DYNAMIC MECHANICAL BEHAVIOR OF HIERARCHICAL MECHANICAL METAMATERIALS

Jiani Li[1,2], Jianxing Hu[1,2], Haoyu Chen[1,2], Jun Xu[1,2,3,4], Sha Yin [1,2,3*]

[1] Department of Automotive Engineering, School of Transportation Science and Engineering, Beihang University, Beijing, China, 100191
[2] Advanced Vehicle Research Center, Beihang University, Beijing, China, 100191
[3] State Key Laboratory for Strength and Vibration of Mechanical Structures, School of Aerospace Engineering, Xi'an Jiaotong University, Xi'an, China, 710049
[4] State Key Laboratory of Automotive Safety and Energy, Tsinghua University, Beijing, China, 100084

Keywords: Lattice materials, Mechanical properties, Hierarchy

ABSTRACT

The natural material featuring hierarchical structure are always of remarkable mechanism properties. Generally, most researches are focused on the quasi-static mechanical properties while limited researches analyze the dynamic mechanical behavior of hierarchical materials. In this paper, hierarchical mechanical metamaterials were fabricated, and dynamic mechanical properties were studied experimentally and simulationally. Applying 3D laser lithography, we produced hierarchical metamaterials of different orders. After plating with electrodeposited Ni coatings and removing the polymer cores inside, we finally obtained finished samples including three material systems. Compression experiments under different strain rates were performed for dynamic mechanical characterization. The results revealed that the number of orders and material systems of hierarchical metamaterials significantly effected their dynamic mechanical behavior and energy absorption. To further explain the underlying deformation mechanisms, simulation models were established and validated by comparing with experiments. This study will shed light on designing hierarchical materials of different length scales for crushing protection.

1 INTRODUCTION

The natural material featuring hierarchical structure such as cancellous bone, radiolarians and fruit peels are always of remarkable mechanism properties such as high strength to weight ratios, tunable mass density, near-infinite bulk to shear modulus ratios [1-2], and negative Poisson's ratios [3-5]. Thus, understanding about how hierarchical construction enhances material properties is vital for designing artificial biomimeticing materials. Generally, most researches are focused on the quasi-static mechanical properties [6-8] while limited researches analyze the dynamic mechanical behavior of hierarchical materials. In this paper, hierarchical mechanical metamaterials were fabricated, and dynamic mechanical properties were studied experimentally and simulationally.

2 EXPERIMENTAL

2.1 Fabrication

Hierarchical architected materials were designed following a recursive method, where FCC (face center cubic) unit cells were arranged along the axes of the higher-order FCC lattice element, as illustrated in Fig.1. Applying 3D laser lithography, we produced hierarchical metamaterials of different orders. After plating with electrodeposited Ni coatings and removing the polymer cores inside, we finally obtained finished samples including three material systems, (i) solid polymer, (ii) composites with a polymer core and a nickel coating, and (iii) hollow nickel.

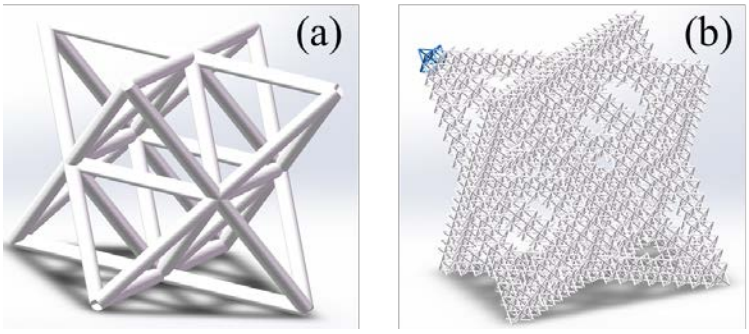

Fig.1 Hierarchical mechanical metamaterials of different orders. (a) Image of the first-order FCC sample. (b) Image of the second-order FCC sample. FCC unit cells were arranged to create the second-order FCC lattice element.

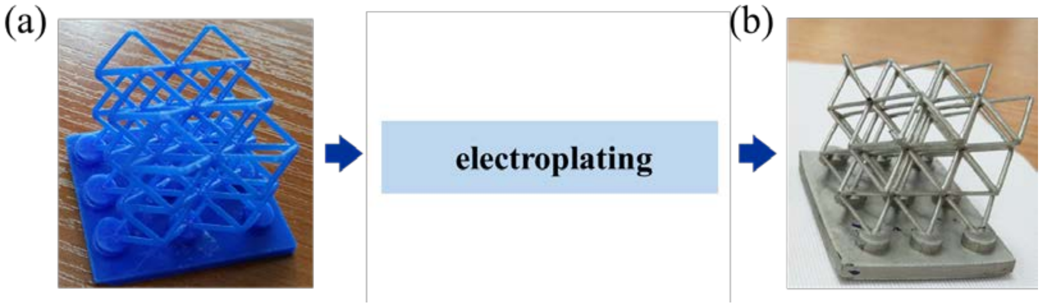

Fig.2 Samples by different fabrication processes: (a) The polymer architected materials by 3d printing; (b) hollow nickel architected materials or composites by electro and coating.

2.2 Testing

Compression experiments under different strain rates were performed by HPB tests for dynamic mechanical characterization. The test was first performed without a lattice sample at the impact plane of the HPB to establish the baseline of the load generated by the impactor. Then high rate impact experiments were conducted on samples with different material systems and hierarchical orders. At least two repeated tests for each type of structure were performed to ensure the repeatability. The results revealed that the number of orders, the material systems of hierarchical metamaterials and different strain rates significantly effected their dynamic mechanical behavior and energy absorption.

2.3 Simulation

To further explain the underlying deformation mechanisms, simulation models were established and validated by comparing with experiments. The finite element method can be effective and credible for the prediction of the mechanical behavior and failure modes of lattices.

3 CONCLUSIONS

Hierarchical mechanical metamaterials were fabricated, and dynamic mechanical properties were studied experimentally and simulationally. The results demonstrated that the number of orders, material systems of hierarchical metamaterials and strain rates significantly effected their dynamic mechanical behavior and energy absorption. This study will shed light on designing hierarchical materials of different length scales for crushing protection.

ACKNOWLEDGEMENTS

This work is financially supported by Opening fund of State Key Laboratory for Strength and Vibration of Mechanical Structures, Xi'an Jiaotong University (SV2015-KF-07, SV2016-KF-20), and Opening fund of State Key Laboratory for Automotive Safety and Energy, Tsinghua University (Grant No. KF16142).

REFERENCES

[1] Kadic, M., et al., On the practicability of pentamode mechanical metamaterials (vol 100, 191901, 2012). *Applied Physics Letters*, 2012. 101(4).

[2] Bueckmann, T., et al., An elasto-mechanical unfeelability cloak made of pentamode metamaterials. *Nature Communications*, 2014. 5.

[3] Mousanezhad, D., et al., Hierarchical honeycomb auxetic metamaterials. *Scientific Reports*, 2015. 5.

[4] Kroedel, S., et al., 3D Auxetic Microlattices with Independently Controllable Acoustic Band Gaps and Quasi-Static Elastic Moduli. *Advanced Engineering Materials*, 2014. 16(4): p. 357-363.

[5] Bueckmann, T., et al., Tailored 3D Mechanical Metamaterials Made by Dip-in Direct-Laser-Writing Optical Lithography. *Advanced Materials*, 2012. 24(20): p. 2710-2714.

[6] Meza, L.R., et al., Resilient 3D hierarchical architected metamaterials. *Proceedings of the National Academy of Sciences of the United States of America*, 2015. 112(37): p. 11502-11507.

[7] Yin, S., L. Wu, and S. Nutt, Stretch–bend-hybrid hierarchical composite pyramidal lattice cores. *Composite Structures*, 2013. 98(0): p. 153-159.

[8] Torrents, A., et al., Characterization of nickel-based microlattice materials with structural hierarchy from the nanometer to the millimeter scale. *Acta Materialia*, 2012. 60(8): p. 3511-3523.