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COMMENTARY

From Defect Suppression to Programmed Heterogeneity in Additive Manufacturing of High-Performance Alloys

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Abstract

Metal additive manufacturing (AM) has traditionally combined suppression of detrimental manufacturing defects with control of process-induced heterogeneity. Pores, cracks, and lack-of-fusion regions must be distinguished from crystallographic features such as dislocation substructures, whose effects depend on their organization and service conditions. Reliable processing remains essential, but microstructural uniformity should not be the only design objective. Controlled variations in phase constitution, grain structure, dislocation density, precipitation, and local mechanical response can provide useful interactions between mechanically contrasting regions. This commentary proposes a performance-driven framework for programmed heterogeneity that builds on heterostructured materials, functionally graded materials, and site-specific AM processing rather than claiming spatial microstructure control as a new capability. Four propositions are advanced: detrimental manufacturing defects must be distinguished from potentially functional heterogeneity; AM should be used to prescribe microstructural architectures within process-dependent spatial limits; mechanical contrast, characteristic domain size, volume fraction, interface density, connectivity, and spatial arrangement should become measurable design descriptors; and experimentally constrained digital twins and artificial intelligence (AI) should connect target performance to feasible process prescriptions. Descriptor-based design is framed as a constrained optimization problem, not a maximization of heterogeneity. Thermal interactions, manufacturing reproducibility, strain localization, interfacial damage, and fatigue requirements must be considered alongside strength and ductility. The proposed goal is the right heterogeneity, at the right length scale, in the right location, verified against the required function.

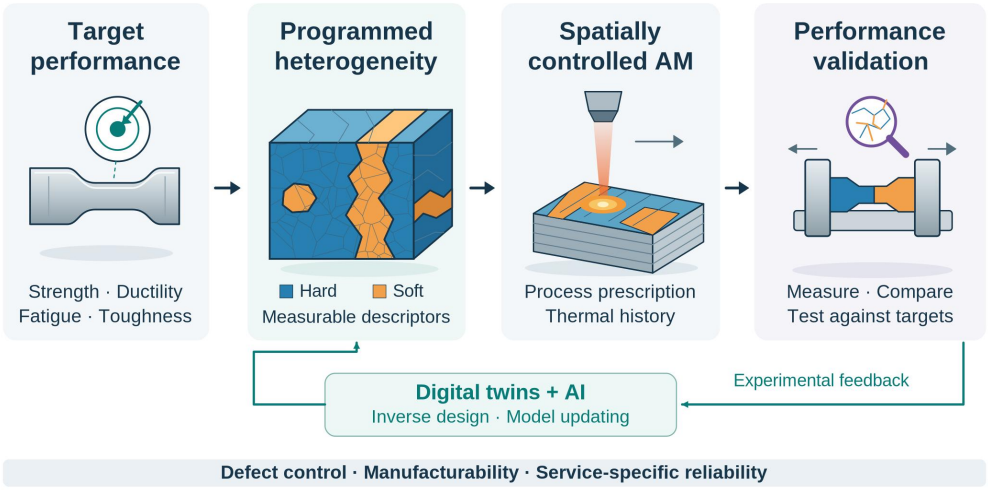
Keywords

Additive manufacturing; Heterostructured materials; Microstructure design; Mechanical heterogeneity; HDI strengthening; Digital twin; Artificial intelligence; High-performance alloys

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Graphical Abstract



NOTE: AM: additive manufacturing. Copyright: Created by the author.

Highlights

- Programmed heterogeneity extends defect-controlled metal additive manufacturing.
- Six measurable descriptors link heterozone architecture to performance targets.
- Thermal coupling limits independent spatial control of microstructures.
- Digital twins and AI can guide feasible, descriptor-based inverse design.
- Strength and ductility gains do not establish improved fatigue resistance.

1. Introduction: Should Heterogeneity Always be Eliminated?

A central objective of metallurgy is reproducible processing and reliable performance. Suppressing porosity, cracks, and lack of fusion remains essential, whereas segregation, residual stress, and microstructural variations require evaluation against the intended service conditions. Here, detrimental manufacturing defects denote process-generated discontinuities that compromise integrity, rather than all crystallographic defects. Dislocation substructures, for example, should be assessed according to their density, arrangement, and interactions rather than classified as intrinsically harmful.

The same logic should not automatically be applied to microstructural heterogeneity. Heterogeneous lamellae, gradient dislocation structures, and related architectures can generate strain partitioning, geometrically necessary dislocations, and hetero-deformation-induced (HDI) hardening, improving combinations of strength and ductility[1-4]. These effects depend on mechanical interactions between regions; heterogeneity alone does not guarantee superior performance[1].

Metal additive manufacturing (AM) provides an especially compelling platform for this concept. Rapid solidification, repeated thermal cycling, steep temperature gradients, localized remelting, and highly concentrated energy input naturally generate cellular segregation, dislocation networks, microstresses, texture gradients, phase variations, and hierarchical microstructures. In laser powder bed fusion (LPBF) 316L stainless steel, for example, the as-built hierarchical microstructure was directly linked to a combination of high strength and sustained work hardening rather than behaving simply as a collection of processing imperfections[3]. The question for next-generation AM metallurgy should therefore evolve from "How can all heterogeneity be removed?" to "Which heterogeneity should be eliminated, which should be retained, and which should be deliberately created?"

Here, programmed heterogeneity denotes the intentional spatial prescription of microstructural architecture, linked to local performance requirements through measurable descriptors and manufacturing constraints. This framework builds on heterostructured materials, functionally graded materials, and site-specific microstructure control[1,5,6]; it does not claim that spatial programming is new. Its proposed contribution is to connect mechanical contrast, characteristic domain size, volume fraction, interface density, connectivity, and spatial arrangement to feasible process prescriptions and service-specific validation. Graded, discrete, and hierarchical architectures can all be considered. Digital twins and artificial intelligence (AI) are enabling tools rather than prerequisites for the definition. Programmed heterogeneity should therefore extend defect-controlled processing, not replace it.

2. Proposition I: Distinguishing Detrimental Manufacturing Defects from Functional Heterogeneity

The first requirement is to distinguish detrimental manufacturing defects from potentially functional microstructural heterogeneity. Pores, hot cracks, and lack-of-fusion regions should be suppressed when they compromise integrity. Embrittling phases and uncontrolled inclusions must likewise be assessed against service requirements. Compositional gradients, cellular structures, grain-size gradients, heterogeneous dislocation densities, precipitate

populations, and phase distributions may instead provide useful interactions, but their benefit must be demonstrated rather than assumed.

This distinction matters because AM process optimization is still frequently framed around a homogeneous target state. Processing windows are identified, density is maximized, residual stress is reduced, and post-processing is used to erase the remaining process signature. Such a strategy is appropriate when process heterogeneity is uncontrolled, but it can also remove features that contribute positively to deformation and damage tolerance.

The central design principle is mechanical coupling between heterozones. Plastic incompatibility generates internal stresses, including back stresses opposing plastic flow in softer domains and forward stresses assisting deformation in harder domains. HDI hardening reflects the additional macroscopic hardening associated with their coupled evolution, rather than back-stress hardening alone[7]. These interactions can produce strengthening and strain hardening beyond simple mixture-rule expectations[1,2]. Detrimental manufacturing defects must remain controlled while potentially beneficial heterogeneity is quantified and validated. The design target is therefore a spatial field of heterogeneity descriptors tailored to local service requirements.

3. Proposition II: Additive Manufacturing is a Microstructure-Architecting Technology

AM offers opportunities for microstructure architecture as well as geometric freedom. Available controls depend on the process: LPBF can vary laser power, scan speed, hatch spacing, and remelting strategy, whereas multi-feed deposition can additionally vary feedstock composition. Cooling rate and thermal history are coupled responses to these inputs, component geometry, and neighboring processing events, rather than independently assignable variables at every location. Geometry and material state can therefore be designed concurrently, but not with unrestricted spatial independence.

Existing demonstrations provide foundations for this framework. Site-specific LPBF has programmed subsequent recrystallization to create contrasting regions within a component[5], while multi-feed deposition has produced compositionally graded alloys[6]. Powder-size selection and phase metastability also offer routes to modifying grain morphology[8,9]. More recently, Tan *et al.* used programmed phase transformations during LPBF of AISI 1080 steel to create alternating martensitic and bainitic layers[10]. Their model for evaluating a minimum layer thickness for property contrast links architecture design to a process-dependent length-scale constraint. These results establish practical precedents, not universal design limits.

Spatial programming resolution must be distinguished from microstructural feature size. Fine cells or precipitates may form without being independently addressable as separate programmed regions. Melt-pool overlap, heat diffusion, remelting, subsequent thermal cycles, and compositional dilution couple neighboring locations and can modify previously formed structures[5,6]. The achievable resolution should therefore be evaluated from the final distribution of material states after the complete build and relevant post-processing, not inferred from laser spot size or layer thickness alone. Quantifying the deviation between prescribed and realized heterozone dimensions and transition widths is a necessary validation step. The minimum maintainable contrast and domain size will depend on the alloy, processing route, and transformation kinetics.

4. Proposition III: Mechanical Contrast and Length Scale should become Design Variables

Mechanical contrast should be quantified under specified temperature, strain-rate, and loading-direction conditions. For a two-domain architecture, a useful starting descriptor is

$$C_y = \frac{\sigma_{y,h} - \sigma_{y,s}}{\sigma_{y,s}}$$

where $\sigma_{y,h}$ and $\sigma_{y,s}$ are reference yield strengths of the harder and softer domains. These may be estimated from representative reference materials or calibrated local mechanical measurements; indentation hardness should not automatically be equated with tensile yield strength. This initial contrast does not replace the constituent flow curves, because hardening and phase evolution can change the mechanical contrast during deformation.

Length scale is equally important, but mechanical coupling does not require every constituent to form a connected network. Gu *et al.* demonstrated pronounced HDI hardening in multimodal Ti containing individual micro-grains surrounded and constrained by ultrafine grains[11]. Isolated domains can therefore interact mechanically through a contrasting matrix. Connectivity should be treated as an architecture-dependent descriptor, not a universal prerequisite. Domain size, spacing, and arrangement should be evaluated together with the constraints imposed by neighboring regions[2,4,11].

The six descriptors can be operationalized as follows: mechanical contrast by C_y and constituent flow curves; characteristic domain size by heterozone thickness or equivalent diameter; volume fraction by the fraction of each defined domain type; interface density by heterozone interfacial area per unit volume, $S_v = A_{int}/V$; connectivity by three-dimensional connected-cluster measures and directional percolation; and spatial arrangement by domain spacing, orientation, and position relative to loading and component geometry. Heterozone size is not necessarily grain size, and S_v refers to interfaces between the defined heterozones, not all grain boundaries. These descriptors are coupled and do not constitute an exhaustive description. AM-induced heterogeneity already spans nanoscale segregation and precipitates, submicrometre cellular structures, micrometre grains, melt-pool-scale features, and millimetre-scale compositional gradients[3,12,13].

Gao *et al.* reported yield strengths of 322 MPa and 440 MPa for recrystallized and non-recrystallized SS316L reference microstructures and compared layered architectures with similar constituent fractions but different layer thicknesses and interface counts[5]. These are reference-specimen properties, not direct measurements of local yield stress within a heterogeneous specimen. Such comparisons illustrate how contrast and architecture can inform mechanical modeling. A practical optimization route is to calibrate constituent responses, evaluate candidate descriptor combinations using micromechanical models, and validate selected architectures against strength, ductility, and damage constraints. No universal optimal contrast or domain size is implied.

5. Proposition IV: From Empirical Heterogeneity to Digitally Prescribed Heterogeneity

Programmed heterogeneity creates a coupled design space involving composition, thermal history, grain structure, dislocation density, phase fraction, and precipitate state. Operando characterization, physics-based digital twins, and artificial intelligence (AI) should connect selected, measurable descriptors

to feasible process prescriptions rather than assume independent control of every material-state variable.

First, operando measurements can constrain process-history models and test proposed formation mechanisms. Synchrotron observations of crystal rotation and stray-grain formation during laser processing illustrate this capability[14]. Such observations should be combined with controlled processing changes and mechanistic analysis; observing temporal coincidence alone does not establish causality. In-process sensing and post-build characterization should be treated as complementary sources of information.

Second, a materials digital twin should connect process inputs to thermal history, microstructural evolution, and mechanical response, rather than only estimating porosity or cracking probabilities[15]. Its state description should distinguish dislocation substructures from detrimental manufacturing defects. For LPBF, an initial implementation could map laser power, scan speed, hatch spacing, and remelting strategy to selected quantities such as recrystallized fraction and heterozone size. Post-build heat treatment must be included when it determines the final architecture. This mapping requires experimental calibration and uncertainty estimates.

Third, a calibrated mechanical model would relate candidate descriptor fields to component response, including interactions between neighboring regions. An uncertainty-aware surrogate could accelerate the search for process prescriptions that meet target properties while satisfying manufacturing and damage constraints. Pareto active learning in LPBF Ti-6Al-4V provides a precedent for iterative process and heat-treatment optimization[16], and AI-assisted testing supports this broader direction[17]. Neither example is treated here as proof of a complete spatial heterogeneity-control loop.

Candidate builds should then be evaluated using in-process measurements, spatially resolved microstructural characterization, and mechanical testing. For a recrystallization-based architecture, thermal observations could constrain the process model, while post-build orientation mapping and mechanical measurements would test the predicted domain distribution and response. Discrepancies would update the model, and active learning would select subsequent experiments. The proposed sequence is therefore performance target, descriptor-based architecture, constrained process prescription, fabrication, validation, and model updating. **Figure 1** separates this forward process-structure-performance chain from inverse design and experimental feedback. The illustrated performance metrics are validation targets, not guaranteed benefits.

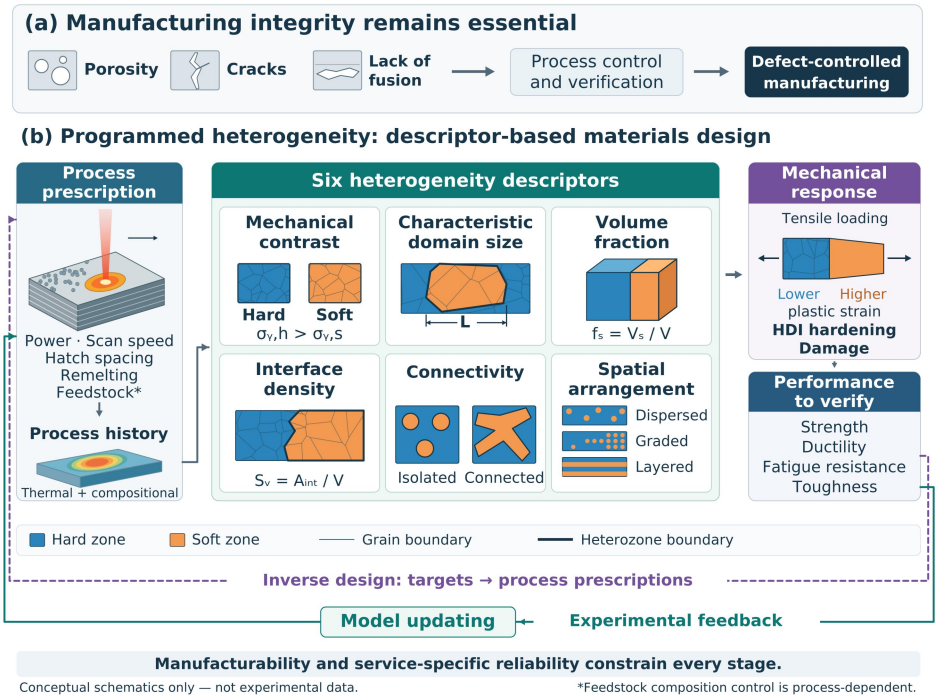


Figure 1. Descriptor-based design of programmed heterogeneity within a defect-controlled manufacturing envelope. (a) Manufacturing integrity remains a prerequisite: porosity, cracking, and lack of fusion are controlled rather than reclassified as beneficial heterogeneity; (b) Process prescriptions and the resulting thermal and compositional histories are linked to six heterogeneity descriptors, mechanical response, and performance verification. The descriptors are mechanical contrast, characteristic domain size, volume fraction, interface density, connectivity, and spatial arrangement. Blue and orange distinguish hard and soft heterozones, respectively; thin and thick lines distinguish grain boundaries from heterozone boundaries. These architectures influence strain partitioning, HDI hardening, and damage, which together determine component performance. The forward pathway is complemented by inverse design and experimental feedback for model updating. Strength, ductility, fatigue resistance, and toughness are evaluation criteria, not universally improved outcomes. Manufacturability and service-specific reliability constrain every stage. All illustrations are conceptual schematics and do not represent experimental micrographs or measured data. **NOTE:** HDI: hetero-deformation-induced. Copyright: Original AI-assisted SVG illustration prepared for this Commentary. The final artwork was exported using CairoSVG 2.8.2 (Python 3.13.5). No third-party micrographs or measured data were reproduced.

6. Outlook and Suggestions: The Right Heterogeneity at the Right Location

Reliability remains a constraint throughout heterostructure design, not a separate stage that can be considered complete before optimization. Suppression of detrimental manufacturing defects must accompany spatial programming. Excessive mechanical contrast, abrupt transitions, unfavorable domain arrangements, or local tensile residual stresses may promote strain localization, interfacial damage, and fatigue-crack initiation. These risks should be evaluated for the

intended loading mode and environment rather than inferred from microstructural contrast alone.

A strength-ductility improvement under monotonic loading should not be taken as evidence of improved fatigue performance. Candidate architectures should be assessed for cyclic strain localization, damage initiation, and reproducibility, using comparisons that account for porosity, surface condition, and residual stress. The optimization objective should therefore balance beneficial mechanical coupling against service-specific damage susceptibility. Multi-objective selection can identify acceptable trade-offs, but targeted validation remains necessary. A prescribed architecture is successful only when the realized material state and its performance satisfy the stated requirements.

Metal AM offers an opportunity to co-design shape and microstructural architecture. The next advance should be deliberate rather than accidental: neither maximum uniformity nor maximum heterogeneity is the objective. The goal is the right heterogeneity, at the right length scale, in the right location, verified against the required function. Programmed heterogeneity should extend reliable manufacturing through constrained, measurable, and experimentally validated materials design.

Author Contributions

Hyoung Seop Kim: conceptualization; writing - original draft; writing - review & editing.

Data Availability

No new experimental or computational datasets were generated for this Commentary.

Conflicts of Interest

The author declares no competing interests.

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Ethics Approval

Not applicable.

Artificial Intelligence (AI) Statements

Generative AI was used to assist with language refinement and programmatic preparation of the conceptual illustration in **Figure 1**. The author is responsible for reviewing all AI-assisted content and for the accuracy, originality, and conclusions of the manuscript. No AI-generated experimental or computational results are presented.

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