Bioinspired Mechanical Metamaterial Composites by Additive Manufacturing

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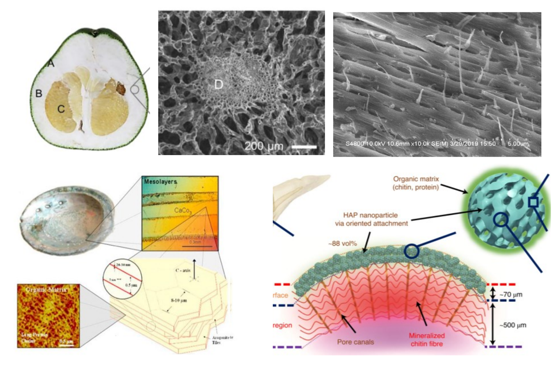
1 Background

- In order to realize sustainable development, automobile lightweight is imperative. The introduction of new lightweight materials on the body and parts is one of the effective ways to realize automobile lightweight.
- Nature materials, exhibiting superior mechanical properties, are generally hybrid composites typically consisting of a hard mineral phase within a soft phase of organic molecules.



Multiphase materials in nature

2 Design and Fabrication

- Akin to the precipitation hardening mechanism in metals, dual-phase lattices (DPLs) were designed as novel mechanical metamaterials consisting of architected truss materials (single-phase lattices, SPLs) with a matrix phase (MP) and reinforcement phase (RP).
- Depending on the spatial distribution distance among reinforcement phase grains, these dual-phase lattices can be classified as dispersion type and compaction type

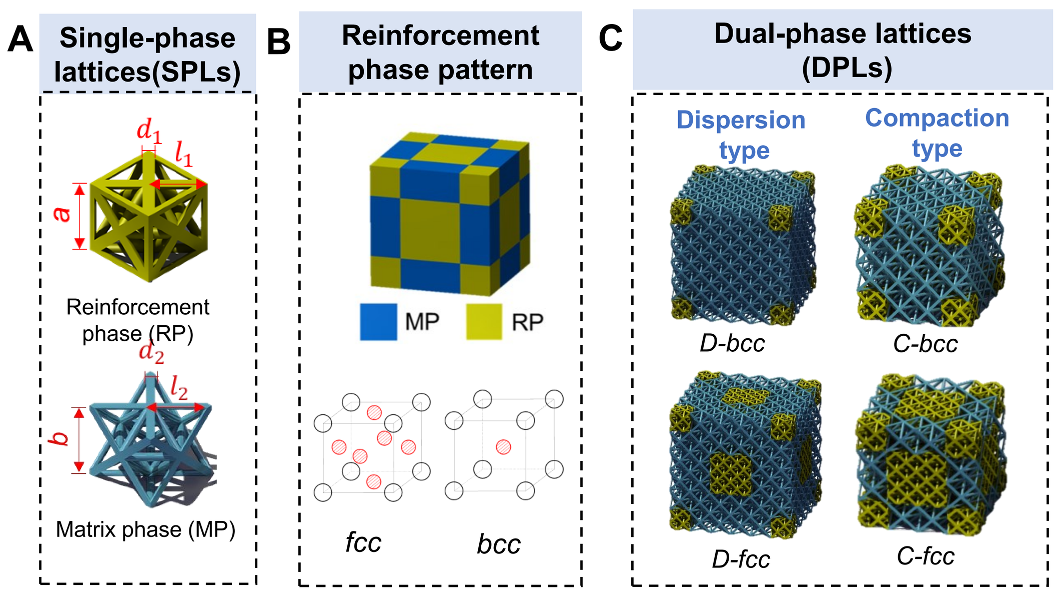


Fig. 1 Architecture design and fabrication of dual-phase lattices (DPLs). (A) Geometrical illustrations of two types of lattice materials, respectively as matrix phase (MP) and reinforcement phase (RP) of DPLs. (B-C) DPLs with bcc and fcc patterns of RP classified as dispersion type and compaction type according to interactions between the reinforcement grains.

- The dual-phase mechanical metamaterials were fabricated by additive manufacturing using stainless steel powders, together with constituent single-phase truss lattice materials.
- Selective laser melting (SLM) based additive manufacturing was employed for the fabrication of all the dual-phase metamaterials on an EOS M280 printer using stainless steel powder.

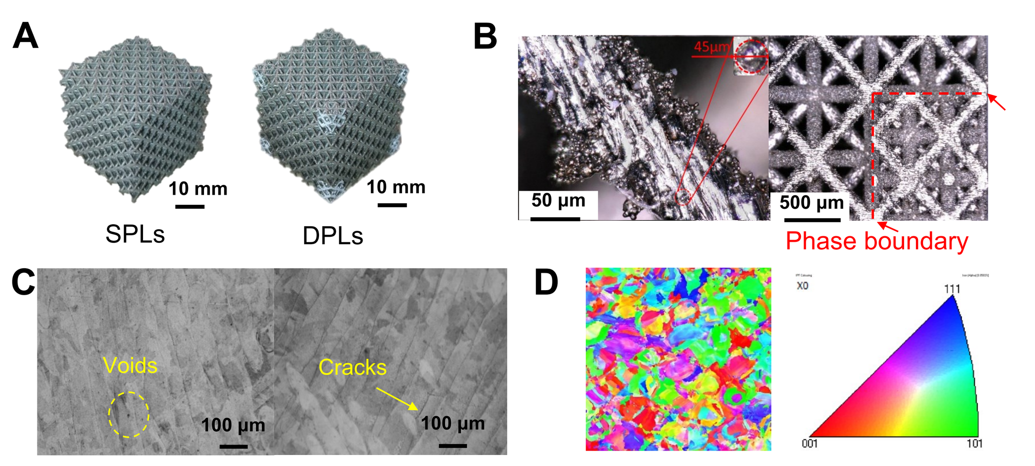


Fig. 2 (A) DPL samples fabricated by selected laser melting based additive manufacturing together with the single-phase counterparts. (B) Mesoscopic printing details. (C) Manufacturing defects observed. (D) EBSD characterization

3 Influence of phase distribution on energy absorption

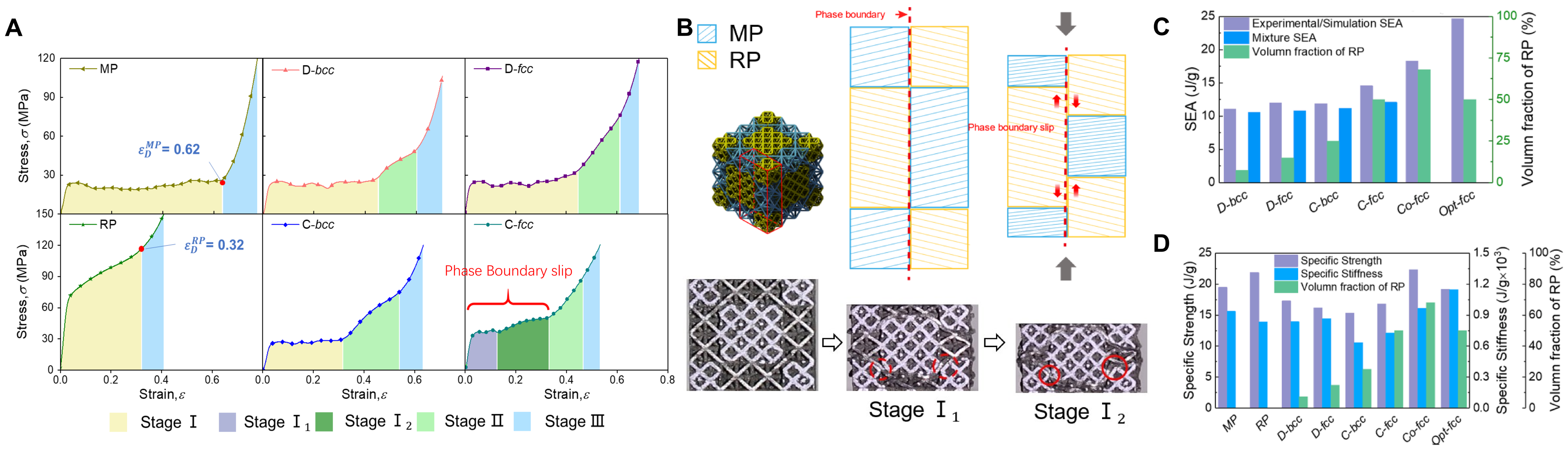


Fig. 3. (A) Compressive stress-strain curves. (B) Illustration of phase boundary accompanying RGs sliding for C-fcc type DPLs. (C) Specific energy absorption (SEA) of DPLs with different volume fractions of RP, compared to results computed from the simple law of mixtures. (D) Specific stiffness and strength compared to constituent SPLs.

- Based on the specific phase distribution mode, phase boundary slip will occur, accompanied by further deformation, friction and fracture of the bar, which is conducive to energy absorption.

4 Effect of phase distribution on deformation patterns

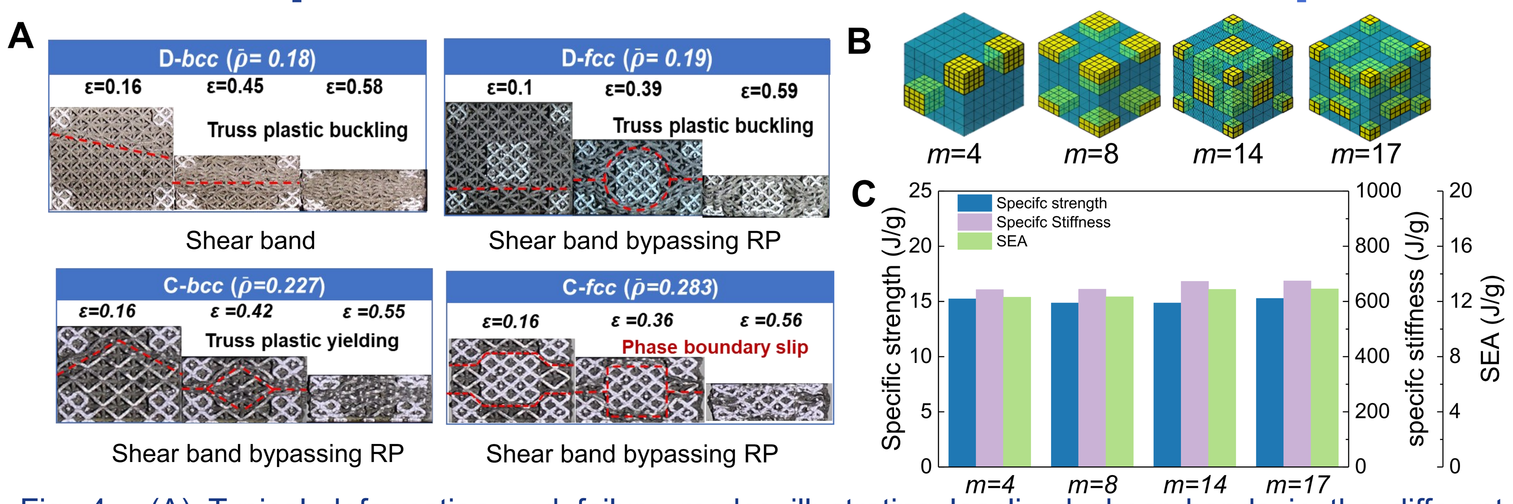


Fig. 4. (A) Typical deformation and failure modes illustrating localized shear bonds in the different materials. (B-C) Stiffness, strength and energy absorption of DPLs with increasing complexity and reinforcement grain numbers *m* at constant volume fraction V_{RP}.

- The shear band appears in the matrix phase and expands around the reinforcement phase.
- The different distribution patterns of reinforcement phase affect the distribution of shear band, but have little effect on the strength and energy absorption capacity.

5 Fracture toughness

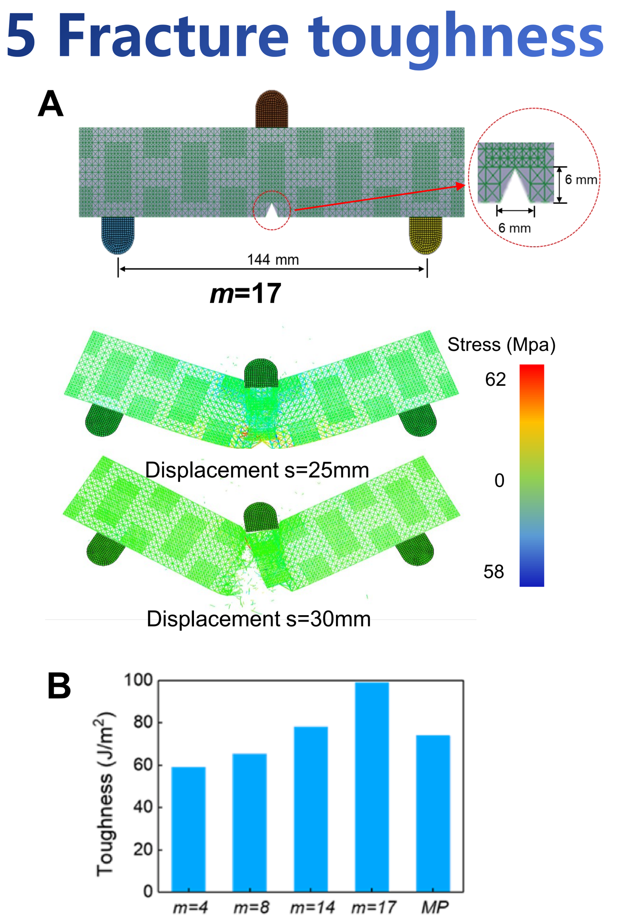
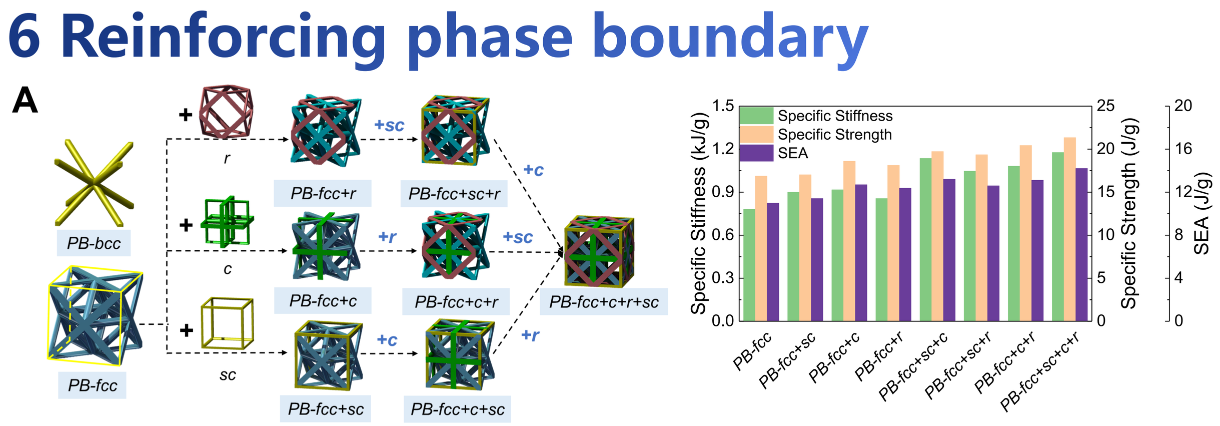


Fig. 5. Toughness simulation models of DPLs. (A) Cracked DPLs in three-point bending. (B) Toughness comparison for DPLs with different RP distribution complexity.

- The reinforced phase hinders crack propagation, and the more complex the phase distribution, the higher the fracture toughness

6 Reinforcing phase boundary



- strengthening the phase boundary structure can effectively improve the lattice specific stiffness (60%) and specific energy absorption (40%).

Fig. 6. Specific stiffness, strength and SEA of DPLs with reinforcing phase boundary.

7 Effect of phase boundary slip area on energy absorption

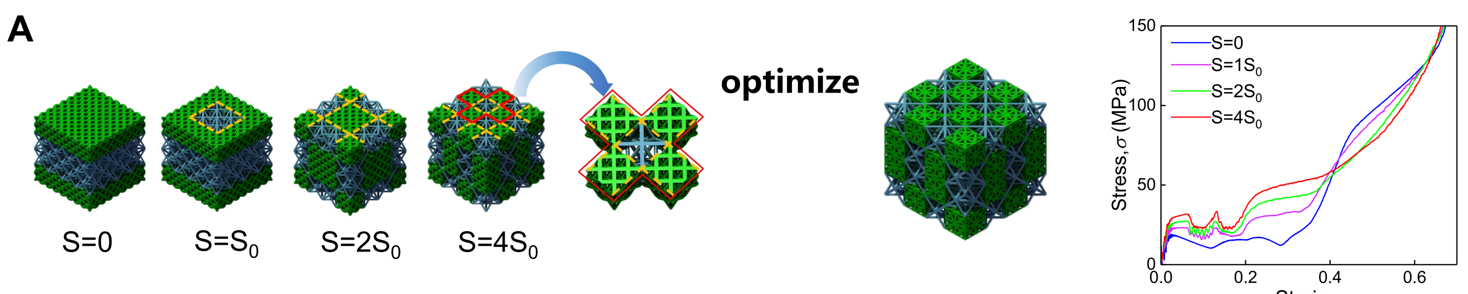


Fig. 7. DPLs with various phase-boundary slip areas and their compressive performance.

- The larger the slip area of the phase boundary, the higher the energy absorption, and the slip area is the largest when a matrix phase cell is surrounded by the enhanced phase cell, and the Opt-fcc specific absorption energy increases by 150%.

8 Conclusion

- Deformation and failure in the dual-phase lattice materials initiate in the matrix phase which subsequently triggers shear localization bands that bypass the reinforcement grains.
- The addition of the reinforcement grains, the stiffness, strength and specific energy absorption of the DPLs all increase, respectively by ~50%, 49%, 45%, as compared to the corresponding properties of the constituent matrix phase. By fully utilizing the energy dissipation associated with phase-boundary slip, DPLs with a maximum slip area between the reinforcement and matrix phases exhibit a maximum specific energy absorption capability which is up to ~2.5 times of that of their constituent SPLs.
- The rationale for designing dual-phase metamaterials with excellent energy absorption capacity is summarized with a focus on phase patterning as:
  a) The mechanical properties of the reinforcement phase SPLs should be greater than those of matrix phase.
  b) The densification strain and stress of each phase, and the difference between the densification stress of two phases, should be as high as possible for greater energy absorption.
  c) The volume fraction of reinforcement phase should be the same in each column to make sure each lattice cell can be fully compressed.
  d) The reinforcement grains should be connected but not overlapping, satisfying L = 2LRG with the greatest phase-boundary area, where every truss unit in the matrix phase is completely surrounded by reinforcement phase lattices.