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Review

Recyclability in Metal Additive Manufacturing: Bridging Powder Lifecycle, Defect Evolution and Fatigue-Critical Reliability Across SLM and EBM

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Abstract

Powder recyclability in metal additive manufacturing has become a critical requirement for improving sustainability, cost-efficiency, and industrial scalability, particularly in powder bed fusion processes such as Selective Laser Melting (SLM) and Electron Beam Melting (EBM). Despite growing interest in powder reuse, the available literature remains fragmented, often addressing powder degradation, process defects, or mechanical performance as isolated topics. This separation limits understanding of how powder lifecycle evolution affects fatigue-critical reliability, where small variations in powder condition may strongly influence long-term structural integrity. This review aims to establish a unified process–structure–performance perspective linking powder reuse, degradation mechanisms, defect evolution, and mechanical reliability in SLM and EBM. A structured literature analysis was conducted to examine changes in powder morphology, particle size distribution, chemical composition, oxygen uptake, moisture interaction, flowability, and thermal history across reuse cycles. Attention was given to the relationship between powder degradation mechanisms and defect formation during processing. The review shows that static mechanical properties, including tensile strength and hardness, may remain comparatively stable after multiple reuse cycles. In contrast, fatigue performance is markedly more sensitive to powder condition, owing to the accumulation of defects such as oxide inclusions, porosity, lack-of-fusion regions, and irregular melt-pool features. Distinct degradation pathways were identified: SLM is mainly governed by oxidation-related effects, whereas EBM is more strongly influenced by particle coarsening, morphology changes, and thermal exposure. Powder recyclability should be considered not only as a sustainability issue but also as a reliability-driven engineering challenge. The proposed framework supports reuse decisions by integrating powder lifecycle assessment with defect tolerance and fatigue-critical performance requirements.

Keywords: recycling; metal powder reuse; process–structure–property relationships; circular manufacturing; mechanical performance; sustainable manufacturing

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1. Introduction

Additive manufacturing (AM) has undergone a rapid transformation from prototyping technology to a key enabler of advanced manufacturing systems, supporting the production of complex geometries, functional integration, and distributed production models [1]. Among the various AM approaches, powder bed fusion (PBF) technologies, particularly Selective Laser Melting (SLM) and Electron Beam Melting (EBM), have gained significant industrial relevance due to their ability to process metallic materials with high precision and mechanical performance [2,3]. These technologies are increasingly applied in high-value sectors such as aerospace, biomedical engineering, and energy systems, where performance, reliability, and material efficiency are critical [4–6].

Within this context, powder recyclability has emerged as a central issue for the economic and environmental sustainability of metal AM. In PBF, the metallic feedstock is not a passive input material but a process-defining element that governs powder spreading, layer uniformity, energy absorption, melt-pool stability, defect formation, and ultimately component performance. Ganta et al. [7] studied the challenge of powder recycling in LPBF, where physicochemical degradation alters powder-bed density, defect formation, and fatigue-critical reliability. Established a process-linked framework connecting powder deterioration, melt-pool behaviour, mechanical performance, monitoring strategies, and replenishment routes for sustainable LPBF. Guimarães et al. [8] studied the challenge of recycling PLA-based 3D-printing waste into dimensionally stable filament while controlling extrusion flow, screw design, cooling, and winding consistency. A modular shredder–extruder–winder system was developed, capable of producing recycled PLA filament with a controlled diameter of 1.75 $\pm$ 0.03 mm. Pacheco et al. [9] investigated the challenge of achieving circularity in polymer AM despite degradation, anisotropy, support contamination, multi-material waste, and limited recycling infrastructure. It was determined that polymer AM circularity requires Design for Recycling, resilient materials, specialised collection systems, feedstock standards, and realistic lifecycle assessment.

Feedstock quality is determined by a combination of intrinsic and extrinsic characteristics, including alloy chemistry, atomisation route, particle size distribution, morphology, surface condition, oxygen and moisture content, apparent density, tap density, and flowability [10]. Gorji et al. [11] investigated the challenge of reusing 316L powder for biomedical implants while controlling surface oxidation, particle circularity, porosity, roughness, and mechanical degradation. They determined that recycled powder increased oxygen and surface roughness (SR), while reducing implant hardness and effective modulus relative to virgin-powder builds.

These attributes are particularly important in SLM and EBM, where only a fraction of the powder is consolidated into the final part while the remaining material is repeatedly exposed to thermal cycling, atmosphere interaction, mechanical handling, sieving, and recovery operations. Consequently, any discussion of powder recyclability must first recognise that reused feedstock represents an evolving material system whose properties progressively diverge from those of the virgin powder. This evolution provides the starting point for understanding how powder reuse affects process repeatability, defect generation, microstructural development, and fatigue-critical reliability. The reuse of metal powders is commonly practised in industrial settings to reduce material costs and minimise waste generation, especially given the high price of atomised powders and the relatively low material utilisation efficiency during processing [12]. As a result, multiple reuse cycles are often implemented, with powders being sieved and reintroduced into the process. However, this practice introduces progressive changes in powder characteristics, which may ultimately affect process stability and component performance [13].

A growing body of research has investigated the evolution of powder properties during reuse cycles. Key parameters such as particle size distribution, morphology, surface chemistry, and flowability have been identified as critical factors influencing processability and final part quality [14]. Oxidation phenomena have been widely reported in SLM processes, where repeated exposure to elevated temperatures and residual oxygen levels leads to the formation of oxide layers on powder particles [15]. These changes can alter surface energy, reduce wettability, and promote the formation of defects during melting and solidification [16].

In contrast, EBM processes, which operate under vacuum conditions, exhibit different degradation mechanisms. Studies have shown that powder reuse in EBM is more strongly associated with physical changes, such as particle coarsening, sintering effects, and alterations in particle morphology due to thermal exposure [17]. These differences highlight the process-dependent nature of powder degradation, indicating that recyclability cannot be assessed independently of the manufacturing technology employed. Powell et al. [18] studied the challenge of powder degradation in metal AM, where reuse progressively alters morphology, chemistry, flowability, and component quality without clear end-of-life criteria. Plasma spheroidisation can upcycle degraded powders, reducing disposal and restoring particle characteristics closer to virgin feedstock.

Despite these advances, most existing studies focus on isolated aspects of powder degradation, often analysing individual properties or specific process conditions without establishing a comprehensive link to structural integrity and mechanical performance [19]. In particular, the relationship between powder reuse and mechanical properties remains insufficiently explored from an integrated perspective. While several studies report that static properties such as tensile strength and hardness are relatively insensitive to powder reuse under controlled conditions [20], increasing evidence suggests that fatigue performance is significantly more affected due to the accumulation of defects such as porosity, lack-of-fusion regions, and oxide inclusions [21].

This distinction between static and fatigue behaviour is critical for industrial applications. In many high-performance components, failure is governed by cyclic loading conditions rather than static strength limits. Therefore, even minor increases in defect population or size can lead to substantial reductions in fatigue life, raising concerns regarding the reliability of components produced using recycled powders [22]. However, this issue is often under-represented in the literature, where the focus remains predominantly on static characterisation.

Another limitation of current research lies in the lack of a unified framework linking powder degradation mechanisms to process behaviour and component performance. Although numerous studies provide valuable experimental insights, their findings are often fragmented and difficult to generalise across different materials, processes, and application domains. As a result, there is a clear need for approaches that integrate these elements into a coherent structure, enabling a more systematic understanding of powder recyclability and its implications. Furthermore, emerging strategies such as powder rejuvenation and upcycling have been proposed to mitigate degradation effects and extend the usable lifecycle of metal powders [23]. These approaches, which include chemical treatments, mechanical reconditioning, and blending strategies, highlight the potential for moving beyond simple reuse toward more advanced lifecycle management concepts [24]. However, their integration into a broader decision-making framework remains limited.

The novelty of the present review lies in its integrated treatment of powder recyclability as a process–structure–performance problem rather than as an isolated feedstock-management issue. Existing reviews have commonly addressed powder reuse, powder degradation, sustainability, or AM processability as separate topics. By contrast, this review

explicitly links powder lifecycle evolution to process-dependent degradation mechanisms, defect formation, microstructural response, and mechanical reliability. Particular emphasis is placed on the distinction between static mechanical properties, which may remain comparatively stable after several reuse cycles, and fatigue performance, which is often more sensitive to small defect populations, oxide inclusions, lack-of-fusion regions, and powder-history-dependent discontinuities. In addition, the review compares the different degradation pathways observed in SLM and EBM, thereby clarifying why powder recyclability cannot be assessed through a single universal reuse criterion. This approach supports a transition from empirical reuse-cycle limits towards reliability-based powder qualification and application-specific lifecycle management. The scope of this review is deliberately focused on metal powder recyclability in powder bed fusion processes, with SLM and EBM selected as the principal process families because they represent two industrially relevant but mechanistically distinct powder-reuse environments. The alloy systems considered, including Al alloys, stainless steels, Ni superalloys, and Ti alloys, are treated as representative material families through which process-dependent powder degradation can be compared. The review does not aim to provide an exhaustive survey of all metallic materials, all AM routes, or all fatigue-modelling approaches. Instead, it examines degradation mechanisms only insofar as they influence powder lifecycle evolution, powder-bed behaviour, defect formation, microstructural response, and mechanical reliability. Within this defined boundary, fatigue is addressed as a critical reliability outcome governed by powder-induced defect populations, rather than as a standalone fatigue-design review.

In response to these challenges, this study aims to provide a comprehensive and structured review of powder recyclability in metal AM, with a particular focus on its implications for fatigue-critical reliability. Building upon the analysis of the existing literature, this work adopts a process–structure–performance perspective, linking powder lifecycle evolution to defect formation mechanisms and mechanical behaviour. By comparing SLM and EBM processes and identifying process-dependent degradation pathways, the study seeks to bridge the gap between material degradation and structural performance. To address these limitations, this study proposes a process–structure–performance framework (Figure 1) for powder recyclability in metal AM, which integrates powder lifecycle evolution, degradation mechanisms, process conditions, microstructure development, and defect formation into a unified structure.

Unlike conventional reviews, this framework explicitly links powder degradation to fatigue-critical performance, identifying defects as the governing mechanism controlling structural reliability. By bridging material evolution and mechanical response, the proposed approach enables a generalisable and decision-oriented understanding of recyclability across different AM processes.

This paper presents a systematically structured and critically informed review of powder recyclability in metal AM, organised into seven interrelated sections designed to provide conceptual depth, methodological transparency, and analytical coherence. Collectively, these sections examine the material, process, structural, and reliability-related factors governing powder reuse in powder bed fusion technologies, with particular emphasis on SLM and EBM. Section 1 introduces the study by establishing the industrial and scientific relevance of powder recyclability, situating the topic within the broader contexts of sustainability, circular manufacturing [25], process stability, and fatigue-critical component reliability. It also defines the central rationale of the review by highlighting the need to connect powder lifecycle evolution with degradation mechanisms, defect formation, and mechanical performance.

In the interest of scholarly transparency and critical reflection, the manuscript also recognises the limitations of the current literature, particularly the heterogeneity of reuse

protocols, the inconsistent reporting of powder history, the scarcity of long-term fatigue data, and the absence of universally accepted certification thresholds for recycled powders. Taken together, the structure of the paper provides a coherent and technically grounded account of powder recyclability in metal AM, while also delineating the scientific and industrial priorities required to move from empirical powder reuse towards controlled, reliability-based lifecycle management. The remainder of this review is organised as follows. Section 2 describes the research methodology, including the bibliographic search strategy, selection procedure, filtering criteria, and analytical scope adopted to construct a technically relevant literature corpus. This section supports the transparency and reproducibility of the review process, while ensuring balanced coverage of powder degradation phenomena, process-dependent behaviour, and performance-related outcomes. Section 3 presents the literature review, structured around the principal technological and material domains relevant to powder recyclability. It critically examines powder reuse in SLM, with attention to AlSi10Mg, 316L stainless steel, and INCONEL® 718; powder degradation in EBM, particularly for Ti-6Al-4V and Ni-based alloys [26]; solid scrap recovery and reconditioning routes; and the role of standardisation, certification, and industrial qualification in enabling reliable powder reuse.

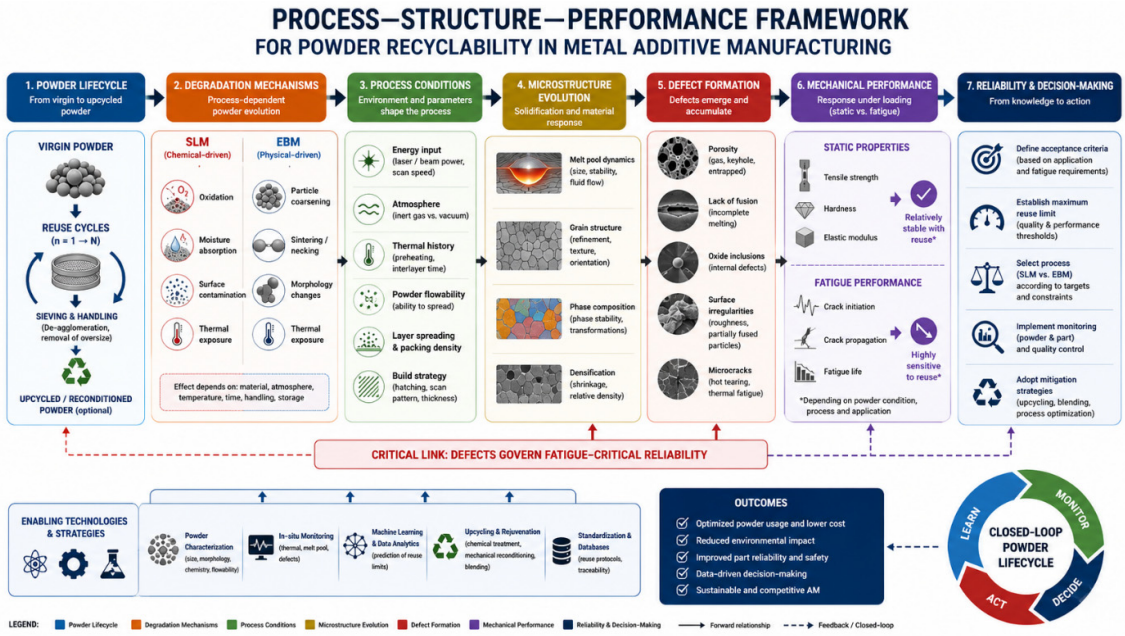


Figure 1. Process–structure–performance framework proposed in this work.

Section 4 develops the critical analysis by integrating the reviewed evidence within a process–structure–performance perspective. This section identifies the main degradation pathways affecting recycled powders, distinguishes chemically driven mechanisms in SLM from predominantly physical degradation in EBM, and explains how these changes propagate into microstructural evolution, defect populations, and mechanical behaviour. Attention is given to the asymmetry between static properties and fatigue performance, emphasising that tensile strength and hardness may remain comparatively stable, whereas fatigue life is highly sensitive to oxide inclusions, porosity, lack-of-fusion defects, and powder-history-dependent discontinuities.

Section 5 outlines future trends in powder recyclability, including artificial intelligence for powder qualification, feedstock digital twins, advanced traceability, plasma re-spheroidisation, chemical rejuvenation, cold spray routes for secondary powder use, and the development of alloys designed for improved recyclability. These perspectives frame

powder reuse as an active lifecycle-engineering problem rather than a passive material-recovery practice. Section 6 consolidates the discussion by positioning powder recyclability as a reliability-driven engineering challenge, requiring application-specific acceptance criteria, process-specific lifecycle management, and closer integration between powder characterisation, defect tolerance, and fatigue-critical qualification. Finally, Section 7 presents the conclusions, synthesising the principal findings and clarifying the contribution of the review to the development of safer, more sustainable, and industrially robust metal AM routes.

2. Method of Research

This review was developed through a structured literature survey guided by the principles of the PRISMA 2020 statement [27,28], in order to ensure transparency, traceability, and reproducibility in the identification, screening, and selection of relevant studies. The search focused on peer-reviewed publications addressing powder recyclability in metal AM [29], with particular emphasis on powder bed fusion processes, namely SLM/L-PBF and EBM/E-PBF. The review scope was limited to studies in which metal powder reuse, feedstock degradation, powder-bed processability, defect formation, or mechanical reliability were explicitly connected, with primary emphasis on SLM and EBM rather than on the full spectrum of metal AM processes.

Bibliographic records were collected primarily from Crossref, which was used as the central source for DOI-linked bibliographic metadata across multiple publishers. Dimensions.ai was used as a complementary search engine to broaden retrieval coverage and support metadata verification, while Scopus and Web of Science were consulted where appropriate to cross-check indexing consistency and reduce the risk of database-specific omission. The search covered peer-reviewed publications from 2015 to 2025, a period selected to capture recent developments in powder reuse, powder degradation, defect formation, mechanical performance, and reliability-oriented qualification in metal additive manufacturing.

The search strategy was structured around three keyword groups. The first group addressed metal additive manufacturing and powder bed fusion processes, including terms such as "*metal additive manufacturing*", "*powder bed fusion*", "*selective laser melting*", "*laser powder bed fusion*", "*SLM*", "*L-PBF*", "*electron beam melting*", "*EBM*", and "*E-PBF*". The second group focused on powder reuse and lifecycle degradation, including "*powder reuse*", "*metal powder recycling*", "*powder recyclability*", "*powder ageing*", "*powder degradation*", "*powder oxidation*", "*particle morphology*", "*particle size distribution*", "*powder flowability*", and "*powder reconditioning*". The third group addressed defect formation and performance-related outcomes, including "*porosity*", "*lack of fusion*", "*oxide inclusions*", "*spatter*", "*microstructure*", "*mechanical properties*", "*fatigue performance*", "*fatigue life*", "*structural integrity*", "*reliability*", and "*circular manufacturing*".

The inclusion criteria considered peer-reviewed journal articles, review papers, and selected technically relevant conference contributions written in English. Studies were retained when they addressed powder reuse, powder lifecycle evolution, feedstock degradation, processability, defect formation, microstructural response, mechanical performance, or reliability in metal AM. Priority was given to studies involving representative metallic alloy systems, including Al alloys, stainless steels, Ni superalloys, and Ti alloys, and to investigations providing comparative evidence between virgin and reused powders, different reuse-cycle histories, or process-dependent degradation mechanisms.

The exclusion criteria removed publications that addressed AM only in general terms, focused exclusively on polymers or non-powder feedstocks, lacked a clear connection to powder reuse, or did not provide sufficient technical detail to support comparison across

powder degradation, process behaviour, defect formation, and performance outcomes. Records were screened in successive stages, beginning with title, abstract, and keyword assessment, followed by full-text evaluation of studies considered potentially eligible.

A Quality Assessment (QA) procedure was applied to ensure that the final corpus was technically robust and conceptually aligned with the objectives of the review. The appraisal considered research design, clarity of the powder lifecycle and processing framework, methodological rigour, analytical transparency, and industrial relevance. Particular attention was given to whether studies reported powder history, reuse-cycle number, material system, processing atmosphere, powder recovery or sieving strategy, characterisation methods, defect-assessment procedures, and mechanical-performance indicators. The final selection therefore provided a coherent basis for analysing powder recyclability through a process–structure–performance perspective, linking feedstock degradation to defect evolution and fatigue-critical reliability. Where quantitative values were available in the reviewed studies, they were retained to support comparison between powder states, reuse cycles, defect populations, and mechanical-performance outcomes. However, direct numerical comparison across studies remains limited by differences in powder history reporting, reuse-cycle definitions, sieving and top-up strategies, atmosphere control, specimen geometry, post-processing condition, and testing protocols.

Further details concerning the extended screening procedure, eligibility rationale, and supplementary methodological clarifications are provided in Appendix A.

3. Literature Review

3.1. Recyclability in Selective Laser Melting (SLM/L-PBF)

In this review, the term Selective Laser Melting (SLM) is used as the primary designation for the laser-based powder bed fusion process discussed in this section. Equivalent terms such as laser powder bed fusion, L-PBF, LPBF and PBF-LB/M are acknowledged because they appear frequently in the literature and in database indexing; however, SLM is used consistently in the authors' narrative to improve readability and avoid terminological fluctuation.

SLM, commonly referred to as laser powder bed fusion, represents one of the most widely investigated metal AM routes for powder reuse due to its industrial maturity, high dimensional capability, and broad material applicability. However, the repeated exposure of unfused powder to laser irradiation, elevated chamber temperatures, residual oxygen, moisture, and spatter generation progressively modifies the feedstock condition. These changes may involve particle-size redistribution, surface oxidation, satellite formation, agglomeration, altered flowability, and chemical contamination, all of which can affect powder spreading, melt-pool stability, porosity formation, and final part integrity. The severity and consequences of these degradation mechanisms are strongly alloy-dependent, since Al alloys, stainless steels, and Ni superalloys exhibit distinct sensitivities to oxidation, thermal cycling, and defect accumulation. Accordingly, this section analyses powder recyclability in SLM through representative alloy systems, linking powder lifecycle evolution to processability, microstructural response, and mechanical performance.

3.1.1. Al Alloys (AlSi10Mg)

The study of recyclability in Al alloys, specifically AlSi10Mg, is complex due to the material's high reactivity with oxygen and its hygroscopic nature (high capacity to absorb water—moisture—from the environment). Bauer et al. [30] studied the challenge of controlling aluminium powder ageing during LBM-relevant storage and handling, particularly humidity-driven oxidation, hydrogen uptake, whisker growth, and flowability

loss. Elevated humidity and temperature accelerate surface degradation, whereas vacuum drying partially restores powder flowability and supports reconditioning strategies.

Aboulkhair et al. [1] provide a comprehensive framework for achieving near-full density in AlSi10Mg parts produced via SLM, a process traditionally hindered by the alloy's high reflectivity and thermal conductivity. By systematically evaluating the relationship between hatch spacing, scanning speed, and laser power, the researchers identified two primary defect types: small, spherical metallurgical pores (gas-related) and large, irregular keyhole pores, presented in Figure 2 (caused by incomplete melting). The study's most critical finding was that implementing a double-scan strategy—specifically a "pre-sinter" approach where each layer is scanned first at low power and then at full power—effectively "heals" defects from the initial pass. This optimised process, combined with a narrow hatch spacing of 50–100 µm, allowed the production of Al alloy components with a relative density of 99.8%, effectively overcoming the porosity barriers that previously limited the use of Al alloys in high-end AM.

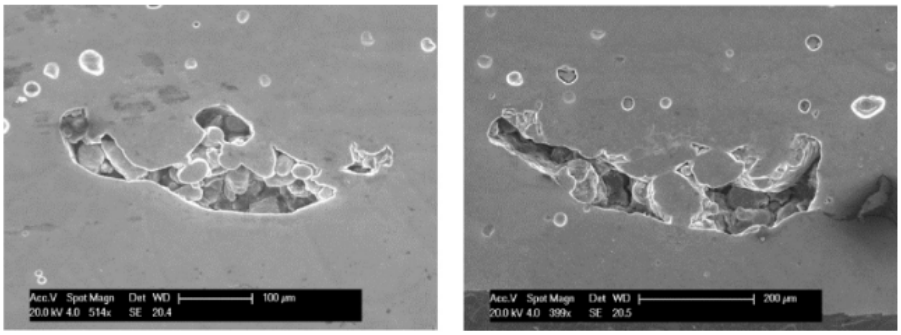


Figure 2. Keyhole pore enclosing non-molten powders [1].

Fiegl et al. [21] investigate the impact of long-term powder reusage (over 30 months) on the quality and performance of AlSi10Mg. While reusing powder is economically essential for large-scale industrial AM, this research demonstrates that significant powder degradation occurs over time due to the accumulation of spatters and the formation of hydroxides and oxides on the particle surfaces, as we can see in Figure 3. These chemical changes increase the oxygen and hydrogen content in the feedstock, leading to a quadrupling of porosity (from <1% in virgin powder to ~3% in reused powder) and a 15% reduction in key mechanical properties, including tensile strength, yield strength, and elongation at break. The core mechanism for this degradation is the increased oxide layer thickness on particles, which reduces melt pool wetting and promotes "lack of fusion" defects, combined with moisture-driven hydrogen supersaturation that triggers pore formation during solidification. Ultimately, the study highlights that process parameters optimised for virgin powder are insufficient for long-term reused powder, necessitating a better understanding of powder ageing to maintain part integrity in industrial settings.

Asgari et al. [22] deepened the relationship between microstructure and mechanical properties by using recycled AlSi10Mg powder in heated platform systems. The research revealed that preheating to 200 °C acts as an "in situ" heat treatment, mitigating residual stresses that tend to be exacerbated by the irregular morphology of the recycled powder. By comparing virgin, recycled (sieved), and "condensate" (coarse, heated but unmelted) powders, the authors found that recycled powder maintains morphology, particle size, and chemical composition similar to virgin powder, whereas condensate powder is significantly coarser. Most importantly, the study confirmed that parts manufactured with recycled powder exhibit microstructures and mechanical properties comparable to those made with virgin powder, including similar yield and tensile strengths. A key mechanical finding was the anisotropy based on build direction: horizontal samples showed higher elongation

(8.8%) compared to vertical samples (5.8%), despite similar tensile strengths (~390 MPa). Fractography revealed that this difference is due to the orientation of the "melt pool" boundaries relative to the tensile load, which influences the fracture mode. Bartošák et al. [31] brought an innovation by using the Physics-Informed Neural Network (PINN) model. Once developed in this study, it overcomes the limitations of conventional AI by fusing the computational power of deep learning with the fundamental laws of material mechanics, specifically the Basquin and Coffin–Manson equations. Instead of treating the process as a "black box", the network is trained to respect the mathematical relationships between the amplitude of elastic/plastic deformation and the number of cycles to failure, using as input variables the construction orientation (horizontal or vertical), the condition of the powder (virgin or recycled) and the tenacity of the material. This integration of physics into the algorithm's cost function allows the model to accurately identify how the increase in oxygen and porosity from recycling AlSi10Mg powder accelerates crack nucleation, as we can see in Figure 4, resulting in extremely reliable lifetime predictions, even with reduced datasets, and ensuring that the final results are not only statistically valid, but mechanically coherent.

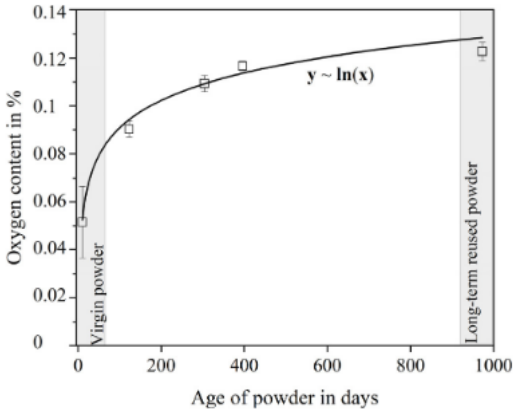


Figure 3. Oxygen content depends on powder age, beginning with virgin and ending with long-term reused powder [21].

Raza et al. [23] focused on powder degradation over a 30-month period of continuous reusage. The research identifies two primary mechanisms for ageing: the formation of heavily oxidised spatter particles and a steady increase in the overall oxide layer thickness on all particles. Over 30 months, the volume fraction of these oxidised spatters rose to 3%, while the average thickness of the uniform oxide layer increased from ~4 nm to ~38 nm. Using advanced surface analysis (XPS and STEM), the authors found that these spatters feature a "nodular" oxide scale up to 125 nm thick, caused by the extreme heat and residual oxygen (~1000 ppm) in the build chamber. This degradation is directly linked to an increase in bulk oxygen content (from 500 ppm to 1250 ppm), which impairs the melt pool's ability to "wet" the powder bed and ultimately introduces lack-of-fusion defects in the final parts. Complementing the conclusion of Raza et al. [23], Lubkowitz et al. [32] identify in-process laser drying as the most effective method for mitigating moisture-induced hydrogen porosity. While traditional furnace and vacuum drying successfully reduce powder moisture, the researchers discovered that these external methods are inherently flawed because their prolonged thermal cycles accelerate oxide layer growth, which ultimately degrades the final part density. In contrast, the study validates an "in-process" approach—using a defocused, low-power laser beam to scan each layer immediately before melting—to vapourise surface moisture without providing the time or temperature necessary for further oxidation. Guo et al. [33], with this study, deepen the understanding of structural integrity

in the AM of AlSi10Mg by introducing the "powder sheets" methodology, which allows isolating and analysing mass transfer and defect formation with a precision impossible in conventional powder beds. Through in situ monitoring with high-speed filming and subsequent metallographic analyses, the authors identified that the dynamics of the weld pool are governed by a competition between surface tension and vapour pressure recoil, where any instability in the liquid metal flow directly results in gaseous porosity or "lack of fusion" defects. Figure 5 illustrates these microsecond dynamics, capturing the melt pool lag and the ejection of droplets as the laser interacts with the powder sheet. Experimental details reveal that the geometric distribution of the powder and the variation in layer thickness influence laser energy absorption, demonstrating that spatter formation and denudation zones are critical byproducts of inefficient mass transfer. In summary, the article establishes a direct correlation between the physical phenomena observed in microseconds and the final microstructure, offering quantitative parameters for the thermal and hydrodynamic control necessary to eliminate porosity and ensure metallurgical homogeneity in critical components.

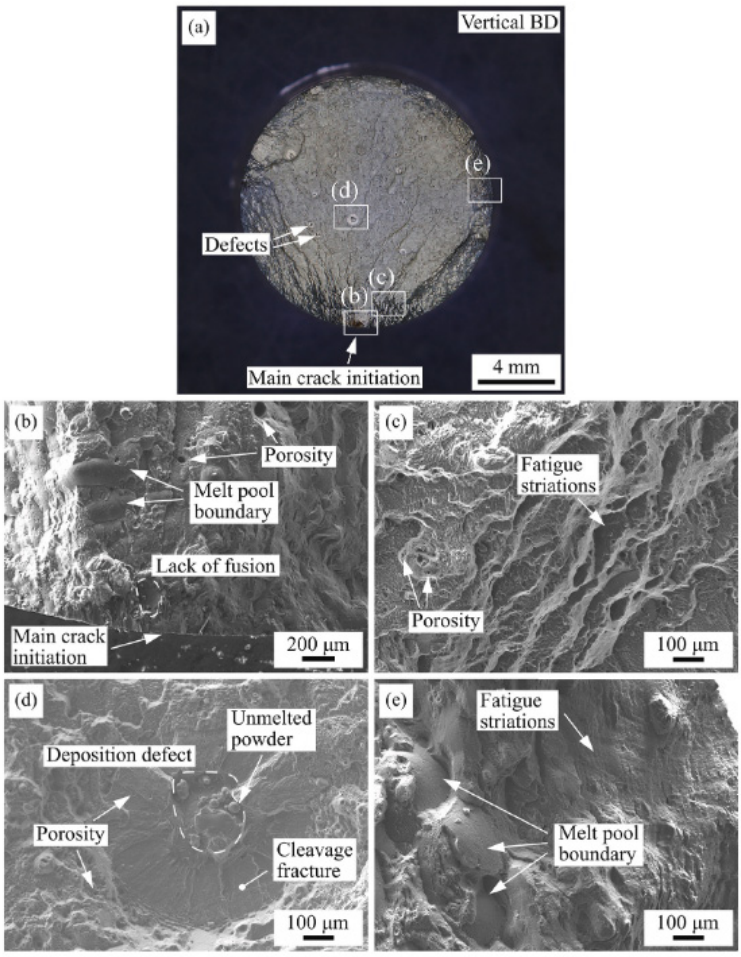


Figure 4. The fracture surface of the vertically built specimen from the performed LCF test with $\varepsilon a = 6 \times 10^{-3}$. An overview of the entire fracture surface is shown in (**a**), with a detailed view of the main crack-initiation site presented in (**b**). The transgranular crack propagation is depicted in (**c**). The fracture morphology around a deposition defect resulting from the deposition strategy is observed in (**d**), while cracking along the boundaries of melt pools is documented in (**e**) [31].

In addition, Lutter-Günther et al. [34] investigate the dynamics of spatter formation during the melting of AlSi10Mg and its direct impact on the degradation of the metal powder quality, correlating the stability of the Laser Beam Melting process with the integrity

of the reused material. Through systematic experiments, the authors demonstrated that spatter is mainly generated by vapour recoil forces and instabilities in the melt pool, resulting in particles with irregular morphology, greater surface oxidation, and a distinct (often coarser) microstructure compared to virgin powder. The research details that these contaminant particles frequently have altered reflectivity and a higher defect density, which, when reincorporated into the powder bed, impairs the material's flowability and induces porosity formation in the final parts. In conclusion, the article establishes that monitoring and controlling spatter formation are fundamental to ensuring the sustainability of the powder's lifecycle, warning that recycling without rigorous criteria for removing these byproducts can compromise the mechanical properties and homogeneity of the manufactured components.

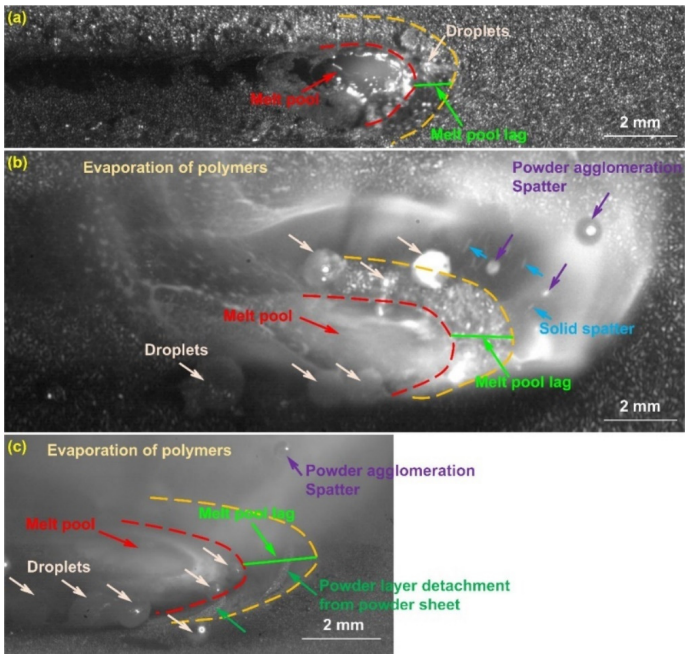


Figure 5. Defects during melting of AlSi10Mg (**a**) Initial melt-pool formation, with droplet ejection and visible melt-pool lag during laser interaction with the powder sheet, (**b**) Polymer evaporation intensifies plume formation, promoting powder agglomeration, solid spatter, droplet ejection and melt-pool instability, (**c**) Powder-layer detachment occurs as melt-pool lag, droplets and agglomerated spatter indicate unstable mass transfer during melting [33].

Chebil et al. [35] investigated quantifying spatter ejection in aluminium LPBF, including particle size, velocity, emission angle, alloy dependence, and powder-bed contamination. It was determined that oxygen content had limited influence, whereas laser intensity increased spatter velocity, size, ejection angle, and process-pollution severity.

Maurer et al. [36] identified the principal challenge as determining whether LPBF smoulder, normally discarded, can be safely reused without impairing processability, porosity, surface quality, or tensile performance. Sieved AlSi10Mg smoulder showed comparable phase composition, acceptable flowability, similar part quality, and tensile properties meeting or exceeding reference values. Weiss et al. [37] studied the challenge of recycling AlSi10Mg powder in LPBF while controlling particle coarsening, spatter contamination, oxygen uptake, flowability, and build-direction effects. Ten reuse cycles improved powder flowability and static strength, while maintaining density above 99% and largely stable chemistry.

Cordova et al. [38] studied the challenge of reusing Al–Mg–Sc–Zr LPBF powder while controlling PSD coarsening, agglomerates, porosity growth, and property repro-

ducibility. They determined that four reuse cycles, combined with sieving and 40% virgin-powder rejuvenation, preserved microstructure and broadly comparable tensile behaviour. Smolina et al. [39] studied the challenge of continuously reusing AlSi7Mg0.6 powder in LPBF while maintaining PSD, morphology, flowability, laser absorption, porosity, and tensile reliability. Five consecutive reuse cycles produced largely repeatable powder and part properties, with only minor initial degradation in the fifth cycle. Beal et al. [40] explored the challenge of reusing 6061-Zr aluminium powder in LPBF while controlling oxygen enrichment, Mg loss, morphology, moisture, toxicity, and part quality. Six severe reuse cycles preserved granulometry, density, roughness, mechanical response, and toxicological behaviour, while sieving limited degraded residues. Muñiz-Lerma et al. [41] looked to define Al powder reuse limits in LPBF while accounting for feedstock morphology, PSD, oxide growth, flowability, and mechanical reliability. The authors demonstrated that initial powder quality governs the degradation rate, with spherical AlSi10Mg powder retaining properties better than irregular feedstock over 15 reuse cycles.

3.1.2. Steel Alloys and Stainless Steel

Steel alloys constitute one of the most important material families for powder recyclability studies in laser powder bed fusion, owing to their broad industrial relevance, relatively high processability, and diverse microstructural responses to repeated powder reuse. Within this group, austenitic stainless steels, precipitation-hardening stainless steels, and maraging steels exhibit distinct sensitivities to thermal cycling, oxygen uptake, spatter incorporation, particle-size redistribution, and phase evolution. Stainless steel, especially 316L, is widely used in medical, marine, and chemically aggressive environments due to its corrosion resistance and generally robust processability. Its recyclability is often considered comparatively high, although the literature identifies critical changes in powder morphology, oxygen content, magnetic response, δ-ferrite retention, and inclusion formation that may affect powder-bed stability and defect generation. Maraging steels, particularly MS1 and 18Ni300, add a further level of complexity because their performance depends strongly on martensitic transformation, precipitation hardening, residual-stress development, and post-processing conditions. Accordingly, the recyclability of steel powders should be assessed not only through chemical stability and static strength retention, but also through microstructural evolution, defect tolerance, surface integrity, and application-specific reliability.

Ahmed et al. [2] conducted a detailed study on 17-4 PH steel, a precipitation hardening alloy. The research focused on the preservation of the spherical morphology of the powder after ten reuse cycles in SLM. The authors concluded that, although the overall chemistry remains stable, there is a slight reduction in the hardness of the parts due to the change in cooling kinetics induced by particles that have undergone minimal surface oxidation. The study suggests that, for this alloy, recycling should be accompanied by solution and ageing heat treatments to ensure that the final mechanical properties are equivalent to those of the virgin material, i.e., they exhibit strength, hardness and toughness identical to the initial ones.

Delacroix et al. [42] carried out an exhaustive analysis on the 316L alloy, focusing on oxygen accumulation. Using energy-dispersive spectroscopy (EDS), the researchers quantified that the oxygen content in the dust increased from around 450 ppm to 680 ppm after multiple cycles. However, tensile test results showed that this increase was not sufficient to significantly degrade the ductility of the material. The fundamental conclusion is that 316L has a very wide "recyclability window," provided that the argon atmosphere in the building chamber is kept below 100 ppm of residual oxygen to prevent the formation of chromium oxides.

Gorji et al. [43] conducted a study of the flow and deformation of matter in 316L powder and how physical changes impact the density of parts. They observed that recycled powder exhibits superior SR due to "bombardment" by metallic spatter during melting. This roughness increases friction between particles, reducing flowability. Through X-ray computed tomography, the authors proved that this reduction in fluidity can lead to small deposition voids in the powder bed, resulting in stochastic porosity that affects the structural integrity in thin-walled components.

In the complementary mode, Akeweje et al. [4] introduced an automated, unsupervised machine learning framework designed for high-throughput morphological profiling of 316L. This research addresses the limitations of conventional characterisation methods, which are typically too slow and qualitative to capture the heterogeneity of industrial-scale powder batches. The researchers evaluated three computational pipelines: an orientation-invariant variational autoencoder (VAE), a functional-data clustering approach (GPmix), and a pipeline using traditional shape descriptors, ultimately identifying Fourier-descriptor + K-means as the most effective due to its accuracy and sub-millisecond processing speed per particle.

Pinto et al. [44] explored a specific metallurgical phenomenon: the retention of delta-ferrite (δ) in 316L samples processed with recycled powder. While virgin 316L powder is fully austenitic and non-magnetic, several reuse cycles (16 cycles in this study) lead to the formation of approximately 6 vol.% δ-ferrite. This phase change is triggered by the thermal cycles imposed on particles near the melt pool and through the formation of oxidised spatter droplets.

The presence of δ-ferrite introduces ferromagnetic behaviour to the powder feedstock, causing attractive magnetic interactions that lead to particle clustering in the powder bed. These clusters result in poor packing and non-uniform powder layers, which induce severe defects such as porosity, delamination, warping, and lack of fusion, particularly at the beginning of the build process when using unstable support structures like pin supports. To mitigate these issues and ensure the sustainability of the powder lifecycle, the authors propose implementing magnetic separation after sieving to remove the magnetic δ-ferrite particles and restore the homogeneity of the austenitic feedstock.

Douglas et al. [45] and Jandaghi and Moverare [46] are fundamentally related as they provide a contemporary, multi-angled investigation into the sustainability of 316L stainless steel powder reuse in LPBF. Both research groups reach a consensus on the physical and chemical degradation of the feedstock, noting that repeated thermal cycles and residual oxygen in the build chamber lead to a coarsening of the particle size distribution, a steady increase in oxygen content (approximately 10% after 30 cycles), and the undesirable formation of δ-ferrite (up to 7 wt.%), which introduces magnetic properties and particle clustering.

Huang et al. [47] studied the challenge of controlling MS1 top-up powder reuse, where mixed powder histories, feed-chamber residues, spatter, and agglomeration complicate lifecycle tracking. Findings reveal that optimised virgin-to-recycled powder ratios can preserve density, hardness, porosity, and tensile performance while improving LPBF material sustainability. Jose and Mishra [48] studied the challenge of preserving wear resistance in LPBF 18Ni300 maraging steel when powder reuse, hatch strategy, and residual-stress evolution degrade surface integrity. Chessboard scanning, heat treatment, and laser shock peening improve hardness, compressive residual stress, and wear resistance, particularly in recycled-powder specimens.

However, the studies offer diverging conclusions regarding the mechanical consequences of this degradation: while Douglas et al. [45] argue that the macro-mechanical performance, including tensile strength and low cycle fatigue, remains remarkably stable

or even slightly improves in ductility over thirty recycles, Jandaghi and Moverare [46] warn that even five reuse cycles can accumulate sub-micron oxide inclusions that cannot be sieved out. These fragile inclusions act as stress concentrators that promote sudden rupture and weaken the material's tensile strength.

3.1.3. Ni Superalloys

Ni superalloys are fundamental to the aerospace industry due to their resistance to extreme temperatures. Their recycling is an economic imperative given the rarity and cost of alloying elements such as Niobium.

Lassègue et al. [5] studied the challenge of converting Ti alloy machining chips into AM-grade aeronautical feedstock while controlling contamination, oxidation, hydrogen uptake, and energy demand. The authors determined that continuous rotary extrusion and ball milling are promising routes for producing sustainable AM wire and powder from Ti waste. Bhowmik et al. [49] and Paccou et al. [50] analysed the behaviour of recycled INCONEL® 718 under fatigue and creep conditions. The authors demonstrated that the material maintains remarkable structural integrity even after fifteen reuse cycles. However, they observed that the precipitation of the strengthening phases γ' and γ'' can become less homogeneous in powders that have undergone multiple heating and cooling cycles in the bed. The study concludes that thermal management of the powder bed is more critical to the recyclability of INCONEL® 718 than chemical oxidation itself, since the unmelted powder acts as a heat sink.

Lee et al. [51] proposed an innovative concept of accidental oxide dispersion (ODS) strengthening. While ten cycles of reuse resulted in traditional powder deterioration—including a 5 µm increase in average particle size, non-spherical shape formation, and an oxygen increase of up to 200 ppm—this chemical contamination manifested as finely dispersed alumina particles, as illustrated in Figure 6.

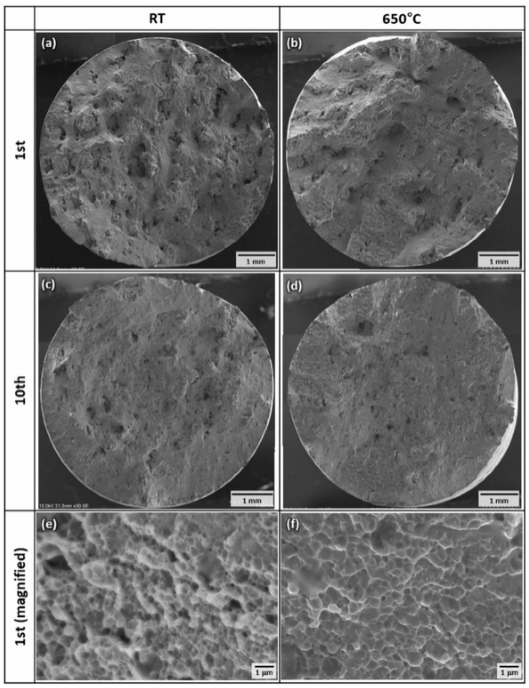


Figure 6. SEM fractographs of the (**a**,**b**,**e**,**f**) 1st and (**c**,**d**) 10th specimens after tensile tests at (**a**,**c**,**e**) 25 and (**b**,**d**,**f**) 650 °C showing voids originating from defects formed during the SLM process. (**e**,**f**) are magnified fractographs of (**a**,**b**), showing coarser ductile dimples at 650 °C [51].

Specifically, the fractographic analysis in Figure 6, which shows the fracture surfaces of tensile specimens, shows that these oxides proved advantageous by refining the dislocation substructure and pinning grain boundaries during post-process heat treatments; it also compares specimens from the 1st and 10th iterations at both room temperature (RT) and 650 °C, revealing that the increased oxide fraction contributes to simultaneous improvements in tensile strength and elongation. The 10th-iteration specimens (c,d) show a more refined dimple structure compared to the 1st-iteration (a,b,e,f), indicating that controlled powder degradation can serve as an in situ strengthening mechanism for high-performance Ni superalloys.

Ardila et al. [13] focused on morphological characterisation using sieving techniques and image analysis. They demonstrated that the SLM recycling system tends to remove the finest particles (below 15 μm), which narrows the particle size distribution (PSD). This narrowing, although improving flowability, alters the thermal conductivity of the powder bed. The results suggest that, for INCONEL® 718, adding a small percentage (about 20%) of virgin powder to each cycle is sufficient to stabilise these physical variables and ensure process repeatability.

Castillo et al. [52] conducted an in-depth investigation into the surface evolution of INCONEL® 718 particles over extended reuse cycles in SLM. The authors demonstrated that degradation is not merely morphological, but rather a progressive chemical transformation. Through XPS (X-ray Photoelectron Spectroscopy), they identified that the native oxide layer (composed mainly of Cr_2O_3 and Al_2O_3) increases in thickness significantly with reuse. This layer acts as a thermal barrier during laser melting, reducing energy absorption efficiency and causing instability in the melt-pool flow.

The study by Luo et al. [53] demonstrates that the superior performance of Plasma Rotating Electrode Process (PREP) powder over Gas Atomised (GA) powder is fundamentally rooted in its high apparent density and satellite-free morphology, which optimises the laser–matter interaction to suppress deleterious phases. As shown in Figure 7, GA powder (b) often contains “satellite” particles and irregular shapes that reduce flowability, alongside internal gas pores (c) that introduce defects into the final part. In contrast, PREP powder (e) consists of near-perfect spheres with a dense internal structure (f), ensuring a more uniform and tightly packed powder bed. This improved morphology and higher laser absorption facilitate a more stable melt pool and a faster cooling rate, which is critical for INCONEL® 718 as it prevents Niobium from segregating into the brittle, interdendritic Laves phase. By trapping Niobium within the matrix, PREP-built parts not only achieve a finer grain structure with higher dislocation density, enhancing yield strength, but also significantly improve ductility (elongation), as there are fewer brittle intermetallic “islands” to act as crack-initiation sites. Ultimately, while particle size distribution (PSD) is often scrutinised, this research demonstrates that the preparation method is the primary driver of quality, as both powder types can reach high relative densities (>99%), yet only the PREP method provides microstructural refinement and the defect-free internal structure required for peak mechanical performance.

Wang et al. [54] studied the challenge of reusing GH3536 nickel superalloy powder in LPBF while controlling oxidation, irregular particles, hollow-particle defects, and property stability. Up to 16 reuse cycles caused limited powder and microstructural change, with acceptable porosity and only modest tensile-property variation.

He et al. [55] assessed the challenge of recycling Hastelloy X powder in LPBF while controlling oxygen enrichment, particle coarsening, keyhole instability, porosity growth, and ductility loss. Six reuse cycles increased powder size and oxygen content, raising laser absorptivity, porosity, and fatigue-relevant defects above 40 μm.

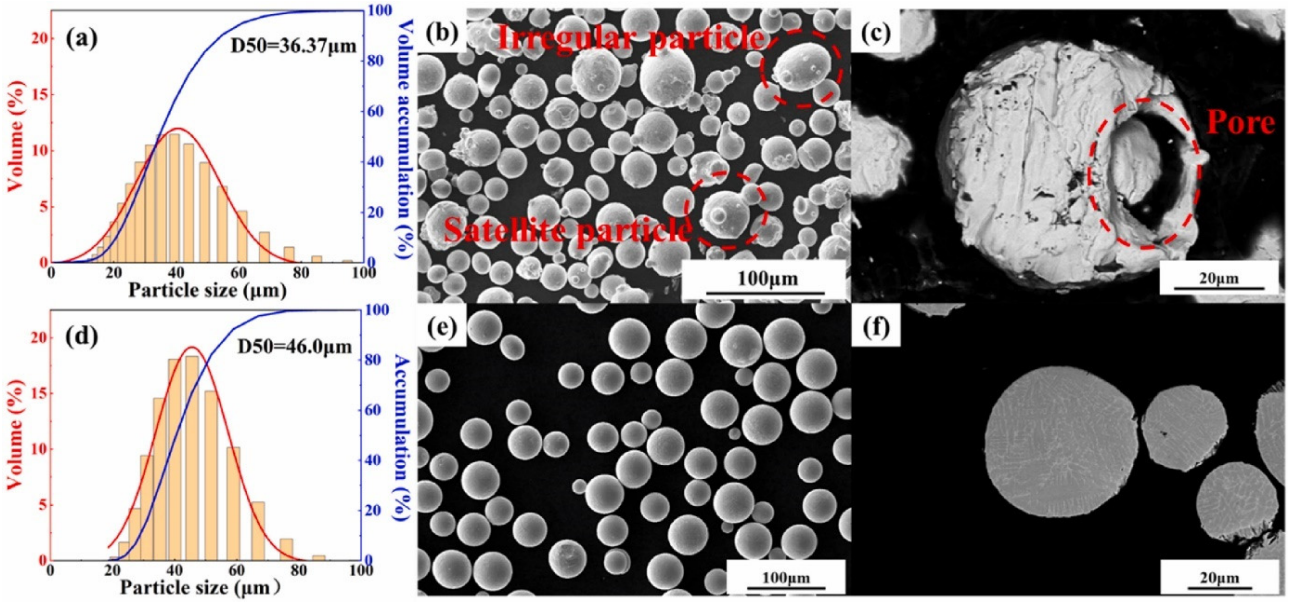


Figure 7. Comparison of particle size distribution (**a**,**d**), powder morphology (**b**,**e**) and powder cross section (**c**,**f**) of GA powder (**a**–**c**) and PREP powder (**d**–**f**) [53].

Gruber et al. [56] studied the challenge of distinguishing reusable INCONEL® 718 powder from genuinely degraded material by assessing morphology, flowability, chemistry, oxygen enrichment, and spatter contamination. Findings highlight that used and overflow INCONEL® 718 powders remained suitable for LPBF reuse, whereas spatter powder showed excessive oxidation and degradation.

Locatelli et al. [57] investigated the challenge of processing industrial waste-derived INCONEL® 725 powder by LPBF while controlling density, roughness, hardness, and parameter sensitivity. They determined that Gaussian-process-regression optimisation enabled dense recycled INCONEL® 725 parts, achieving 99.99% relative density, 7.3 μm roughness, and 311 HV.

For AlSi10Mg, prolonged reuse emerges as a critical factor, where increased hygroscopy and oxide accumulation result in loss of ductility and hydrogen gas porosity formation after only 10 cycles. In contrast, 316L stainless steel exhibits remarkable robustness, maintaining chemical conformity and phase stability even after eight cycles, although there is a narrowing of the particle size distribution (PSD) that can affect bed fluidity.

Particularly interesting is the behaviour of the INCONEL® 718 superalloy, where cyclic recycling induces a slight increase in tensile strength (UTS) due to the oxide dispersion strengthening (ODS) effect generated in situ, as validated by Lee et al. [51]. However, this static advantage is offset by the drop in dynamic performance, since the accumulation of surface oxides acts as a nucleation site for cracks, confirming that, in SLM, atmosphere management and contaminant removal are more crucial for the powder's lifespan than the mechanical wear of the particles.

To improve readability and facilitate comparison between the SLM/LPBF studies reviewed, the main evidence concerning powder recyclability in laser-based powder bed fusion is summarised in Table 1. The table organises the findings according to the alloy system, powder-reuse condition, powder lifecycle changes, defect-related observations, and mechanical or reliability implications. This structure allows the reader to compare the behaviour of AlSi10Mg, stainless steels, nickel superalloys, and other SLM/LPBF alloys more directly, while retaining the detailed discussion required to interpret the mechanisms governing powder degradation, processability, and part performance.

Table 1. Summary of powder recyclability studies in SLM/LPBF.

Alloy System	Reuse Condition/Powder State	Main Powder Changes	Defect-Related Observations	Mechanical/Reliability Implications	Ref.
AlSi10Mg	Long-term powder reuse, recycled powder, sieved powder and smoulder-containing feedstock	Increased oxygen and hydrogen content, surface oxidation, oxide/hydroxide formation, spatter or smoulder accumulation, moisture sensitivity and particle-size redistribution	Gas porosity, lack-of-fusion regions, oxide-related discontinuities, unstable melt-pool wetting and local melt-pool instability	Tensile properties may remain acceptable under controlled conditions, but ductility, porosity sensitivity and fatigue-related crack initiation are strongly affected by powder condition	[12–14,19–22]
316L stainless steel	Multiple reuse cycles, sieved recycled powder and reused industrial powder batches	Moderate oxygen increase, altered surface morphology, rougher particle surfaces, reduced flowability, possible δ-ferrite formation and magnetic particle clustering	Powder-bed heterogeneity, porosity, delamination, warping and lack-of-fusion defects under unstable build conditions	316L generally exhibits a broad recyclability window under controlled atmosphere; however, oxide inclusions, phase changes and particle clustering may compromise reliability-sensitive applications	[23–27]
17-4 PH stainless steel	Repeated powder reuse in SLM	Largely preserved spherical morphology and limited chemical variation, with minor surface oxidation effects	No severe powder degradation reported, although reuse-induced changes may affect local cooling conditions and microstructural response	Mechanical performance remains broadly stable, but solution and ageing heat treatments may be required to restore target hardness and strength	[2]
INCONEL® 718	Multiple reuse cycles, powder top-up strategies, sieving and powder blending	Particle-size increase, oxide accumulation, non-spherical particle formation, chemical surface evolution and possible nano-oxide formation	Oxide inclusions, melt-pool instability, crack-sensitive discontinuities and local solidification defects	Static tensile properties may remain stable or improve through oxide-dispersion effects, but fatigue, creep and crack-sensitive reliability require stricter qualification	[5,28–32]

3.2. Recyclability in Electron Beam Melting (EBM/E-PBF)

EBM technology differs fundamentally from laser-based processes due to the nature of its energy source and processing environment. Operating under partial vacuum and using high preheating temperatures (often exceeding 600 °C for Ti), the dust degradation mechanisms and recycling strategies take on unique characteristics.

3.2.1. Dynamics of Ti-6Al-4V and Atmospheric Protection

Ti is extremely reactive to oxygen at high temperatures, which makes its recycling a challenge in atmospheric processes. However, EBM offers an essential solution to this problem.

Bellini et al. [58,59] conducted comparative studies on the chemical purity of Ti-6Al-4V ELI (Extra Low Interstitials). By comparing virgin plasma-atomised powder with batches recycled over one hundred times, the researchers observed that the microscopic internal structure of the particles remained relatively stable, although part quality was influenced by an accumulation of internal defects such as macropores and lack of fusion (LOF). The authors demonstrated that the high-vacuum environment used acts as a superior protective barrier, successfully keeping oxygen, nitrogen, and hydrogen levels significantly below the limits imposed by the ASTM F 2924-13 standard [60], even after 30 reuse cycles. This finding is crucial as it suggests that the technical "death" of the powder in EBM does not occur through chemical oxidation—a primary failure mode in laser powder bed fusion (SLM)—but rather through gradual physical changes in particle morphology and the resulting increase in internal imperfections.

Wei et al. [61] detailed a critical phenomenon: microstructural evolution and slight surface oxidation accumulated in extreme cycles alter the electrical resistivity and energy absorption of the electron beam. While the initial plasma-atomised powder primarily consists of a non-equilibrium martensitic α phase, repeated thermal cycles—characterised

by reheating and slow cooling within the EBM chamber—cause the microstructure to transform into a more stable equilibrium state of α and β phases.

This microstructural shift leads to significant enhancement in the powder's physical properties: after seven reuse cycles, the average micro-hardness increased by approximately 29%, and the Young's modulus rose by 24%. The study finds that the process effectively manages chemical purity, as the high-vacuum environment not only minimises oxygen and nitrogen pickup but can even reduce interstitial elements in the final bulk material through refining effects and metal oxide evaporation. Consequently, the tensile properties of components fabricated from a mixture of fresh and reused powders were found to be equal or even superior to those made from 100% virgin powder. These results reinforce the findings of Bellini et al. [58,59] by confirming that the EBM environment provides exceptional protection against chemical degradation, allowing for the sustainable large-scale reuse of Ti-6Al-4V powder without compromising mechanical performance.

Ghasempour-Mouziraji et al. [62] investigated the morphological evolution of particles and their impact on the porosity of parts. Through image analysis algorithms and computed tomography, the researchers observed that recycled powder tends to lose its "satellites" (small particles attached to larger ones) due to mechanical friction in the powder recovery system (PRS). Interestingly, this loss of satellites can increase the apparent density of the dust and improve its initial fluidity.

Soundarapandiyan et al. [63] investigated the challenge of reusing Ti6Al4V powder in EB-PBF while tracking heterogeneous oxidation, sintering, PSD refinement, morphology evolution, and fatigue-critical defects. Ten reuse cycles preserved tensile, hardness, and impact performance, but reduced high-cycle fatigue life through increased lack-of-fusion defects. Montelione et al. [64] analysed the challenge of reusing Ti6Al4V powder in EBM while identifying oxidation-driven alpha-case formation, particle hardening, and microstructural coarsening. Thirty reuse cycles promoted oxygen diffusion and near-surface hardening, whereas mechanical recovery alone caused negligible work hardening.

Popov et al. [65] studied the challenge of recycling Ti-6Al-4V powder in EBM while controlling oxidation, powder defects, lack-of-fusion formation, and fatigue reliability. They determined that highly recycled powder increased strength but reduced ductility and fatigue life, while HIP partially restored performance by closing porosity.

Koushik et al. [66] studied the challenge of recycling Ti-6Al-4V powder in LPBF while accounting for powder history, oxygen uptake, morphology stability, and process repeatability. They determined that a recycle-index-based top-up strategy preserved powder characteristics, maintained Grade 23 chemistry, and delivered stable density and tensile performance. Emminghaus et al. [67] studied the challenge of isolating powder recycling and residual oxygen effects in LPBF Ti-6Al-4V while accounting for interacting process parameters. Residual oxygen and recycled powder significantly affected hardness and tensile strength, whereas microstructural changes remained comparatively limited.

Mahtabi et al. [68] examined the challenge of reusing Ti-6Al-4V DED-LB powder while controlling PSD evolution, flowability, chemistry, defect formation, and fatigue reliability. Powder reuse altered elemental composition, microstructure, defect populations, hardness, tensile response, and fatigue scatter in a PSD-dependent manner. Wang et al. [69] studied the challenge of reusing TA15 Ti powder in LPBF while controlling hollow particles, interstitial contamination, porosity, and ductility loss. The authors determined that repeated reuse slightly altered particle size, increased C, N and O contents, raised annealed strength, and reduced plasticity. Harkin et al. [70] studied the challenge of reusing Grade 23 Ti6Al4V powder in LPBF while controlling oxygen uptake, PSD stability, morphology, and flowability. Nine top-up reuse cycles preserved PSD and flowability, but oxygen exceeded Grade 23 limits after eight cycles. Yánez et al. [71] studied the challenge of reusing Ti-6Al-4V ELI

powder in LPBF while controlling oxygen uptake, roughness, ductility loss, and fatigue degradation. Recycled powder was determined to preserve tensile strength but increased SR, reduced elongation, and lowered fatigue life in small- and large-diameter specimens.

Smythe et al. [72] tackled the challenge of converting out-of-specification Ti powders and machining swarf into AM-suitable wire while controlling consolidation, contamination, ductility, and process stability. Conform™ continuous extrusion can recycle Ti-6Al-4V powder and swarf into wire feedstock, supporting lower-cost and more-circular AM supply chains. Judd et al. [73] examined the challenge of replacing virgin Ti feedstock with battlefield-scrap-derived powder while preserving chemistry, morphology, moisture control, and particle-scale mechanical response. Recycled Ti powders met relevant compositional limits and showed particle size distribution (PSD), morphology, microstructure, hardness, and strength comparable to virgin feedstock. Weston and Jackson [74] analysed the recycling of Ti-6Al-4V machining swarf while controlling oxygen pickup, feedstock heterogeneity, densification, microstructural homogenisation, and forgeability. They demonstrated that FAST-forge consolidated swarf to 99.9% density, producing forgeable billets with flow behaviour comparable to HDH powder and wrought Ti.

3.2.2. The Sintering (Caking) Phenomenon and Dust Recovery

One of the most debated aspects of recyclability in EBM is the need to process powder that was not melted but was deliberately preheated and sintered.

Nandwana et al. [17] explored the processing of Ni superalloys (INCONEL® 718 and 625) and Ti alloys, focusing on the integrity of the material after passing through the PRS. The EBM process requires that the powder bed be lightly sintered to ensure electrical and thermal conductivity, avoiding the phenomenon of "smoke" (electrostatic dispersion of particles). The authors concluded that the mechanical blasting process is necessary to break this "cake" of sintered powder and is the most aggressive phase of recycling. Although it does not alter chemistry, this blasting can induce plastic deformations on the surface of the particles, which alter the energy absorption of the electron beam in subsequent cycles.

Gruber et al. [75] examined the reuse of Alloy 718 powder in EBM while controlling powder degradation, oxide formation, bonding defects, and fracture-critical cleanliness. Recycled powder increased Al-rich oxide defects, particularly near contour regions, promoting weak interfaces and fracture-relevant discontinuities.

Chandrasekar et al. [76] introduced a novel in situ data-driven approach to monitor metal powder recycling in E-PBF by analysing process log data from the Arcam system, moving beyond traditional ex situ physical testing. By leveraging internal sensor data—specifically rake position and sensor pulse data—the researchers were able to quantify real-time powder behaviour and spreadability across multiple reuse cycles. The analysis revealed that INCONEL® 718 powders exhibit an increased tendency to agglomerate over time, necessitating more frequent rake passes to maintain a level powder bed, whereas Ti-6Al-4V demonstrated more consistent spreading behaviour due to its rapid sintering characteristics regardless of the reuse-cycle number. This methodology offers a scalable, real-time alternative for detecting powder degradation, allowing manufacturers to identify shifts in flowability and packing efficiency directly from the machine's log files before they result in structural defects in the final parts.

Popov et al. [65] specifically focused on validating the mechanical properties for the medical and aerospace sectors. Their research proved that the resulting α- and β-phase microstructure in Ti-6Al-4V parts produced with recycled powder is indistinguishable from those produced with virgin powder. Their research utilised static tensile tests to prove that elongation and ultimate tensile strength (UTS) remain constant despite reuse, although fatigue life can be significantly reduced if surface oxidation or lack of fusion (LOF)

defects are present. The authors emphasise that rigorous cleaning of the powder recovery system (PRS) is vital to the success of this recycling, as any external contamination—such as dust or particles from other materials—is exacerbated by the high build temperatures characteristic of the EBM process. To mitigate the impact of defects induced by long-term recycling, the study identifies hot isostatic pressing (HIP) as a critical post-processing step that can restore the mechanical quality of recycled powder samples to levels achieved with virgin feedstock.

Pereira et al. [77] assessed the challenge of reusing Stellite® 21 and UNS S32750 powders in DED-LB while controlling oxidation, morphology changes, catch efficiency, defects, and phase balance. Stellite® 21 tolerated three reuse cycles, whereas UNS S32750 was limited by oxidation, porosity, ferrite reduction, and hardness variation.

3.2.3. Microstructural Stability and Induced Defects

Shanbhag and Vlasea [78] investigated the influence of reuse cycles on Ti-6Al-4V powder properties in electron beam powder bed fusion (E-PBF), finding that morphology, flowability, and spreadability degrade due to partial sintering and mechanical recovery in the powder recovery system (PRS). Their analysis of the particle size distribution (PSD) showed a distinct narrowing over cycles, as finer particles are progressively removed or melted during the preheating phase. While this narrowing reduces the powder's specific surface area—which, paradoxically, helps maintain chemical stability—the resulting change in bed density may necessitate precise adjustments to the electron beam focus to maintain consistent melting. Despite these physical shifts, the oxygen content was observed to increase swiftly from 0.13% to 0.17%, nearing the ASTM F2924 limit of 0.20% even within early iterations.

Muñiz-Lerma et al. [41] evaluated the impact of Ti-6Al-4V powder reuse over 10 build cycles in E-PBF, focusing on the heterogeneous degradation that occurs during the process. Their research reveals that powder degradation is dependent on the location; particles closer to the melt zone undergo more severe changes, including hard sintering, agglomeration, and a significant increase in oxygen content compared to those at the edges of the bed. While the recovery and sieving process resulted in a refined particle size distribution (PSD), likely due to the loss of fine particles, the morphology remained mostly stable. Mechanically, the increased oxygen levels led to a slight rise in yield and tensile strengths, with negligible impact on elongation or impact energy.

However, although chemical integrity is preserved, the particle morphology undergoes continuous mechanical erosion due to friction in the recovery system and the breakage of sintering "necks" formed during bed preheating. This phenomenon results in particle rounding, loss of fines, and the appearance of fracture facets, which, although they do not penalise static properties such as tensile strength and hardness, induce a marginal reduction in fatigue life after extreme cycles (25+), suggesting that the physical integrity of the particle is the true limiting factor in recycling via EBM.

To support a clearer interpretation of the EBM/E-PBF literature, Table 2 summarises the main findings related to powder recyclability in electron beam powder bed fusion. The table compares the reviewed studies according to the alloy system, reuse condition, powder recovery behaviour, physical and chemical powder evolution, defect formation, and mechanical-performance implications. This organisation highlights the specific degradation pathways associated with EBM/E-PBF, particularly powder-bed sintering, caking, particle coarsening, satellite loss, and powder recovery effects, enabling a direct comparison with the mechanisms observed in SLM/LPBF.

Table 2. Summary of powder recyclability studies in EBM/E-PBF.

Alloy System/Powder Condition	Reuse Condition/Powder State	Main Powder Changes	Defect-Related Observations	Mechanical/Reliability Implications	Ref.
Ti-6Al-4V	Long-term powder reuse in EBM/E-PBF, including highly recycled batches and powder recovery system processing	Limited chemical degradation under vacuum, but progressive particle coarsening, partial sintering, satellite loss, oxygen increase, morphology changes and altered powder-bed behaviour	Lack-of-fusion defects, internal pores, powder-bed heterogeneity and location-dependent degradation may appear when powder recovery and reuse are not properly controlled.	Static tensile properties are often retained within acceptable ranges, but fatigue performance may deteriorate due to lack-of-fusion defects, oxygen-related embrittlement and defect-sensitive crack initiation	[33–41]
Ti-6Al-4V powder exposed to repeated thermal cycles	Reused powder subjected to high build temperatures, vacuum exposure and repeated preheating during EBM processing	Transformation from non-equilibrium powder microstructures towards more stable α- and β-phase conditions, with increased hardness and stiffness in reused powder particles	Changes in energy absorption and powder spreading may affect local consolidation, particularly if morphology or electrical behaviour evolves with reuse	Reuse may preserve or even improve some static properties, but qualification must account for powder history, oxygen content, and fatigue-sensitive defect populations	[35,40,41]
Ti-6Al-4V powder cake/recovered powder	Powder recovered from the sintered EBM powder cake through mechanical powder recovery systems	Caking, sintering-neck formation, broken sintering bridges, mechanically induced surface damage and particle irregularity	Reduced spreadability, local powder-bed density variations and possible gas entrapment during melting	Reuse limits in EBM are governed primarily by physical degradation, powder recovery quality and powder-bed spreading stability, rather than oxidation alone.	[9,36,40,41]
Ti-6Al-4V powder with location-dependent degradation	Powder recovered from different positions within the EBM build chamber or powder bed	Particles closer to the melt zone may experience stronger sintering, agglomeration and oxygen enrichment than powder located further from the build area	Heterogeneous powder condition may contribute to inconsistent layer deposition, localised lack-of-fusion defects and variable internal porosity	Powder reuse should consider spatial powder history, not only the total number of reuse cycles, particularly for fatigue-critical parts	[41]
INCONEL® 718 and nickel-based superalloys	EBM powder reuse involving high-temperature preheating, powder-bed sintering and post-build powder recovery	Agglomeration, altered spreadability, powder-bed caking and possible mechanical damage during powder recovery	Irregular powder spreading and local powder-bed density variations may promote incomplete consolidation and defect formation	Reuse is technically feasible, but process repeatability depends strongly on powder recovery, rake-spreading behaviour and control of agglomerated particles	[9,38]
EBM powder recovery system behaviour	Reused powder processed through mechanical blasting or recovery procedures after build completion	Mechanical separation of sintered powder cake may deform particle surfaces, modify particle morphology and alter subsequent beam–powder interaction	Disturbed powder spreading, inconsistent layer formation and local consolidation defects may arise when recovered powder is not sufficiently conditioned	Powder recovery should be treated as an active part of the powder lifecycle, requiring monitoring, sieving and acceptance criteria before reuse	[9,36,38]
Process-log-based EBM powder monitoring	Reuse cycles assessed through in situ machine log data, including rake-position and sensor-pulse information	Powder degradation inferred from changes in spreading behaviour, agglomeration tendency and powder-bed interaction during recoating	Increased rake passes or abnormal spreading behaviour may indicate powder degradation before visible part defects occur	In situ monitoring provides a promising route for reliability-driven powder lifecycle management and earlier detection of reuse-induced process instability	[38]
HIP-treated EBM parts from reused powder	Components manufactured from reused Ti-6Al-4V powder followed by hot isostatic pressing	Powder reuse may introduce internal defects, but HIP can close internal porosity and reduce defect severity	Lack-of-fusion and internal pores can be mitigated, although surface-connected defects and oxygen-related effects may remain relevant	HIP can restore part quality in some cases, but it should complement rather than replace powder-quality control and fatigue-oriented qualification	[39]

3.3. Solid Scrap Recycling and Reconditioning (DED)

While previous sections focused on the degradation rate of dust remaining in bed, Section 3.3 addresses the final frontier of sustainability in AM: the recovery of discarded

solid components, such as support structures, rejected parts, and machining scraps, which can represent between 40% and 60% of the total material in a project.

3.3.1. Re-Atomisation and Closed-Cycle Powder Production

The transformation of solid scrap into high-quality spherical powder is a technically demanding process that requires mastery of fluid thermodynamics. Within this broader lifecycle-management context, DED should be considered as an alternative reuse and reconditioning route rather than as an SLM/LPBF process. Da Silva et al. [79] studied the challenge of processing aged AlSi10Mg powder in DED while controlling oxidation, hydrogen uptake, porosity, track geometry, and tensile degradation. Aged powder increased porosity and altered melt-pool wetting, reducing strength but increasing elongation through coarser microstructure formation.

Ren et al. [80] conducted important investigations into the effectiveness of Plasma Atomisation for the recovery of Ti and INCONEL® alloys. The authors demonstrated that this process, by using plasma torches to melt the metal (in the form of wire or crushed scrap), produces particles with almost perfect sphericity and zero internal porosity. The critical advantage identified by Ren is the ability of plasma to "clean" volatile impurities, resulting in a recycled powder that, in many cases, exhibits higher purity than virgin powder obtained by conventional gas atomisation.

Cacace et al. [81] explored the economic and technical feasibility of gas atomisation for internal recycling in factories. The study proved that using scrap from failed parts as feedstock for the atomiser reduces the carbon footprint of production by 60%, as it eliminates the need for mining and primary refining. However, the authors warn of the need for rigorous control of alloy element segregation during induction melting before atomisation.

Yankin et al. [82] and Priyadarshi et al. [83] conducted investigations on the use of ultrasonic vibrations for fragmentation of metal flows. Unlike conventional gas atomisation, where energy is supplied by high-pressure jets, ultrasonic atomisation is based on capillary wave theory.

Priyadarshi et al. [83] demonstrated, using high-speed imaging and synchrotron radiation, that when the amplitude of ultrasonic vibrations reaches a critical value, standing waves are formed on the surface of the molten metal. These waves evolve into crests that, upon collapsing, eject droplets of extremely uniform dimensions. Complementing this physics, Yankin et al. [82] introduced the concept of an AM suitability factor for 316L steel. The authors proved that this method allows the production of powders with a significantly narrower particle size distribution (PSD) and with less incidence of internal porosity (satellites) than gas atomisation. This morphological precision reduces the need for extensive sieving and ensures superior flowability of the recycled feedstock, making it ideal for applications requiring high density and rigorous surface finish.

Bhaduri et al. [84] studied the challenge of converting machining chips into AM-suitable metal powders by ball milling while controlling morphology, particle size, flowability, and oxidation. They demonstrated that ball-milled Al chip powders can enable LPBF single-track melting and cube fabrication, with microhardness comparable to rolled AA5083.

3.3.2. Recovery of Machining Chips and Shavings

The integration of AM with subtractive processes (hybrid systems) generates a new byproduct: machining chips.

Dhiman et al. [85] propose a sustainable alternative for producing AM feedstock by recycling Ti-6Al-4V machining swarf through a multi-stage ball milling process. This method utilises an in-house tumbler ball mill to convert high-value industrial waste into

powder, employing larger 25 mm balls for size reduction and smaller 6.25 mm balls to refine the morphology from irregular to near-spherical shapes. After 18 h of processing, the resulting powder (40–200 μm) exhibited characteristics comparable to traditional Gas Atomised powder and was successfully validated through Direct Metal Laser Sintering (DMLS). Furthermore, a lifecycle assessment (LCA) revealed that this mechanical recycling route is significantly more eco-friendly than gas atomisation, consuming 59% less energy and reducing the global warming potential by 68%.

Saboori et al. [86] and Terrassa et al. [87] demonstrated that while AISI 316L powder recycled in Directed Energy Deposition (DED) maintains a spherical morphology, it undergoes significant surface degradation through the accumulation of splats and surface oxides. This degradation leads to a critical mechanical decline in the final components, most notably a reduction in elongation of more than 50% compared to parts produced with fresh powder. This drastic loss in ductility is not caused by changes in the metallic microstructure itself, but rather by the increased frequency and size of Mn- and Si-rich oxide inclusions (7–15 μm) that act as internal stress concentrators.

Alavizadeh et al. [88] studied the challenge of recycling Ti6Al4V machining chips by mechanical milling while controlling BPR, ball-size distribution, oxidation, contamination, and powder morphology. They determined that optimised milling reduced crystallite size, produced nanoscale particles, improved morphology, and enabled TiO-to-TiO_2 transformation through annealing. Tebaldo et al. [89] researched the challenge of recovering Ti alloy swarf for AM while addressing contamination, oxygen sensitivity, energy-intensive production, and feedstock-quality requirements. Severe-plastic-deformation routes, particularly ECAP, FAST-forge, and Conform, offer promising sustainable pathways, while gas atomisation remains central for powder feedstock.

Cherezov and Alymov [90] researched the challenge of converting Ti-6Al-4V machining chips into AM-suitable powder while controlling hydrogenation, impurity uptake, particle size, and microstructure. It was shown that SHS-hydrogenation, ball milling, and vacuum dehydrogenation produced 10–40 μm powder with low impurities and refined $\alpha + \beta$ microstructure. Lister et al. [91] analysed the challenge of solid-state recycling Ti-6Al-4V swarf and oversized powder while controlling densification, texture, microstructure, and feedstock heterogeneity. Field-Assisted Sintering Technology (FAST) and HIP successfully consolidated low-cost Ti feedstocks, with briquetted swarf improving process stability and microstructural control.

3.3.3. Plasma Re-Spheroidisation and Upcycling

Often, recycled powder is not chemically degraded, but physically deformed (presence of satellites or elongated shapes). Singh et al. [92,93] advance the sustainability of AM by exploring high-performance architectures and novel reclamation methods for AlSi10Mg and other waste powders. The first study demonstrates that TPMS-based cellular materials, such as Gyroid and Schwarz–Diamond structures, offer superior energy absorption and stiffness, with post-process heat treatments proving essential to transform the brittle as-built microstructures into ductile, fatigue-resistant components. Complementing this, the 2026 study introduces a circular economy strategy using Cold Spray AM (CSAM) to recycle powders that have undergone plastic deformation and work-hardening during previous deposition attempts. While the researchers successfully fabricated parts using a 50/50 blend of recycled and virgin powder, they noted a significant drop in ductility from 19% to 4% due to coarse porosity, establishing that while CSAM is a viable low-cost route for non-structural applications, it requires further optimisation for extreme mechanical performance.

Yi et al. [94] established the feasibility of extended powder reuse in laser-based powder bed fusion (LPBF) for high-performance alloys. In their investigation of INCONEL® 718, they observed that while reuse cycles can increase average particle size, they do not negatively impact chemical composition. Paradoxically, reusing the powder up to 14 times improved flowability and apparent density, resulting in parts with similar tensile properties (approx. 1025 MPa UTS and 27–30% elongation) and refined pore structures.

Similarly, Zhou et al. [95] found that for Ti-6Al-4V, successive reuse cycles lead to minor morphological changes and a predictable increase in oxygen content, yet mechanical properties remain within industry-standard limits with a slight improvement in tensile strength. Both studies underscore that controlled powder recycling—supported by standardised protocols like sieving—not only maintains process stability and structural integrity but also significantly enhances economic viability and environmental sustainability by reducing material waste and carbon footprints.

Sojoodi et al. [96] studied the challenge of integrating circular economy principles into NiTi AM by converting waste streams into high-quality powder while controlling contamination. The authors determined that ultrasonic plasma atomisation can generate spherical, compositionally stable NiTi powder from recycled feedstock, supporting closed-loop AM workflows.

3.4. Standardisation, Certification, and Barriers to Industrial Adoption

The transition of AM from a prototyping phase to the production of components with critical requirements in sectors such as aerospace, defence, and medical forces a robust standardisation infrastructure. Currently, uncertainty about the consistency of the properties of recycled materials is the main barrier to their certification by entities such as the FAA (Federal Aviation Administration) or the EASA (European Union Aviation Safety Agency).

3.4.1. The Current Regulatory Framework: ISO and ASTM

The AM industry has been working hard to create standards that define the requirements for metallic feedstock but still lacks clear quantitative definitions.

ISO/ASTM 52900 [97] and ASTM F 3049-14 [98]: These standards establish foundational terminology and characterisation guidelines for metal AM, yet Lanzutti and Marin [19] note they remain vague regarding the specific limit of permitted reuse cycles. The current lack of "acceptance/rejection" criteria based on chemical degradation—such as precise oxygen content thresholds—forces companies to develop expensive internal protocols to ensure part reliability. This regulatory gap is critical because recycling induces complex changes in chemical composition, morphology, and particle size distribution that can degrade mechanical performance, particularly ductility and fatigue resistance. To bridge this gap, Lanzutti and Marin [19] advocate advanced traceability systems and closed-loop strategies, such as plasma cleaning or controlled blending, to maintain feedstock quality throughout its lifecycle.

Demiralay et al. [99] address the growing economic and environmental necessity of circularity in metal AM by proposing a conceptual framework to assess the lifecycle impacts of recycled and reused powders. The authors highlight that while previous research has focused heavily on the physical and chemical degradation of particles, there is a significant gap in understanding how these changes translate into broader operational consequences for companies, such as shifting production performance and long-term economic viability. By analysing the relationship between powder quality, printing reliability, and production outcomes from a life cycle perspective, the framework provides a structured approach for manufacturers to evaluate the trade-offs between the reduced raw material costs of

recycling and the potential risks to final part quality. This work aligns with the concerns raised by Lanzutti and Marin [19] regarding the lack of standardised "acceptance/rejection" criteria, offering a strategic tool to help industries navigate the complexities of circular supply chains in the absence of definitive international regulations.

Piepoli et al. [100] examined recycled versus virgin materials in AM from a supply-chain risk perspective, highlighting the potential of recycled feedstocks to mitigate uncertainty in material availability. However, their contribution should be interpreted mainly in terms of supply-chain resilience, rather than as direct evidence for powder-specific certification requirements. Riyad et al. [101] examined the challenge of repurposing out-of-spec LPBF powders, whose degraded morphology and size distribution create storage burdens, safety risks, and recycling limitations. Low-temperature ultrasonic consolidation can transform rejected metal powders into filament feedstock, reducing energy demand and enabling secondary AM routes. Weston et al. [102] researched the challenge of recycling out-of-specification Ti-6Al-4V AM powder while preserving density, microstructural control, and static–fatigue performance. They demonstrated that FAST consolidation produced ASTM-grade Ti-6Al-4V, with strong tensile properties and fatigue behaviour comparable to conventionally processed material.

3.4.2. Challenges in Process and Part Certification

AM certification does not focus solely on the final part, but on the "freezing" of the process (Process Locking). This study by Emminghaus et al. [103] demonstrates that while powder recycling and residual oxygen content do not significantly alter the overall porosity of additively manufactured Ti-6Al-4V parts, they are critical factors in determining SR and process stability. Researchers found that reusing powder increases both top and side SR due to a coarsening of the particle size distribution, while higher levels of atmospheric oxygen led to greater inconsistency in relative density and poorer surface quality. Although the primary process parameters—laser power, scanning speed, and hatch spacing—remain the most influential drivers of part quality, the presence of oxygen impairs wetting and reinforces the balling effect, ultimately making the manufacturing process less reproducible. Consequently, the paper emphasises that maintaining low oxygen levels and monitoring powder degradation are essential for achieving the high-precision standards required in industrial and biomedical applications, such as the Cavaliere et al. [104] study, where the challenge is reusing WE43 Mg powder in PBF-LB while controlling morphology degradation, oxidation, spreadability loss, and implant-relevant consistency. The authors reached 18 reuse cycles with minimally affected printed density and hardness, despite reduced spreadability, increased oxidation, and particle agglomeration. Matsko et al. [105] studied the challenge of reusing Ti-6Al-4V powder for PBF dental implants while controlling nanoscale oxidation, surface chemistry, and biocompatibility risks. Recycled-powder implants retained broadly comparable surface chemistry, with TiO_2-rich layers supporting osseointegration, antibacterial resistance, and corrosion protection. Prandi et al. [106] investigated the challenge of producing hybrid Ti alloys from recycled Ti-5553/Ti–42Nb powders while controlling oxygen uptake, sintered particles, and compositional heterogeneity. The recycled powders can yield LPBF hybrid Ti alloys with β-phase stability, 725 MPa tensile strength, and 24% elongation.

3.4.3. Perception Barriers and Fatigue Risk

In addition to technical barriers, there is the "perception risk". Many original equipment manufacturers (OEMs) still contractually prohibit the use of recycled powder in Class 1 parts (critical for safety) due to a lack of long-term historical fatigue data.

Soltani-Tehrani et al. [107] demonstrate that while Ti-6Al-4V powder can be reused for up to twenty cycles without significantly altering the material's microstructure or static tensile properties, it introduces subtle "lack-of-fusion" defects that are detrimental to fatigue performance. Even as the parts maintain a high relative density (above 99.9%), these microscopic pores act as crack-initiation sites, leading to a reduced fatigue life compared to parts made from virgin powder. Because of this unpredictable degradation in long-term durability, the authors argue that industrial adoption of recycled powder will remain restricted to non-structural components or prototypes until a public, shared database is established to correlate powder reuse with fatigue reliability.

To overcome the limitations of recycled powder, Du et al. [108] and Lanzutti and Marin [19] propose a shift from arbitrary reuse limits to data-driven certification through digital twins and real-time sensor monitoring. By integrating sensors into the laser powder bed fusion process, manufacturers can monitor "dust health" and powder bed quality at the layer level, providing a real-time assessment of physical conditions like particle distribution and thermal consistency. This approach creates a digital replica of the build process, allowing for the validation of part integrity based on actual physical data rather than the number of times a powder has been recycled. Ultimately, this transition to digital certification could provide the necessary transparency to approve recycled Ti-6Al-4V for critical structural components, ensuring safety through continuous monitoring rather than conservative estimates.

To provide a cross-process synthesis of the literature review, Table 3 consolidates the principal degradation mechanisms, defect consequences, and reliability implications associated with reused metallic powders. Rather than focusing on individual alloy systems alone, the table links powder lifecycle changes to process-specific defect formation and performance-sensitive outcomes. This structure clarifies how mechanisms such as oxidation, moisture uptake, spatter accumulation, particle coarsening, powder-bed heterogeneity, and lack-of-fusion defects influence structural integrity and fatigue-critical reliability across SLM/LPBF and EBM/E-PBF.

Table 3. Main degradation mechanisms, defect consequences and reliability implications of reused metallic powders in metal AM.

Degradation Mechanism	Dominant Process Route	Typical Affected Alloys	Defect or Process Consequence	Reliability Implication
Surface oxidation and oxygen uptake	Mainly SLM/LPBF, but also relevant to EBM/E-PBF after extensive reuse	AlSi10Mg, 316L, INCONEL® 718, Ti-6Al-4V	Formation of oxide films, oxide inclusions, reduced melt-pool wettability and unstable melt-pool flow	May reduce ductility and fatigue life even when tensile strength, hardness or yield strength remain within acceptable ranges
Moisture interaction and hydrogen pickup	Mainly SLM/LPBF	AlSi10Mg and other reactive light alloys	Hydrogen porosity, gas-pore formation and reduced melt-pool stability during solidification	Particularly critical for fatigue-sensitive components, thin-walled geometries and parts exposed to cyclic loading
Spatter and smoulder accumulation	Mainly SLM/LPBF	AlSi10Mg, 316L, INCONEL® 718	Irregular particles, local contamination, altered powder-bed packing, oxide-rich particles and possible porosity formation	Can reduce powder quality if not removed or controlled; selected smoulder reuse may be possible after sieving and validation
Particle coarsening and particle size distribution narrowing	SLM/LPBF and EBM/E-PBF	INCONEL® 718, 316L, Ti-6Al-4V, Al alloys	Modified flowability, altered apparent density, changed thermal behaviour and non-uniform powder-bed packing	May improve flowability in some cases, but can alter energy absorption, layer homogeneity and process repeatability
Satellite loss and morphology evolution	Mainly EBM/E-PBF, also possible in reused SLM/LPBF powders	Ti-6Al-4V, nickel superalloys and stainless steels	Changes in particle sphericity, spreadability and packing behaviour	Reuse limits must consider morphology evolution, not only chemical composition or reuse-cycle number

Table 3. *Cont.*

Degradation Mechanism	Dominant Process Route	Typical Affected Alloys	Defect or Process Consequence	Reliability Implication
Sintering and caking of surrounding powder	Mainly EBM/E-PBF	Ti-6Al-4V and nickel-based alloys	Formation of powder cake, broken sintering necks, agglomerates and mechanically damaged recovered particles	Powder recovery and sieving become critical lifecycle steps for maintaining powder-bed stability and part consistency
Mechanical damage during powder recovery	Mainly EBM/E-PBF	Ti-6Al-4V, INCONEL® 718 and other EBM powders	Surface deformation, irregular particles and altered powder–beam interaction	Recovered powder requires acceptance criteria based on morphology, spreadability and process response before reuse
Lack-of-fusion defect formation	SLM/LPBF and EBM/E-PBF	AlSi10Mg, INCONEL® 718, Ti-6Al-4V, stainless steels	Incomplete consolidation, irregular melt tracks and internal discontinuities	Strongly detrimental to fatigue life because lack-of-fusion defects act as preferential crack-initiation sites
Gas porosity	Mainly SLM/LPBF, especially in moisture-sensitive alloys	AlSi10Mg, Mg-based alloys and other reactive powders	Entrapped gas pores, hydrogen-related porosity and reduced local density	May have limited influence on static strength when small and isolated, but can reduce fatigue performance depending on size, morphology and location
Oxide inclusions and non-metallic discontinuities	Mainly SLM/LPBF	AlSi10Mg, 316L, INCONEL® 718	Brittle inclusions, local stress concentrations and reduced metallurgical continuity	Critical for fatigue and fracture performance, even when monotonic tensile properties appear stable
Powder-bed heterogeneity	SLM/LPBF and EBM/E-PBF	316L, Ti-6Al-4V, INCONEL® 718, Al alloys	Non-uniform layer deposition, local packing-density variations, porosity and dimensional inconsistency	Requires powder-history traceability, process monitoring and defect-tolerant qualification for safety-critical use
Phase or microstructural evolution during reuse	SLM/L-PBF and EBM/E-PBF	316L, INCONEL® 718, Ti-6Al-4V, Al alloys	δ-ferrite formation, precipitation changes, α/β evolution, altered grain structure and heterogeneous solidification response	May preserve or even improve static properties, but fatigue-critical reliability remains governed by defect populations and local microstructural discontinuities
Inadequate powder-history control	SLM/L-PBF and EBM/E-PBF	All reused metallic powders	Uncertain reuse-cycle number, unknown oxygen exposure, mixed powder states and inconsistent recovery conditions	Prevents robust qualification and makes reuse decisions dependent on empirical practice rather than reliability-based acceptance thresholds
Insufficient post-processing or defect mitigation	SLM/L-PBF and EBM/E-PBF	Ti-6Al-4V, INCONEL® 718, AlSi10Mg and stainless steels	Persistent internal pores, lack-of-fusion defects, surface-connected defects and residual-stress effects	HIP, heat treatment and surface finishing may improve part quality, but cannot replace powder-quality control and fatigue-oriented qualification

To further improve readability and facilitate comparison between the principal studies reviewed, Table 4 summarises representative contributions according to the powder type, process route, reuse condition, properties assessed, and key findings. The table highlights the diversity of reuse protocols and evaluation criteria across SLM and EBM, while also showing that powder recyclability must be interpreted through the combined assessment of powder condition, defect formation, and mechanical-performance response.

Table 4. Comparative summary of representative powder-reuse studies in metal additive manufacturing.

Powder Type/Alloy	Process	Reuse Condition/Cycles	Properties Assessed	Key Findings	Ref.
AlSi10Mg	SLM	Long-term powder reuse over approximately 30 months	Oxygen and hydrogen content, oxide/hydroxide formation, porosity, tensile properties	Prolonged reuse increased oxide formation and hydrogen-related porosity, leading to higher porosity and reductions in tensile-related properties	[21,23]
AlSi10Mg	SLM	Virgin, recycled and condensate powders	Morphology, particle size, chemistry, microstructure, tensile properties, build-orientation effects	Recycled powder produced comparable microstructure and mechanical properties when combined with suitable preheating, although build direction influenced elongation	[22]

Table 4. *Cont.*

Powder Type/Alloy	Process	Reuse Condition/Cycles	Properties Assessed	Key Findings	Ref.
AlSi10Mg	SLM	Virgin and recycled powder under fatigue loading	Porosity, oxygen content, crack initiation, low-cycle fatigue response	Reuse-induced oxygen and porosity promoted crack nucleation, confirming the higher sensitivity of fatigue behaviour compared with static strength	[33]
AlSi10Mg smoulder	SLM	Approximately 50% smoulder-containing feedstock after sieving	Flowability, apparent density, phase composition, porosity, SR, tensile properties	Sieved smoulder showed comparable processability and part quality, suggesting potential for secondary reuse when carefully controlled	[38]
AlSi10Mg/Al-based powders	SLM	Multiple reuse cycles, including 5–15 cycles depending on the powder and study	Particle size distribution, morphology, flowability, laser absorption, porosity, tensile response	Reuse can preserve part quality under controlled sieving and powder handling, but the degradation rate depends strongly on initial powder quality and alloy sensitivity	[39–43]
316L stainless steel	SLM	Multiple reuse cycles	Oxygen content, particle morphology, powder-bed behaviour, tensile response	316L generally shows a broad recyclability window, although oxygen uptake and morphology changes may affect local powder-bed stability	[44,45]
316L stainless steel	SLM	Recycled powder, including 16 reuse cycles in selected studies	δ-ferrite retention, magnetic behaviour, particle clustering, porosity, lack-of-fusion defects	Reuse may promote δ-ferrite formation and magnetic clustering, leading to powder-bed heterogeneity and defect-sensitive behaviour	[46]
316L stainless steel	SLM	Five to thirty reuse cycles	Oxygen accumulation, oxide inclusions, δ-ferrite, tensile and low-cycle fatigue behaviour	Some studies report stable macro-mechanical response, whereas others identify oxide inclusions and sudden failure risks, showing the need for defect-sensitive qualification	[47,48]
MS1/18Ni300 maraging steel	SLM	Top-up powder reuse and recycled-powder conditions	Density, porosity, hardness, tensile properties, residual stress, wear resistance	Appropriate top-up strategies and post-processing can preserve density and mechanical performance, but powder history and surface integrity remain critical	[49,50]
INCONEL® 718	SLM	Multiple reuse cycles, including studies up to approximately 10–15 cycles	Powder morphology, particle size distribution, oxide formation, fatigue, creep and tensile properties	Static properties may remain stable or even improve through oxide-dispersion effects, but fatigue, creep and crack-sensitive reliability require stricter qualification	[51–54]
INCONEL® 718	SLM	Powder preparation comparison and reused-powder management	Powder morphology, apparent density, satellites, internal porosity, microstructure, ductility	Powder production route and morphology strongly affect processability and defect formation, showing that reuse assessment must consider initial powder quality	[55]
Ti-6Al-4V/Ti-6Al-4V ELI	EBM	Long-term reuse and highly recycled powder batches	Oxygen, nitrogen and hydrogen content, morphology, internal defects, tensile properties	Vacuum processing limits chemical degradation, but physical powder evolution and internal defects may still affect part quality	[60,61]
Ti-6Al-4V	EBM	Repeated reuse cycles and thermal exposure	Microstructure, oxygen content, hardness, Young's modulus, tensile properties	Repeated EBM thermal exposure can stabilise powder microstructure and preserve static properties, but qualification must consider powder history and defect formation	[63]
Ti-6Al-4V	EBM	Recovered and recycled powder	Particle morphology, satellite loss, flowability, porosity, computed tomography	Mechanical recovery and morphology evolution can affect spreadability and promote internal defects if powder handling is not controlled	[64,81]
Ti-6Al-4V	EBM	Approximately 10 build cycles and location-dependent powder recovery	Oxygen content, sintering, agglomeration, morphology, impact properties, fatigue behaviour	Powder degradation varies with build-chamber location; static properties may remain stable, but fatigue may deteriorate due to lack-of-fusion defects	[66,67]
Ti-6Al-4V	EBM	Reused powder with post-processing	Microstructure, tensile properties, fatigue behaviour, HIP response	HIP can reduce internal porosity and improve part quality, but powder quality control remains necessary for fatigue-critical applications	[68]
INCONEL® 718/Ni-based powders	EBM	Reuse after powder-bed sintering and recovery	Caking, agglomeration, spreadability, powder recovery behaviour, process-log response	Recyclability is governed mainly by physical degradation, powder recovery and spreading behaviour rather than oxidation alone	[17,78,79]

4. Critical Analysis

Powder recyclability in metal AM is often approached in the literature as a practical or economic consideration; however, a deeper examination reveals that it is fundamentally a multi-scale, process-dependent phenomenon, where powder evolution, process physics, and structural performance are intrinsically coupled. When interpreted through the process–structure–performance framework proposed in this work, the apparently disparate findings reported across studies used in this work as sources of information converge into a coherent and physically meaningful narrative.

4.1. A Shift in Perspective: From Reuse Practice to Material–Process System

A central limitation of the existing literature lies in the implicit assumption that powder reuse can be evaluated independently of the manufacturing process. Yet, as consistently suggested across multiple studies [2,14,19,33,45,58], AM technologies must be understood as energy–material interaction systems, where the behaviour of the feedstock cannot be decoupled from the processing environment. Within this context, powder recyclability ceases to be an intrinsic material property and becomes instead an emergent system-level response, shaped by repeated exposure to thermal, chemical, and mechanical fields. This perspective immediately explains the divergence observed between different AM processes. As reflected in a wide body of experimental work [15–17,33,49,62], SLM and EBM do not merely differ in operating conditions; they impose fundamentally distinct degradation pathways on the powder. The framework introduced in this study captures this distinction explicitly, positioning degradation mechanisms as a transitional layer between the powder lifecycle and structural outcome.

Qi et al. [109] investigated the powder spreading optimisation in LPBF Al–Mg–Sc–Zr alloys while balancing laser absorption, layer stability, density, and surface integrity. A 50 μm layer thickness produced 99.23% density, refined grains, 518 MPa tensile strength, and 15.6% elongation after ageing.

4.2. Process-Dependent Degradation: Chemical Versus Physical Pathways

The literature consistently reports that SLM processes are dominated by chemically driven degradation mechanisms, particularly oxidation and moisture interaction [15,34,50,110]. Even under controlled inert atmospheres, residual oxygen and repeated thermal cycling promote the formation of surface oxides, which progressively alter particle chemistry and surface energetics. These changes, although subtle at early stages, accumulate over reuse cycles and influence melt pool dynamics and wetting behaviour [16,42,52].

In contrast, EBM processes, operating under vacuum and elevated temperatures, exhibit degradation mechanisms that are predominantly physical in nature, including particle coarsening, sintering, and morphological evolution [17,43,53]. These phenomena affect particle packing and flowability, ultimately modifying local density and thermal behaviour during processing. The comparison between variables used in both systems can be observed in Table 5.

Table 5. Comparison of recyclability variables: SLM vs. EBM.

Technical Specifications	SLM	EBM
Power Source	Fibre laser (photons)	Electron beam
Construction Atmosphere	Inert gas (argon or nitrogen)	High vacuum (10^{-4} to 10^{-5} mbar)
Preheating the Bed	Low to moderate (e.g., 200 °C for AI)	High (>600 °C for Ti; >1000 °C for Ni)
Main Degradation Mechanism	Chemical: oxidation and moisture absorption	Physical: bed sintering (caking) and PRS impact
Morphological Evolution	Accumulation of irregular splashes (spatters)	Satellite loss and mechanical rounding
Limiting Factor for Reuse	Oxygen saturation and loss of fluidity	PSD change and surface plastic deformation
Reconditioning Requirement	Sieving and vacuum drying (100 °C)	Intensive mechanical blasting (PRS)

Representative quantitative evidence reinforces this process-dependent distinction. In SLM of AlSi10Mg, long-term powder reuse has been associated with oxygen increases from approximately 500 to 1250 ppm, oxide-layer growth from ~4 to ~38 nm, porosity increases from <1% to ~3%, and reductions of about 15% in tensile-related properties [21,23]. For 316L stainless steel, oxygen content has been reported to increase from approximately 450 to 680 ppm after multiple reuse cycles, although this did not necessarily produce a proportional loss of ductility under controlled processing conditions [44]. In reused INCONEL® 718 powder, reported changes include an average particle-size increase of approximately 5 μm and oxygen enrichment of up to 200 ppm, with mixed consequences for static strength and defect-sensitive reliability [53,54]. By contrast, EBM studies on Ti-6Al-4V show a different quantitative pattern: oxygen contents may remain within ASTM limits even after extensive reuse, while selected studies report increases from approximately 0.13% to 0.17% and progressive PSD narrowing caused by the loss of fine particles during preheating, recovery and sieving [60,61,81,82]. Therefore, the available data indicate that SLM degradation is more strongly expressed through chemical contamination and oxide-mediated defect formation, whereas EBM degradation is more strongly expressed through physical powder evolution, including particle coarsening, satellite loss, sintering-neck fracture, powder-cake recovery effects and altered spreadability. Direct oxygen-increase-per-cycle or PSD-change-per-cycle comparisons remain limited because the reviewed studies do not use harmonised reuse-cycle definitions, powder-refreshment strategies or powder characterisation protocols.

The effect of powder reuse must also be interpreted in relation to the processing window, since powder degradation does not translate into defects independently of the energy input and thermal conditions imposed during fabrication. In SLM, laser power, scan speed, hatch spacing, layer thickness, scan strategy, shielding-gas purity, and platform preheating collectively determine the effective energy density, melt-pool geometry, wetting behaviour, spatter generation, keyhole instability, and lack-of-fusion susceptibility. Consequently, a powder batch showing moderate oxidation, altered flowability, particle coarsening, or spatter contamination may still produce acceptable components when processed within a sufficiently robust parameter window, whereas the same powder may generate porosity, balling, oxide-rich discontinuities, or lack-of-fusion defects when energy input, hatch overlap, or atmosphere control are inadequate. This explains why some studies report acceptable static properties after several reuse cycles, while others identify defect amplification under apparently similar powder-reuse conditions.

For EBM, the relevant process variables differ but remain equally important. Beam current, scan speed, focus offset, line offset, preheating temperature, powder-bed temperature, vacuum condition, and scan strategy govern powder-bed sintering, charge dissipation, melt-pool stability, thermal exposure, powder-cake strength, and recovery-induced particle damage. The higher thermal exposure and partial sintering typical of EBM can reduce the dominance of oxidation-related degradation, but it also intensifies physical powder evolution, including particle coarsening, satellite loss, caking, agglomeration, and changes in spreadability. Therefore, the distinction between SLM and EBM should not be reduced to powder chemistry alone; it reflects the interaction between powder condition and process parameters. From a qualification perspective, reused-powder acceptance should therefore be linked not only to powder descriptors such as oxygen content, morphology, and particle size distribution, but also to the validated processing window within which those powders can be converted into components with controlled defect populations and reliable mechanical performance.

What emerges from this comparison is not simply a difference in degradation mechanisms, but a deeper insight: recyclability is process-contingent. The same powder material,

subjected to different AM processes, evolves along distinct thermodynamic and kinetic pathways. This observation, supported across multiple studies [20,44,107,111], reinforces the need for process-specific lifecycle-management strategies.

4.3. From Powder Evolution to Defect-Mediated Behaviour

The transition from powder degradation to microstructural development represents a critical amplification stage in the process–structure–performance chain. Variations in particle size distribution, morphology, and surface chemistry directly affect powder bed density, thermal conductivity, and melt-pool stability [14,46,59,80]. Guo et al. [111] analysed resolving stochastic melt-flow instabilities in Al-LPBF, particularly powder impact, keyhole oscillation, and melting-mode switching. Through in situ synchrotron X-ray imaging, they found that melt-flow instabilities disturb energy balance, solidification behaviour, and surface quality.

These effects propagate into the solidification process, influencing grain structure, phase distribution, and defect formation.

It is important, however, to distinguish between correlation and causation when interpreting the relationship between powder degradation and defect formation. In many studies, increases in oxygen content, oxide layer thickness, particle-size redistribution, spatter contamination, moisture interaction, or reduced flowability are reported together with higher porosity, oxide inclusions, lack-of-fusion regions, or unstable melt-pool behaviour. These observations provide strong associative evidence that powder history contributes to defect susceptibility. Nevertheless, defect formation in powder bed fusion is also governed by processing parameters, atmosphere control, recoating behaviour, layer thickness, scan strategy, part geometry, thermal history, and post-processing condition. Therefore, powder degradation should not be interpreted as a single deterministic cause of defects unless these variables are experimentally controlled or mechanistically isolated.

A more robust interpretation is that degraded powder modifies the probability and severity of defect formation within a given processing window. For example, oxide-enriched powder may reduce wetting and promote oxide-rich discontinuities, moisture-affected powder may increase susceptibility to hydrogen-related porosity, and coarser or irregular particles may reduce powder-bed packing uniformity and increase the likelihood of lack-of-fusion defects. In these cases, the link between powder condition and defect formation is mechanistically plausible and supported by the reviewed evidence, but it remains process-dependent. Accordingly, this review treats powder degradation as a contributing and amplifying factor in defect formation, rather than as an isolated causal variable independent of process conditions.

A key insight emerging from the literature [16,51,76,82] is that defect formation is not solely governed by processing parameters, but is strongly influenced by the historical state of the powder. Oxide inclusions, lack-of-fusion defects, and porosity are frequently associated with degraded powders, acting as structural discontinuities that compromise integrity. This is particularly evident in SLM, where oxide films can inhibit full melting and promote heterogeneous solidification [42,65,83].

Within the framework proposed in this study, defects occupy a central role as the linking mechanism between material degradation and performance loss. This interpretation shifts the focus from powder properties per se to their downstream consequences, enabling a more physically grounded understanding of recyclability.

4.4. The Overlooked Asymmetry: Static Properties Versus Fatigue Performance

One of the most critical, and often underestimated, findings across the literature is the asymmetry between static and fatigue behaviour. Numerous studies report that tensile

strength, hardness, and other static properties remain relatively stable across multiple powder reuse cycles [20,63,85]. At first glance, this suggests that powder recyclability has a limited impact on performance.

However, this interpretation is fundamentally incomplete. Fatigue behaviour, governed by crack initiation and propagation mechanisms, is highly sensitive to microstructural heterogeneities and defects [21,78,86]. Even minor increases in defect density or size can drastically reduce fatigue life, as consistently demonstrated in fatigue-focused studies [22,81,87].

From a mechanistic perspective, the stronger sensitivity of fatigue performance arises because powder-induced defects act as local crack-initiation sites rather than merely as reductions in effective load-bearing area. In static tensile testing, small and spatially dispersed pores or inclusions may have limited influence when the matrix retains sufficient ductility and strain hardening capacity. Under cyclic loading, however, the same defects can produce local stress concentration, early plastic localisation, oxide–matrix decohesion, and short-crack nucleation. The fatigue relevance of a defect is therefore governed not only by its presence, but by its projected size, morphology, sharpness, orientation relative to the loading direction, and position within the component. Surface and near-surface defects are particularly detrimental because they experience higher effective stress intensity and are less constrained by the surrounding material than internal defects.

This behaviour can be interpreted using defect-tolerant fatigue concepts such as Kitagawa–Takahashi-type threshold diagrams, El Haddad-type intrinsic crack length corrections, and Murakami-type area parameters. These approaches show that there is no universal "safe" porosity level independent of defect size and applied stress amplitude. Instead, fatigue failure becomes increasingly likely when a pore, oxide inclusion, lack-of-fusion region, or unmelted-particle cluster exceeds the effective threshold condition for non-propagating cracks. For reused powders, this is particularly important because degradation mechanisms such as oxidation, spatter incorporation, particle coarsening, moisture interaction, and powder-bed heterogeneity may not substantially alter average tensile strength, but can increase the probability of rare, large, sharp, or poorly bonded defects that control fatigue life. Consequently, qualification of recycled powder for fatigue-critical components should include defect-population analysis, defect-size statistics, surface-integrity assessment, and, where appropriate, fatigue-threshold or crack-growth-based interpretation rather than relying exclusively on monotonic mechanical properties.

Surface roughness represents an additional fatigue-relevant pathway through which powder reuse can influence component reliability. Reused powders may contain higher fractions of spatter, partially oxidised particles, irregular particles, agglomerates, or coarser fractions, all of which can impair powder spreading, local packing density, melt-pool stability, and contour-track regularity. These effects may promote partially melted particles, balling, local overmelting or undermelting, and surface-connected discontinuities, thereby increasing as-built roughness. Although surface roughness is not governed by powder condition alone, since it also depends on process parameters, part orientation, layer thickness, scan strategy, contour settings, support removal, and post-processing, powder reuse can increase the probability of roughness-related fatigue initiation when the processing window is not sufficiently robust.

From a fatigue perspective, surface roughness is critical because it converts geometric surface irregularities into local stress concentrators. Surface asperities, attached particles, re-entrant features, and partially fused particles may behave as notch-like crack-initiation sites, particularly under tensile cyclic loading. This effect is especially important in as-built AM components, where fatigue failure often initiates at the surface rather than from internal pores. Consequently, a reused powder that produces acceptable density and tensile

properties may still be unsuitable for fatigue-critical applications if it increases surface-connected defects or roughness amplitude. Surface finishing, machining, polishing, shot peening, or controlled contour remelting may reduce this risk, whereas HIP can mitigate internal porosity without necessarily removing surface roughness. Therefore, qualification of reused powders for fatigue-critical parts should include surface-integrity assessment in addition to internal defect analysis and monotonic mechanical testing.

To support this defect-tolerant interpretation, Table 6 provides a qualitative classification of the principal defect families according to their relative severity for fatigue performance. This classification should not be interpreted as a universal ranking, since the criticality of a defect depends strongly on its size, morphology, sharpness, location, loading mode, surface condition, residual stress state, and post-processing route. Nevertheless, the classification helps to distinguish defects that are intrinsically more likely to act as fatigue crack-initiation sites from those whose influence is more conditional.

Table 6. Relative severity of powder- and process-related defect types for fatigue performance in reused-powder AM components.

Defect Type	Typical Origin in Reused-Powder Processing	Relative Fatigue Severity	Mechanistic Rationale
Surface or near-surface lack-of-fusion defects	Insufficient energy input, poor hatch overlap, reduced powder-bed packing, irregular spreading, altered powder morphology	Very high	Sharp, irregular and poorly bonded defects generate strong local stress concentration and can behave as pre-existing cracks, especially when located near the surface
Oxide inclusions and oxide-rich discontinuities	Powder oxidation, spatter incorporation, surface-oxide growth, moisture-related degradation	Very high	Brittle inclusions and weak oxide–matrix interfaces promote decohesion, early crack nucleation and reduced crack-initiation resistance
Unmelted or partially melted particles	Inadequate melting, unstable melt-pool wetting, coarse particles, insufficient local energy density	High	Poor metallurgical bonding and irregular geometry create local discontinuities that can initiate cracks under cyclic loading
Irregular melt-pool boundaries and melt-track discontinuities	Melt-pool instability, spatter contamination, altered absorptivity, unsuitable scan strategy	High	Local microstructural and geometrical discontinuities favour strain localisation and short-crack initiation
Large or clustered gas pores	Hydrogen porosity, entrapped gas, moisture interaction, unstable solidification	Moderate to high	Fatigue effect depends strongly on pore size, clustering, proximity to surface and interaction with local stress fields
Small isolated spherical pores	Entrapped gas or metallurgical porosity under otherwise stable processing	Low to moderate	Rounded morphology produces lower stress concentration; influence may be limited if pores are small, internal and isolated
Powder-bed heterogeneity-induced porosity	Reduced flowability, particle clustering, PSD changes, magnetic particle attraction, non-uniform recoating	Moderate to high	Criticality depends on whether heterogeneity produces isolated pores or connected/sharp lack-of-fusion regions
Surface roughness and partially attached particles	Reused-powder spatter, poor surface finish, incomplete contour melting, insufficient machining	High for as-built fatigue	Surface asperities reduce effective fatigue strength by promoting crack initiation at the free surface
Sintering-neck fragments and mechanically damaged recovered particles	EBM powder-cake recovery, sieving, mechanical handling, fractured agglomerates	Conditional	Indirectly critical when they impair spreading, packing or melting, thereby increasing lack-of-fusion or inclusion-related defects

Overall, lack-of-fusion defects, oxide-rich discontinuities, unmelted-particle clusters and surface-connected defects are generally the most severe for fatigue-critical applications because they combine sharp morphology, weak bonding and high effective stress intensity. By contrast, small isolated spherical pores may be less damaging under comparable stress amplitudes, although they can become critical when they are large, clustered, near the surface, or located in regions of high tensile stress. This hierarchy reinforces the need to qualify reused powders through defect-population analysis and fatigue-sensitive acceptance criteria rather than through density or tensile properties alone.

This divergence reveals a critical limitation of conventional evaluation approaches: static properties are poor indicators of reliability in AM components. The framework developed in this work explicitly highlights this discrepancy, emphasising that recyclability must be assessed in relation to fatigue-critical performance, particularly in high-value applications where cyclic loading dominates failure modes.

4.5. Reconciling Conflicting Evidence in Powder-Reuse Studies

Although the reviewed literature reveals several recurring trends, the reported effects of powder reuse are not fully uniform across studies. Apparent contradictions are particularly evident when comparing investigations that report negligible changes in powder quality or static mechanical performance with those identifying oxidation, porosity growth, oxide inclusions, ductility reduction, or fatigue degradation. These discrepancies should not be interpreted simply as inconsistencies in the literature, but rather as evidence that powder recyclability is strongly conditional on alloy chemistry, process environment, powder handling history, reuse strategy, and performance metric.

For AlSi10Mg processed by SLM, some studies report substantial degradation after prolonged reuse, including increased oxygen and hydrogen content, surface-oxide growth, spatter accumulation, higher porosity, and reductions in tensile-related properties. Other studies, however, indicate that recycled or smoulder-containing AlSi10Mg powder can still produce parts with acceptable density, surface quality, and tensile properties when sieving, preheating, drying, or controlled processing strategies are applied. The apparent conflict reflects differences in powder age, storage humidity, oxygen exposure, spatter fraction, rejuvenation strategy, and whether the assessment focuses on bulk tensile response or defect-sensitive reliability.

A similar contrast is observed for 316L stainless steel. Several studies suggest that 316L has a comparatively broad powder-reuse window, with moderate oxygen uptake and limited deterioration in static tensile behaviour. Conversely, other investigations report δ-ferrite formation, magnetic particle clustering, sub-micron oxide inclusions, and local powder-bed heterogeneity, which may promote porosity, lack-of-fusion defects, or sudden tensile failure. This indicates that static strength retention alone is insufficient to qualify reused 316L powder, particularly where local inclusions or clustering phenomena may control failure initiation.

For INCONEL® 718 and related Ni superalloys, conflicting interpretations are also evident. In some cases, reuse-induced oxide formation and particle-size evolution do not significantly degrade static strength and may even contribute to apparent strengthening through oxide-dispersion effects. However, this does not necessarily imply improved reliability, since oxide inclusions, solidification defects, Laves-phase-related heterogeneity, and crack-sensitive discontinuities may remain detrimental under fatigue, creep-fatigue, or high-temperature service conditions. Therefore, the same powder evolution mechanism may appear beneficial under monotonic tensile testing but harmful under defect-sensitive loading conditions.

The EBM literature further reinforces the need for process-specific interpretation. For Ti-6Al-4V, the vacuum environment can limit chemical degradation and preserve static tensile properties across multiple reuse cycles. Nevertheless, repeated thermal exposure, powder-cake formation, particle coarsening, satellite loss, mechanical recovery damage, and spatially heterogeneous powder histories can still affect powder-bed spreading and promote lack-of-fusion defects or internal porosity. Consequently, the apparent stability of chemical composition or tensile strength does not eliminate the need for fatigue-oriented qualification. Table 7 summarises the principal sources of divergence among powder-reuse studies, showing how alloy chemistry, reuse definitions, handling conditions, process atmosphere, performance metrics, and post-processing routes can lead to apparently conflicting conclusions regarding powder recyclability and component reliability.

Table 7. Main sources of conflicting evidence in powder-reuse studies.

Source of Discrepancy	Effect on Reported Conclusions	Relevance to Powder Recyclability
Alloy chemistry	Reactive alloys such as AlSi10Mg and Ti alloys show stronger sensitivity to oxygen, moisture, and interstitial contamination than more stable alloys	Reuse limits must be alloy-specific
Reuse-cycle definition	"Reuse cycle", "build cycle", "powder age", and "powder refreshment" are not used consistently	Direct comparison between studies may be misleading
Powder handling and storage	Humidity, oxygen exposure, storage time, and sieving conditions alter powder degradation before reuse	Powder history must be reported alongside reuse number
Top-up or blending strategy	Addition of virgin powder can mask degradation trends and stabilise flowability or chemistry	Recyclability depends on lifecycle-management strategy, not reuse alone
Process atmosphere	SLM is more sensitive to residual oxygen and moisture, whereas EBM is more affected by thermal exposure and powder recovery	Process-specific degradation pathways must be distinguished
Performance metric	Static tensile properties may remain stable, while fatigue performance may deteriorate due to small defects	Qualification should include defect-sensitive reliability metrics
Post-processing condition	HIP, heat treatment, machining, or surface finishing may reduce or amplify reuse-related effects	Powder reuse should be evaluated together with the full process chain

4.6. Case-Based Validation of the Process–Structure–Performance Framework

Although the process–structure–performance framework proposed in this review is intended primarily as a unifying interpretative structure, the evidence synthesised across the reviewed literature also allows its core relationships to be validated through representative process- and alloy-specific cases. In particular, the literature consistently supports a directional relationship in which powder lifecycle evolution modifies feedstock characteristics, these changes alter process stability and powder-bed behaviour, and the resulting defect populations govern the final mechanical response. Within this chain, defects constitute the critical transfer mechanism linking powder degradation to structural integrity, especially under fatigue-critical loading conditions. While the exact magnitude of these relationships remains material- and process-dependent, the framework is not purely conceptual; rather, it is grounded in recurrent patterns observed across SLM and EBM studies.

In SLM processing of AlSi10Mg, the reviewed studies show that prolonged powder reuse promotes oxygen uptake, moisture-related degradation, spatter accumulation, and

surface-oxide growth, which in turn increase the likelihood of porosity, lack-of-fusion defects, and unstable melt-pool wetting. These changes are accompanied by measurable reductions in structural integrity and, in some cases, by approximately 15% losses in tensile-related properties, together with a markedly greater sensitivity of fatigue behaviour to defect accumulation. In 316L stainless steel, the framework is validated in a more nuanced manner: although moderate powder ageing may not strongly degrade static tensile properties, reuse-related changes in morphology, oxygen content, δ-ferrite retention, and particle clustering can still impair powder-bed homogeneity and increase the likelihood of localised defects. In SLM of INCONEL® 718, repeated reuse has been shown to modify particle size distribution, oxide content, and particle morphology, while the resulting defect populations and microstructural inhomogeneities may influence crack sensitivity, creep behaviour, and long-term reliability even where static strength remains broadly acceptable.

A similarly consistent validation pattern emerges for EBM, although the dominant degradation mechanisms differ. For Ti-6Al-4V processed by EBM, the vacuum environment reduces oxidation-driven degradation, but repeated thermal exposure promotes particle coarsening, partial sintering, satellite loss, morphology evolution, and powder-cake-related recovery effects. These physical changes influence powder spreading and local bed-density uniformity, thereby increasing susceptibility to lack-of-fusion defects, internal pores, and process heterogeneity. Across the reviewed EBM studies, static tensile properties often remain comparatively stable, whereas fatigue behaviour is more strongly affected when reuse-induced defect populations persist. This contrast reinforces the core proposition of the framework: the key determinant of reliability is not powder degradation in isolation, but the extent to which it propagates through the process chain into defect formation and defect-sensitive mechanical response.

Taken together, these representative cases confirm that the proposed framework is supported by cross-material and cross-process evidence. Its principal value lies in making explicit that powder recyclability should not be assessed solely by changes in powder chemistry or morphology, nor solely by static property retention, but by the coupled evolution of feedstock condition, process stability, defect populations, and reliability-critical performance.

4.7. Recyclability Redefined: A Reliability-Driven Continuum

The integration of these insights leads to a fundamental redefinition of powder recyclability. Rather than a binary condition (reusable vs. non-reusable), recyclability should be understood as a continuous variable governed by defect accumulation and performance thresholds. This perspective is increasingly supported by recent studies [31,92–95], which emphasise the need for application-specific criteria when defining acceptable reuse limits. Within this framework, the concept of a fixed number of reuse cycles becomes insufficient. Instead, the acceptable lifecycle of a powder must be defined in terms of its impact on structural integrity, particularly under fatigue loading conditions. This transition from material-centric to performance-centric thinking represents a significant conceptual shift in the field.

From an implementation perspective, performance-based powder reuse requires a staged qualification strategy rather than a single universal reuse-cycle threshold. In the first stage, each powder batch should be assigned a traceable lifecycle record, including virgin-powder origin, number of thermal exposures, build history, storage condition, sieving route, top-up ratio, recovery procedure, and atmosphere exposure. In the second stage, powder acceptance should be based on measurable descriptors such as oxygen, nitrogen and hydrogen content, particle size distribution, morphology and sphericity, satellite or spatter fraction, apparent and tap density, flowability, moisture sensitivity, and chemical

stability. These indicators should not be interpreted independently, but compared with alloy-specific baseline values, machine-specific control limits, and the validated processing window for the intended application.

A third stage should link powder descriptors to process and defect monitoring. For SLM, this may include oxygen monitoring in the build chamber, recoating quality, melt-pool emissions, spatter monitoring, layer-wise imaging, and post-build defect assessment. For EBM, relevant indicators include powder-bed preheating behaviour, cake strength, sintering level, recovery-induced particle damage, PSD narrowing, and changes in powder spreading after mechanical recovery. Where reused powder is intended for fatigue-critical applications, powder qualification should also be coupled with part-level evidence, including X-ray computed tomography, surface-roughness measurement, metallographic defect analysis, and fatigue-relevant witness coupons manufactured under the same powder and process conditions.

In this context, practical thresholds should be defined as application-specific acceptance windows rather than as fixed cycle numbers. For non-critical components, acceptable reuse may be based on powder chemistry, flowability, density and the absence of major process instability. For structural components, additional requirements should include internal defect limits, surface-integrity control, tensile-property retention and process repeatability. For fatigue-critical or safety-critical applications, acceptance should further require defect-size statistics, surface-condition assessment, fatigue testing or fatigue-relevant coupon validation, and evidence that the reused powder does not increase the probability of critical surface-connected defects, lack-of-fusion regions, oxide-rich inclusions or large pore clusters. This staged approach enables powder reuse to be managed as a controlled qualification process rather than as a simple count of previous build cycles.

The studies by Singh et al. [92] on plasma re-spheroidisation and by Yankin et al. [82] on ultrasonic atomisation change the paradigm. Recycling ceases to be a "controlled degradation" and becomes a "regeneration of raw materials". These processes allow solid scrap (such as supports and non-conforming parts, according to Ren et al. [80]) to return to the production chain with superior quality to virgin gas atomized powder, representing the pinnacle of the circular economy in Industry 4.0 (I4.0).

Cabrioli et al. [112] studied the challenge of upcycling offshore copper-cable scrap into AM-grade powder while controlling purity, flowability, DED printability, and environmental burden. They have demonstrated that ultrasonic atomisation produced ~99.5 wt.% copper powder, compatible with DED, while reducing global warming potential by over 70%.

Table 8 summarises a practical route for implementing performance-based powder reuse qualification, linking powder-batch traceability, powder-condition assessment, process-window verification, defect-population control, and mechanical validation to the monitoring tools and decision outputs required for application-specific reuse acceptance.

Table 8. Practical implementation route for performance-based powder reuse qualification.

Qualification Level	Main Indicators	Monitoring Tools	Typical Decision Output
Powder-batch traceability	Powder origin, reuse history, storage condition, sieving route, top-up ratio, build exposure	Digital powder logbook, batch identification, machine records	Accept for screening, quarantine, or recondition
Powder-condition assessment	Oxygen, nitrogen, hydrogen, moisture, PSD, morphology, satellites, spatter, apparent/tap density, flowability	Chemical analysis, PSD measurement, SEM/image analysis, Hall/Carney flow, density testing	Accept, blend, sieve, dry, recondition, or reject

Table 8. *Cont.*

Qualification Level	Main Indicators	Monitoring Tools	Typical Decision Output
Process-window verification	Recoating behaviour, melt-pool stability, spatter level, atmosphere quality, preheating behaviour, powder-cake recovery	Oxygen monitoring, layer-wise imaging, melt-pool/spatter monitoring, process logs	Confirm whether reused powder remains processable
Defect-population control	Porosity, lack-of-fusion, oxide inclusions, unmelted particles, surface-connected defects	X-ray CT, metallography, SEM, surface profilometry	Define defect acceptability for the target component class
Mechanical and fatigue validation	Tensile retention, hardness, ductility, fatigue response, crack-initiation sensitivity	Mechanical testing, fatigue coupons, witness specimens, fracture analysis	Release for non-critical, structural, or fatigue-critical use

4.8. Toward Controlled Lifecycle Engineering: Upcycling and Mitigation Strategies

The limitations of conventional reuse strategies have led to the emergence of advanced approaches aimed at restoring or extending powder usability. Techniques such as chemical treatment, mechanical reconditioning, and controlled blending have been explored as means of mitigating degradation effects [23,99,103,108,113,114]. These approaches, often referred to as powder upcycling, represent a transition from passive reuse to active lifecycle engineering.

Within the process–structure–performance framework, these strategies can be interpreted as targeted interventions at the powder lifecycle stage, designed to reduce downstream defect formation and preserve mechanical performance. Their effectiveness, however, depends on the ability to quantitatively relate powder modifications to structural outcomes, highlighting the need for integrated and predictive models.

4.9. Toward a Unified and Generalisable Understanding

By integrating findings across a broad range of studies, this work demonstrates that powder recyclability in metal AM is best understood as a multi-dimensional and system-level phenomenon, where material degradation, process physics, and performance are tightly interconnected. The proposed framework provides a structured representation of these interactions, enabling the consolidation of fragmented knowledge into a generalisable and transferable understanding.

This unified perspective supports a transition from descriptive analysis toward reliability-oriented engineering, where powder reuse strategies are defined not only by economic or environmental considerations, but by their impact on structural integrity and long-term performance. Such an approach is essential for the safe and scalable adoption of AM technologies in fatigue-critical applications, where performance margins are narrow and failure consequences are significant.

4.10. Risk Management and Technical Contradictions (FMEA and TRIZ)

When applying FMEA, it becomes evident that the industry overvalues visible risks (such as flowability/PSD) and undervalues invisible risks. Cross-contamination (High RPN), discussed by Sutton et al. [115], is the perfect example—a small percentage of a foreign alloy can invalidate the safety of an entire batch.

Muñiz-Lerma et al. [116] proposed to examine and characterise AlSi7Mg powder feedstock beyond conventional PSD, morphology, density, and flowability metrics for reliable PBF processing. Fine particles increase moisture absorption, surface energy, and cohesion, whereas particles above 48 µm improve spreadability.

To resolve the contradiction between “limited cost” and “maximum safety”, the application of the TRIZ Segmentation Principle emerges as the most viable solution. Instead

of using a single batch of powder, the proposal is functional separation: use recycled powder (with a higher risk of oxide inclusions, according to [52]) only for filling, reserving virgin powder for the boundary. This approach directly addresses the vulnerability identified by Luo et al. [53], where fatigue failures tend to nucleate from surface imperfections.

5. Future Trends

The evolution of powder recyclability in metal AM is undergoing a profound transformation, shifting from empirical reuse practices toward data-driven, adaptive, and fully integrated lifecycle engineering systems. Future developments are expected to converge around the principles established in the process–structure–performance framework proposed in this work, where the powder lifecycle, defect evolution, and performance are continuously monitored, predicted, and controlled.

A further research priority concerns the harmonisation of powder characterisation protocols. Although the reviewed studies employ techniques such as SEM, XPS, particle size distribution analysis, chemical analysis, apparent and tap density measurements, Hall or Carney flow testing, and image-based morphology assessment, direct comparison remains difficult because these methods are applied using different sampling procedures, reporting units, reuse-cycle definitions, sieving strategies, and powder-refreshment conditions. Consequently, a fully systematic comparison of characterisation techniques across the literature is currently constrained by methodological heterogeneity. Future work should therefore aim to establish standardised reporting frameworks that link powder morphology, surface chemistry, flowability, oxygen content, particle size distribution, and defect statistics to validated process windows and mechanical-performance outcomes.

Harkin et al. [117] examined the challenge of removing oxygen- and nitrogen-enriched spatter from reused Grade 23 Ti6Al4V powder through two-stage sieving. The authors found that 63 μm and 50 μm sieving removed spatter-rich particles, restoring blended powder chemistry within Grade 23 limits.

5.1. Artificial Intelligence and Machine Learning (ML) in Powder Qualification

One of the most disruptive trends is the integration of artificial intelligence (AI) and ML into powder qualification and process optimisation. Recent studies [31,108,118] demonstrate that deep learning models trained on multi-modal datasets—combining SEM imaging, particle size distribution, and process signals—can predict powder flowability, packing density, and defect probability with high accuracy.

However, the true paradigm shift lies beyond offline prediction. Future AM systems are expected to operate under closed-loop control architectures, where powder condition is continuously assessed during the build process. By integrating in situ monitoring techniques—such as melt pool imaging, acoustic emission, and layer-wise thermal mapping—machines will be able to dynamically adjust process parameters in real time. For example, adaptive laser scanning strategies may compensate for reduced flowability or increased particle irregularity, mitigating the formation of lack-of-fusion defects previously identified in SLM systems [1,33,34].

Within the proposed framework, these developments represent a transition from static process settings to adaptive process–structure control, where degradation at the powder level is actively counterbalanced at the processing stage.

5.2. Feedstock Digital Twins and Traceability

A second major trend is the emergence of feedstock digital twins, enabling full traceability and predictive management of the powder lifecycle. As highlighted by Lanzutti and Marin [19] and further supported by data-driven approaches [108], the concept

of assigning a digital identity to each powder batch allows the continuous tracking of key variables, including thermal exposure history, reuse cycles, oxygen content, and morphological evolution.

By integrating Discrete Element Method (DEM) simulations with real-time process data, digital twins will enable predictive models capable of estimating defect formation probability and fatigue risk before manufacturing occurs. This capability directly addresses the current lack of standardised reuse limits, replacing arbitrary cycle-based criteria with performance-based thresholds.

From a framework perspective, digital twins establish a direct link between the powder lifecycle and the reliability layer, enabling decision-making based on predicted structural integrity rather than empirical assumptions.

Yakubov et al. [119] studied the challenge of integrating recycled aluminium feedstock into metal AM while balancing contamination tolerance, alloy sorting, feedstock preparation, and process reliability. The authors determined that solid-state AM offers superior direct-recycling potential, whereas fusion AM requires stricter powder quality control and cleaner recycling pathways.

5.3. Plasma Re-Spheroidisation and Advanced Upcycling

Future strategies for powder recyclability will increasingly rely on active regeneration technologies, moving beyond traditional sieving and blending approaches. Plasma re-spheroidisation, as demonstrated in recent studies [92,114], enables the restoration of particle sphericity and flowability through rapid melting and surface tension-driven reshaping [96].

More significantly, emerging research suggests the possibility of chemical rejuvenation, where controlled atmospheres during reprocessing can reduce oxide layers and partially reverse oxidation phenomena. This capability represents a fundamental shift, as powder degradation would no longer be an irreversible process but a recoverable state within a controlled lifecycle loop.

Additionally, advanced atomisation techniques, including ultrasonic atomisation and plasma-based processes [80,82,83], are expected to play a critical role in closed-loop manufacturing systems, where solid scrap is continuously reintroduced into the production chain as high-quality feedstock.

Within the proposed framework, these technologies act directly on the powder lifecycle node, reducing the propagation of defects downstream and extending the usable lifecycle of materials.

5.4. Solid-State Deposition Technologies (Cold Spray)

The concept of recyclability is also expanding beyond powder bed fusion processes. Hybrid manufacturing systems and alternative deposition technologies, such as CSAM, offer new pathways for utilising degraded or non-conforming powders [93].

Unlike PBF processes, solid-state deposition techniques rely on kinetic energy rather than melting, making them less sensitive to oxidation and particle morphology. This enables the reclassification of “end-of-life” powders as viable feedstock for secondary processes, effectively creating multi-stage recyclability pathways.

Yoder et al. [120] investigated the challenge of upcycling automotive cast-Al chips via Additive Friction Stir Deposition (AFSD) while avoiding melt-related oxidation, dross losses, porosity, and poor ductility. They demonstrated that AFSD converted porous chip feed-rods into fully dense deposits, refining Si/Fe phases and increasing tensile elongation to 17.8%. Bruzzo et al. [121] tackled the processing and recycling of aluminium powders in LMD while controlling oxidation, hydrogen uptake, flowability loss, porosity, and process

instability. AM-specific Al alloys improved LMD properties, whereas recycled AlSi10Mg powder showed reduced processability and nozzle-damage risk.

This approach introduces a hierarchical view of recyclability, where powders are not discarded but redirected across different process windows, maximising material utilisation and minimising waste.

5.5. Machining-Chip-to-Feedstock Circularity

Beyond the reuse and reconditioning of powder already circulated within AM systems, an emerging circularity route concerns the conversion of machining-derived metallic waste into feedstock suitable for AM.

Baruah et al. [122] studied the challenge of making machining-chip upcycling for AFSD economically viable by modelling labour, maintenance, compaction, automation, and feedstock costs. Automation, die/ramrod optimisation, and increased compactor output could reduce the upcycled-bar cost by 82.4% versus commercial feedstock. Shah et al. [123] studied the challenge of designing LPBF-compatible Al–Fe alloys from recycled aluminium while overcoming the usual strength–ductility trade-off caused by Fe-rich intermetallics. ML identified 95 candidate compositions with predicted yield strength above 470 MPa and elongation above 10%. Müller et al. [124] studied the challenge of converting nickel–aluminium–bronze grinding chips into DED-LB feedstock while controlling flowability, oxidation, ceramic contamination, porosity, and nozzle stability. The impact of whirl milling produced usable chip-powder, enabling DED-LB specimens with competitive tensile strength and ductility in the vertical build direction.

Buffa et al. [125] examined the scaling friction stir extrusion for AA6082 chip recycling into thin wires while ensuring solid bonding, ductility, and low energy demand. Conical tooling, higher force, and increased rotation improved bonding, enabling reel-wrappable recycled wires with reduced specific energy consumption.

5.6. New Alloys Developed for Recycling

A particularly promising direction involves the development of alloys specifically engineered for recyclability. Current AM processes largely rely on conventional alloys not optimised for repeated thermal cycling or oxidation exposure. Future alloy design strategies are expected to incorporate:

- Enhanced resistance to oxidation and moisture interaction;
- Controlled formation of beneficial oxide dispersions (e.g., ODS effects [28]);
- Improved tolerance to defect-induced fatigue.

This shift aligns with broader trends in materials engineering, where performance is no longer defined solely by intrinsic properties, but by robustness under process-induced variability.

Within the framework proposed in this study, such alloys effectively reduce the sensitivity of the defect–performance link, enhancing reliability even under extended reuse conditions.

5.7. Standardisation, Certification, and Reliability-Based Qualification

The lack of standardised criteria for powder reuse remains one of the main barriers to industrial adoption. Current standards (e.g., ISO/ASTM 52900) provide general guidelines but fail to define quantitative acceptance limits for recycled powders [19].

Future certification strategies are expected to shift toward data-driven and reliability-based qualification, integrating real-time monitoring, digital twins, and predictive modelling. This approach would allow regulatory bodies to move beyond conservative restric-

tions and establish performance-based certification frameworks, where recycled powder can be approved for critical applications based on demonstrated structural integrity.

Such developments are essential to overcome the current perception barriers identified in industry, where fatigue risk remains the primary concern limiting the use of recycled materials [107].

5.8. Toward Autonomous and Circular AM Ecosystems

Ultimately, the convergence of AI, digital twins, advanced upcycling, and process integration will lead to the emergence of autonomous and circular AM ecosystems. In these systems, powder lifecycle management will be fully integrated into the manufacturing process, enabling continuous monitoring, prediction, and optimisation.

Within this vision, recyclability is no longer a constraint but a design parameter, actively controlled to balance cost, sustainability, and performance. The process–structure–performance framework proposed in this work provides a foundational structure for this transition, enabling the integration of material evolution, defect control, and reliability assessment into a unified and scalable approach. Tang et al. [126] investigated the modelling of aluminium LPBF powder spatter and denudation while linking powder-bed instability to melt-pool behaviour and surface quality. Track spacing governs powder-bed stability, with 140 μm reducing roughness, whereas excessive spacing promotes spatter-driven surface degradation.

6. Discussion

The findings synthesised in this review demonstrate that powder recyclability in metal AM cannot be interpreted as a simple matter of material reuse, nor can it be reduced to the number of times a powder batch has been processed. Instead, recyclability emerges as a coupled material–process–performance problem, in which powder history, degradation mechanisms, process environment, defect formation, and mechanical reliability interact across multiple length scales [127]. This interpretation is particularly important for powder bed fusion technologies, where the feedstock is repeatedly exposed to thermal, chemical, and mechanical conditions that progressively alter its behaviour during spreading, melting, solidification, and subsequent mechanical loading.

To synthesise the discussion, Figure 8 presents an integrated reliability–lifecycle–qualification framework that connects powder lifecycle evolution, process-mediated defect formation, fatigue-critical performance, industrial qualification, and implementation requirements for powder reuse in SLM and EBM.

A central outcome of the present review is the identification of a clear process-dependent divergence between SLM/L-PBF and EBM/E-PBF. In SLM, powder degradation is predominantly associated with chemically driven mechanisms, especially oxidation, moisture interaction, surface contamination, and spatter incorporation [35]. These effects are intensified by the presence of residual oxygen in the processing chamber, repeated laser-induced heating, and the recirculation of partially degraded particles. As a result, the powder surface evolves progressively, with consequences for wettability, laser absorption, melt-pool stability, and defect formation. For highly reactive or hygroscopic materials, such as AlSi10Mg, these effects are especially critical, since oxide formation and hydrogen-related porosity may rapidly compromise ductility and local structural integrity. In contrast, more oxidation-tolerant alloys, such as 316L stainless steel, may exhibit a broader reuse window, although phase evolution, particle clustering, and oxide inclusions may still affect powder-bed homogeneity and defect populations.

In EBM, the degradation pathway is fundamentally different. The vacuum environment provides substantial protection against chemical contamination, particularly for

reactive materials such as Ti-6Al-4V. Consequently, powder reuse in EBM is less strongly governed by oxidation than by physical and thermomechanical evolution. High bed-preheating temperatures, partial sintering, powder caking, satellite loss, particle coarsening, and mechanical recovery in the powder recovery system become the dominant factors controlling feedstock evolution. These changes may improve some powder characteristics in the short term, for example by narrowing the particle size distribution or increasing apparent density, but excessive reuse may generate irregular particles, fractured sintering necks, or morphology-induced spreading heterogeneity. This confirms that powder recyclability cannot be generalised across powder bed fusion technologies; rather, reuse limits and qualification criteria must be defined with explicit consideration of the process environment.



Figure 8. Integrated reliability–lifecycle–qualification framework for powder recyclability in metal additive manufacturing, showing the interaction between powder lifecycle condition, process–defect evolution, performance and reliability requirements, and industrial implementation pathways.

The comparison between SLM and EBM also highlights the importance of distinguishing between powder degradation mechanisms and their actual structural consequences. A reused powder may show measurable changes in oxygen content, morphology, flowability, or particle size distribution without necessarily producing unacceptable mechanical properties. Conversely, apparently moderate powder degradation may produce critical defect populations if the altered feedstock condition destabilises the melt pool or reduces powder-bed packing uniformity. Therefore, powder characterisation alone is insufficient as a basis for qualification. Recyclability must be evaluated through its effect on defect generation and component reliability, rather than through isolated feedstock descriptors. The heterogeneity of powder characterisation protocols across the literature also limits direct comparison between studies, highlighting the need for standardised reporting of SEM-based morphology, surface chemistry, particle size distribution, flowability, density, oxygen content, and powder-history descriptors.

Within this context, defects represent the governing link between the powder lifecycle and structural performance. Oxide inclusions, lack-of-fusion regions, gas porosity, spatter-derived discontinuities, and irregular melt-pool features act as the physical mechanisms through which powder degradation is translated into performance loss. This

defect-mediated interpretation explains why several studies report relatively stable tensile strength, hardness, or yield strength after multiple powder reuse cycles, while fatigue behaviour may deteriorate more substantially [71]. Static properties are often controlled by the average microstructure and bulk density of the component, whereas fatigue life is governed by the most critical local discontinuities, particularly those located near the surface or aligned with unfavourable stress fields. Consequently, even a small increase in defect size, aspect ratio, or spatial clustering may reduce fatigue life without producing a proportionate change in conventional tensile properties [75].

This asymmetry between static and cyclic behaviour is one of the most important implications of the review. In many industrial studies, powder reuse is considered acceptable when tensile strength, elongation, hardness, or density remain within specification. However, such criteria may be insufficient for fatigue-critical applications, particularly in aerospace, biomedical, energy, and tooling sectors, where component failure is frequently governed by crack initiation and propagation under cyclic loading. The evidence reviewed indicates that fatigue performance is highly sensitive to powder-history-dependent defects, including oxide films, lack-of-fusion discontinuities, and internal pores derived from unstable melting or poor powder-bed packing. As such, static mechanical equivalence between virgin- and reused-powder components should not be interpreted as proof of reliability equivalence.

The alloy-dependent nature of powder recyclability further complicates the establishment of universal reuse criteria. Al alloys, stainless steels, Ni superalloys, and Ti alloys respond differently to reuse because of differences in oxidation behaviour, thermal conductivity, absorptivity, phase stability, interstitial sensitivity, and strengthening mechanisms. In AlSi10Mg, moisture interaction and oxide accumulation can strongly influence porosity and ductility. In 316L stainless steel, chemical degradation may be comparatively moderate, but repeated reuse can introduce magnetic phases, particle clustering, and sub-micron oxide inclusions. In INCONEL® 718, controlled oxide formation may in some cases contribute to strengthening effects, although this apparent static benefit may be offset by fatigue sensitivity and melt-pool instability. In Ti-6Al-4V processed by EBM, chemical stability can remain high under vacuum, but physical powder evolution and lack-of-fusion defects may still affect high-cycle fatigue behaviour. These examples reinforce that recyclability is not an intrinsic property of a powder material, but a conditional response determined by the combined material–process–application system.

From an industrial perspective, the results point towards the need for a transition from cycle-count-based reuse rules to performance-based powder lifecycle management. Fixed reuse limits are attractive because they are simple to implement, but they fail to account for differences in alloy chemistry, machine architecture, atmosphere control, powder handling, build geometry, thermal exposure, and recovery strategy [128]. A powder reused for a limited number of cycles under poorly controlled conditions may be less reliable than a powder reused many times within a stable and well-monitored process chain. Therefore, industrial qualification should increasingly rely on measurable powder-health indicators, defect-tolerance criteria, and application-specific performance thresholds.

This transition requires stronger integration between powder characterisation, process monitoring, non-destructive evaluation, and mechanical testing. Powder morphology, particle size distribution, oxygen content, flowability, and apparent density remain essential indicators, but they should be interpreted in conjunction with melt-pool signatures, layer-wise monitoring data, computed tomography, metallography, surface-integrity assessment, and fatigue testing. Such integration would allow the development of more robust correlations between powder condition, defect populations, and reliability. In this regard, the process–structure–performance framework proposed in this review provides a

useful conceptual basis for organising future qualification strategies, since it links powder lifecycle evolution to defect formation and final mechanical behaviour.

The review also suggests that powder upcycling and reconditioning should be understood as active lifecycle-engineering strategies rather than auxiliary sustainability measures. Conventional sieving and blending may reduce coarse contamination and partially restore particle size balance, but they cannot fully eliminate oxide films, internal porosity, surface contamination, or subtle chemical changes. More advanced approaches, including plasma re-spheroidisation, ultrasonic atomisation, chemical rejuvenation, controlled drying, and digital feedstock traceability, offer the possibility of extending powder usability while reducing downstream defect formation. Nevertheless, the effectiveness of these strategies must be assessed not only by restored powder morphology or flowability, but also by their ability to preserve fatigue-critical reliability in the final component.

Another important implication concerns standardisation and certification. Current qualification routes remain insufficiently mature for recycled powder use in safety-critical applications. The lack of harmonised acceptance thresholds for oxygen content, morphology evolution, reuse history, defect tolerance, and fatigue performance creates uncertainty for both manufacturers and regulatory bodies. This uncertainty encourages conservative industrial practice, including restrictions on reused powders for critical parts, even when experimental evidence suggests that reuse may be technically feasible under controlled conditions. A reliability-based certification framework would need to define powder acceptance not only by chemical and physical descriptors, but also by demonstrated process stability, defect control, and mechanical performance under representative service conditions.

From an industrial perspective, powder reuse is rarely treated as a purely academic question of how many times a powder can be recycled. In regulated sectors such as aerospace, spaceflight hardware, energy systems, and biomedical manufacturing, reuse policies are commonly embedded within broader qualification systems that control powder traceability, machine qualification, process stability, post-processing, inspection, and part release. In this context, a powder batch is not accepted solely because it has remained below a given number of reuse cycles; rather, it must remain within a validated material–process window that is compatible with the intended component class and service environment.

Industrial practice therefore tends to combine powder-batch management with process qualification and part-level verification. Relevant controls may include powder lot identification, virgin-to-reused powder ratio, sieving route, storage condition, oxygen and moisture exposure, build-chamber atmosphere, recoating behaviour, melt-pool or spatter monitoring, chemical analysis, particle size distribution, flowability, apparent and tap density, morphology assessment, and contamination screening. For higher-criticality applications, these powder-level controls are typically complemented by witness coupons, tensile testing, fatigue-relevant testing where required, metallographic inspection, X-ray computed tomography, surface-integrity assessment, and documentation of post-processing routes such as heat treatment, hot isostatic pressing, machining, or surface finishing.

This industrial perspective reinforces the central argument of the present review: powder recyclability should be implemented as a qualified lifecycle-management strategy rather than as an empirical reuse-cycle rule. Aerospace and spaceflight qualification frameworks place strong emphasis on repeatable processing, material traceability, process control, inspection, and evidence-based release criteria. Consequently, reused powders intended for structural or fatigue-critical applications should be qualified through application-specific acceptance windows that link powder condition to process stability, defect population, surface integrity, and mechanical performance. This approach is more demanding than simple reuse counting, but it is more consistent with the requirements of industrial certification and safety-critical AM production.

The economic implications of powder reuse should also be interpreted through this qualification perspective. Direct powder reuse after sieving is generally the least expensive lifecycle strategy because it reduces the demand for virgin atomised powder and minimises waste disposal. However, the apparent saving can be reduced or even negated when reused powder increases the probability of build failure, component rejection, additional inspection, post-processing, or fatigue-related non-conformance. Consequently, the economic value of reuse depends not only on the number of reuse cycles achieved, but also on powder recovery yield, virgin-powder top-up ratio, testing frequency, defect rate, component criticality, and the cost of demonstrating compliance with application-specific acceptance criteria.

Reconditioning techniques introduce different cost–benefit balances. Low-intensity routes such as sieving, drying, blending with virgin powder, and controlled storage are comparatively inexpensive and may be sufficient when degradation is moderate. More intensive routes, including plasma spheroidisation, chemical rejuvenation, cold-spray-based secondary use, or re-atomisation, require additional energy, equipment, powder handling, and quality-control steps, but may be economically justified for high-value powders such as Ti alloys and Ni superalloys, or when degraded powder would otherwise be discarded. Re-atomisation or full powder remanufacture may offer the highest restoration potential, but it is economically viable only when the recovered material volume, alloy value, contamination level, and expected qualification benefit outweigh the additional processing cost.

Therefore, powder reuse should not be evaluated only in terms of immediate feedstock saving. A more realistic economic assessment should compare the cost of virgin powder replacement with the combined cost of powder characterisation, reconditioning, process monitoring, defect inspection, post-processing, rejected builds, and fatigue-critical qualification. Within this framework, direct reuse is most attractive for non-critical applications and stable powder streams, whereas reconditioning becomes more relevant when it prevents material downgrading, extends the usable life of expensive alloys, or reduces the risk of failure in high-value components.

Despite the progress identified, several limitations remain in the current literature. Many studies rely on different powder handling procedures, reuse definitions, sieving strategies, atmosphere controls, and characterisation methods, which makes direct comparison difficult. The number of reuse cycles is often reported without sufficient detail regarding actual thermal exposure, build duration, powder-bed location, or cumulative processing history. Fatigue data remain comparatively scarce, especially for long-term reuse, complex geometries, surface-finished components, and post-processed parts [48]. Furthermore, many studies focus on specific alloy–machine combinations, limiting the generalisability of the findings to broader industrial environments. These limitations reinforce the need for standardised reporting practices and more systematic multi-variable studies.

Overall, the discussion confirms that powder recyclability in metal AM should be reframed as a reliability-driven engineering problem. Sustainability and cost reduction remain important motivations, but they cannot be separated from structural integrity, defect tolerance, and application-specific performance requirements. The safe reuse of metallic powders depends on understanding how powder degradation propagates through the process chain and how this propagation affects the most critical failure mechanisms. For non-critical components, broader reuse windows may be acceptable, particularly when dimensional and static mechanical requirements are satisfied. For fatigue-critical applications, however, powder reuse must be controlled through stricter monitoring, defect assessment, and performance validation.

Accordingly, the future development of powder recyclability should move towards adaptive lifecycle management, in which powder condition is continuously monitored, degradation mechanisms are quantified, process parameters are adjusted where necessary, and reuse decisions are based on predicted reliability rather than empirical practice. Such an approach would enable metal AM to reconcile circular manufacturing objectives with the stringent reliability demands of high-value engineering applications. By bridging the powder lifecycle, defect evolution [126], and fatigue-critical performance, this review provides a technical foundation for that transition.

7. Conclusions

This study provides a comprehensive and integrated perspective on powder recyclability in metal AM, demonstrating that it must be understood not as a simple reuse practice, but as a process-dependent, defect-mediated, and reliability-critical phenomenon. By synthesising evidence across a broad body of literature, the work consolidates previously fragmented findings into a unified and physically grounded interpretation.

Overall, this review provides an integrated interpretation of powder recyclability in metal additive manufacturing by linking powder lifecycle evolution, process-dependent degradation, defect formation, and reliability-critical performance. To summarise the principal conclusions of the present review, Figure 9 provides an integrated synthesis of the relationships between powder lifecycle evolution, process-dependent degradation pathways, defect formation, performance response, and qualification-oriented implementation in SLM and EBM.

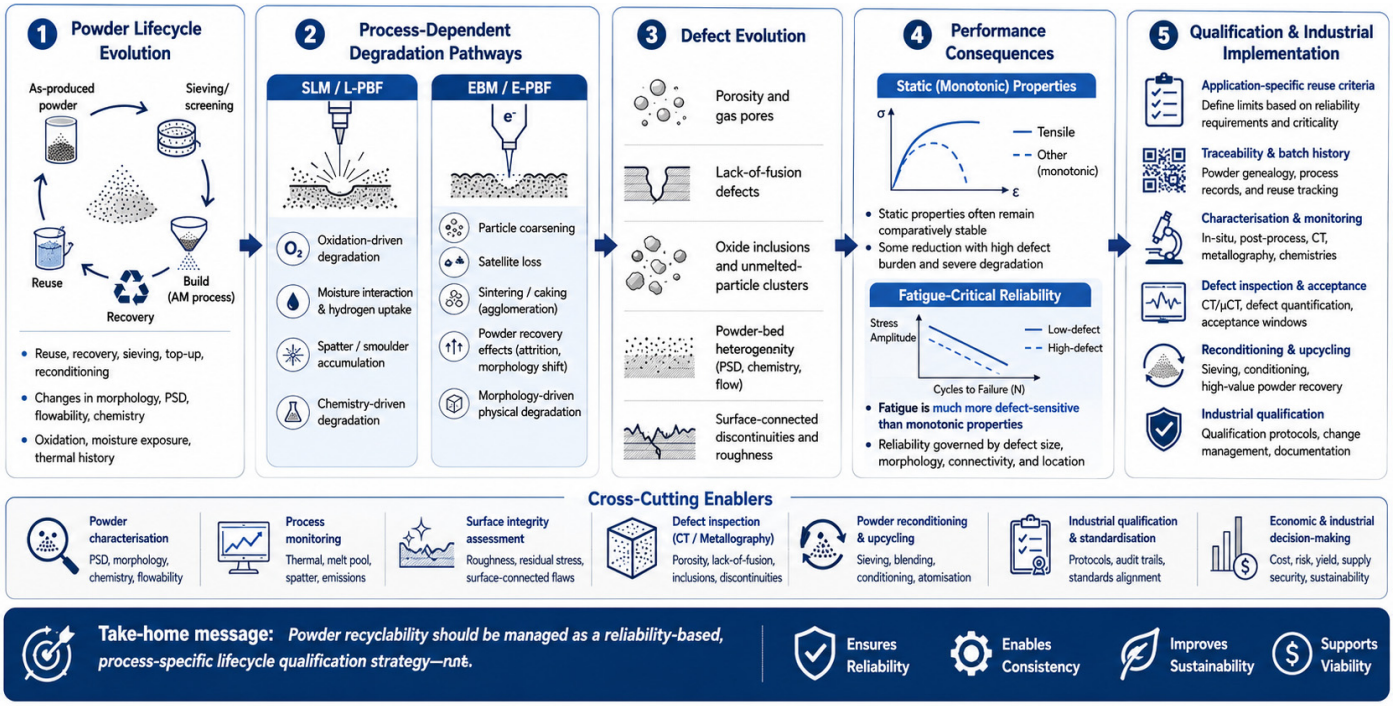


Figure 9. Concluding synthesis of powder recyclability in metal additive manufacturing, illustrating the progression from powder lifecycle evolution to process-dependent degradation, defect formation, performance response, and qualification-oriented industrial implementation in SLM and EBM.

A central conclusion is that powder degradation is inherently process-contingent. Distinct degradation pathways are consistently observed between powder bed fusion technologies, with SLM predominantly affected by chemically driven mechanisms, such as oxidation and moisture interaction, and EBM governed mainly by physical transformations, including particle coarsening and morphological evolution [7–9,19,22,30]. This

distinction highlights that recyclability cannot be generalised across AM processes and must be evaluated within the specific thermo-physical context of each technology.

The study further establishes that the impact of powder reuse propagates through a process–structure–performance chain, where changes in powder characteristics influence melt pool dynamics, microstructural evolution, and ultimately defect formation. Defects, including porosity, lack-of-fusion regions, and oxide inclusions, emerge as the critical intermediaries linking powder degradation to performance loss [8,28,37,44]. This finding shifts the analytical focus from powder properties alone to their downstream structural consequences.

A key contribution of this work is the identification of a fundamental asymmetry between static mechanical properties and fatigue behaviour. While tensile strength and hardness often remain relatively stable across multiple reuse cycles [11,39,46], fatigue performance is significantly more sensitive to defect populations and distributions [12,40,47]. This divergence demonstrates that static properties are insufficient indicators of structural reliability, particularly in fatigue-critical applications, where failure is governed by crack initiation and propagation mechanisms.

Building upon these insights, powder recyclability is redefined as a continuum governed by defect accumulation and performance thresholds, rather than a binary condition. The acceptable extent of powder reuse is therefore application-dependent and must be determined in relation to reliability requirements, especially under cyclic loading conditions [13,43,48]. This represents a shift from material-centric evaluation toward performance- and reliability-driven assessment.

The conceptual framework proposed in this study constitutes a major advancement beyond conventional reviews. By explicitly linking powder lifecycle evolution, degradation mechanisms, process conditions, microstructure, defect formation, and mechanical response, the framework provides a generalisable and transferable structure for interpreting recyclability across different AM systems. This integrative approach enables more consistent comparison of results and supports the development of structured decision-making strategies for industrial implementation.

From a practical perspective, the findings underscore that effective powder reuse strategies must be process-specific and reliability-oriented, incorporating control of environmental conditions, monitoring of powder evolution, and, where necessary, implementation of mitigation strategies. Emerging approaches such as powder upcycling and rejuvenation offer promising pathways to extend powder lifecycles, but their effectiveness depends on the ability to control defect formation and preserve performance.

Overall, this work advances the state of the art by transforming the understanding of powder recyclability from a descriptive and fragmented topic into a coherent, system-level, and engineering-driven framework. By bridging the gap between powder degradation and fatigue-critical performance, it provides a robust foundation for the safe, efficient, and scalable adoption of metal AM technologies in industrial environments where structural reliability is paramount.

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Appendix A

Appendix A.1. Expanded Explanation on the Method of Research

This review was developed through a structured and transparent survey of the literature, guided by the principles of the PRISMA 2020 statement [27,28] to strengthen consistency, traceability, and reproducibility in the identification and selection of sources. Relevant publications were screened and critically assessed according to their technical relevance to powder recyclability, methodological robustness, contribution to process–structure–performance understanding, and suitability for informing reliability-oriented metal AM [29]. Bibliographic records were collected from major scientific databases and indexing platforms, with the search centred on peer-reviewed studies published between 2015 and 2025. The Crossref database was the preferred source for collecting the representativeness of the review corpus. The search strategy combined predefined terms associated with metal powder reuse, powder bed fusion, Selective Laser Melting, Electron Beam Melting, powder degradation, defect formation, mechanical performance, and fatigue-critical reliability. Retrieved records were subsequently filtered through a staged procedure based on abstract relevance, keyword alignment, experimental representativeness, material coverage, and balance between SLM and EBM technologies [129]. This workflow enabled the construction of a technically coherent bibliographic corpus addressing powder morphology, particle size distribution, chemical evolution, flowability, oxidation, moisture interaction, thermal exposure, defect generation, and the mechanical consequences of powder reuse across representative metallic alloy systems.

Appendix A.2. Search Strategy and Information Sources

Building upon the PRISMA-oriented methodological framework outlined above, the literature search strategy was specifically designed to identify studies addressing powder recyclability in metal AM, with particular emphasis on powder lifecycle evolution, reuse-induced degradation mechanisms, defect formation, and fatigue-relevant mechanical performance in powder bed fusion processes. The search was deliberately focused on contributions linking powder condition to processability, microstructural development, structural integrity, and reliability, rather than on broader AM studies where feedstock reuse was only marginally considered. To ensure thematic precision and maximise the technical relevance of the retrieved literature, the search protocol was organised around three complementary conceptual groups of keywords.

The first group addressed metal AM and powder bed fusion processes, including terms such as "*additive manufacturing*", "*metal additive manufacturing*", "*powder bed fusion*", "*laser powder bed fusion*", "*selective laser melting*", "*electron beam melting*", "*SLM*", "*L-PBF*", "*EBM*", and "*E-PBF*". The second group focused on powder reuse and lifecycle degradation, incorporating terms such as "*powder reuse*", "*metal powder recycling*", "*powder recyclability*", "*powder ageing*", "*powder degradation*", "*powder oxidation*", "*particle morphology*", "*particle size*

distribution", "*powder flowability*", and "*powder reconditioning*". The third group concerned defect formation and performance-related criteria, including "*porosity*", "*lack of fusion*", "*oxide inclusions*", "*spatter*", "*microstructure*", "*mechanical properties*", "*fatigue performance*", "*fatigue life*", "*structural integrity*", and "*reliability*".

The Boolean search logic followed the general structure:

("Additive Manufacturing" OR "Metal Additive Manufacturing" OR "Powder Bed Fusion" OR "Laser Powder Bed Fusion" OR "Selective Laser Melting" OR "Electron Beam Melting" OR "SLM" OR "L-PBF" OR "EBM" OR "E-PBF")

AND

("Powder Reuse" OR "Metal Powder Recycling" OR "Powder Recyclability" OR "Powder Ageing" OR "Powder Degradation" OR "Powder Oxidation" OR "Particle Morphology" OR "Particle Size Distribution" OR "Powder Flowability" OR "Powder Reconditioning")

AND

("Porosity" OR "Lack of Fusion" OR "Oxide Inclusions" OR "Spatter" OR "Microstructure" OR "Mechanical Properties" OR "Fatigue Performance" OR "Fatigue Life" OR "Structural Integrity" OR "Reliability").

Search queries were applied to the title, abstract, and keyword fields of the selected databases wherever this option was available. To ensure scientific relevance, technical comparability, and consistency with the scope of the review, the following eligibility criteria were adopted:

- Publication period: 2015–2025;
- Document type: peer-reviewed journal articles, review papers, and selected technically relevant conference contributions;
- Language: English;
- Topical relevance: studies addressing powder reuse, powder degradation, defect formation, processability, mechanical performance, or reliability in metal AM;
- Process scope: primary emphasis on powder bed fusion technologies, particularly SLM/L-PBF and EBM/E-PBF;
- Material scope: representative metallic alloy systems relevant to industrial powder reuse, including Al alloys, stainless steels, Ni superalloys, and Ti alloys.

These criteria were introduced to ensure that the review captured both recent and technically significant developments in powder recyclability for metal AM, particularly where feedstock evolution could be related to downstream defect populations and mechanical response. Publications were excluded when they addressed AM only in general terms, lacked a clear connection to powder reuse or the feedstock lifecycle, or did not provide sufficient technical detail to support comparison across degradation mechanisms, process behaviour, and performance outcomes. This search strategy is consistent with the manuscript's focus on powder recyclability, SLM/EBM comparison, defect evolution, and fatigue-critical reliability.

Appendix A.3. Study Selection and Screening

The identification and selection of relevant studies were undertaken in accordance with the principles of the PRISMA 2020 framework, thereby supporting methodological transparency, traceability, and reproducibility throughout the review process. The bibliographic search was conducted primarily through ScienceDirect, owing to its strong coverage of metal AM, powder bed fusion, feedstock characterisation, and mechanical-performance studies. Complementary searches were also performed in Scopus, Web of Science, and MDPI databases to broaden retrieval coverage and improve the representativeness of the final corpus. The search focused on the peer-reviewed literature published between 2015 and 2025, reflecting the rapid development of powder reuse, process monitoring, fatigue

assessment, and circular manufacturing strategies in metal AM. This approach is consistent with the manuscript's methodological scope, which reports a structured corpus of 120 references and a search centred on powder reuse, SLM, EBM, powder degradation, and fatigue-critical reliability.

Given the broad indexing coverage of the selected databases, the initial search returned a substantial number of records, including publications only tangentially related to AM or powder reuse. To refine the dataset, the search strategy was progressively narrowed from general terms such as "*Additive Manufacturing*" to more specific combinations including "*Powder Reuse*", "*Metal Powder Recycling*", "*Powder Bed Fusion*", "*Selective Laser Melting*", "*Electron Beam Melting*", "*Powder Degradation*", "*Defect Formation*", and "*Fatigue Performance*". Search queries were applied, where possible, to the title, abstract, and keyword fields to prioritise studies with direct relevance to the scope of the review.

To address overlap between databases and improve consistency, retrieved records were consolidated through metadata comparison and manual verification. Duplicate entries, non-relevant records, and publications outside the technical scope of the study were removed prior to detailed screening. The resulting dataset was then subjected to preliminary evaluation based on the title, abstract, and keyword relevance.

Screening and eligibility decisions were undertaken according to predefined inclusion and exclusion criteria established before detailed analysis, with the objective of minimising subjective bias and ensuring methodological consistency. Titles, abstracts, and keywords were examined to assess their relevance to powder recyclability in metal AM, with particular emphasis on powder lifecycle evolution, particle morphology, particle size distribution, chemical composition, oxygen uptake, moisture interaction, flowability, thermal exposure, process stability, defect generation, and mechanical response. Particular attention was given to studies addressing the relationship between feedstock degradation and defects such as porosity, lack-of-fusion regions, oxide inclusions, spatter-induced contamination, melt-pool instability, and fatigue-critical discontinuities.

Publications were excluded when they addressed AM only in broad terms, lacked a clear connection to metal powder reuse, or did not provide sufficient technical detail on feedstock characterisation, powder lifecycle management, defect formation, processability, or mechanical performance. Studies focusing exclusively on polymer AM, non-powder feedstocks, general sustainability assessment without material-process correlation, or static mechanical behaviour without discussion of powder condition were also excluded. A considerable proportion of the discarded literature concerned general AM process optimisation or component production studies in which powder reuse was not treated as a governing variable.

The final stage involved full-text assessment of the remaining studies to determine their methodological robustness, technical relevance, and conceptual coherence with the objectives of the review. Priority was given to studies providing experimentally supported evidence on powder degradation across reuse cycles, comparative analysis between virgin and reused feedstock, process-dependent behaviour in SLM/L-PBF and EBM/E-PBF, and links between powder condition, defect formation, microstructural evolution, and fatigue-sensitive performance. Scientific relevance, technical depth, citation influence, and the balance between material systems and powder bed fusion technologies were also considered to reduce publication-source bias and avoid over-representation of isolated alloy-process combinations.

During the review process, a recurrent challenge concerned the absence of standardised terminology in the literature on powder reuse and recyclability. Closely related concepts are frequently reported using different terms, including "*powder reuse*", "*powder recycling*", "*powder recyclability*", "*powder ageing*", "*feedstock degradation*", "*powder lifecycle*",

and "*powder reconditioning*". Comparable inconsistencies also arise in process nomenclature, where SLM, laser powder bed fusion, L-PBF, Laser Beam Melting, and LPBF are often used interchangeably, while EBM, electron beam powder bed fusion, E-PBF, and PBF-EB/M are similarly applied across different publications. These terminological variations required careful cross-verification of process conditions, powder histories, material systems, and reported performance indicators during classification and synthesis.

The formulation of precise research questions constituted a fundamental element of the systematic review, as it defined the analytical scope and conceptual direction of the study. To ensure internal coherence and close alignment with the objectives of the manuscript, the Population–Intervention–Comparison–Outcome–Context framework was adapted as follows:

- Population: Experimental, computational, and review studies addressing metal AM using powder-based feedstocks, particularly those focused on powder bed fusion technologies and industrially relevant metallic alloys such as Al alloys, stainless steels, Ni superalloys, and Ti alloys.
- Intervention: Powder reuse, recycling, reconditioning, and lifecycle-management strategies applied to metal AM feedstocks, including sieving, blending, powder recovery, moisture control, oxidation mitigation, plasma re-spheroidisation, upcycling, and other approaches intended to preserve or restore powder quality.
- Comparison: Comparative analyses between virgin and reused powders, different reuse-cycle histories, distinct material systems, and process-dependent degradation pathways in SLM/L-PBF and EBM/E-PBF, particularly with respect to morphology, particle size distribution, chemical stability, flowability, processability, defect formation, and mechanical performance.
- Outcomes: Identification of the effects of powder reuse on feedstock quality, process stability, microstructural evolution, defect populations, static mechanical properties, fatigue behaviour, structural integrity, and reliability-critical performance, together with the definition of persistent limitations and future requirements for qualification and certification.
- Context: Peer-reviewed academic publications addressing powder recyclability, powder bed fusion, defect evolution, fatigue-sensitive reliability, and circular manufacturing strategies in metal AM.

Based on this framework, a structured and hierarchically organised set of research questions was established to guide the extraction, critical evaluation, and synthesis of the selected literature. These questions are presented in Table A1.

The present review considered peer-reviewed publications spanning both foundational and contemporary contributions to powder recyclability in metal AM, with particular emphasis on studies addressing metal powder reuse, feedstock degradation, powder lifecycle evolution, processability, defect formation, and mechanical-performance implications. This temporal scope was selected to capture the recent technological development of powder reuse strategies in powder bed fusion processes, particularly with respect to SLM/L-PBF and EBM/E-PBF. Attention was devoted to studies examining particle morphology, particle size distribution, surface chemistry, oxygen uptake, moisture interaction, flowability, apparent density, thermal exposure, powder recovery procedures, and the suitability of reused powders for producing components with reliable structural integrity.

The literature search procedure, as illustrated in Figure A1, was implemented using structured Boolean queries designed to identify studies situated at the intersection of metal AM, powder reuse, feedstock degradation, defect evolution, and reliability-oriented performance assessment. The search strategy therefore incorporated combinations of keywords related to powder-based metal AM, including "*metal additive manufacturing*", "*powder bed*

fusion", "*laser powder bed fusion*", "*selective laser melting*", "*electron beam melting*", "*SLM*", "*L-PBF*", "*EBM*", and "*E-PBF*", together with terms associated with powder lifecycle and reuse, such as "*powder reuse*", "*metal powder recycling*", "*powder recyclability*", "*powder ageing*", "*powder degradation*", "*powder oxidation*", "*particle morphology*", "*particle size distribution*", "*powder flowability*", and "*powder reconditioning*". A third group of terms addressed defect formation, structural integrity, and performance-related considerations, including "*porosity*", "*lack of fusion*", "*oxide inclusions*", "*spatter*", "*microstructure*", "*mechanical properties*", "*fatigue performance*", "*fatigue life*", "*structural reliability*", and "*circular manufacturing*".

Table A1. PICOC RQs.

ID	Research Question
RQ1	What are the principal technical challenges governing the recyclability of metallic powders in powder bed fusion processes, particularly in relation to powder degradation, process stability, defect formation, and reliability-critical performance?
RQ1.1	How do reuse-induced changes in powder morphology, particle size distribution, surface chemistry, oxygen content, moisture uptake, flowability, and apparent density evolve across multiple reuse cycles, and how do these changes affect powder processability?
RQ1.2	Which material-specific characteristics, including alloy reactivity, oxidation susceptibility, thermal stability, particle morphology, and sensitivity to interstitial contamination, exert the greatest influence on the degradation behaviour of reused powders?
RQ2	How do powder lifecycle evolution and process-dependent degradation mechanisms influence defect formation and structural integrity in metal AM?
RQ2.1	To what extent do oxidation, spatter accumulation, particle coarsening, agglomeration, satellite loss, sintering, and powder-bed heterogeneity promote defects such as porosity, lack-of-fusion regions, oxide inclusions, and melt-pool instability?
RQ2.2	How do the degradation pathways observed in SLM/L-PBF differ from those occurring in EBM/E-PBF, and how do these differences affect defect populations, microstructural development, and final component quality?
RQ3	How does the reuse of metallic powders affect the mechanical performance of additively manufactured components, particularly under fatigue-critical loading conditions?
RQ3.1	Why do static mechanical properties, such as tensile strength, yield strength, hardness, and elongation, often remain comparatively stable after powder reuse, whereas fatigue performance may deteriorate significantly?
RQ3.2	Which defect types, defect locations, and microstructural discontinuities are most strongly associated with fatigue-life reduction in components produced from reused powders?
RQ4	How can powder reuse strategies be assessed and controlled within a process–structure–performance framework for reliable metal AM?
RQ4.1	How can powder characterisation, process monitoring, defect analysis, and mechanical testing be integrated to define application-specific powder reuse limits and reliability thresholds?
RQ4.2	What are the principal trade-offs between sustainability, cost reduction, powder lifecycle extension, process repeatability, defect tolerance, and fatigue-critical qualification in industrial powder reuse?
RQ5	What emerging approaches and future research directions can support safer, more sustainable, and reliability-driven powder recyclability in metal AM?
RQ5.1	Which advanced strategies, including powder blending, sieving, drying, reconditioning, plasma re-spheroidisation, upcycling, feedstock digital twins, artificial intelligence, and in situ monitoring, show the greatest potential for improving powder lifecycle management?
RQ5.2	What key knowledge gaps remain regarding standardisation, certification, fatigue databases, process-specific acceptance criteria, and the industrial qualification of reused powders for safety-critical applications?

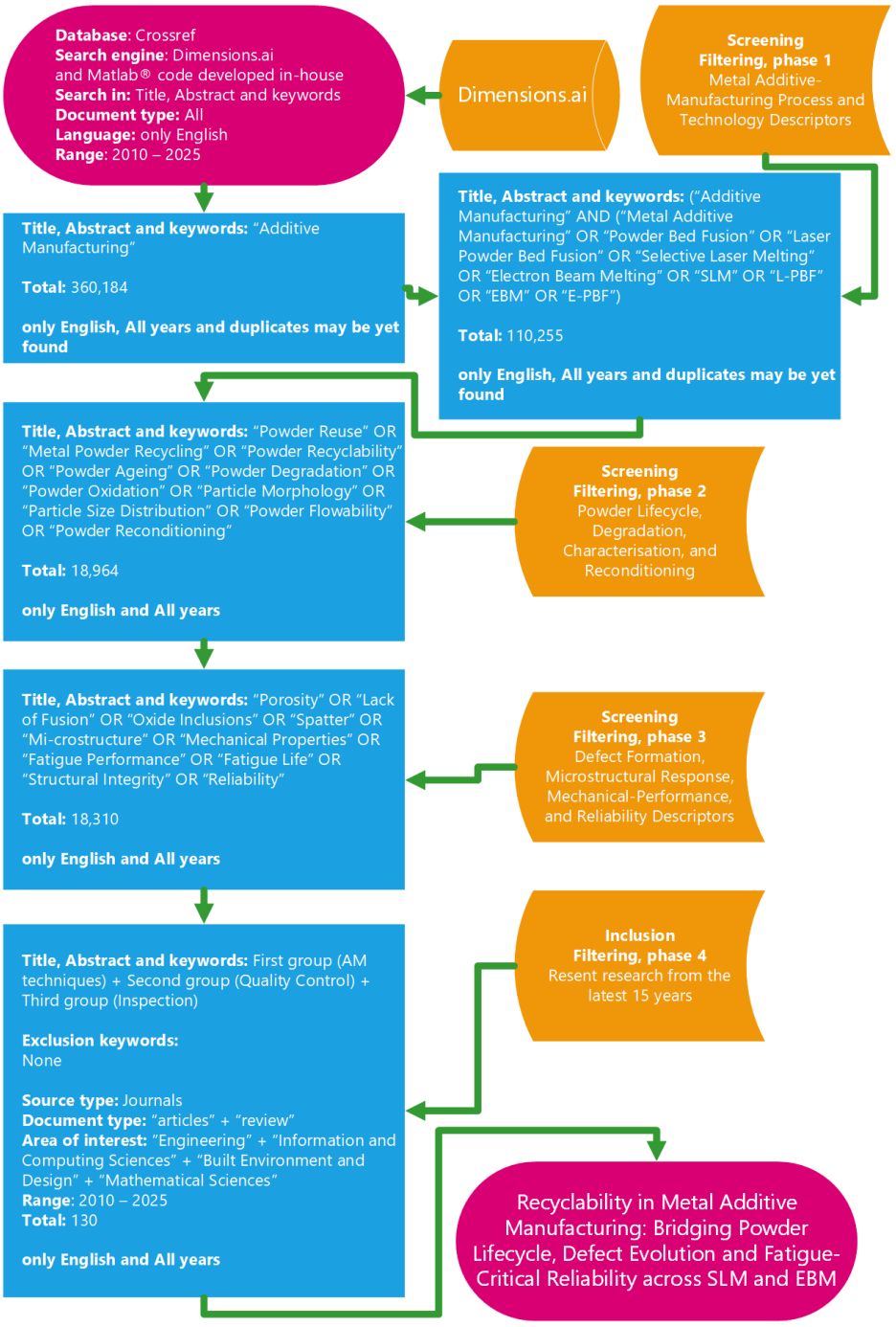


Figure A1. PRISMA-based multi-stage screening and study-selection workflow applied to the literature on powder recyclability in metal AM, with particular emphasis on powder reuse, lifecycle-induced degradation, process-dependent defect formation, fatigue-critical performance, and reliability-oriented qualification across SLM/L-PBF and EBM/E-PBF technologies.

A preliminary search using only the generic term "Additive Manufacturing" retrieved 360,019 records. However, this expression was considered too restrictive, as many relevant studies refer to specific AM routes rather than to the generic term itself. The search was therefore expanded to include process-specific terminology, including metal AM, laser powder bed fusion, Selective Laser Melting, Electron Beam Melting, Directed Energy Deposition, and related expressions. This broader process-domain query retrieved 639,589 records and was used as the initial search set for subsequent filtering.

This structured search strategy enabled the targeted retrieval of scientific contributions directly concerned with powder recyclability in metal AM, particularly studies addressing powder reuse, feedstock lifecycle evolution, degradation mechanisms, defect formation, and performance implications in powder bed fusion processes. It was designed to capture the literature relevant to the characterisation of recycled metallic powders, including particle morphology, particle size distribution, surface chemistry, oxygen uptake, moisture interaction, flowability, and apparent density, as well as the downstream effects of these variables on melt-pool stability, microstructural development, porosity, lack-of-fusion defects, oxide inclusions, and fatigue-critical reliability. In this way, the search protocol supported a technically rigorous assessment of the principal mechanisms, methodological trade-offs, and emerging opportunities associated with reliable powder reuse in SLM/L-PBF and EBM/E-PBF systems.

An examination of the publication records retrieved during the review process indicates a clear increase in scholarly output between 2015 and 2025, as illustrated in Figure A2. This upward trend reflects the growing academic and industrial interest in powder recyclability as a key enabler of cost reduction, material efficiency, sustainability, and circular manufacturing in metal AM. The increase appears particularly pronounced from the late 2010s onwards, coinciding with the broader industrial maturation of powder bed fusion technologies and the rising need to qualify reused feedstock for high-value applications in aerospace, biomedical, energy, and tooling sectors.

Collectively, these developments underscore the growing recognition that powder recyclability cannot be treated solely as a material-saving practice, but must instead be understood as a reliability-driven engineering challenge. Advances in powder characterisation, lifecycle monitoring, defect analysis, fatigue assessment, and process-specific qualification frameworks are increasingly essential for defining safe reuse limits, preserving component integrity, and enabling the industrial adoption of recycled metallic powders in applications where structural reliability and long-term performance are critical.



Figure A2. Annual distribution of publications retrieved from the selected scientific databases addressing powder recyclability in metal AM, illustrating the temporal evolution of research activity related to powder reuse, feedstock degradation, defect formation, process–structure–performance relationships, and reliability-oriented qualification in powder bed fusion technologies.

Appendix A.4. Study Selection and Quality Assessment (QA)

The appraisal of methodological quality constitutes an essential component of any systematic review, since the credibility of the resulting synthesis depends directly on the reliability, transparency, and analytical robustness of the studies included. In the present

investigation, a structured Quality Assessment (QA) procedure was established to evaluate the scientific rigour, reporting clarity, and technical relevance of each selected publication. The assessment strategy was conceived as a multi-dimensional framework capable of capturing not only academic robustness, but also the extent to which each study contributes meaningfully to the understanding of powder recyclability, degradation mechanisms, defect evolution, and reliability-critical performance in metal AM.

The QA framework was organised into four equally weighted domains, each intended to examine a distinct dimension of methodological quality and technical contribution. The criteria were informed by established principles of systematic review design and were applied through a three-level ordinal scoring system, in which **Yes** was assigned a score of **1**, **Partly** a score of **0.5**, and **No** a score of **0**.

The four evaluation domains were defined as follows:

- Research design and conceptual coherence (25%)—assessing the clarity of the study aims; the suitability of the experimental, computational, or review methodology; and the extent to which the investigation is supported by a coherent scientific and technical rationale related to powder reuse, feedstock degradation, process stability, or mechanical performance.
- Definition of powder lifecycle and processing framework (25%)—examining whether the powder condition, material system, AM process, reuse history, powder recovery procedure, sieving or reconditioning strategy, and relevant processing parameters are described with sufficient precision. Particular attention was given to reproducibility-related details, including reuse-cycle number, atmosphere control, oxygen content, particle size distribution, morphology, flowability, build conditions, and post-processing procedures.
- Methodological rigour and analytical transparency (25%)—evaluating the robustness of the experimental, computational, or analytical procedures; the adequacy of powder and part characterisation methods; and the consistency with which data interpretation is conducted and reported. This included consideration of techniques such as SEM, particle size analysis, chemical analysis, flowability testing, density measurement, computed tomography, metallography, tensile testing, fatigue testing, and defect assessment.
- Technological and industrial relevance (25%)—determining the degree to which the findings contribute to the practical understanding of powder recyclability in metal AM, particularly in relation to processability, defect formation, structural integrity, fatigue-critical reliability, sustainability, circular manufacturing, and qualification of reused powders for industrial applications.

To preserve the reliability of the final synthesis, only studies achieving a QA score above a predefined acceptance threshold were retained for detailed analysis, as summarised in Figure A3. The use of this threshold enabled the exclusion of contributions with insufficient methodological clarity, while avoiding the unnecessary removal of studies addressing emerging powder-reconditioning strategies, feedstock digitalisation, in situ monitoring, or reliability-oriented qualification frameworks, where reporting practices may differ across experimental, computational, and application-driven investigations. The QA procedure therefore functioned as a baseline filter for methodological dependability, ensuring a consistent evidential standard while maintaining appropriate breadth in the range of materials, powder bed fusion processes, degradation mechanisms, and performance outcomes represented within the review. This is aligned with the manuscript's focus on powder recyclability across SLM/L-PBF and EBM/E-PBF, with emphasis on powder lifecycle evolution, defect formation, and fatigue-critical reliability.

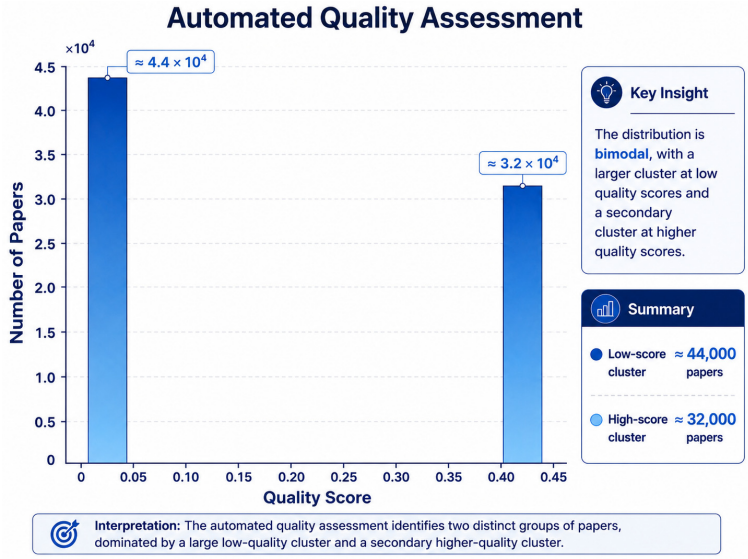


Figure A3. QA outcomes for the publications included in the systematic review on powder recyclability in metal AM, with particular emphasis on powder reuse, feedstock degradation, defect evolution, process–structure–performance relationships, fatigue-critical reliability, and reliability-oriented qualification across SLM/L-PBF and EBM/E-PBF technologies.

Publications achieving scores close to the predefined inclusion threshold were subjected to an additional stage of qualitative appraisal to confirm their technical relevance, methodological integrity, and consistency with the aims of the present review. This supplementary scrutiny ensured that studies within the marginal range nevertheless provided a sufficiently clear description of the powder lifecycle investigated, the metallic alloy system considered, the AM process employed, the reuse or recovery strategy adopted, the powder-characterisation methods applied, and the principal performance-related outcomes reported. As a result, the final corpus consisted exclusively of contributions demonstrating an acceptable standard of methodological soundness, technical relevance, and conceptual alignment with the objectives of the review, particularly in relation to powder reuse, feedstock degradation, processability, defect formation, microstructural evolution, mechanical response, and fatigue-critical reliability in metal AM.

Studies with QA scores within the borderline interval of 50–60% were re-examined through detailed full-text assessment undertaken by the authors. This stage focused on verifying the adequacy with which powder history, reuse-cycle number, material condition, processing atmosphere, powder recovery procedure, sieving or reconditioning strategy, characterisation methods, defect-assessment criteria, and mechanical-performance indicators had been reported. The purpose of this additional assessment was to ensure that only studies offering substantive and technically meaningful insight into powder recyclability were retained within the final analytical synthesis. The identification and selection of relevant publications followed a three-stage screening procedure consistent with the PRISMA 2020 framework, thereby ensuring a transparent and methodologically systematic progression from the initial retrieval of records to the final inclusion of eligible studies. In the first stage, all search results were consolidated into a single dataset, and duplicate records were removed through a combination of metadata comparison, database filtering, and manual verification.

As illustrated in Figure A4, the geographical distribution of authorship and institutional affiliation within the reviewed literature indicates a marked concentration of research activity in countries with established strengths in AM, powder metallurgy, aerospace materials, biomedical manufacturing, and advanced characterisation. The United States of America, China, Germany, the United Kingdom, Italy, and other technologically advanced

manufacturing economies emerge as prominent contributors to the literature on powder reuse, powder bed fusion, feedstock degradation, and reliability-oriented qualification. This distribution reflects the strategic importance of powder recyclability in sectors where material efficiency, process repeatability, structural integrity, and certification readiness are critical, including aerospace, biomedical engineering, energy systems, tooling, and high-value metallic component production.

This geographical pattern is of particular significance because it shows that research on powder recyclability in metal AM is not confined to a narrow set of national research systems. Rather, the field exhibits an increasingly international profile, reflecting the global importance of reducing material waste, extending powder lifecycles, improving process stability, and defining reliable acceptance criteria for reused feedstocks. Collectively, these trends suggest that powder recyclability has evolved from a primarily economic or sustainability-related topic into a strategically important engineering challenge, supported by sustained contributions from both established and emerging centres of expertise in metal AM, powder characterisation, defect analysis, fatigue assessment, and qualification science.

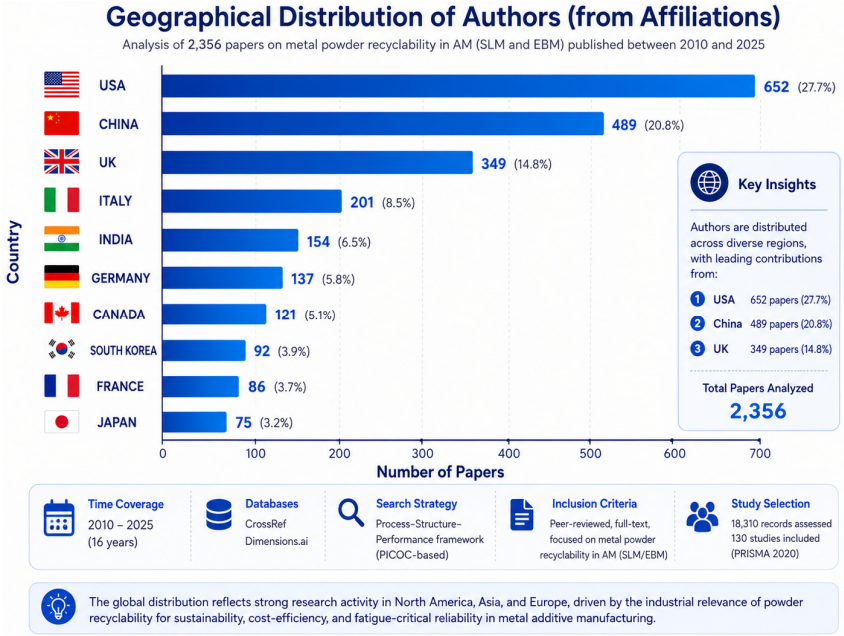


Figure A4. Geographical distribution of authors' institutional affiliations across the publications included in the systematic review on powder recyclability in metal AM, with particular emphasis on powder reuse, feedstock degradation, defect evolution, fatigue-critical reliability, and reliability-oriented qualification in SLM/L-PBF and EBM/E-PBF processes.

Appendix A.5. Descriptive Analysis and Taxonomic Synthesis

The descriptive synthesis of the final body of literature reveals a technically diverse and progressively expanding field of research, characterised by the growing convergence of powder metallurgy, powder bed fusion process science, feedstock lifecycle management, defect analysis, mechanical performance assessment, and reliability-oriented qualification. The selected studies were classified according to their process focus, material system, degradation mechanism, characterisation depth, and relevance to structural integrity, thereby enabling the identification of the principal trajectories along which contemporary research on powder recyclability in metal AM is developing. Overall, the reviewed literature may be understood as converging around two closely related research domains.

1. Powder lifecycle evolution and process-dependent degradation: This domain encompasses investigations concerned with the evolution of metallic powder feedstocks

during repeated reuse cycles in powder bed fusion processes. Particular attention is given to changes in particle morphology, particle size distribution, surface chemistry, oxygen uptake, moisture interaction, apparent density, flowability, and thermal exposure history. Studies within this category examine how reuse-induced degradation differs between SLM/L-PBF and EBM/E-PBF, with SLM being more strongly associated with oxidation, spatter contamination, and moisture-related effects, whereas EBM is more closely linked to particle coarsening, sintering, satellite loss, and morphology changes induced by high-temperature vacuum processing. Research in this area is directed towards improving the understanding of powder ageing, defining reliable reuse limits, and supporting more consistent powder lifecycle management.

2. Defect formation, mechanical performance, and reliability assessment: The second domain concerns the downstream consequences of powder degradation on processability, microstructural development, defect populations, and component performance. This body of work includes studies focused on melt-pool stability, powder-bed packing, porosity formation, lack-of-fusion defects, oxide inclusions, spatter-induced discontinuities, and fatigue-critical crack-initiation sites. Particular emphasis is placed on the distinction between static and cyclic mechanical behaviour, since tensile strength, hardness, and yield strength may remain comparatively stable after powder reuse, whereas fatigue performance is often more sensitive to small variations in defect size, morphology, and spatial distribution. These studies support a transition from powder reuse as a material-efficiency practice towards powder recyclability as a reliability-driven engineering problem.

This classification highlights the inherently multidisciplinary character of current research on powder recyclability in metal AM, in which powder metallurgy, surface chemistry, thermophysical process behaviour, defect mechanics, mechanical testing, sustainability assessment, and qualification science intersect to address the complex relationship between feedstock condition and component reliability. Across the reviewed literature, four principal thematic directions may be distinguished.

1. Powder degradation mechanisms and lifecycle characterisation: A substantial proportion of the literature is devoted to identifying and quantifying the physical and chemical changes that occur during powder reuse. These studies examine oxidation, moisture absorption, spatter accumulation, particle coarsening, satellite loss, agglomeration, surface contamination, particle-size redistribution, and changes in flowability or packing density. Their objective is to clarify how powder condition evolves during repeated exposure to AM processing environments and how these changes affect subsequent manufacturing performance.
2. Process-specific recyclability in SLM/L-PBF and EBM/E-PBF: Another major line of investigation concerns the process-dependent nature of powder degradation. In SLM/L-PBF, the literature frequently emphasises residual oxygen, laser-induced spatter, moisture interaction, and oxide-film formation as critical drivers of powder deterioration. In EBM/E-PBF, the high-vacuum and high-temperature operating environment shifts the dominant mechanisms towards physical evolution, including powder-bed sintering, particle coarsening, mechanical recovery damage, and changes in powder spreadability. This thematic direction demonstrates that powder recyclability cannot be generalised independently of the manufacturing process.
3. Defect evolution, microstructural response, and mechanical reliability: Recent studies increasingly examine how reused powders influence part quality through defect-mediated mechanisms. This includes the formation of porosity, lack-of-fusion regions, oxide inclusions, irregular melt-pool features, and microstructural heterogeneities. Particular attention is given to fatigue performance, since defects originating from de-

graded powder may act as preferential crack-initiation sites even when static mechanical properties remain within acceptable ranges. This body of research is central to understanding the reliability implications of powder reuse in safety-critical applications.

4. Mitigation strategies, upcycling, and qualification frameworks: A further area of development involves powder lifecycle extension through sieving, blending, drying, reconditioning, plasma re-spheroidisation, chemical rejuvenation, ultrasonic atomisation, cold spray routes, digital traceability, and feedstock monitoring. These studies address the transition from passive reuse towards active powder lifecycle engineering, in which powder condition is assessed, restored, or redirected according to process requirements and component criticality. Increasing attention is also devoted to standardisation, certification, and reliability-based qualification, particularly where reused powders are intended for aerospace, biomedical, energy, or other high-value applications.

Across the reviewed studies, several recurrent technical gains are reported, including:

- Improved understanding of powder degradation pathways across reuse cycles;
- Clearer differentiation between SLM/L-PBF and EBM/E-PBF recyclability mechanisms;
- Improved characterisation of powder morphology, chemistry, flowability, and particle-size evolution;
- Stronger links between powder condition, process stability, and defect formation;
- Improved recognition of the fatigue sensitivity of components produced from reused powders;
- Growing development of powder reconditioning, upcycling, and lifecycle-management strategies;
- Increasing movement towards reliability-based qualification rather than arbitrary reuse-cycle limits.

Notwithstanding these advances, the literature also identifies several persistent challenges that continue to limit broader industrial implementation. These include the absence of universally accepted acceptance criteria for recycled powders, inconsistent reporting of powder reuse history, limited availability of long-term fatigue data, insufficient correlation between powder degradation and defect tolerance, and the difficulty of defining process-specific reuse limits across different alloys and AM platforms. Additional constraints arise from the variability in powder characterisation protocols, differences in sieving and recovery practices, inconsistent terminology, and the limited integration of powder monitoring, defect assessment, and mechanical qualification into a unified decision-making framework.

The three-stage screening procedure adopted in the present review, in accordance with the PRISMA 2020 framework, commenced with an initial appraisal of titles, abstracts, and keywords in order to identify publications relevant to powder recyclability, metal AM, powder bed fusion, feedstock degradation, defect evolution, and mechanical reliability. This preliminary screening was followed by detailed full-text assessment designed to verify conformity with the predefined inclusion criteria, with particular emphasis on methodological rigour, technical depth, material-process relevance, and alignment with the objectives of the review.

Only peer-reviewed publications providing sufficient methodological detail and technical relevance were retained for the final analysis. Publications written in languages other than English, grey literature, studies addressing polymer or non-powder-based AM, and contributions lacking a clear connection between powder reuse and process or performance outcomes were excluded. The resulting dataset therefore constitutes a carefully curated and scientifically robust body of literature, providing the evidential foundation for the analytical and interpretative framework developed in the present study.

Appendix A.6. PRISMA 2020 Flow Diagram for New Systematic Reviews, Which Included Searches of Databases and Registers

This appendix provides the detailed PRISMA 2020 flow diagram documenting the identification, screening, eligibility assessment, and final inclusion of studies considered in this systematic review. The diagram strengthens the methodological transparency and reproducibility of the literature selection process, in accordance with the PRISMA 2020 statement and the review strategy adopted in this manuscript. The systematic search was conducted across multiple scientific databases and relevant indexing platforms to identify the peer-reviewed literature addressing powder recyclability in metal AM, with particular emphasis on powder bed fusion technologies, namely SLM and EBM. The search strategy combined predefined keywords related to metal powder reuse, powder lifecycle evolution, degradation mechanisms, defect formation, process–structure–property relationships, and fatigue-critical reliability. Boolean operators and database-specific search fields were applied where appropriate to improve both sensitivity and specificity. The resulting study selection pathway, from initial record identification to final inclusion, is summarised in the PRISMA flowchart presented in Figure A5. This procedure supports the traceability of the review corpus and provides a structured basis for the subsequent technical synthesis.

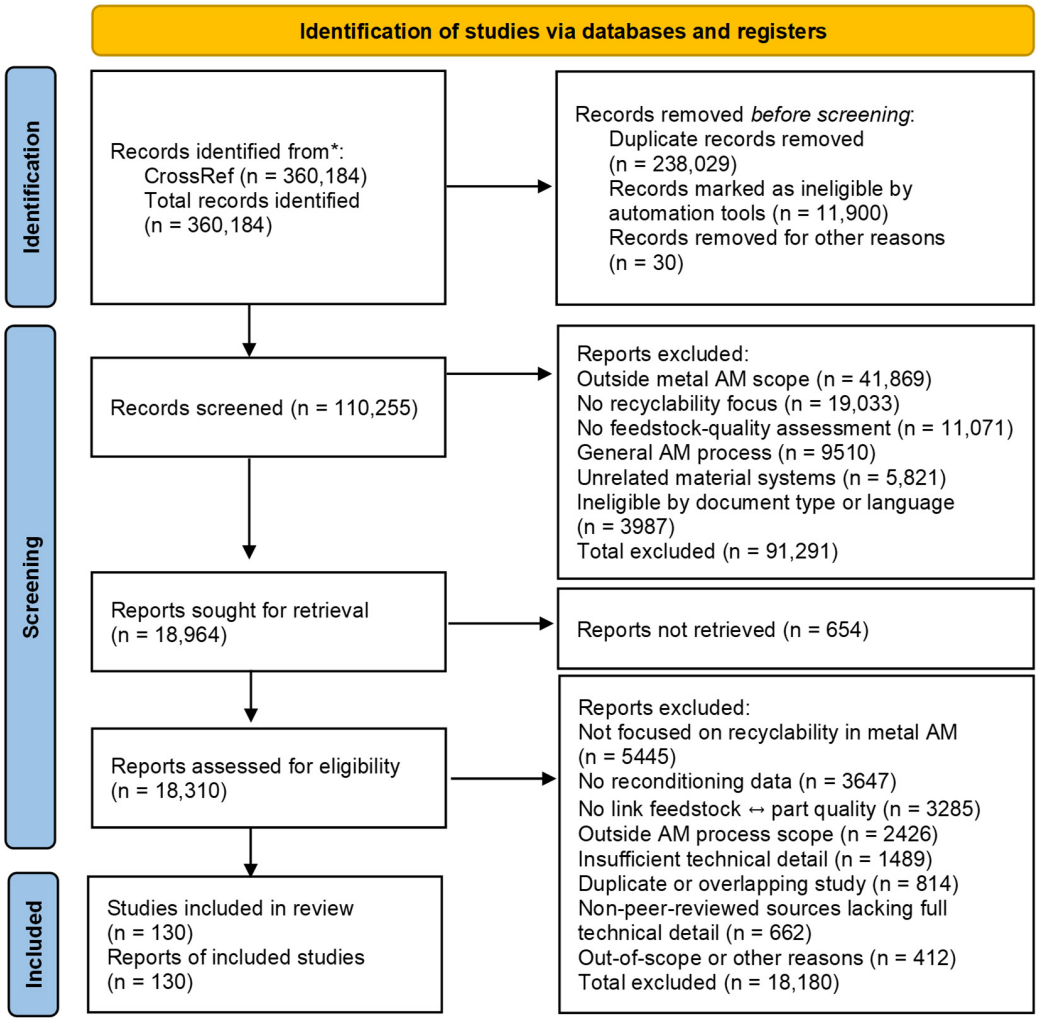


Figure A5. PRISMA 2020 flow diagram illustrating the identification, screening, eligibility assessment, and final inclusion of studies considered in the systematic review on powder recyclability in metal AM. *: highlighting.

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