Supporting Information

Failure mode engineered high-energy-absorption metamaterials with biomimetic hierarchical microstructures and artificial grain boundaries

1. **Supporting figures and tables**

In this section, the supporting figures and tables described in the main text of the paper is provided.

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**Figure S1.** Element distributions of AlMgScZr powder measured by SEM: (a) Al; (b) Mg; (c) Sc; (d) Zr.

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**Figure S2.** Representative unit areas and beam thicknesses of BH-SHS unit cells fabricated by SLM: (a) optical microscope images of representative unit areas for the BHC-SHS and SHC-SHS unit cells; and (b) the experimentally measured beam thicknesses for the BHC-SHS and SHC-SHS unit cells.

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**Figure S3.** Optical microscope measurement of the beam thickness from representative unit areas for BHC-SHS unit cells: (a1-a6) BHC132; (b1-b6) BHC162; (c1-c6) BHC212; (d1-d6) BHC252; and (e1-e6) BHC282.

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**Figure S4.** Optical microscope images of the beam thickness from the representative unit areas for the SHC-SHS unit cells: (a1-a6) SHC180; (b1-b6) SHC260; (c1-c6) SHC320; (d1-d6) SHC380; and (e1-e6) SHC420.

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**Figure S5.** Additional case studies for applying BH-SHS lattice structures and failure mode engineering method in aerospace industries: (a) a space rover wheel with protective damage deflection design using BH-SHS infills; and (b) a quadradrone with impact-resistant BH-SHS infills.

**Table S1.** Summary of the design parameter values for the BH-SHS unit cells.

|  |  |
| --- | --- |
| Design parameter | Selected range |
| Beam thickness [mm] | 1 |
| Shell thickness [mm] | 1 |
| Topological density for BHC-SHS unit cells | 132 ~ 282 |
| Topological density for SHC-SHS unit cells | 180 ~ 420 |

**Table S2.** Material composition of AlMgScZr powder.

|  |  |
| --- | --- |
| Material | Weighted percentage [%] |
| Al | 93.6 |
| Mg | 4.7 |
| Sc | 0.79 |
| Zr | 0.32 |
| Mn | 0.59 |

**Table S3.** Dimensions of the specimen.

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Specimen # | Diameter 1 [mm] | Diameter 2 [mm] | | Diameter 3 [mm] | Average diameter [mm] | Standard deviation of diameter [mm] | Gauge length of extensometer [mm] |
| 1 | 5 | | 4.97 | 4.97 | 4.98 | 0.01 | 20 |
| 2 | 4.99 | | 4.97 | 4.97 | 4.98 | 0.01 |
| 3 | 4.97 | | 4.97 | 4.99 | 4.98 | 0.01 |

**Table S4.** Standard deviations of the experimentally measured mechanical properties for different unit cell topologies.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Topology | First wavy strength [MPa] | Secondary wavy strength [MPa] | Relative density [%] | Density [kg/] | EAC  [104 J/] |
| BHC132 | 0.11 | 0.04 | 0.24 | 3.10 | 1.53 |
| BHC162 | 0.07 | 0.02 | 0.12 | 1.49 | 4.20 |
| BHC212 | 0.01 | 0.02 | 0.11 | 1.29 | 5.85 |
| BHC252 | 0.09 | 0.10 | 0.19 | 2.20 | 1.72 |
| BHC282 | 0.06 | 0.01 | 0.09 | 1.06 | 0.27 |
| SHC180 | 0.20 | NA | 0.08 | 0.99 | 3.14 |
| SHC260 | 0.09 | NA | 0.14 | 1.66 | 17.07 |
| SHC320 | 0.04 | NA | 0.06 | 0.75 | 16.55 |
| SHC380 | 0.04 | NA | 0.07 | 0.86 | 10.57 |
| SHC420 | 0.04 | NA | 0.08 | 0.90 | 3.46 |

**Table S5.** Compressive stages of the BHC-G1/2 and SHC-G1/2 lattice unit cells at different strain values.

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| BHC-G1/2 | G1 | | | | | G2 | | | | |
| Compressive stage | Substage | F1 | F2 | F3 | Compressive stage | Substage | F1 | F2 | F3 |
|  | 1-2 |  | - | - |  | 1-2 | I | - | - |
| 2-3 |  | - | - | 2-3 | II | - | - |
|  | 3-5 |  |  | - |  | 3-4 | III | I | - |
| 5-6 |  |  |  | 4-5 | III | I | I |
|  | 6-7 |  |  |  | 5-6 | III | II | II |
| 7-8 |  |  |  |  | 6-7 | IV | III | III |
| 8-9 |  |  | III-IV | 7-8 | IV | III-IV | III-IV |
|  | 9- |  |  |  |  | 8- | IV | IV | IV |
| SHC-G1/2 | G1 | | | | | G2 | | | | |
| Compressive stage | Substage | F1 | F2 | F3 | Compressive stage | Substage | F1 | F2 | F3 |
|  | 1-2 | I-II | - | - |  | 1-2 | I | - | - |
| 2-3 | III | I | - | 2-3 | II | I | - |
|  | 3-4 | III | II | I |  | 3-4 | III | I | - |
| 4-5 | III | III | II | 4-5 | III | II | I |
|  | 5-6 | III | III | III | 5-6 | III | III | II |
| 6-7 | IV | IV | III |  | 6-7 | III | III | III |
| 7-8 | IV | IV | III-IV | 7-8 | IV | III | III |
|  | 8- | IV | IV | IV | 8-9 | IV | IV | III-IV |
|  | 9- | IV | IV | IV |

**Table S6.** Compressive stages of the CHC-SHS lattice unit cells at different strain values.

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Compressive stage | Substage | BHC-SHS unit cells | | | SHC-SHS unit cells | | |
| F1 | F2 | F3 | F1 | F2 | F3 |
|  | 1-2 | I | - | - | - | - | - |
| 2-3 | II | - | - | I | - | - |
|  | 3-4 | III | I | - | II | - | - |
| 4-5 | III | I | - | III | I | - |
| 5-6 | IV | II-III | I | III | I | I |
| II | 6-7 | IV | III | II | III | II | II |
| 7-8 | IV | III | III | IV | III | II |
| 8-9 | IV | IV | IV | IV | III | III |
| 9-10 | IV | IV | IV | IV | III-IV | III-IV |
| III | 10- | IV | IV | IV | IV | IV | IV |

1. **Supporting videos**

In this section, the supporting videos mentioned in the main text of the paper is provided. Specifically, the simulation videos of two distinctive failure modes for the BH-SHS unit cells are provided in **Video S1** and **Video S2**. **Video S3** to **Video S7** delivers the progressing compressive curves and their corresponding experimental compressive recordings for BHC-G1/2, SHC-G1/2, and CHC-SHS lattice structures, respectively.

**Video S1.** A1-A2-B failure mode simulation.

**Video S2.** B1-B2-A failure mode simulation.

**Video S3.** Experimental compressive curve and video of BHC-G1 lattice structure.

**Video S4.** Experimental compressive curve and video of BHC-G2 lattice structure.

**Video S5.** Experimental compressive curve and video of SHC-G1 lattice structure.

**Video S6.** Experimental compressive curve and video of SHC-G2 lattice structure.

**Video S7.** Experimental compressive curve and video of CHC-SHS lattice structure.