AIAS2025

ID contributo: **88**

Tipo: **Presentazione orale**

Metamateriali bioispirati: una nuova sinergia tra twinning e ottimizzazione topologica per prestazioni meccaniche avanzate

mercoledì 3 settembre 2025 12:45 (15 minuti)

Architected materials represent a transformative advancement in material science, offering unprecedented control over mechanical properties by tailoring structural topology. These materials are poised to revolutionize industries where lightweight, high-strength, and damage-tolerant materials are essential, including aerospace, biomedical implants, and mechanical metamaterials. However, a persistent challenge in their design is the trade-off between strength and ductility, where enhancing one property often compromises the other. Addressing this issue is critical to unlocking new frontiers in engineering materials capable of withstanding extreme conditions while maintaining structural integrity. Nature offers a blueprint for overcoming these limitations through hierarchical structuring and controlled deformation mechanisms. In particular, twinning mechanisms, which are well-documented in metallic and mineral structures, provide an effective way to enhance ductility while delaying catastrophic failure. In natural materials such as α-Ti, brass, and even some crystalline biominerals, twin boundaries act as stress redistribution pathways, enabling greater deformation tolerance and energy dissipation under load.

Objectives

Inspired by these natural strategies, this study presents an integrated approach combining boundary twinning (TB) and topology optimization to simultaneously enhance strength and ductility in architected materials. By leveraging these mechanisms, we aim to bridge the gap between brittleness and mechanical resilience, paving the way for materials with superior energy absorption and failure resistance. The integration of these bio-inspired principles can lead to the development of novel structural solutions capable of withstanding impact, fatigue, and extreme environmental conditions while maintaining high performance over time.

Methods

Three lattice configurations were investigated: (i) a baseline FCC strut-based lattice, (ii) a twinned variant introducing mirror-symmetric unit cell arrangements to redistribute stress, and (iii) an optimized version incorporating topology optimization to minimize peak stresses within struts. Finite element analysis (FEA) simulations were conducted alongside experimental validation through uniaxial compression tests on 3D-printed specimens (40 × 40 × 40 mm), fabricated from photopolymer resin via digital light processing (DLP). Digital Image Correlation (DIC) was employed to obtain full-field strain distributions, providing a detailed characterization of local deformation patterns, stress redistributions, and failure mechanisms.

Results

Results indicate that twinning enhances ductility by approximately 15% through stress delocalization and the formation of symmetric shear bands yet does not significantly alter ultimate strength. The optimized lattice, incorporating both TBs and topology-driven modifications, exhibits an 89% increase in deformation capacity and a 60% improvement in peak load capacity compared to the baseline. Furthermore, energy absorption was improved by over 75%, as evidenced by the integrated area under the stress-strain curves obtained from both numerical simulations and experimental testing. This increase in energy absorption is particularly relevant for applications that require impact resistance and fatigue tolerance, such as protective gear, crash-resistant automotive components, and high-performance aerospace materials.

FEA simulations predict failure modes with high accuracy but underestimate the role of self-contact interactions in large-strain deformation. Computationally, topology optimization led to a redistribution of material in high-stress regions, reducing peak stress by approximately 30%, as confirmed by von Mises stress maps. The transition from stretching-dominated to bending-dominated deformation in the optimized lattice was further validated using modal analysis, revealing an increase in first-mode buckling resistance by a factor of 2.1.

These results suggest that such architected materials can not only sustain higher loads but also maintain structural integrity over extended loading cycles, a key requirement for materials intended for long-term structural applications.

Conclusion

The findings demonstrate that combining twinning and topology optimization effectively shifts the failure mechanism from stretching-dominated to bending-dominated behavior, thereby improving energy absorption, mechanical resilience, and overall damage tolerance. This research highlights a scalable, bio-inspired design approach for architected materials, with far-reaching implications for the next generation of lightweight, damage-tolerant materials in structural and biomedical applications. Beyond their use in aerospace and mechanical components, the implications of this research extend to regenerative medicine, where architected scaffolds with tailored mechanical properties could improve bone regeneration and tissue integration.

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Classifica Sessioni: Progettazione Meccanica

Classificazione della track: Progettazione Meccanica