Research on the Design Method of Multi-Material Heterogeneous Lattice Energy-Absorbing Structures

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Abstract. Aiming to address the challenges posed by the current single-material 3D printing technology in meeting the requirements of complexity and diversity, this paper introduces an innovative design approach for a multi-material heterogeneous lattice energy-absorbing sandwich structure. This design method draws inspiration from the hierarchical gradient structure found in natural porous materials like tortoise shells and pomelo skins and the design of multi-material gradient structures seen in products like helmets. The multi-material gradient lattice structure has proven superior in energy absorption by introducing the integrated design of multi-materials and gradients. This advancement aims to enhance further multi-material 3D printing technology to meet various demands.

Keywords: Multi-material Objects, Heterogeneous Energy-absorbing Structures, Lattice Structure, Additive Manufacturing.
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1 INTRODUCTION

Due to the modern manufacturing industry's rapid development, 3D printing technology is widely used in a variety of fields, including the biomedical, aerospace, and construction industries [17]. However, the demands for multifunctional and multi-layered structures are now too great for the current traditional single-material 3D printing technology, and multi-material 3D printing technology can achieve integrated molding of heterogeneous structures as well as parallel design and manufacturing of part structure and function [20]. This technology has grown to be crucial for a breakthrough in the market. By contrasting multi-material structures with single-material designs, the superior benefits of multi-material structures in terms of performance and design freedom have been confirmed [15,18].

Lattice structures have excellent properties, such as high specific stiffness and high specific strength, and are widely used in energy-absorbing structures. At present, energy-absorbing structures primarily consist of homogeneous lattice structures or gradient lattice structures made of a single material. Further development is needed in the research on energy-absorbing structures composed of multi-material heterogeneous lattices. When compared to conventional single-material uniform lattice sandwich constructions, single-material gradient sandwich architectures perform better [1,4]. The choice of materials still limits single-material gradient sandwich structures, despite their greater flexibility as compared to single-material uniform lattice sandwich structures. This work addresses this difficulty by presenting a novel structure that is intended to satisfy intricate performance requirements. To address the shortcomings of the existing technology and advance multi-material 3D printing to meet a wider range of needs, we are introducing the integrated design of multi-material, gradient, and multi-type lattices.

In this paper, an innovative approach to designing multi-material heterogeneous lattice energy-absorbing structures is presented. The remaining sections of the paper are allocated as follows: in Section 2, the current research status of related work is briefly described. In Section 3, the multi-material heterogeneous lattice energy-absorbing structure is designed, and a finite element model setup is performed. In Section 4, simulated impact experimental results are analyzed. In Section 5, a multi-material 3D printed model is produced using the FDM process. In Section 6, a conclusion is made, and future work is proposed.

2 RELATED WORK

2.1 Research Status of Multi-Material 3D Printing Technology

Currently, research in the field of multi-material 3D printing is rapidly advancing. There have been many research studies dedicated to developing new multi-material 3D printing technologies and materials to meet the diverse needs of various fields [32]. The current research focuses on the selection of multiple materials, optimization of printing parameters, and interfacial bonding between these materials. Some studies have explored ways to combine different materials for printing, such as by mixing materials, using multiple nozzles, or employing multiple beams [2]. Scholars like Nazir have comprehensively summarized the operations of multi-material additive manufacturing systems and their underlying processes, systematically reviewing multi-material combinations and their design, modeling, and analysis strategies [22]. Venumbaka and others have demonstrated the potential of achieving a fully customized orthosis through multi-material 3D printing. Two different materials, polylactic acid (PLA) and thermoplastic polyurethane (TPU), were chosen to enhance the orthosis's flexibility and rigidity. The results showed that the method was able to solve some of the problems associated with traditional plaster models [26]. Liu et al. conducted experimental and statistical studies to investigate the effect of soft and hard material process parameters on the bending behavior of multi-material structures prepared by material extrusion and multi-material additive manufacturing. The study examined the impact of printing speed and nozzle temperature on the bending behavior of soft and hard sandwich beams [19].

There are also studies focusing on process optimization for multi-material 3D printing to enhance print quality and efficiency. Broadly speaking, there are several categories of multi-material 3D printing technologies. Material Jetting (MJ): This process can utilize multiple materials for component fabrication and is capable of printing with high precision using multiple light-curing materials simultaneously [27,30]. It works similarly to traditional inkjet printing by stacking tiny droplets layer by layer to create components on a build platform. Material Extrusion (ME) is a process that utilizes thermoplastic materials [23,28], composites [7,8,9], metal-filled thermoplastic materials [13,21], and flexible elastomers [31] to create components layer by layer. Among them, Fused Deposition Modeling (FDM) is the more common material extrusion method in which filamentary materials are melted by an extrusion head and then deposited on the build plate point by point and layer by layer. Another method, Direct Ink Writing (DIW), is capable of fabricating multi-material components at a lower cost. DIW operates in a similar manner to FDM, but DIW uses a direct heating source to create the components. In this process, the material is introduced as a liquid, then pressure is applied, mixed by a rotating impeller, and finally exits through a nozzle [24]. Powder Bed Fusion (PBF) is a process in which a thermal energy source selectively melts powder particles (plastics, metals, or ceramics) within a build area to create solid objects layer by layer. Powder Bed Fusion 3D printers spread a thin layer of powder material on a print bed, usually using a blade, roller, or wiper. Energy from a laser fuses specific points on the powder layer then deposits another powder layer and fuses it to the previous layer. The process is repeated until the entire object is fabricated, with the final product being encapsulated and supported by the unfused powder [10,11]. Vat-photopolymerization (VAT) is performed using Stereolithography Appearance (SLA) technology, using photosensitive resins to fabricate materials with very high precision and excellent surface roughness [3,16]. Light curing is a process in which the polymer molecules of the deposited materials combine to form crosslinked polymer macromolecules when UV light is irradiated onto the deposited materials, transforming the deposited materials from a liquid or semi-solid state to a solid state. Directional Energy Deposition (DED) includes Laser Metal Deposition (LMD) and DED. Deposition (LMD), Laser Engineered Net Shaping (LENS), and Digital Micromirror Device (DMD) are some of the techniques used [6]. In these processes, the material is melted by a laser, electron beam, or plasma arc in a controlled area. The melting process necessitates the use of inert gas to prevent oxidation of the melt pool. The DED process involves blowing powdered material through a nozzle, which is then melted and deposited layer by layer onto a substrate before being cured. Figure 1 shows a schematic of various types of multi-material 3D printing technology processes.

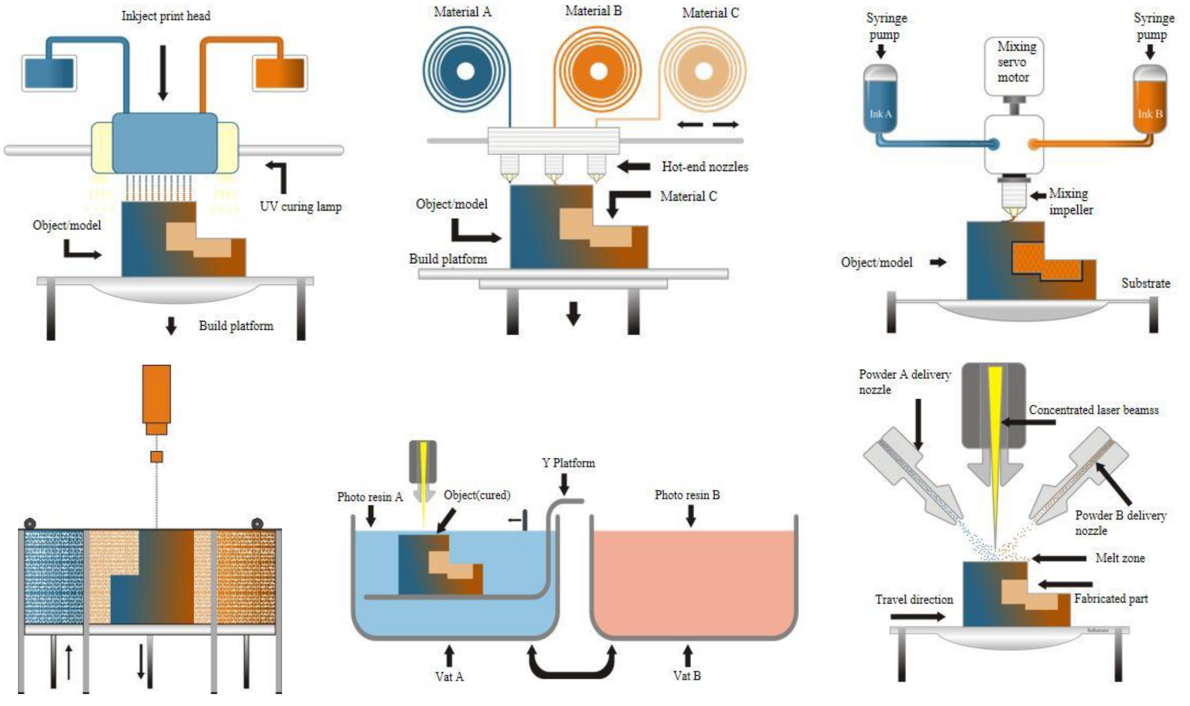

Figure 1: (a) Schematic diagram of multi-material MJ process, (b) Schematic diagram of FDM process of multi-extrusion head, (c) Multi-material DIW process diagram, (d) Process diagram of multi-material PBF, (e) Schematic diagram of multi-material VAT process, and (f) Schematic diagram of multi-material DED process.

Numerous studies have focused on the issue of interfacial bonding between different materials to enhance the strength and stability of structures. However, despite some progress, there are still challenges in multi-material 3D printing, such as material selection, compatibility, and material distortion during the printing process. Therefore, future research needs to delve deeper into all aspects of multi-material 3D printing to enhance the application of this technology across various fields.

2.2 Research Status of Heterogeneous Energy-Absorbing Structure Design Methods

Research on the design method of heterogeneous energy-absorbing structures has also received wide attention. This structural design method aims to achieve the absorption and dispersion of impact or vibration energy by selecting and arranging different materials rationally. In recent years, researchers have proposed a variety of design ideas and optimization strategies. On the one hand, methods based on topological optimization have been applied to the design of heterogeneous energy-absorbing structures. These methods aim to optimize the structure's topology to enhance its energy absorption capacity by determining the best material distribution and connection methods. On the other hand, research on material selection and combination is also a current hot topic. Researchers have explored different materials' mechanical properties, energy-absorbing mechanisms, and interactions to achieve more efficient energy-absorbing structural designs. San et al. proposed a new bionic layered circular honeycomb to investigate the structure's mechanical properties and energy-absorbing characteristics through quasi-static compression tests and finite element (FE) analyses. The results indicate that it has higher specific energy absorption, and the relative stiffness, strength, and energy absorption are significantly greater than those of other cellular structures [25]. Gao and colleagues were inspired by the foam-filled structure and proposed a thin-walled structure with a gradient to study its energy absorption characteristics. They developed a theoretical model to predict energy absorption, which was validated through numerical simulations to predict the energy absorption properties [12]. He and colleagues investigated several multicellular lattice structures using experimental and simulation analysis methods and identified lattice structures with excellent energy absorption properties. These structures were fabricated using a fused deposition modeling (FDM) 3D printer [14].

Computational simulation methods play a crucial role in designing heterogeneous energy-absorbing structures. With the assistance of numerical methods like finite element analysis (FEA) and molecular dynamics simulation, the performance of energy-absorbing structures can be assessed and optimized. These methods can also offer guidance for experimental validation [29]. Although some progress has been made, the design methodology of heterogeneous energy-absorbing structures still faces challenges. Therefore, future research needs to further explore various design methods and material combinations in depth to promote the widespread application of heterogeneous energy-absorbing structures in engineering practice.

3 MULTI-MATERIAL HETEROGENEOUS LATTICE ENERGY ABSORBING STRUCTURES

3.1 Structural Design

There are many porous structures in nature. Two examples are grapefruit peels and turtle shells, which feature amazing multilayered gradient systems that serve a number of purposes in addition to providing supporting qualities. Locally, the structure of nature is non-regular, but there is also a gradient from dense to sparse, and as a whole, the structure of nature is somewhat regular; it is a gradient. For instance, the hierarchical structure of a turtle shell, as illustrated in Figure 2, is composed of cuticle, hard outer dense bone, soft fibrous closed-cell foam that is arranged randomly, and hard inner dense bone that runs from top to bottom. It is important to note that the fibrous closed-cell foam exhibits a gradient structure with a gradual thinning, making it possible to defend the body's interior tissues from external impacts more effectively. As illustrated in Figure 2, the gradient distribution of grapefruit skin, which is composed of three parts: exocarp, mesocarp, and endocarp, is likewise comparable. These gradient patterns in nature with several materials offer important insights.

Similar multi-material gradient structures are used in the fabrication of helmets and other items in the current industries. Helmets, for instance, usually have three layers of material: an EPS inner shell, an ABS outer shell, and a skin-friendly mesh. This work proposes a novel multi-material heterogeneous energy-absorbing sandwich construction that is inspired by these multi-material gradient structures. The structure mimics the multi-level gradient structure found in nature and possesses a regular design.

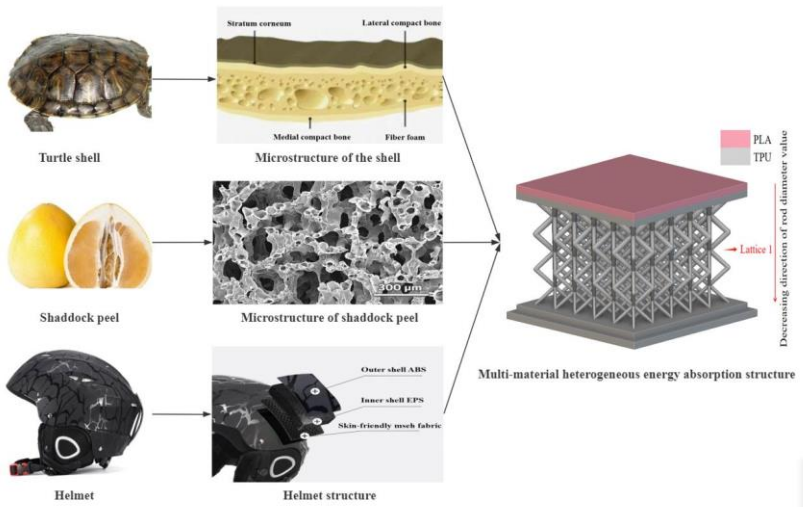

Figure 2: Design process of multi-material heterogeneous energy-absorbing sandwich structure.

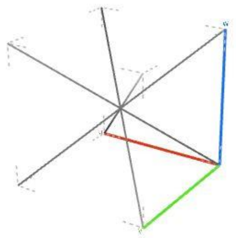

Figure 3: Lattice 1 cell unit.

More specifically, as Figure 2 illustrates, we created a multi-material heterogeneous energy-absorbing structure. The initial layer of material in its composition is PLA, and the second, third, and fourth layers are made of TPU. The third layer's lattice core, which is made up of lattice1 with a gradient of rod sizes ranging from large to small, is of special interest. Figure 3 displays the cellular unit of the lattice 1. Consequently, this construction has a good energy absorption effect, a stiff exterior, and a flexible inside. It also offers a novel concept for the creation of a multi-material heterogeneous energy-absorbing sandwich structure.

3.2 Finite Element Model Setup

In this study, the Explicit Dynamics analysis method in the simulation software ANSYS Workbench is used to impact the finite element model and solve the dynamic impact process. As demonstrated in Figure 4, the simulation model of the impact established in this study, the energy-absorbing structure is subjected to a punching impact, kinetic impact collision, and fall analysis, and glass is used as a protected part to analyze the equivalent force on the protected part as well as the specific energy absorption of the energy-absorbing structure. In this simulation, an elastic material model is used to describe the behavior of the projectile. The model is mainly based on Hooke's law, which states that stress is proportional to strain. This means that when the projectile is impacted, elastic deformation occurs, but no permanent deformation occurs. Instead, a nonlinear elastic model is used for structures subjected to impact. This model better captures the non-linear behavior of the material over a large strain range, thus improving the accuracy and reliability of the response to the structure.

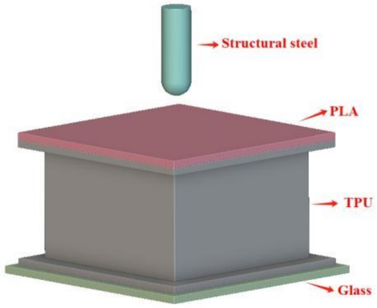

Figure 4: Impact simulation model.

In addition to the lattice area around the other surfaces and the bottom of the glass of the protected parts to add boundary conditions, a total of 13 surfaces are taken into account by the finite element model while reducing and simplifying the working conditions. The dynamic impact test is conducted using bound contact as the contact mode and 22℃ as the impact simulation's ambient temperature. The punch's form and shape are used in the impact energy absorption test. According to Figure 4, impact energy absorption studies utilizing a punch with a height of 20 mm and a radius of 4 mm are defined as a projectile; tetrahedral meshing was used with a mesh size of 5 mm. At this point, the equivalent force transmitted to the protected components should not exceed 60 MPa. The projectile model in the energy-absorbing structure above 10 mm is only permitted to move in the impact direction at an initial speed of 15 m/s. This allows the projectile mass to be weighted at 6 kg by utilizing the increased equivalent density. Simulation affects experiment material parameter settings, as Table 1 illustrates.

Materials	*Density*	*Young's Modulus*	*Poisson's Ratio*
PLA	1260kg/m^3	1820MPa	0.33
TPU	1200kg/m^3	26MPa	0.33
Projectile Rigid Material	5.27×10^6kg/m^3	200GPa	0.3
Glass	2500kg/m^3	80GPa	0.3

Table 1: Parameter settings of materials for simulated impact experiments.

We set up a total of 7 simulation experimental structures in this research because we need to investigate the impacts of material type, lattice type, and rod diameter gradient on energy absorption, respectively. As seen in Figure 5, seven simulation experimental structure finite element models, referred to as S1-S7, are produced by importing the geometric model of the experimental structure into Explicit Dynamics in ANSYS Workbench for pre-processing.

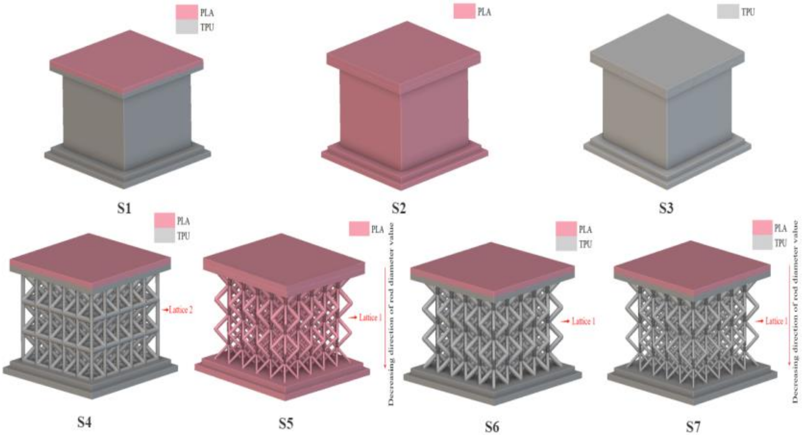

Figure 5: Simulated experimental structure finite element model.

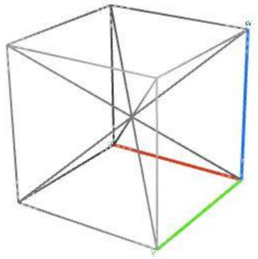

Figure 6: Lattice 2 cell unit.

The simulation impact experimental framework is configured as Table 2 illustrates. S1 is a monolithic construction composed of TPU and PLA materials. The PLA and TPU solids, respectively, are denoted by S2 and S3. S4 is the sandwich structure of lattice 2 made of PLA and TPU materials without a gradient in rod diameter. Figure 6 depicts the lattice 2-cell unit. Among them, S5 is borrowed from Cheng Shuliang [5] et al., who used the drop hammer impact test to study the local impact dynamic characteristics of the X-type dot-matrix sandwich structure. S6, which consists of PLA and TPU materials, is the sandwich structure of lattice 1 without a gradient in rod diameter. The sandwich structure of lattice 1, or S7, is made of PLA and TPU and has a rod diameter that decreases from top to bottom. As demonstrated in Figure 7, The lattice structure and the upper and lower plates are contacted with Boolean Union, and rounded corners are made at the contact locations with a size of 0.5mm to avoid buckling and stress concentration in the corners of the lattice structure.

3.3 Evaluation Indicators for Energy Absorption

In order to analyze and evaluate the energy absorption effect of the seven structures, the Specific Energy Absorption (SEA) and the Von Mises stress on the protected parts were used as the evaluation indices for the energy absorption characteristics of the six structures. SEA and Von-Mises stress on the protected parts are used as the evaluation indices of energy absorption.

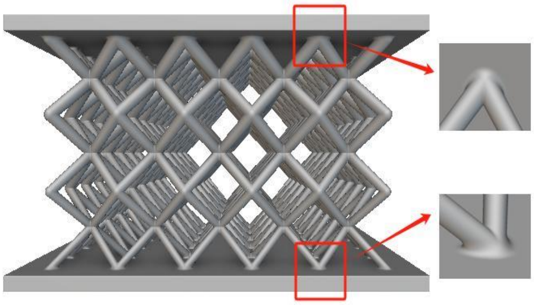

Figure 7: Lattice structure and localized contact position of the upper and lower plates.

Structural parameters / *Name of structure*	*Material type*	*Lattice type*	*Gradient of rod diameter*
S1	PLA+TPU	No	No
S2	PLA	No	No
S3	TPU	No	No
S4	PLA+TPU	Lattice 2	No
S5	PLA	Lattice 1	Rod diameter decreases from top to bottom
S6	PLA+TPU	Lattice 1	No
S7	PLA+TPU	Lattice 1	Rod diameter decreases from top to bottom

Table 2: Structure of the simulated impact experiment.

(1) Specific Energy Absorption (SEA). SEA is the energy absorbed per unit mass, which characterizes the energy absorption rate of the material. In other words, the larger the SEA, the more energy is absorbed by the material. It characterizes the energy absorption efficiency of the material; that is, the larger the specific absorption energy, the stronger the energy absorption capacity of the structure. It is defined as:

$$SEA = \frac{EA}{M} \tag{3.1}$$

Where EA represents the total energy absorbed by the energy-absorbing structure in the impact process, and M stands for the mass of the energy-absorbing structure.

(2) Von-Mises stress on the protected parts. The lower the stress on the protected parts, the greater the energy absorption capacity of the structure.

4 SIMULATION OF IMPACT EXPERIMENT RESULTS ANALYSIS

As demonstrated in Figure 8 for the S1-S7 group of structural simulation impact experiments than the energy absorption, the results of the stress on the protective sections, shown in Table 3 S1-S7 group of structural simulation results data.

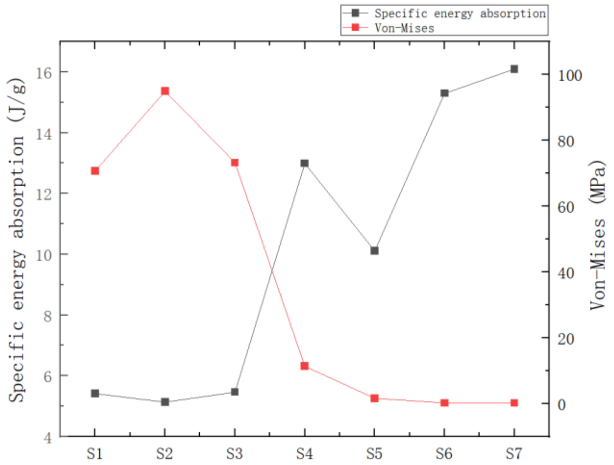

Figure 8: Comparison of the absorbed energy and stress on the protected parts in the simulated impact experiments of group S1-S7 structures.

Contrast index / *Name of structure*	*Specific energy absorption/J•g^{-1}*	*Von Mises on the protected object/MPa*
S1	5.41	70.76
S2	5.13	94.92
S3	5.46	73.21
S4	12.99	11.34
S5	10.11	1.6
S6	15.3	0.19
S7	16.1	0.16

Table 3: S1-S7 group structure simulation result data.

Comparing and analyzing the results of simulation compression experiments in Figure 7 and Table 3, the following conclusions can be drawn:

(1) We thoroughly compared S1, S2, and S3 in the first set of comparative experiments. With a specific absorption energy of 5.41 J·g^{-1}, S1 produced an equivalent force of 70.76 MPa on the protected parts; S2 produced an equivalent force of 94.92 MPa with a specific absorption energy of

5.13 $J \cdot g^{-1}$; and S3 produced an equivalent force of 73.21 MPa with a specific absorption energy of 5.46 $J \cdot g^{-1}$ on the protected parts. It is clear that S1 absorbs energy more efficiently than S2, and even though S1 and S3 have nearly identical specific absorption energies, S1's protected areas are under less stress than S3's.

(2) In the second set of comparative experiments, we analyzed S1, S4 and S6: the specific absorption energy of S1 was 5.41 $J \cdot g^{-1}$, resulting in an equivalent force of 70.76 MPa on the protected part; the specific absorption energy of S4 was 12.99 $J \cdot g^{-1}$, resulting in an equivalent force of 11.34 MPa; and the specific absorption energy of S6 was 15.3 $J \cdot g^{-1}$, resulting in an equivalent force of only 0.19 MPa. It is evident that S4 and S6 have the same specific absorption energy as S1, and that S6 has a greater energy absorption impact than S4.

(3) We conducted a thorough comparison between S5, S6 and S7 in the third set of comparative studies. S5 has a specific absorption energy of 10.11 $J \cdot g^{-1}$, and the protected part's equivalent stress is 1.6 MPa. S6 has a specific absorption energy of 15.3 $J \cdot g^{-1}$, and the protected part's equivalent stress is 0.19 MPa. S7 has a specific absorption energy of 16.1 $J \cdot g^{-1}$, which means that the shielded component would experience an equivalent stress of 0.16 MPa. S7's energy absorption effect is generally noticeably superior to S5's and S6's.

When considering all of the materials combined, the multi-material solid structure performs better in terms of energy absorption than the single-material solid structure. Further observation suggests that the multi-material uniform lattice sandwich construction is superior than the multi-material solid structure in energy absorption. In the meantime, the multi-material gradient lattice structure performs better in terms of energy absorption than the multi-material uniform lattice sandwich construction.

5 MULTI-MATERIAL 3D PRINTING MODEL FABRICATION

Using the FDM process, PLA and TPU materials were selected for the fabrication of the multi-material 3D printed model. As illustrated in Figure 9, the white area is the PLA material, while the red area represents the TPU material.

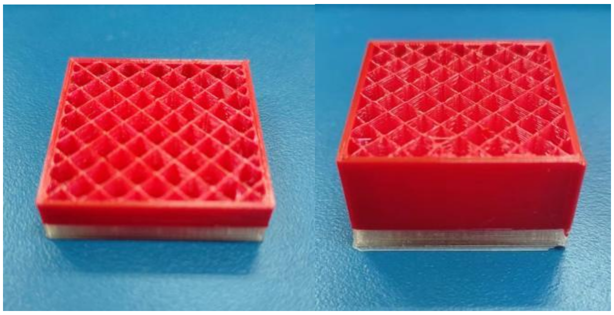

Figure 9: Multi-material 3D printing model.

6 CONCLUSIONS

In this work, we have effectively created a novel, multi-material, heterogeneous sandwich construction that absorbs energy, modeled after structures like turtle shells. Multiple materials and gradient variations are used in the building. The printing procedure of the multi-material heterogeneous energy-absorbing sandwich structure is more complex than that of the already existing energy-absorbing structures because it necessitates varying the rod diameter gradient and selecting a dot matrix type. Consequently, more research is required to determine the best choice of dot matrix units and to enhance the process of printing multi-material heterogeneous energy-absorbing sandwich structures.

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REFERENCES

[1] B, J.; Muthukannan, D.: Investigations on the compressive behaviour of novel cell size graded primitive lattice structure produced by Metal Additive Manufacturing, Materials Letters, 2023, 333. https://doi.org/10.1016/J.MATLET.2022.133643

[2] Bandyopadhyay, A.; Heer, B.: Additive manufacturing of multi-material structures[J]. Materials Science and Engineering: R: Reports, 2018, 129: 1-16. https://doi.org/10.1016/j.mser.2018.04.001

[3] Bagheri, A.; Jin, J.: Photopolymerization in 3D Printing, ACS Applied Polymer Materials, 2019, 1(4): 593-611. https://doi.org/10.1021/acsapm.8b00165

[4] Cui, L.; Kiernan, S.; Gilchrist, D.-M.: Designing the energy absorption capacity of functionally graded foam materials, Materials Science & Engineering A, 2008, (1), 215-225. https://doi.org/10.1016/j.msea.2008.12.011

[5] Cheng, S.-L.; Wu, L.-J.; Sun, S.: Experiment and numerical simulation of dynamic mechanical properties of X-lattice sandwich structure under local impact, Acta Materiae Compositae Sinica, 2022, 39(7): 3641-3651.https://doi.org/10.13801/j.cnki.fhclxb.20210903.005

[6] Dass, A.; Moridi, A.: State of the art in directed energy deposition: From additive manufacturing to materials design, Coatings, 2019, 9(7): 418. https://doi.org/10.3390/coatings9070418

[7] Gupta, A.; Fidan, I.; Hasanov, S.: Processing, mechanical characterization, and micrography of 3D-printed short carbon fiber reinforced polycarbonate polymer matrix composite material, The International Journal of Advanced Manufacturing Technology, 2020, 107(7-8): 3185-3205. https://doi.org/10.1007/s00170-020-05195-z

[8] Gupta, A.; Hasanov, S.; Fidan, I.: Homogenized modeling approach for effective property prediction of 3D-printed short fibers reinforced polymer matrix composite material, The International Journal of Advanced Manufacturing Technology, 2021, 118(11-12): 4161-4178. https://doi.org/10.1007/s00170-021-08230-9

[9] Gupta, A.; Hasanov, S.; Fidan, I.: Processing and characterization of 3D-printed polymer matrix composites reinforced with discontinuous fibers, 2019. http://dx.doi.org/10.26153/tsw/17341

[10] Gokcekaya, O.; Ishimoto, T.; Todo, T.: Influence of powder characteristics on densification via crystallographic texture formation: Pure tungsten prepared by laser powder bed fusion, Additive Manufacturing Letters, 2021, 1: 100016. https://doi.org/10.1016/j.addlet.2021.100016

[11] Glerum, J.-A.; Hocine, S.; Chang, C.-S.-T.: Operando X-ray diffraction study of thermal and phase evolution during laser powder bed fusion of Al-Sc-Zr elemental powder blends, Additive Manufacturing, 2022, 55: 102806. https://doi.org/10.1016/j.addma.2022.102806

[12] Gao, Q.; Liao, W.-H.: Energy absorption of a thin-walled tube filled with gradient auxetic structures-theory and simulation, International Journal of Mechanical Sciences, 2021, 201: 106475. https://doi.org/10.1016/j.ijmecsci.2021.106475

[13] Hasanov, S.; Fidan, I.: Manufacturing of Soft Magnets using the Fused Filament Fabrication Process, MatEDU Resource Center, 2020. https://doi.org/doi.org/10.13140/RG.2.2.32731.90407
[14] He, G.; Yang, H.; Chen, T.: Lattice Structure Design Method Aimed at Energy Absorption Performance Based on Bionic Design, Machines, 2022, 10(10): 965. https://doi.org/10.3390/machines10100965
[15] Imbalzano, G.; Tran, P.; Ngo, D.-T.; Lee, P.-VS.: Three-dimensional modelling of auxetic sandwich panels for localised impact resistance, Journal of Sandwich Structures Materials, 2017, 19(3): 291-316. https://doi.org/10.1177/1099636215618539
[16] Ian Gibson, I.-G.: Additive manufacturing technologies 3D printing, rapid prototyping, and direct digital manufacturing[J]. 2015. https://doi.org/10.1007/978-1-4939-2113-3
[17] Lu, B.; Li, D.: Additive Manufacturing (3D printing) technology development, Mechanical manufacturing and automation, 2013, 42(04): 1-4. https://doi.org/10.19344/j.cnki.issn1671-5276.2013.04.001
[18] Liu, B.; Cui, Y.: Topology optimization of multi-material structures considering anisotropic yield strengths, Computer Methods in Applied Mechanics and Engineering, 2024, 418: 116520. https://doi.org/10.1016/J.CMA.2023.116520
[19] Liu, Q.; Zhang, Z.; Yavas, D.: Multi-material additive manufacturing: effect of process parameters on flexural behavior of soft-hard sandwich beams, Rapid Prototyping Journal, 2023, 29(5): 885-896. https://doi.org/10.1108/RPJ-07-2022-0231
[20] Liu, Y.; Yang, H.; Zhao, Y.-F.; Zheng, G.: A heterogeneous lattice structure modeling technique supported by multiquadric radial basis function networks, Journal of Computational Design and Engineering, 9(1), 68–81. https://doi.org/10.1093/jcde/qwab069
[21] Mohammadizadeh, M.; Lu, H.; Fidan, I.: Mechanical and thermal analyses of metal-PLA components fabricated by metal material extrusion, Inventions, 2020, 5(3): 44. https://doi.org/10.3390/inventions5030044
[22] Nazir, A.; Gokcekaya, O.; Billah, K.-M.-M.: Multi-material additive manufacturing: A systematic review of design, properties, applications, challenges, and 3D Printing of materials and cellular metamaterials, Materials & Design, 2023: 111661. https://doi.org/10.1016/j.matdes.2023.111661
[23] Nasirov, A.; Hasanov, S.; Fidan, I.: Prediction of mechanical properties of fused deposition modeling made parts using multiscale modeling and classical laminate theory, 2019. http://dx.doi.org/10.26153/tsw/17367
[24] Rocha, V.-G.; Saiz, E.; Tirichenko, I.-S.: Direct ink writing advances in multi-material structures for a sustainable future, Journal of Materials Chemistry A, 2020, 8(31): 15646-15657. https://doi.org/10.1039/D0TA04181E
[25] San, Ha.-N.; Pham, T.-M.; Tran, T.-T.: Mechanical properties and energy absorption of bio-inspired hierarchical circular honeycomb, Composites Part B: Engineering, 2022, 236: 109818. https://doi.org/10.1016/j.compositesb.2022.109818
[26] Venumbaka, S.-A.; Covarubias, M.; Cesaro, G.: Application of multi materials additive manufacturing technique in the design and manufacturing of hand orthoses[C]//Computers Helping People with Special Needs: 17th International Conference, ICCHP 2020, Lecco, Italy, September 9–11, 2020, Proceedings, Part II 17. Springer International Publishing, 2020: 461-468. https://doi.org/10.1007/978-3-030-58805-2_55
[27] Vu, I.-Q.; Bass, L.-B.; Williams, C.-B.: Characterizing the effect of print orientation on interface integrity of multi-material jetting additive manufacturing, Additive Manufacturing, 2018, 22: 447-461. https://doi.org/10.1016/j.addma.2018.05.036
[28] Wickramasinghe, S.; Do, T.; Tran, P.: FDM-based 3D printing of polymer and associated composite: A review on mechanical properties, defects and treatments, Polymers, 2020, 12(7): 1529. https://doi.org/10.3390/polym12071529
[29] Wu, Y.; Fang, J.; Wu, C.: Additively manufactured materials and structures: A state-of-the-art review on their mechanical characteristics and energy absorption, International Journal of Mechanical Sciences, 2023: 108102. https://doi.org/10.1016/j.ijmecsci.2023.108102

[30] Yap, Y.-L.; Wang, C.; Sing, S.-L.: Material jetting additive manufacturing: An experimental study using designed metrological benchmarks, Precision Engineering, 2017, 50: 275-285. https://doi.org/10.1016/j.precisioneng.2017.05.015
[31] Yin, J.; Lu, C.; Fu, J.: Interfacial bonding during multi-material fused deposition modeling (FDM) process due to inter-molecular diffusion, Materials & Design, 2018, 150: 104-112. https://doi.org/10.1016/j.matdes.2018.04.029
[32] Zheng, X.; Williams, C.; Spadaccini, C.-M.: Perspectives on multi-material additive manufacturing, Journal of Materials Research, 2021, 36: 3549-3557. https://doi.org/10.1557/s43578-021-00388-y