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Hybrid Manufacturing of Architected Titanium and Nickel-based Interpenetrating Phase Composite Materials

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Abstract

Architected metallic materials and interpenetrating phase composites (IPCs) represent a rapidly emerging class of multifunctional systems that transcend the limitations of conventional cellular solids. By exploiting topology-driven design freedom and hybrid manufacturing, such materials can be tailored to simultaneously deliver high mechanical efficiency, enhanced damage tolerance, and improved thermal and impact performance. In this work, architected materials based on Ti-6Al-4V and Nickel alloys are systematically investigated, alongside their corresponding metal–metal IPCs, to elucidate structure–property–performance relationships under quasi-static and impact-relevant loading conditions. Sheet-based triply periodic minimal surface (TPMS) architectures, exemplified by the Gyroid topology, and stochastic spinodal architectures are employed as reinforcement phases. These two design classes represent fundamentally different load-transfer mechanisms: periodic, curvature-continuous pathways in TPMS structures versus statistically isotropic, disorder-driven connectivity in spinodal networks. Ti-6Al-4V and Nickel lattices are fabricated via laser powder bed fusion, while IPCs are produced using a hybrid approach combining additive manufacturing with vacuum-assisted infiltration of a secondary metallic phase. Microstructural characterization using SEM, EDS, and XRD confirms high-fidelity architectural reproduction, co-continuous phase formation, and strong metallurgical bonding at metal–metal interfaces. For single-phase architected materials, both Ti-6Al-4V and Nickel lattices exhibit high stiffness-to-weight ratios but limited post-yield deformation, with Ti-6Al-4V showing earlier strain localization due to its intrinsic low ductility. Nickel architected materials demonstrate comparatively enhanced plasticity and delayed collapse, particularly in spinodal configurations. Upon formation of IPCs, the mechanical response is transformed: Young's modulus and peak strength increase by factors of 2–4, while ductility and toughness are dramatically enhanced through stable, distributed plastic flow in the infiltrated phase. Gyroid-based IPCs consistently exhibit higher stiffness and peak strength due to continuous load paths, whereas spinodal IPCs provide superior damage tolerance and more progressive collapse. Impact and crashworthiness-relevant metrics, including energy absorption, specific energy absorption, mean crushing force, and crush force efficiency, reveal a strong dependence on reinforcement topology. TPMS-based reinforcements maximize peak load-bearing capacity, beneficial for structural protection, while spinodal reinforcements mitigate force spikes and promote uniform energy dissipation, advantageous for impact mitigation. Nickel-based systems further outperform titanium counterparts under impact-relevant deformation due to their higher intrinsic ductility and strain-rate tolerance. Thermal performance analysis shows that single-phase Ti-6Al-4V lattices possess inherently low thermal conductivity, whereas Nickel architectures provide moderate improvements. In contrast, IPCs achieve order-of-magnitude enhancements in effective thermal conductivity through co-continuous metallic pathways, without compromising mechanical integrity. These multifunctional gains position Ti- and Ni-based IPCs within a previously inaccessible performance space combining strength, toughness, energy absorption, and heat dissipation. Overall, the results demonstrate that reinforcement phase topology and base alloy selection critically govern mechanical, thermal, and impact responses. By judiciously combining Ti-6Al-4V or Nickel architected reinforcements with suitable infiltrated phases, next-generation multifunctional architected materials can be engineered for demanding aerospace, defense, and energy applications where simultaneous load-bearing, impact resistance, and thermal management are required.

Keywords:

Metamaterials Hybrid Manufacturing Titanium Nickel IPC Impact