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Metallic Materials COMMENTARY

The marriage of flexibility and high strength through strain-glass transformation pathway engineering

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Strength, governed by interatomic bonding and microstructure, is a fundamental property of structural metals. In conventional metallic systems, strengthening is typically achieved by suppressing dislocation motion, but this often increases stiffness and compromises deformability, leading to the well-known strength-flexibility trade-off. Emerging technologies, including alloy-based artificial muscles and elastocaloric cooling, increasingly demand metals that combine ultrahigh strength and flexibility, large recoverable deformation, and long-term cyclic stability. Although conventional high-strength steels can achieve yield strengths above 1.5 GPa, their elastic moduli remain near 200 GPa, resulting in a strength-to-modulus ratio far below that of elastomeric materials. Bridging this gap remains a long-standing challenge in materials science. One promising route is to introduce alternative deformation pathways beyond conventional dislocation-mediated plasticity. In this sense, phase-transforming materials are particularly attractive, as they accommodate external stimuli through reversible lattice rearrangement rather than irreversible defect accumulation. This transformation-mediated mechanism enables large recoverable strain while maintains structural integrity. Among them, shape memory alloys (SMAs), especially those incorporating strain glass, offer a particularly promising strategy. By introducing frozen nanoscale precursor domains, strain glass engineering reshapes the transformation energy barrier and enables nucleation-free crossover transformations, providing a pathway to overcome the conventional trade-off between strength, flexibility, and recoverable deformation.

PROMISING APPLICATIONS AND CHALLENGES OF SHAPE MEMORY ALLOYS

Shape memory alloys (SMAs) are important class of functional materials because they accommodate deformation through reversible martensitic transformation rather than irreversible plasticity. This transformation-mediated mechanism enables large recoverable strain and moderate stiffness, making SMAs attractive for applications requiring flexible actuation and adaptive mechanical responses. Among them, NiTi-based alloys stand out for their exceptional mechanical properties,[1] with yield strengths typically reaching ~200-700 MPa (depending on composition: 200 MPa, 500 MPa and 700MPa for Ti-50Ni, Ti-51Ni and Ti-52Ni, respectively), and an elastic modulus of ~30-80GPa (depending on phase state: 50-80GPa for austenite and 30-40 for martensite), offering a promising route toward "strong yet flexible" metallic systems.

Despite these advantages, conventional SMAs still face intrinsic limitations. A pronounced hysteresis exists during loading and unloading, typically 150-200 MPa in NiTi alloys, leads to significant energy dissipation, reduced reversibility, and residual strain accumulation. In addition, their relatively high initial modulus limits flexibility at small strains. Both limitations originate from the nucleation barrier associated with stress-induced martensitic transformation (Figure 1A). Although strategies such as phase boundary engineering and microstructural refinement can partially reduce hysteresis and improve fatigue resistance, they often increase stiffness or compromise transformation reversibility. These limitations highlight the need for alternative design strategies that can simultaneously reduce transformation barriers, suppress hysteresis, and maintain both high strength and flexibility.

STRAIN GLASS AND STRAIN GLASS TRANSITION

Strain glass is a frozen disordered ferroelastic state composed of nanoscale strain domains,[2] originally discovered in martensitic alloys but more broadly belonging to the family of ferroic glass. Beyond metallic systems, strain-glass-like states have also been identified in ferroelastic ceramics, such as $CaTiO_3$ and $LaAlO_3$, highlighting the broader relevance of this concept. For typical SMAs, strain glass can be introduced through composition tuning, defect engineering, heat treatment, or thermomechanical processing. The common feature of these approaches is the frustration of long-range martensitic ordering by defects and local structural heterogeneity. Instead of a conventional first-order martensitic transformation, the system first undergoes a strain-glass transition, where local strain fluctuations freeze into nanoscale non-ergodic domains. These frozen precursor domains subsequently act as transformation embryos, enabling a nucleation-free crossover transformation under external stimuli. This fundamentally reshapes the transformation pathway by lowering the activation barrier for stress-induced transformation. As a result, the crossover strain glass systems give rise to low-modulus superelasticity, reduced hysteresis, and highly reversible deformation over a broad temperature range. These characteristics make strain glass an attractive platform for designing metallic systems that reconcile strength, flexibility, and functional stability.

MAKING SMAS FLEXIBLE

Inspired by the strain glass engineering, Xu and co-workers recently developed a NiTi alloy that combines ultrahigh strength with exceptional flexibility through a dual-seed strain glass (DS-STG) architecture.[3] In conventional NiTi alloys, two major transformation pathways exist: the weakly first-order B2 to R transition with a small lattice distortion (~1%) and the strongly first-order B2 to B19' transition with a much larger lattice distortion (~10%). Since B19' is the thermodynamically stable ground state of NiTi, the R phase can serve as an intermediate precursor.

The DS-STG state is introduced through hierarchical thermomechanical processing. Severe pre-deformation introduces dense dislocations and twins, frustrating long-range martensitic ordering and creating a strain glass matrix. Intermediate annealing stabilizes a dual-crossover strain glass state containing nanoscale R-strain domains, while subsequent moderate deformation selectively aligns both R and B19' martensitic seeds within the glassy matrix.

The key innovation lies not in the introduction of a new phase, but in engineering cooperative precursor states to establish a low-barrier transformation pathway. The R seeds, owing to their smaller lattice distortion and lower activation barrier, are preferentially activated during the early stage of deformation and contribute to the ultralow initial modulus, whereas B19' seeds provide the larger transformation strain at higher stress. Their cooperative crossover transformation enables a continuous deformation pathway that reconciles flexibility and strength.

As a result, DS-STG NiTi achieves a yield strength of ~1.8 GPa, an ultralow modulus of ~10.5 GPa, and a recoverable strain of ~8%, giving a strength-to-modulus ratio of ~0.17, which is more than 20 times greater than conventional high-strength steel. This unusual property combination remains stable from −80 °C to +80 °C because the DS-STG microstructure persists over a wide temperature range, while the characteristic shallow U-shaped modulus-temperature dependence of strain glass preserves the ultralow modulus.

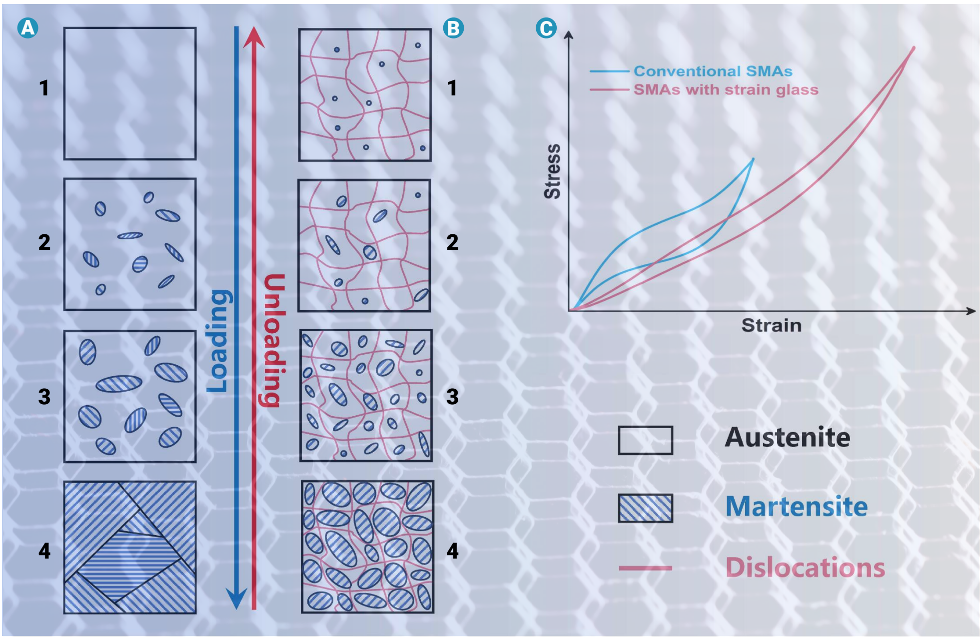

Figure 1. Schematic comparison of deformation pathways in conventional shape memory alloys (SMAs) and strain-glass-embedded SMAs. In conventional SMAs (A), the parent austenite transforms into martensite through heterogeneous nucleation and interface propagation under stress. This process involves critical nucleus formation, martensite growth, and variant reorientation (A1) - (A4), leading to a relatively high initial modulus and pronounced hysteresis. In strain-glass-embedded SMAs (B), a high density of defects and dislocations stabilizes frozen nanoscale strain glass domains that act as pre-existing martensitic embryos. Under stress, these nanodomains continuously evolve, align, and locally transform into martensite without conventional nucleation (B1) - (B4). This nucleation-free crossover pathway lowers the effective transformation barrier, suppresses the initial modulus, and reduces hysteresis while maintaining large recoverable strain. The corresponding stress-strain responses are illustrated in (C): conventional SMAs exhibit distinct stages of (i) elastic loading, (ii) stress-induced martensitic transformation, and (iii) elastic deformation of martensite, whereas strain-glass-embedded SMAs show a more quasi-linear response without clear stage boundaries.

STRAIN GLASS CAN DO MORE

Beyond mechanical flexibility, strain glass engineering offers broader opportunities for energy-related applications by enabling nucleation-free transformations with reduced energy barriers.

One representative example is magnetostriction in ferromagnetic shape memory alloys (FSMAs). Conventional FSMAs such as Ni_2MnGa can generate giant magnetic-field-induced strain up to ~6%, but typically require magnetic fields ranging from ~0.5 to several tesla and often exhibit pronounced hysteresis. In contrast, by introducing frozen martensitic nanodomains embedded in the parent matrix, the strain glass domains can act as highly responsive magnetic units with much lower activation barriers. For example, Fe-Pd strain glass achieves ~800 ppm magnetostriction under an ultralow saturation field of only ~0.8 kOe, demonstrating significantly improved field efficiency.[4]

Besides magnetostriction, strain glass engineering may also benefit elastocaloric refrigeration.[5] Conventional NiTi alloys can exhibit adiabatic temperature changes up to ~20-25 K, but practical application is generally limited by fatigue degradation, where functional instability or crack initiation often emerge after ~10^4-10^5 cycles. By suppressing abrupt nucleation and reducing interfacial friction, strain-glass-mediated crossover transformations can distribute transformation strain more homogeneously and improve cyclic stability. Notably, the recently reported DS-STG alloy maintains stable superelasticity over >10^6 loading cycles, suggesting a promising route toward durable solid-state cooling and other cyclic energy-conversion technologies.

SUMMARY AND OUTLOOK

Rather than introducing a new phase, strain-glass engineering establishes transformation-pathway engineering as a new paradigm for materials-design, demonstrating that programmable precursor architectures can overcome property trade-offs beyond conventional strengthening routes.

At the same time, several fundamental challenges remain. First, the major challenge is establishing predictive structure-transformation-property relationships, enabling precursor architectures to be designed rather than empirically obtained. Second, whether this concept represents a universal design principle across ferroelastic and ferroic systems, while maintaining stable precursor architectures under repeated thermal, mechanical, and magnetic loading, also remains unknown. In addition, achieving these goals will likely require the integration of advanced characterization, multiscale modeling, and data-driven materials design.

More broadly, the strain-glass engineering may transform materials design from optimizing phases and microstructures to programming transformation pathways, providing a general paradigm for designing ferroic materials with tailored mechanical and functional responses.

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DECLARATION OF INTERESTS

The authors declare no competing interests.