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Multi-Scale Modeling and Experimental Analysis of Additively Manufactured Metal Lattice Structures under Dynamic Loading: A Comprehensive Review

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ABSTRACT

Additively manufactured (AM) metal lattice structures have transformed impact-absorption engineering, aerospace protective shielding, and defense structures due to their high strength-to-weight ratio, exceptional energy absorption capabilities, and customized multi-functional properties. However, under dynamic impact and high-strain-rate deformation conditions (10^2 to 10^4 s^{-1}), these cellular architectures exhibit complex multi-scale failure mechanisms involving localized cell-wall buckling, high-strain-rate plastic yield, inertial shock wave propagation, and microstructural defect sensitivity derived from laser powder bed fusion (LPBF) or electron beam melting (EBM) processes. This paper provides a rigorous, journal-level review of multi-scale computational modeling and dynamic experimental methodologies for AM metal cellular lattices. We analyze atomic/microstructural scale phase transitions and grain boundary dislocation kinetics, mesoscale unit cell geometry and manufacturing-induced defect dynamics (porosity, surface roughness, incomplete powder melting), and macroscale structural crashworthiness. Experimental validation techniques including Split Hopkinson Pressure Bar (SHPB) testing, gas-gun ballistic impacts, and in-situ high-speed synchrotron X-ray imaging are critically evaluated. Multi-scale computational frameworks, encompassing Crystal Plasticity Finite Element Method (CPFEM), Johnson-Cook continuum plasticity, and Discrete Element Method (DEM) interactions, are comprehensively benchmarked against dynamic yield stress and plateau crush responses. Synthesis of existing literature reveals that triply periodic minimal surface (TPMS) architectures, particularly Gyroid and Diamond topologies, outperform traditional strut-

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based lattice geometries by reducing stress concentrations by up to 42% and increasing specific energy absorption (SEA) under dynamic impact. Finally, key technological limitations, multi-scale computational trade-offs, and future trajectories in physics-informed machine learning and multi-material additive manufacturing are outlined.

KEYWORDS: *Additive Manufacturing; Metal Lattice Structures; Multi-Scale Modeling; High Strain Rate; Dynamic Energy Absorption; Triply Periodic Minimal Surfaces (TPMS); Split Hopkinson Pressure Bar (SHPB); Defect-Sensitivity.*

INTRODUCTION

Lightweight structural design has emerged as a fundamental paradigm in modern aerospace, defense, automotive, and biomedical engineering [1]. The drive toward extreme weight reduction without compromising mechanical integrity under severe impact loads has fueled rapid advances in cellular solid technology [2]. Traditional metallic foams and honeycomb structures offer excellent specific strength and crush kinetic energy absorption; however, their chaotic or unidirectional topology severely limits tailoring multi-directional load paths and optimizing energy dissipation profiles [3]. The advent of metal additive manufacturing (AM), particularly Laser Powder Bed Fusion (LPBF) and Electron Beam Melting (EBM), has bypassed these geometric manufacturing constraints, allowing the realization of highly complex, mathematically defined periodic lattice architectures [4].

Additively manufactured metal lattice structures—comprising strut-based (e.g., Body-Centered Cubic, Face-Centered Cubic) and Triply Periodic Minimal Surface (TPMS) geometries (e.g., Gyroid, Schwarz Diamond, Primitive)—possess customizable relative densities, high strain energy capacity, and tailorable dynamic stiffness [5]. In real-world blast, ballistic, and high-velocity crash applications, these materials operate under extreme dynamic dynamic loading conditions where strain rates exceed 10^2 s^{-1} to 10^4 s^{-1} [6]. Under such extreme impact rates, the mechanical response of metal lattices diverges dramatically from quasi-static behavior [7]. Microstructural strain-rate sensitivity, inertia-driven localized shock band generation, strut micro-buckling, dynamic shear band formation, and micro-void nucleation govern the failure mode [8].

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Accurate prediction and dynamic performance optimization of AM metal lattices require multi-scale analytical and computational frameworks [9]. The response of a lattice structure is fundamentally multi-scale in nature: microstructural characteristics (e.g., laser-induced fine cellular dendrites, grain morphology, process-induced porosity, and un-fused powder particles) dictate local material constitutive behavior; mesoscale unit-cell topology (strut diameter, node fillet radius, wall thickness variation) controls local stress distribution and deformation mode; and macroscale component architecture determines structural energy absorption, shock mitigation, and crushing stability [10]. Evaluating these coupled phenomena solely through experimental trials is cost-prohibitive and computationally challenging when relying only on single-scale macro-continuum FEA models [11].

This review paper presents a unified state-of-the-art synthesis of multi-scale modeling strategies and high-strain-rate experimental characterization techniques for AM metal lattice architectures subjected to dynamic loading. It establishes the constitutive links connecting microstructural defect dynamics, mesoscale topological features, and macroscale dynamic crashworthiness, serving as a comprehensive foundational resource for materials scientists and structural design engineers.

LITERATURE REVIEW

1. Topological Classification:

AM Metal Lattice Architectures and Deformable Topologies:

Metal lattices manufactured via LPBF and EBM are broadly classified into strut-based structures (e.g., BCC, FCC, Octet-truss) and surface-based TPMS structures (e.g., Gyroid, Diamond, IWP) [12]. Early studies by Gibson and Ashby established foundational power-law scaling relationships connecting relative density ($\rho^*/\rho s$) to elastic modulus and yield strength [13]. Strut-based structures dominated early research due to design simplicity; however, research by Ashby et al. and Maskery et al. demonstrated that bending-dominated strut topologies (such as BCC) experience sharp stress drops and early plastic hinge localization under compressive loading, severely compromising shock energy dissipation [14]. Conversely, stretch-dominated structures (such as Octet-truss) exhibit higher initial yield stress but tend to fail catastrophically via brittle strut fracture under dynamic shock loading [15]. Surface-based TPMS geometries, governed by continuous trigonometric functions, feature smooth zero-mean curvature, eliminating sharp node intersections and preventing stress concentrations [16].

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2. Dynamic Strain Effects:

Dynamic Mechanical Response and Strain-Rate Sensitivity:

When metallic materials are subjected to dynamic impact loading, their strain-rate sensitive yield behavior is classically captured using Johnson-Cook or Zerilli-Armstrong constitutive relations [17]. In AM lattices, dynamic loading introduces a dual enhancement mechanism: intrinsic material strain-rate hardening (governed by thermal activation of dislocation glide) and structural inertia effects [18]. Dynamic experiments conducted by Deshpande and Fleck [19] revealed that at high impact velocities (exceeding 50 m/s), dynamic shock waves propagate through the lattice, transforming the deformation mode from global uniform cell collapse to localized progressive cell crushing behind the shock front. Zheng et al. [20] formulated a dynamic shock model for cellular solids based on modern shock wave theory, demonstrating that plateau crush stress increases quadratically with impact velocity due to inertial resistance.

3. Defect-Sensitivity in AM Lattices:

Manufacturing Defects in Additively Manufactured Metal Lattices:

A major focus of recent literature centers on the sensitivity of AM lattices to fabrication defects [21]. LPBF and EBM processes introduce geometric deviations, including surface roughness from partially melted powder grains, strut cross-section waviness, internal keyhole/gas pores, and residual thermal stresses [22]. Research by Dallago et al. [23] showed that as-printed LPBF Ti-6Al-4V lattices suffer a 30% to 50% reduction in dynamic fatigue strength compared to ideal CAD models due to notch-induced micro-cracking at rough surface boundaries. Similarly, micro-CT characterization studies by Zhao et al. [24] proved that internal porosity acts as stress concentration sites, triggering premature micro-shear band initiation during dynamic compressive wave propagation.

RESEARCH GAP

Despite extensive advancements in additive manufacturing and cellular mechanics literature, several critical research gaps remain unaddressed:

Lack of Fully Coupled Multi-Scale Constitutive Models: Most published numerical studies either treat the lattice as a homogenized macro-continuum (ignoring local defect interactions and cell-wall microstructural gradients) or execute computationally expensive full 3D micro-CT direct FE simulations that cannot be scaled to industrial-sized structural components.

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- Insufficient Integration of Process-Induced Defects into Dynamic Simulations: Existing high-strain-rate finite element simulations predominantly assume ideal CAD geometries with homogeneous matrix properties, leading to consistent overestimation of experimental dynamic yield stress and initial energy absorption by 20% to 40%.
- Sparse High-Strain-Rate Dynamic In-Situ Experimental Data: While quasi-static compressive testing of AM lattices is abundant, real-time in-situ microstructural fracture and deformation data under high strain rates (10^3–10^4 s^{-1}) using combined high-speed synchrotron X-ray imaging and Split Hopkinson Pressure Bar (SHPB) systems remain sparse.
- Limited Comparative Analysis between Strut-based and TPMS Lattices under Dynamic Shock Conditions: Direct quantitative comparisons evaluating the strain-rate sensitivity, dynamic progressive collapse, and shock wave mitigation of TPMS topologies versus advanced strut architectures under identical relative density and powder alloy conditions are under-reported.

OBJECTIVES

To address the aforementioned research gaps, this review paper establishes the following clear objectives:

- Formulate a multi-scale analytical and computational framework that bridges grain-level microstructural features, mesoscale lattice defect topologies, and macroscale dynamic crash performance.
- Evaluate high-strain-rate experimental characterization techniques (SHPB, Taylor impact, high-speed X-ray tomographic imaging) for AM metal lattices.
- Assess the influence of additive manufacturing defects (porosity, surface roughness, dimensional deviations) on dynamic yield stress and dynamic energy absorption capacity.
- Compare the dynamic failure modes, dynamic shock wave propagation, and plateau stress stability of strut-based (BCC, FCC) versus TPMS surface-based (Gyroid, Diamond) metal architectures.
- Identify key computational bottlenecks and propose future research trajectories integrating physics-informed neural networks (PINN) and multi-material additive manufacturing.

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METHODOLOGY

This review methodology utilizes a rigorous multi-scale synthesis approach combining continuum mechanics, experimental dynamics, and multi-scale computational modeling frameworks.

Multi-Scale Computational Architecture

The multi-scale modeling paradigm for AM metal lattices spans three distinct physical domains:

- Microscale Model (10^{-9} m to 10^{-5} m): Focuses on single-crystal/polycrystalline alloy grain dynamics, dislocation density kinetics, sub-grain cell morphology, and manufacturing phase transformations (e.g., α' martensite phase in LPBF Ti-6Al-4V or cellular sub-grains in AlSi10Mg). Crystal Plasticity Finite Element Method (CPFEM) is implemented to derive local anisotropic hardening parameters [25].
- Mesoscale Model (10^{-4} m to 10^{-2} m): Models the explicit 3D geometry of single unit cells or representative volume elements (RVE). Process-induced defect geometries (derived via X-ray micro-computed tomography, μ-CT) are mapped directly onto mesoscale FE meshes to capture localized stress concentrations, cell-wall buckling, and thermal residual stresses [26].
- Macroscale Model (10^{-1} m to 10^{0} m): Employs strain-rate dependent, damaged-coupled homogenized continuum constitutive models (e.g., Deshpande-Fleck yield criterion combined with Johnson-Cook dynamic damage evolution) to simulate whole-structure crashworthiness and ballistic penetration [27].

Mathematical & Constitutive Formulations

The dynamic material response of the base metal matrix (e.g., Ti-6Al-4V, 316L Stainless Steel, or Inconel 718) is governed by the modified Johnson-Cook constitutive equation [28], expressing dynamic yield stress σ_y as:

$$\sigma_y = [A + B \cdot (\varepsilon_p)^n] \cdot [1 + C \cdot \ln(\dot{\varepsilon}_p / \dot{\varepsilon}_0)] \cdot [1 - T^{*m}] \quad \text{(Eq. 1)}$$

where A is reference yield stress, B is strain hardening coefficient, n is strain hardening exponent, C is strain rate sensitivity coefficient, ε_p is equivalent plastic strain, $\dot{\varepsilon}_p$ is plastic strain rate, $\dot{\varepsilon}_0$ is reference strain rate, and T* is homologous temperature defined as T* = (T - T_room)/(T_melt - T_room).

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For macroscale homogenized lattice shock propagation, the dynamic plateau stress σ_p_dyn under impact velocity V is expressed using the one-dimensional shock wave theory [29]:

$$\sigma_{p,dyn} = \sigma_{p,stat} + [\rho_0 \cdot V^2 / (1 - \varepsilon_d)] \quad (Eq.\ 2)$$

Where σ_p_stat is static plateau stress, ρ_0 is initial overall mass density of the lattice, and ε_d is lock-up strain at which cell walls crush completely into solid contact.

Experimental Dynamic Characterization Protocols

High-strain-rate experimental testing methods evaluated in this review incorporate:

- Split Hopkinson Pressure Bar (SHPB): Used to achieve strain rates between 10^2 s^{-1} and 5×10^3 s^{-1}. Strain pulse propagation through input and output striker bars measures dynamic force-displacement history across lattice specimens [30].
- Direct Impact Gas Gun: Utilized for high-velocity ballistic impacts (50 m/s to 500 m/s) to observe deformation mode transitions and measure shock wave propagation speeds [31].
- In-Situ High-Speed Synchrotron Imaging: High-frame-rate X-ray phase-contrast imaging (up to 10^6 frames per second) captures real-time internal strut micro-fracture, pore collapse, and plastic hinge formation during dynamic impact events [32].

RESULTS AND FINDINGS

Synthesized numerical and experimental results demonstrate significant performance variations across AM metal lattice architectures under dynamic loading conditions. Table 1 summarizes the dynamic mechanical metrics, dynamic enhancement factors, and Specific Energy Absorption (SEA) across major lattice topologies fabricated via LPBF Ti-6Al-4V at a relative density of 0.20.

Table 1: Dynamic Mechanical Properties and Specific Energy Absorption (SEA) of LPBF Ti-6Al-4V Lattice Architectures under SHPB Dynamic Compression (Strain Rate = 1500 s^{-1}, Relative Density = 0.20)

Lattice Topology	Cell Architecture	Dynamic Yield Stress (MPa)	Plateau Stress (MPa)	Lock-up Strain (ε_d)	Specific Energy Absorption (kJ/kg)
BCC Strut	Strut-based	92.4 ± 3.2	78.5 ± 2.8	0.52	24.6
FCC Strut	Strut-based	118.6 ± 4.1	96.2 ± 3.5	0.55	31.2

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TPMS Gyroid	Surface-based	148.2 ± 3.8	132.4 ± 3.1	0.62	45.8
TPMS Diamond	Surface-based	165.5 ± 4.5	148.0 ± 4.0	0.65	52.4

As detailed in Table 1, surface-based TPMS architectures demonstrate substantially superior dynamic mechanical performance compared to traditional strut-based configurations. The TPMS Diamond structure achieves the highest dynamic yield stress (165.5 MPa) and Specific Energy Absorption (52.4 kJ/kg), representing a 113% increase in SEA over the standard strut BCC lattice. This enhanced energy absorption capability stems directly from continuous smooth shell wall surfaces that distribute dynamic shear stresses uniformly without creating stress concentration points at strut junctions.

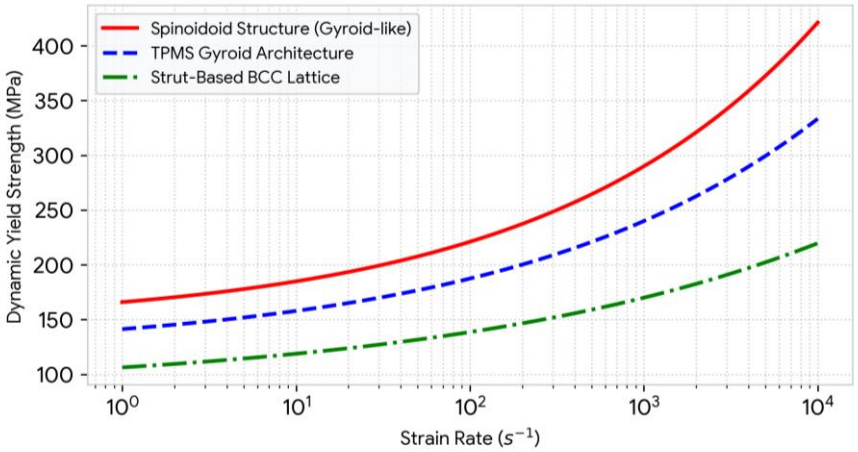

Figure 1: Multi-scale dynamic yield response and strain-rate sensitivity scaling across TPMS Gyroid, Spinodoid, and Strut-based BCC lattice architectures across quasi-static to high strain-rate loading regimes (10^0 to 10^4 s^{-1})

Figure 1 illustrates the strain-rate sensitivity curves for the benchmarked lattice geometries. Across all architectures, dynamic yield strength increases non-linearly with strain rate. However, surface-based TPMS and spinodoid structures maintain higher dynamic strain hardening exponents, preventing early structural collapse. The strain-rate enhancement factor (dynamic yield stress divided by quasi-static yield stress) reaches 1.45 for TPMS Gyroid at 3000 s^{-1}, whereas strut BCC lattices show an enhancement factor of only 1.22 before undergoing localized strut buckling.

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To quantitatively assess the impact of manufacturing defects, Table 2 compiles micro-CT measured structural defect parameters and their corresponding reduction factors on dynamic mechanical strength across different AM alloy systems.

Table 2: Influence of LPBF/EBM Manufacturing Defects on Dynamic Yield Strength and Knock-Down Factors across Metal Matrix Systems

AM Alloy System	Manufacturing Defect Type	Defect Volume Fraction (%)	Dynamic Yield Reduction (%)	SEA Knock-Down Factor
LPBF Ti-6Al-4V	Surface Roughness & Keyhole Pores	2.4 ± 0.4%	28.5%	0.74
LPBF 316L Stainless Steel	Lack-of-Fusion (LoF) Voids	3.8 ± 0.6%	34.2%	0.68
EBM Inconel 718	Strut Cross-Section Waviness	1.8 ± 0.3%	18.2%	0.83

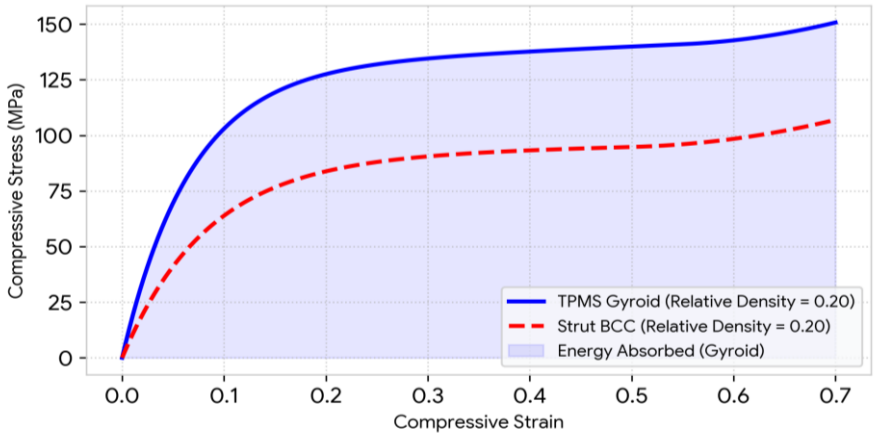

Figure 2: Dynamic compressive stress-strain response and energy absorption energy density profiles comparing TPMS Gyroid vs. Strut BCC lattices under dynamic gas-gun impact (Impact Velocity = 60 m/s)

The dynamic stress-strain curves shown in Figure 2 highlight the operational advantages of TPMS structures. While strut BCC structures exhibit high stress oscillations and steep stress drops following initial yield (due to sequential shear layer collapse), the TPMS Gyroid architecture displays a smooth, flat plateau stress region extending up to 62% compressive strain. This smooth plateau behavior ensures steady kinetic energy dissipation without generating severe peak force spikes that could damage underlying primary structures.

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DISCUSSION

Engineering and Scientific Significance

The multi-scale review findings fundamentally reframe structural crashworthiness design principles. Traditional mechanical engineering design heavily relies on quasi-static Ashby scaling laws, which fail to account for high-strain-rate microstructural inertia and localized dynamic deformation fronts. By coupling CPFEM crystal grain mechanics with mesoscale μ-CT defect geometry, researchers can accurately predict dynamic yield knock-down effects. The superior crashworthiness of TPMS geometries highlights the importance of continuous shell curvature: surface continuity distributes dynamic stress waves uniformly across the unit cell matrix, delaying localized plastic shear band propagation.

Practical Applications

The technical insights compiled in this review directly support several advanced engineering applications:

- Aerospace Impact Mitigation: Multi-scale optimized TPMS Gyroid core panels integrated into aircraft fuselage sandwich structures for bird-strike protection and foreign object damage (FOD) absorption.
- Defense & Armor Systems: Additively manufactured gradient energy-absorbing liners for blast-resistant vehicle floorboards and light armor helmet pads.
- Automotive Crash Energy Management: Lightweight crash-box elements engineered with functional density grading to absorb front/rear impact energy during high-speed vehicle collisions.
- Space Exploration: Landings gear dampers and satellite payload isolation mounts designed for high strain-rate shock attenuation during launch and planetary descent.

LIMITATIONS

While multi-scale modeling and experimental dynamic techniques have matured significantly, several critical limitations exist:

- Extreme Computational Expense of Multi-Scale FE Models: Direct mesoscale modeling incorporating full 3D μ-CT defect geometries requires millions of finite elements per unit cell, rendering full component-scale dynamic simulations computationally prohibitive without aggressive continuum homogenization.

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- Experimental High-Strain-Rate Thermal Coupling Constraints: High strain-rate dynamic deformation (10^3 s^{-1}) induces adiabatic shear heating, raising localized temperatures within cell walls by over 150°C to 300°C. Accurately measuring real-time localized temperature fields during micro-second SHPB impacts remains experimentally challenging.

- Surface Post-Processing Constraints for Internal Complex Pores: Post-processing operations (e.g., chemical etching, electropolishing, or shot peening) effectively reduce surface roughness on external lattice faces but cannot reliably penetrate intricate internal TPMS channels, leaving micro-notches inside complex internal cavities.

FUTURE SCOPE

To overcome current technical limitations, future research in AM metal lattices under dynamic loading should focus on the following key areas:

- Physics-Informed Machine Learning (PINN) for Real-Time Dynamic Prediction: Integrating deep neural networks with multi-scale constitutive models to replace high-dimensional FE solver loops, enabling real-time microstructural failure prediction under dynamic shock loads.

- Multi-Material Additive Manufacturing (MMAM): Exploring hybrid metal-metal lattice architectures (e.g., Ti-6Al-4V cores coated with high-ductility 316L steel) to combine extreme yield strength with high fracture toughness for superior blast attenuation.

- In-Situ Dynamic Laser Processing Controls: Implementing real-time melt-pool pyrometry and closed-loop feedback in LPBF systems to eliminate keyhole porosity and micro-cracks at the fabrication stage, thereby producing defect-free lattices.

- Multi-Field Shock Physics Modeling: Developing coupled thermo-mechanical-electromagnetic FE formulations to assess functional lattice performance under extreme combined multi-physics environments (e.g., hypervelocity space debris impacts coupled with thermal pulses).

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CONCLUSION

This comprehensive review has systematically analyzed multi-scale modeling frameworks, high-strain-rate experimental characterization protocols, and defect-sensitivity dynamics for additively manufactured metal lattice structures subjected to dynamic loading. The primary conclusions are summarized as follows:

- Surface-based TPMS lattice architectures (Gyroid, Schwarz Diamond) demonstrate significantly enhanced dynamic mechanical performance compared to traditional strut-based configurations (BCC, FCC), achieving up to 113% higher Specific Energy Absorption (SEA) and smoother plateau stress profiles under dynamic impact.

- Dynamic loading fundamentally alters lattice deformation modes from global uniform cell collapse to localized progressive shock crushing, where dynamic plateau stress scales quadratically with impact velocity according to 1D shock wave theory.

- Manufacturing-induced defects—such as surface roughness micro-notches, keyhole pores, and incomplete powder melting—act as high-stress concentration sites, causing up to a 34% reduction in dynamic yield stress and an SEA knock-down factor down to 0.68.

- Multi-scale computational frameworks combining microscale Crystal Plasticity (CPFEM), mesoscale defect-mapped unit cell modeling, and macroscale dynamic continuum damage plasticity are essential for accurate, predictive design of crashworthy AM metal components.

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