bulk material composition.

Recent investigations have also emphasized the importance of integrating electrochemical characterization with advanced microstructural analysis. Corrosion performance can only be fully understood when electrochemical measurements are interpreted alongside phase analysis, microstructural characterization, and processing history [68–70]. This integrated approach has become increasingly important for the design of powder-derived materials intended for demanding service environments.

The relationship between powder feedstock characteristics and the final performance of consolidated materials remains insufficiently understood, particularly when different alloy systems and manufacturing routes are compared. Existing studies have provided valuable information regarding powder processing, phase evolution, microstructural development, and engineering behavior; however, these variables are often investigated separately. As a result, the mechanisms through which particle morphology, particle-size distribution, thermal history, and phase stability collectively influence long-term material performance are not yet fully established. Future research should prioritize the development of quantitative frameworks capable of connecting powder-level attributes with microstructural evolution and service behavior, providing a more reliable basis for alloy design, process qualification, and industrial implementation of niobium-containing metallic powder systems [43–50,54–60,71–80].

8. Technological Applications and Functional Performance of Niobium-Containing Metallic Powder Systems

The continuous development of metallic powder systems has expanded their utilization across a broad range of industrial sectors. The combination of compositional flexibility, process adaptability, and microstructural control has enabled powder-derived materials to satisfy increasingly demanding engineering requirements. In recent years, the incorporation of niobium into metallic powder systems has further increased the potential of these materials by contributing to phase stability, corrosion resistance, and long-term reliability in advanced technological applications [71,72].

Additive manufacturing represents one of the fastest-growing application areas for metallic powders. Powder-bed fusion and directed-energy deposition technologies enable the fabrication of complex geometries that would be difficult or economically impractical to produce using conventional manufacturing routes [71]. In these applications, powder quality, processing stability, and microstructural control are critical factors governing component performance. Niobium-containing powders have attracted attention because their enhanced phase stability may improve performance under demanding thermal and mechanical conditions [74].

The technological relevance of niobium-containing powders differs among application sectors. Biomedical systems primarily benefit from improved corrosion resistance, passive-film stability, and favorable mechanical compatibility, particularly in Ti–Nb-based materials developed for long-term implantation [31,33,68,69]. In contrast, energy and aerospace applications emphasize phase stability, high-temperature performance, and microstructural reliability under severe operating conditions, where niobium contributes to thermal resistance and structural integrity [38–40,71–75]. Consequently, future alloy development strategies should be application-driven rather than focused exclusively on composition optimization, considering the specific performance requirements of each technological sector [71–75].

Biomedical engineering is another important field in which niobium-containing metallic powders have demonstrated significant potential. Powder-based manufacturing technologies facilitate the production of customized implants, porous structures, and patient-specific devices while maintaining strict control over material composition and microstructure [72,73]. Representative technological sectors benefiting from niobium-containing metallic powder systems are presented in Figure 10. In addition, niobium-containing systems have been associated with improved corrosion resistance and biocompatibility, characteristics that are particularly important for long-term biomedical applications.

Surface engineering has also benefited from the development of advanced metallic powders. Powder-fed coating technologies and thermal-spray processes are widely employed to improve wear resistance, corrosion resistance, thermal protection, and surface durability [71]. The incorporation of niobium into these systems may contribute to microstructural stabilization and enhanced performance in aggressive service environments, supporting the development of multifunctional surface-engineering solutions.

The energy sector represents an additional area of growing interest for niobium-containing metallic powders. Advanced energy systems frequently require materials capable of operating under severe thermal, mechanical, and chemical conditions. The combination of powder-based manufacturing and niobium alloying strategies offers opportunities to develop materials with improved stability and durability under such conditions [74]. These characteristics are particularly relevant to emerging technologies operating at elevated temperatures and in demanding service environments.

The increasing complexity of modern engineering systems has stimulated interest in multifunctional materials capable of simultaneously providing structural performance, corrosion resistance, thermal stability, and functional behavior. Powder technology offers significant advantages in this context because it allows for precise control over composition and microstructure during manufacturing [71,72]. As a result, powder-derived materials are increasingly integrated into advanced industrial systems that require highly specialized performance characteristics.

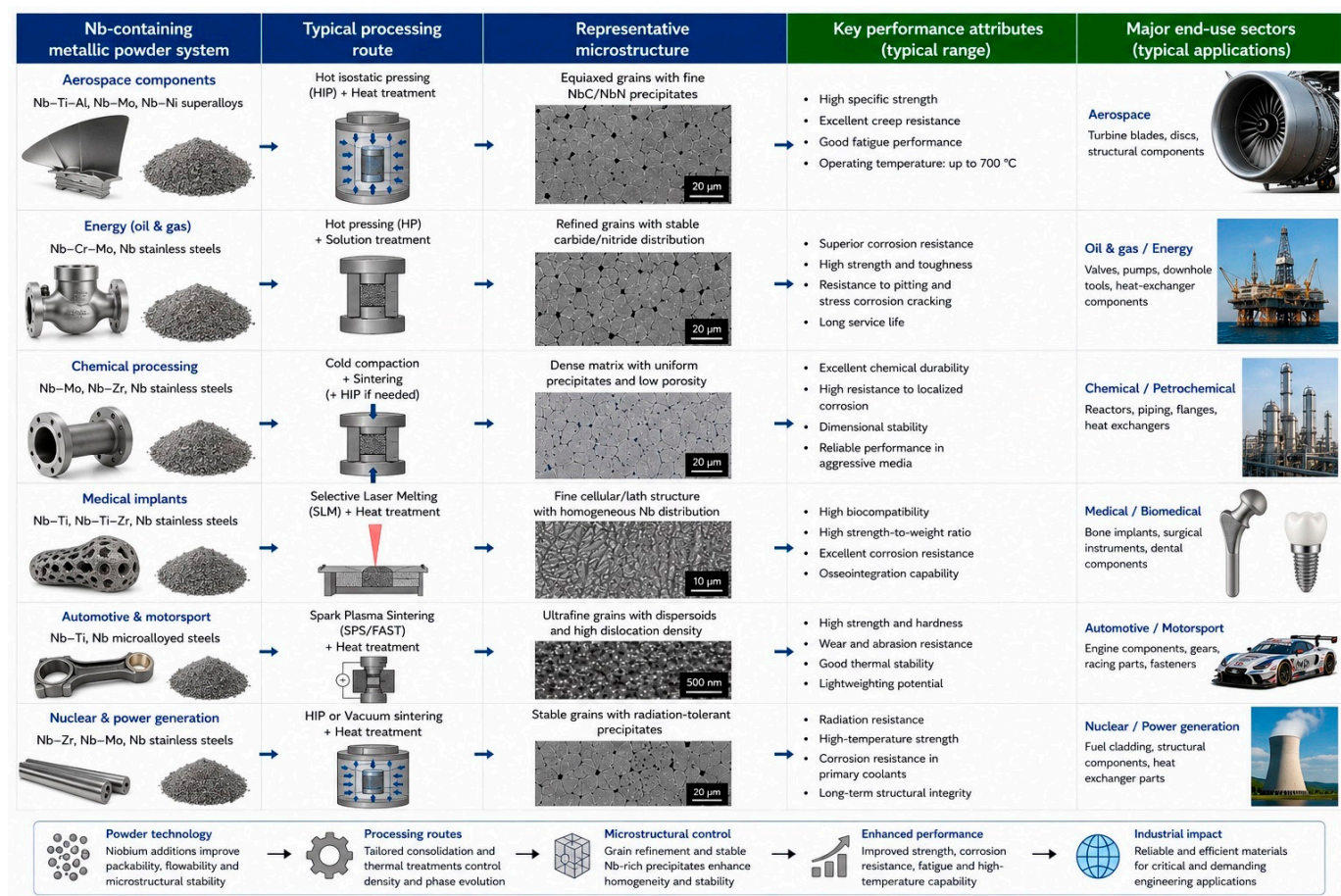


Figure 10. Representative industrial applications of niobium-containing metallic powder systems, highlighting the relationships among powder technology, processing routes, material performance, and end-use sectors.

Although numerous studies have demonstrated the technological potential of niobium-containing metallic powder systems, differences in alloy composition, powder characteristics, processing route, and evaluation methodology often make direct comparisons difficult. Representative findings and limitations reported in the literature are summarized in Table 11.

Table 11. Representative findings and limitations reported for niobium-containing metallic powder systems.

Material System	Processing Route	Principal Finding	Main Limitation	Ref.
Ti–Nb alloys	Powder metallurgy	Improved biomechanical compatibility	Limited long-term corrosion evaluation	[31,33]
Ti–Nb alloys	Additive manufacturing	Grain refinement and phase stabilization	Process-parameter sensitivity	[33,34]
NiTiNb alloys	Powder metallurgy	Improved shape-memory response	Limited fatigue assessment	[30,32]
Fe–Nb systems	Powder metallurgy	Enhanced strength through precipitation	Reduced information on corrosion performance	[36,37]
Ni–Nb systems	Surface engineering routes	Improved corrosion resistance	Limited long-term exposure studies	[29,30]
Refractory Nb alloys	Additive manufacturing	High-temperature stability	Scarcity of industrial-scale validation	[38–40]

Industrial implementation of niobium-containing metallic powders increasingly requires a combination of process qualification, feedstock control, and performance predictability [43–50,71–75]. As manufacturing routes become more complex, particularly in additive manufacturing and advanced surface-engineering applications, the ability to

correlate powder characteristics with microstructural evolution and service behavior becomes a prerequisite for large-scale adoption [43–50,54–60]. Consequently, future industrial growth will depend as much on process reliability as on alloy development itself, especially in sectors where component performance, durability, and manufacturing consistency are critical requirements [71–75].

The range of applications discussed in this section illustrates how niobium-containing metallic powders have expanded beyond conventional powder-metallurgy components and become relevant to advanced manufacturing sectors. Biomedical devices, surface engineering technologies, energy systems, and high-performance structural applications benefit from niobium's ability to influence phase stability, microstructural evolution, corrosion behavior, and long-term reliability [71–75]. The successful implementation of these materials depends not only on alloy design but also on the integration of appropriate powder processing and consolidation strategies. As industrial adoption continues to grow, attention has progressively shifted toward resource efficiency, powder reuse, and life-cycle considerations, topics examined in the following section [76,78–80].

Biocompatibility and Biological Implications of Niobium Release

The growing use of niobium-containing alloys in biomedical applications has stimulated significant interest in the biological effects associated with long-term exposure to niobium-bearing materials. In comparison with conventional alloying elements such as aluminum and vanadium, niobium is generally regarded as a favorable alloying addition because of its high corrosion resistance, chemical stability, and ability to promote the formation of protective oxide layers on metallic surfaces [26–29,72]. These characteristics help reduce ion release under physiological conditions and support the use of niobium-containing alloys in long-term implant applications [26–29].

The biological response to metallic implants is strongly influenced by corrosion behavior and the stability of passive surface films. In Ti–Nb systems, niobium contributes to the formation of stable surface oxides, predominantly niobium pentoxide (Nb_2O_5) and titanium oxides, which act as barriers against metal dissolution and contribute to favorable tissue compatibility [26,27,33,72]. Several studies have associated these surface characteristics with good cytocompatibility and reduced adverse biological reactions when compared with implant alloys containing potentially problematic alloying elements [26–29,72].

Although available evidence generally supports the biological tolerability of niobium-containing materials, it should be recognized that ion release cannot be considered absent under all service conditions. Mechanical wear, fretting, localized corrosion, and long-term exposure to physiological environments may contribute to the release of metallic species from implant surfaces [29,72,73]. Consequently, biological performance depends not only on nominal alloy composition but also on implant design, surface condition, manufacturing route, and in vivo environmental factors [72,73].

Current evidence generally indicates that niobium-containing alloys exhibit a favorable combination of corrosion resistance and biocompatibility; however, important research challenges remain. Additional long-term studies are required to improve understanding of the effects of chronic exposure, ion-release behavior under complex physiological conditions, and interactions between released metallic species and biological tissues over extended implantation periods [9,26–29,72,73]. These considerations are particularly relevant as powder-based manufacturing technologies expand the use of niobium-containing materials in patient-specific and long-term biomedical devices.

The information summarized in Table 12 indicates that the biomedical potential of niobium-containing alloys is primarily associated with their corrosion resistance and surface stability. Nevertheless, long-term biological assessment remains an active area of

investigation, particularly regarding ion-release mechanisms, degradation products, and extended implant service life [9,26–29,72,73].

Table 12. Biological considerations associated with niobium-containing alloys for biomedical applications.

Aspect	Observations Reported in the Literature	Representative References
Corrosion resistance	Stable oxide-film formation contributes to reduced ion release	[26,27,33,72]
Biocompatibility	Generally favorable biological response reported for Ti–Nb systems	[26–29,72]
Surface stability	Nb ₂ O ₅ -containing passive films contribute to chemical stability	[26,27,72]
Potential ion release	May occur under wear, corrosion, or long-term exposure conditions	[29,72,73]
Knowledge gaps	Limited information on long-term biological exposure and degradation products	[9,72,73]

Collectively, the findings summarized in Table 12 indicate that the biomedical performance of niobium-containing alloys is closely linked to the stability of their passive surface films and the resulting resistance to degradation in physiological environments. Although current evidence generally supports the use of niobium as a favorable alloying element in biomedical systems, the long-term interactions between degradation products, released metallic species, and biological tissues remain incompletely understood. Consequently, additional studies should emphasize extended in vitro and in vivo evaluations that correlate ion-release behavior, surface modification, and biological response under clinically relevant conditions [9,26–29,72,73].

9. Sustainability and Industrial Applications

Sustainability has become an increasingly important consideration in the development and industrial implementation of metallic powder systems. Compared with conventional subtractive manufacturing routes, powder-based technologies frequently offer advantages in material utilization efficiency, reduced waste generation, and near-net-shape production [76]. These characteristics contribute to lower raw-material consumption and support manufacturing strategies focused on resource efficiency and environmental responsibility. The growing industrial adoption of additive manufacturing and powder metallurgy has intensified interest in the life-cycle performance of metallic powders. Beyond the production of high-performance components, attention has increasingly shifted toward powder reuse, powder recycling, and process optimization to reduce environmental impact and manufacturing costs [76,77]. As a result, sustainability considerations are becoming integrated into the evaluation of powder systems alongside traditional performance metrics such as strength, corrosion resistance, and microstructural stability.

Powder recycling represents one of the most relevant sustainability challenges in powder technology. Repeated powder utilization may alter particle morphology, particle-size distribution, surface chemistry, and flowability characteristics, potentially affecting process consistency and final component quality [76,78]. Consequently, effective recycling strategies require continuous powder characterization and quality control to ensure that recycled powders maintain acceptable performance during manufacturing operations.

The utilization of industrial by-products and secondary raw materials has also emerged as an important research direction. Steel slag, for example, has attracted attention for its potential applications in construction materials, environmental technologies, and resource-recovery strategies [77,78]. The valorization of industrial residues contributes to waste reduction while supporting circular-economy principles that extend material life cycles and reduce dependence on primary raw materials.

9.1. Environmental Considerations Associated with Niobium Production

Although niobium-containing alloys may contribute to longer service life, improved corrosion resistance, and enhanced resource efficiency during operation, the environmental impact associated with niobium production should also be considered when evaluating overall sustainability [76,78–80]. The extraction and processing of niobium-bearing ores require mining, comminution, concentration, and metallurgical refinement stages that consume energy and generate environmental burdens similar to those associated with other metallic raw materials.

Several factors, including ore grade, mining practices, energy sources, beneficiation efficiency, and waste-management strategies, influence the environmental footprint of niobium production. Ore extraction and concentration operations may generate waste rock, tailings, and other by-products that require appropriate environmental management to minimize impacts on surrounding ecosystems and water resources. Consequently, the sustainability of niobium-containing materials cannot be assessed exclusively in terms of product performance or service life [76,78–80].

At the same time, it should be recognized that the environmental costs associated with primary niobium production may be partially offset by performance-related benefits achieved during material utilization. Extended component life, improved corrosion resistance, reduced maintenance requirements, and increased reliability may decrease the frequency of material replacement and reduce overall resource consumption throughout the life cycle of engineering systems [38–40,68–80].

Taken together, these factors highlight the importance of adopting a life-cycle perspective when evaluating niobium-containing powder systems. Future sustainability assessments should simultaneously consider raw material extraction, powder production, manufacturing efficiency, service performance, reuse strategies, and end-of-life management to develop a more comprehensive understanding of the environmental implications of niobium-containing materials [76,78–80].

From an industrial perspective, the sustainability of metallic powder systems is intricately linked to durability, service life, and resource efficiency throughout the product life cycle [76,78–80]. Materials exhibiting enhanced corrosion resistance, thermal stability, and structural reliability require less frequent replacement and maintenance, and lower material consumption during service, thereby contributing to more sustainable manufacturing and operational practices [76,78–80]. In niobium-containing powder systems, these benefits have been associated with improved phase stability, microstructural integrity, and resistance to degradation under demanding operating conditions [38–40,68–70]. Consequently, the contribution of niobium to sustainability extends beyond alloy composition itself and includes its potential to support long-term performance and life-cycle optimization in advanced engineering applications [71–80].

The transition toward circular-economy models has further increased the importance of sustainable powder technologies. Modern manufacturing strategies increasingly emphasize material recovery, powder reuse, waste minimization, and life-cycle optimization as essential components of industrial competitiveness [79,80]. These principles are particularly relevant to advanced metallic powders because producing high-quality feedstocks often requires significant energy and material inputs.

Recent studies indicate that future developments in powder technology will depend on integrating sustainability objectives with process optimization, materials design, and performance evaluation [76,78–80]. Advances in powder characterization, manufacturing control, and computational modeling may contribute to more efficient utilization of raw materials while meeting the performance requirements of industrial applications.

Sustainability considerations are increasingly influencing the industrial adoption of metallic powder technologies. Powder reuse, recycling protocols, life-cycle optimization, and resource-efficiency strategies are no longer treated as independent objectives but as factors linked to manufacturing competitiveness and process qualification [76,78–80]. For niobium-containing powder systems, the combination of durability, corrosion resistance, and extended service life may reduce material consumption and replacement frequency, reinforcing the relevance of sustainability-oriented materials design.

As sustainability requirements become increasingly important in advanced manufacturing sectors, greater integration between life-cycle assessment methodologies and powder-technology research is expected. Such approaches may improve understanding of the balance between the environmental costs of raw-material production and the technological benefits associated with enhanced durability, corrosion resistance, and extended service life in niobium-containing systems [76,78–80].

9.2. Current Challenges in Niobium-Containing Metallic Powder Systems

Despite considerable progress in powder metallurgy, additive manufacturing, and advanced surface engineering technologies, several challenges continue to limit the broader industrial implementation of niobium-containing metallic powder systems. One of the most critical issues is establishing reliable relationships between powder feedstock characteristics and the final performance of consolidated materials. Variations in particle morphology, particle-size distribution, surface condition, and powder homogeneity may affect densification behavior, phase evolution, defect formation, and long-term engineering performance [18,21,24,43–50].

Another important challenge concerns process reproducibility. Powder-based manufacturing technologies frequently involve complex thermal histories characterized by rapid heating and cooling cycles, repeated thermal exposure, and non-equilibrium phase transformations. As a consequence, even small variations in powder characteristics or processing parameters may generate significant differences in microstructural development and final material properties [43–50,54–60].

The influence of niobium additions also remains strongly dependent on alloy composition and processing route. Although improvements in phase stability, grain refinement, precipitation control, and corrosion resistance have been widely reported, the magnitude of these effects varies among alloy systems and manufacturing technologies [31–40,54–60]. Such variability complicates direct comparisons among studies and highlights the need for standardized methodologies to establish more robust processing–microstructure–performance correlations.

From an industrial perspective, powder reuse and recycling represent additional challenges. Repeated processing cycles may alter particle morphology, oxygen content, flowability, and surface chemistry, potentially affecting manufacturing consistency and component reliability [76,78–80]. The development of qualification protocols that ensure powder quality after multiple reuse cycles remains an important research priority.

Economic considerations also influence industrial adoption. Although niobium provides valuable microstructural and functional benefits, optimizing alloy composition, powder production routes, and manufacturing efficiency remain essential for achieving economically viable large-scale implementation. Consequently, future advances will require not only improvements in alloy design but also enhanced process control, quality assurance, and predictive capability throughout the powder-processing chain [71–80].

9.3. Future Trends in Metallic Powder Systems Containing Niobium

Future developments in metallic powder technology are expected to be driven by the integration of advanced manufacturing, computational materials science, and sustainability-oriented design strategies. In this context, niobium-containing powder systems are likely to play an increasingly key role due to their ability to promote phase stability, microstructural refinement, and corrosion resistance across a broad range of engineering applications [54–60,71–80].

One emerging trend is the growing use of computational thermodynamics and CALPHAD-based methodologies for alloy design and process optimization. These approaches enable the prediction of phase stability, precipitation behavior, and microstructural evolution under different processing conditions, supporting the accelerated development of powder-derived materials with tailored properties [58–60].

The growing availability of machine-learning techniques and data-driven materials engineering platforms is expected to further transform powder technology. By integrating powder characterization data, processing parameters, thermodynamic calculations, and performance measurements, these tools may facilitate process qualification, defect prediction, and accelerated alloy development while reducing experimental costs and development times [58–60].

Advanced additive manufacturing technologies are also expected to expand the applications of niobium-containing powders. Future developments will focus on improved process monitoring, digital manufacturing platforms, and enhanced control of thermal histories, enabling more precise management of phase transformations and microstructural evolution during component fabrication [43–50].

Sustainability considerations will continue to influence future research directions. Powder recycling, resource efficiency, life-cycle assessment, and circular-economy principles are expected to become increasingly integrated into powder production and manufacturing strategies. The combination of enhanced durability, corrosion resistance, and extended service life may further strengthen the role of niobium-containing powder systems in sustainable engineering applications [76,78–80].

Finally, the development of multifunctional materials capable of simultaneously providing structural performance, corrosion resistance, thermal stability, and application-specific functionality represent a promising direction for future investigation. Such advances may contribute to the next generation of powder-derived materials for biomedical, aerospace, energy, and surface-engineering applications [39,40,71–80].

10. Research Opportunities

Despite significant advances in metallic powder technology over the last decade, several scientific and technological challenges remain unresolved. The literature reviewed in this work demonstrates that important opportunities exist to improve understanding of the relationships among powder characteristics, processing conditions, microstructural evolution, and engineering performance. These challenges are particularly relevant to niobium-containing powder systems because the influence of niobium often depends on complex interactions among alloy composition, thermal history, and phase-transformation behavior [24,25,39,40].

A particularly important research challenge is establishing quantitative processing–microstructure–performance relationships that link powder feedstock characteristics to long-term engineering behavior in niobium-containing metallic systems [43–50,54–60]. Although particle-size distribution, morphology, surface condition, and flowability are widely recognized as critical variables, their combined influence on microstructural development, corrosion behavior, and long-term performance remains insufficiently

understood [18,21,24]. Numerous studies have investigated individual aspects of powder processing, microstructural evolution, and mechanical or corrosion performance; however, integrated predictive frameworks that correlate powder characteristics, processing response, and service behavior across different alloy systems and manufacturing routes remain scarce [58–60]. Continued progress in this area will depend on the development of multiscale approaches that integrate powder morphology, particle-size distribution, thermal history, phase evolution, and service conditions into unified design strategies. Such efforts may accelerate alloy optimization, process qualification, and industrial implementation while improving the predictability and reliability of powder-derived materials intended for advanced engineering applications [71–80].

Additional opportunities exist in the field of additive manufacturing. Powder-bed fusion and directed-energy deposition technologies generate complex thermal histories characterized by rapid solidification, repeated thermal cycling, and non-equilibrium phase formation [43–46]. While substantial progress has been made in understanding these phenomena, predictive frameworks that link powder characteristics, process parameters, phase evolution, and engineering performance remain limited. The development of such frameworks would significantly improve process reliability and material optimization.

Microstructural design represents another important research direction. The literature indicates that niobium can influence grain refinement, precipitation behavior, diffusion processes, and phase stability; however, the magnitude of these effects frequently depends on alloy composition and processing route [54–59]. Further studies integrating experimental characterization with computational thermodynamics and CALPHAD-based methodologies may contribute to the development of more robust alloy-design strategies for powder-derived materials.

Corrosion science also offers important opportunities for future investigation. Although numerous studies have reported improvements in corrosion resistance associated with microstructural refinement and phase stabilization, the mechanisms governing passive-film development in powder-derived materials remain incompletely understood [64–70]. Future work should emphasize integrating electrochemical testing, advanced surface characterization, and microstructural analysis to establish stronger correlations between processing history and long-term corrosion performance.

The growing availability of computational tools, machine-learning techniques, and digital-manufacturing platforms is expected to transform powder technology in the coming years. Data-driven methodologies may facilitate powder qualification, process optimization, defect prediction, and alloy design by integrating experimental and computational information into unified development frameworks [58–60]. Such approaches have the potential to accelerate materials development while reducing experimental costs and development times.

Sustainability-related topics are also expected to become increasingly important. Powder reuse, recycling strategies, circular-economy principles, and life-cycle assessment methodologies have emerged as critical issues for industrial implementation [76,78–80]. Future studies should evaluate not only the effects of powder recycling on manufacturing performance but also the broader environmental implications associated with powder production, utilization, and end-of-life management.

Another promising research area involves the development of multifunctional powder-derived materials that simultaneously deliver structural performance, corrosion resistance, thermal stability, and application-specific functional properties. The combination of advanced powder-processing routes with tailored alloy design may create opportunities to develop next-generation metallic materials for biomedical, energy, aerospace, and surface-engineering applications [39,40,71–75].

The research opportunities identified throughout this review indicate that future advances in niobium-containing metallic powder systems will increasingly depend on multidisciplinary approaches that integrate powder engineering, advanced manufacturing, computational materials science, corrosion engineering, and sustainability assessment. Although substantial progress has been made in understanding the influence of niobium on phase stability, precipitation behavior, microstructural evolution, and corrosion performance, significant challenges remain in predicting long-term behavior across different alloy systems and processing routes [43–60].

Attention should be devoted to developing integrated processing–microstructure–performance frameworks that quantitatively correlate powder characteristics, manufacturing parameters, microstructural evolution, and service behavior. Such approaches may provide a more reliable basis for alloy optimization, process qualification, and industrial implementation while reducing reliance on empirical trial-and-error methodologies that still dominate many areas of powder technology [54–60,71–80].

In addition, the increasing availability of computational thermodynamics, machine-learning tools, digital manufacturing platforms, and advanced characterization techniques creates opportunities to accelerate materials development and improve process predictability. The integration of these methodologies with sustainability-oriented strategies, including powder recycling, life-cycle optimization, and resource-efficiency assessment, is expected to play a decisive role in the future evolution of powder-based manufacturing technologies [58–60,76,78–80].

Future progress in niobium-containing metallic powder systems will therefore depend on the ability to establish robust links between powder characteristics, processing conditions, microstructural evolution, and engineering performance. The integration of advanced characterization techniques, computational materials design, data-driven methodologies, and sustainability assessment may enable more efficient alloy development and process optimization. Such efforts are expected to accelerate the transition from laboratory-scale investigations to industrially validated powder technologies.

11. Conclusions

Niobium-containing metallic powder systems represent an important and expanding field within powder technology due to their potential to combine controlled microstructural evolution, improved phase stability, enhanced corrosion resistance, and application-specific functional properties. The literature reviewed demonstrates that the interaction among powder characteristics, processing conditions, alloy chemistry, and resulting microstructural features governs the performance of these systems.

Powder production and particle characterization constitute fundamental stages in the development of reliable metallic powder systems. Parameters such as particle size distribution, morphology, flowability, and chemical homogeneity directly influence processing behavior and subsequent material performance. Consequently, advances in powder characterization methodologies continue to play a vital role in improving the reproducibility and quality of powder-based manufacturing technologies.

The incorporation of niobium provides opportunities for microstructural control through its influence on phase stability, precipitation behavior, grain refinement, and diffusion-controlled transformations. These effects are particularly relevant in powder-derived materials because modern processing routes frequently involve complex thermal histories that can modify phase evolution and long-term material performance.

The review also demonstrates that processing route selection is a decisive factor governing the behavior of niobium-containing metallic powders. Powder metallurgy, additive manufacturing, thermal spraying, and related technologies impose distinct thermal and

consolidation conditions that directly affect microstructural development and engineering performance. As a result, optimizing processing parameters remains essential to maximizing the benefits of niobium additions.

Microstructural evolution and corrosion performance are closely interconnected in powder-derived materials. The available evidence indicates that phase stability, microstructural homogeneity, and passive-film development play fundamental roles in determining long-term durability and environmental resistance. These relationships are particularly important for applications involving aggressive service environments, biomedical devices, advanced coatings, and high-performance engineering components.

The technological relevance of niobium-containing metallic powder systems is reflected in their growing utilization across additive manufacturing, biomedical engineering, surface engineering, energy systems, and other advanced industrial sectors. At the same time, sustainability considerations are becoming increasingly important, emphasizing powder reuse, recycling strategies, circular-economy approaches, and resource-efficient manufacturing practices. This perspective should include not only powder reuse and circular-economy strategies but also the environmental implications of extracting and processing niobium-bearing raw materials, thereby reinforcing the importance of life-cycle-based sustainability assessments.

The body of literature examined in this review demonstrates that the technological relevance of niobium-containing metallic powders extends beyond conventional alloying effects. The available literature suggests that niobium exerts its greatest influence when phase stability, precipitation behavior, microstructural evolution, and corrosion resistance are evaluated as interconnected phenomena rather than as isolated material attributes. Consequently, future advances are expected to arise from integrated processing–microstructure–performance approaches that combine powder engineering, advanced characterization, computational materials design, and sustainability-oriented manufacturing strategies. Such a perspective may facilitate the development of powder-derived materials with improved reliability, predictability, and industrial applicability across a broad range of engineering sectors.

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