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Compressive properties optimization of a bio-inspired lightweight structure fabricated via selective laser melting

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Abstract

Compressive properties optimization of a bio-inspired lightweight structure is developed by Response Surface Methodology (RSM) and Non-dominated Sorting Genetic Algorithm II (NSGA-II). Multi-layered bio-inspired structures of a Ti6Al4V alloy are designed and fabricated by Selective Laser Melting. The results show that the optimized structure parameters of bio-inspired structures can be obtained by RSM and NSGA-II. The relative error rate of experimental results and response values is less than 10%. Moreover, increasing the number of layers cannot effectively improve energy absorption (EA) and specific energy absorption (SEA) for multi-layered bio-inspired structures. The damage process of bio-inspired structures with different core-arranged configurations fails layer by layer. The load-displacement curves and damage process of FE simulations are consistent with the experimental results.

Keywords: Bio-inspired structure; Selective laser melting; NSGA-II; Multi-layers

Introduction

Owing to their high specific strength, anti-vibration, energy absorption, and excellent buffering capacity，lightweight sandwich structures are widely used in aerospace, automobile and military applications [1-5]. However, higher requirements for excellent mechanical properties and lightweight structures are put forward with the rapid development of the aerospace and aviation fields [6]. However, nature has developed a mass of perfect performance structures and materials by evolving for thousands of years [7-9].

Among them, the beetle elytra are considered as a better bio-inspired prototype owing to its particular microstructure and excellent mechanical properties [10]. Thus, inspired by the beetle elytra, a large number of lightweight structures have been designed, fabricated and analyzed [2, 11-12]. However, those investigations also indicated that bio-inspired structures were generally designed according to the shape or profile features of biological prototypes [13-15]. Excellent mechanical properties of bio-inspired structures are closely related to those structural parameters and their interactions though it is difficult to analyze [16]. Thus, the structural optimization plays an essential role in understanding the relationship between structural parameters and mechanical properties. However, traditional optimization methods such as orthogonal design, homogeneous design, and factorial analysis methods not only take a number of experiments but also cannot explain the interactions between structural parameters well [17]. Comparatively, response surface methodology (RSM) [18] is considered as the most relevantly utilized method for optimization analysis, and it is also known for building empirical models and analyzing the influence of independent variables to several dependent variables [19]. Most importantly, RSM can obtain a specific mathematical equation which considers the influence of interactions between structural parameters on optimization variables. Moreover, the multi-objective optimization is very necessary in order to design a multi-functional bio-inspired lightweight structure. Genetic algorithm (GA) is a promising tool for solving multi-objective optimization problems [20], which has a good global search ability, fast process speed and high optimization precision when objective functions have specific equations. Thus, an important method is developed on the multi-objective optimization of bio-inspired structures by combining RSM with GA. The multi-objective optimization functions in GA are obtained by RSM, and there are few investigations on the multi-objective optimization of bio-inspired sandwich structures [21-24].

In addition to the structural parameters, the layer numbers of cores may have a great influence on the mechanical properties. A few references indicated that multilayer structures can improve the compressive performances of sandwich structures under out-of-plane loading [25-26]. However, most studies were mainly focused on single-layered sandwich structures [27-30]. The main reason is that the multilayer bio-inspired sandwich structures are difficult to fabricate by conventional processing methods due to their complex geometric features [21]. Selective Laser Melting (SLM) is a typical powder additive manufacturing process, which has higher dimensional precision and the capability to build any complex shapes of metal parts that would otherwise be difficult or impossible to be produced by using conventional manufacturing processes [31-32]. Thus, SLM is a practical method to manufacture the multilayered bio-inspired sandwich structures.

In this paper, based on the bio-inspired sandwich structure designed by Meng [28], response surface methodology (RSM) and non-dominated sorting genetic algorithm II (NSGA-II) are used for multi-objective optimization in order to obtain lightweight structures with excellent comprehensive performances. Moreover, bio-inspired lightweight structures fabricated by SLM using optimal structural parameters are adapted to identify the accuracy of optimization models. Considering the influences of the layer number, multilayer bio-inspired sandwich structures are designed, fabricated by SLM and analyzed in detail under out-of-plane loading. Moreover, the damage process of bio-inspired structures is also investigated by experiments and FEM.

Multi-objective optimization method

Based on the microstructure of Cybister elytra [28], the lightweight sandwich structure is designed, as shown in **Fig. 1**. Response surface methodology (RSM) is processed in the Design Expert software which is used to optimize the structural parameters in this paper. RSM consists of a set of mathematical and statistical techniques to develop a functional relationship between a response of interest, y, and a number of associated control variables, x_1, x_2,…, x_k[33]. Three structural variables consist of the core height h, the thickness of the core t_0 and thickness of panel t in this paper.

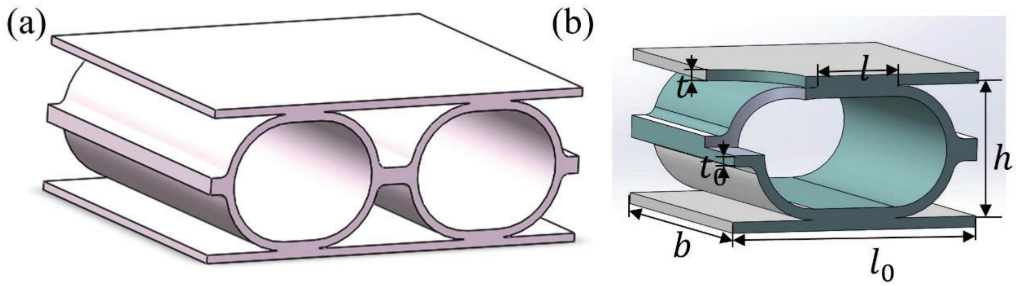


Fig. 1. The geometric model of (a) bio-inspired structure (b) a unit

The response value y_1 is Energy Absorption (EA), the dependency of response with process variables, h, t, t_0, is illustrated in Eq. **(1)**.

$$y_1 = f_1(h, t, t_0) \tag{1}$$

In our work, the relationship between the values of the explanatory variables and the levels of parameterization considered is shown in **Table 1**. Moreover, the Box-Behnken Design method [34] is used in the software and a third order polynomial is adopted to obtain the appropriate model. Thus, the software will automatically present the 17 structural parameters because of the design method using three factors and three levels, and a matrix of structural parameters is shown in Table 2.

Table 1 Levels of independent variables according to RSM

Factors	levels		
	-1	0	1
Core height (mm)	2	6	10
The thickness of cores (mm)	0.2	0.50	0.80
The thickness of panel (mm)	0.2	0.50	0.80

Table 2 Variable values of structural parameters

Test	Order	Core height (mm)	The thickness of cores (mm)	The thickness of panel (mm)
1	11	6	0.20	0.80
2	3	2	0.80	0.50
3	16	6	0.50	0.50
4	17	6	0.50	0.50
5	5	2	0.50	0.20
6	15	6	0.50	0.50
7	13	6	0.50	0.50

8	6	10	0.50	0.20
9	14	6	0.50	0.50
10	1	2	0.20	0.50
11	7	2	0.50	0.80
12	10	6	0.80	0.20
13	2	10	0.20	0.50
14	8	10	0.50	0.80
15	4	10	0.80	0.50
16	12	6	0.80	0.80
17	9	6	0.20	0.20

According to structural parameters listed in **Table 2**, the bio-inspired sandwich structures are fabricated by SLM and the energy absorption of sandwich structures is obtained by compressive tests. Thus, the model for response value is indicated by following Eq. **(2)** according to RSM.

$$y=f_1(h,t,t_0)=158.81-50.51\times h-134.37\times t_0-241.18\times t+63.28\times h\times t_0+58.89\times h\times t+272.40\times t\times t_0+3.79\times h^2-127.52\times t^2-4.37\times h^2\times t_0-4.66\times h^2\times t \quad (2)$$

In this model, the major statistical [35] measures can be deduced as follows,

$$R^2=1-\frac{SSE}{SST} \quad (3)$$

$$R_{adj}^2=1-\frac{(1-R^2)\times(m-1)}{m-p-1} \quad (4)$$

$$SSE=\sum_{i=1}^{m}(y_i-\tilde{y_i})^2 \quad (5)$$

$$SSE=\sum_{i=1}^{m}(y_i-\overline{y_i})^2 \quad (6)$$

Where p is the number of inconstant terms in standard deviation; m is the selected sample design points; $\tilde{y_i}$ represents the result of mean or standard deviation; $\overline{y_i}$ is the mean value of y_i.

The statistical measures are applied to evaluate the accuracy of the model in this paper. The R-squared (0.9787) and adj R-squared (0.9431) values show the goodness of fitting. The experimental results, theoretical values of energy absorption and relative errors are listed in **Table 3**. It can be seen that the relative errors of most tests are less than 10%, which also indicates that the predicted values are well consistent with the experimental values and the optimization model can explain the relationship between the variables and the response well.

Table 3 Comparison of experimental and predicted values of energy absorption.

Test	Experimental value (J)	Theoretical values (J)	Relative error (%)
1	4.34	3.92	9.67

2	6.29	9.03	30.34
3	42.00	44.67	5.97
4	41.00	44.67	8.27
5	30.00	27.26	7.76
6	49.12	44.67	9.06
7	36.16	44.67	19.05
8	33.48	35.38	5.37
9	53.36	44.67	16.28
10	16.28	19.02	14.40
11	26.49	23.75	9.81
12	13.85	13.43	3.03
13	10.32	8.43	18.31
14	44.12	46.01	4.28
15	51.90	50.01	3.64
16	111.20	110.78	0.37
17	5.06	4.64	8.30

Considering the lightweight and crashworthiness of bio-inspired structures, non-dominated sorting genetic algorithm II (NSGA-II) is used to achieve the multi-objective optimization [36]. The equation obtained by RSM is used as one of the objective functions in NSGA-II. It should be noted that the bio-inspired structures in our work have extremely lower energy absorption capacity when the core height is higher than 10 mm or lower than 2 mm [28]. As a typical thin-walled structure [28], the thickness is (t or t_0) about 1/10 of the length (h). However, the whole structure may become an entity structure when the thickness reaches to 1 mm. Thus, h is set from 2 mm to 10 mm and t (t_0) is set from 0.20 mm to 0.80 mm.

The related multi-objective optimization question is expressed as Eq. **(7)**:

$$min[-f_1(h,t,t_0), f_2(h,t,t_0)]$$
$$\boldsymbol{s.t.}\begin{cases} 2.0\,mm \le h \le 10.0\,mm \\ 0.20\,mm \le t \le 0.80\,mm \\ 0.20\,mm \le t_0 \le 0.80\,mm \end{cases} \tag{7}$$

Where $f_1(h,t,t_0)$ represents the energy absorption; $f_2(h,t,t_0)$ represents the density of bio-inspired structures, which is summarized as follows:

$$f_2(h,t,t_0) = \frac{[2l_0 \times (t+t_0) + (\pi-2) \times h \times t_0]}{l_0 \times (2t+h)} \times \rho_0 \tag{8}$$

Where ρ_0 is the density of Ti-6Al-4V alloy (4.43 g/cm^3).

Parameters for NSGA-II are set as follows in this paper: Pareto fraction 0.30, population size 150, generations 1000 and TolFun 1e-100. The Pareto optimal front of multi-objective optimization is shown in **Fig. 2**(a). Every Pareto point in the optimal Pareto fronts is the optimal parameter. However, decision must be made for the most satisfactory (termed as "knee point") from the Pareto-set finally. In this paper, The Minimum Distance Selection Method (TMDSM) [35] is applied to solve this issue, which is given as below mathematically,

$$min\, D = (\sum_{i=1}^{K} (f_{ci} - \min(f_i(x)))^n)^{\frac{1}{n}} \quad (9)$$

Where K is the number of the objective components; f_{ci} is the i^{th} objective value in the c^{th} Pareto solution; n = 2, 4, 6,…; D is the distance from the knee point to the "utopia point" that is given by the optimal values of each individual objective (as shown in **Fig. 3**(b)). The knee point can be obtained by using TMDSM from the Pareto fronts. The structural parameters optimized by NSGA-II and the knee point are listed in **Table 3**.

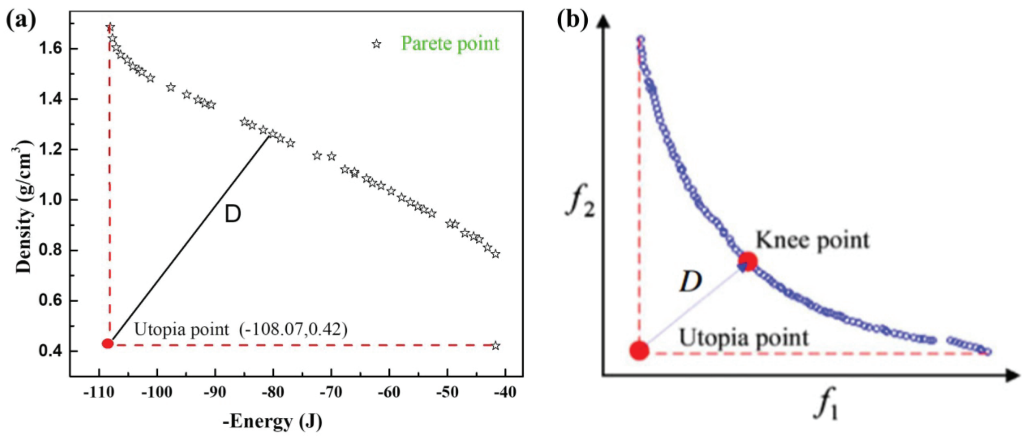


Fig. 2. The Pareto optimal front of multi-optimization (a) and the knee point on the Pareto front having the shortest distance from the utopia point (b).

Table 3 structural parameters of the knee point

Parameters	h, mm	t, mm	t_0, mm	EA,J	ρ, g/cm^3
Value	9.00	0.77	0.67	81.56	1.46

In order to understand the influences of the layer number and core configurations on compressive properties, multilayer bio-inspired sandwich structures with different configurations are designed based on the optimized bio-inspired structures, as shown in **Fig. 3**.

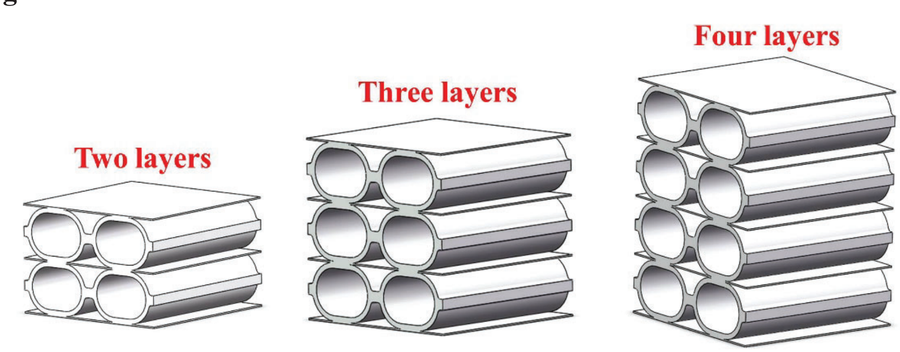


Fig. 3. Multi-layered bio-inspired structures model

Experimental procedures

Gas atomized Ti-6Al-4V powders were used as the raw material in SLM experiments. Bio-inspired structures were fabricated in a self-developed SLM system (LSNF-1) [37]. In order to ensure the fabrication quality of bio-inspired structures, the optimal processing parameters were used to build the sandwich structures [28].

Bio-inspired structures used for response surface analysis are shown in **Fig. 4**(a). **Fig. 4**(b) shows the multi-layered bio-inspired structures fabricated by SLM. It should be noted that the single layer sandwich structure was used to verify the multi-objective optimization model. The electronic universal testing machine (*Shimadzu AG-100KN*) was used for the flatwise compression tests. The indenter impacted the multi-layered bio-inspired structures at a velocity of v=1 mm/min during flatwise compressive tests and a camera recorded the entire process.

EA and SEA [38, 39] are used to judge energy absorption capacity, and they are calculated as follows.

The total energy absorption (EA) is the area under the load-displacement curve:

$$EA = \int_0^d F(x)dx \tag{10}$$

Where d is the displacement. It is generally believed that energy is absorbed before the structure is crushed, and $F(x)$ is the magnitude of the load.

The specific energy absorption is the absorbed energy per unit mass (SEA):

$$SEA = \frac{EA}{w} \tag{11}$$

Where w is the weight of whole bio-inspired structures.

(a) (b)

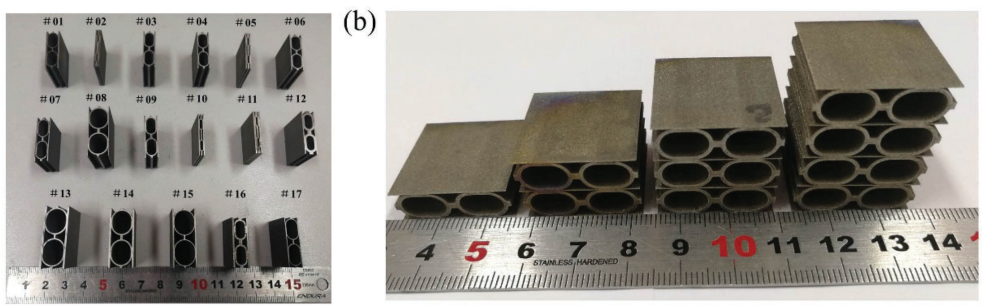


Fig.4. The bio-inspired structure samples of multi-objective optimization (a), multilayer bio-inspired structures fabricated by SLM (b)

Results and discussion

4.1. Verification of the multi-objective optimization model

Comparisons between experiment values of parameters and multi-objective optimization results are summarized in **Table 4**. Results reveal that the experiment value of EA (87.12 J) and density (1.52g/cm^3) are slightly higher than the multi-objective optimization value of EA (81.56 J) and density (1.46g/cm^3). The reason is that a certain manufacturing error exists in structural dimensions during SLM [40]. It can be seen that the relative errors of all parameters are less than 10%, which also indicates that the multi-objective optimization model has a high predictive ability.

Table 4 Comparisons between the experiment value of parameters and multi-objective optimization results

Parameters	Multi-objective optimization value	Experiment values	Relative errors
EA, J	81.56	87.12	6.81%
Density, g/cm^3	1.46	1.52	4.11%
h, mm	9.00	9.08	0.88%
t, mm	0.77	0.80	3.75%
t_0, *mm*	0.67	0.74	9.46%

4.2. The influence of structural parameters on the compressive performance

Response surfaces of EA depending on structural parameters are shown in **Fig. 5**. It shows the influences of the core height, thickness of panel and core on the energy absorption. It can be seen that the high thickness of core and panel will favor the high EA (**Fig. 5**(a) and (c)). Additionally, it seems that a proper core height, around 6 mm, can absorb more energy (**Fig. 5**(b)). Results also indicate that the interactions of structural parameters have a great impact on the compressive performances. Compared with core height, the interaction of the thickness of the panel and core has the greatest influence on the compressive properties.

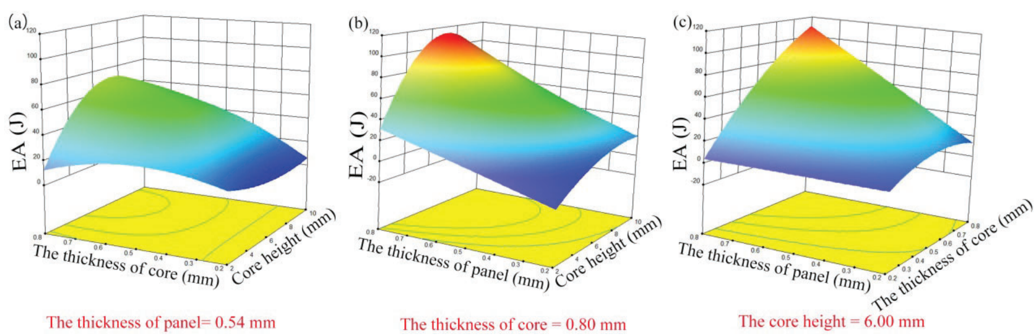


Fig. 5. Response surface with the core height and thickness of core (a), core height and the thickness of panel (b), the thickness of panel and core (c).

4.3. Compressive properties of multi-layered bio-inspired sandwich structures

Force-displacement curves of multi-layered structures with parallel-arranged configurations are shown in **Fig. 6**. Generally, the compressive force-displacement curves for sandwich structures consist of three zones: elastic, buffer and crushing zone. Bio-inspired structures are not damaged in the elastic zone, and most energy is absorbed in the buffer zone. In addition, it is summarized that bio-inspired structures will fail when the force-displacement curves fall in the crushing zone [28]. From **Fig.6**, it should be noted that the sharp drop in force indicates that the multi-layered structures have been fractured. Many peaks appear in the force-displacement curves, which means that several areas of bio-inspired structures have been damaged under the crushing loading. It can be seen that core breaking is the main damage mode during the compression. However, much literature [41-43] showed that the core buckling was the main damage mode for sandwich structures and the force-displacement

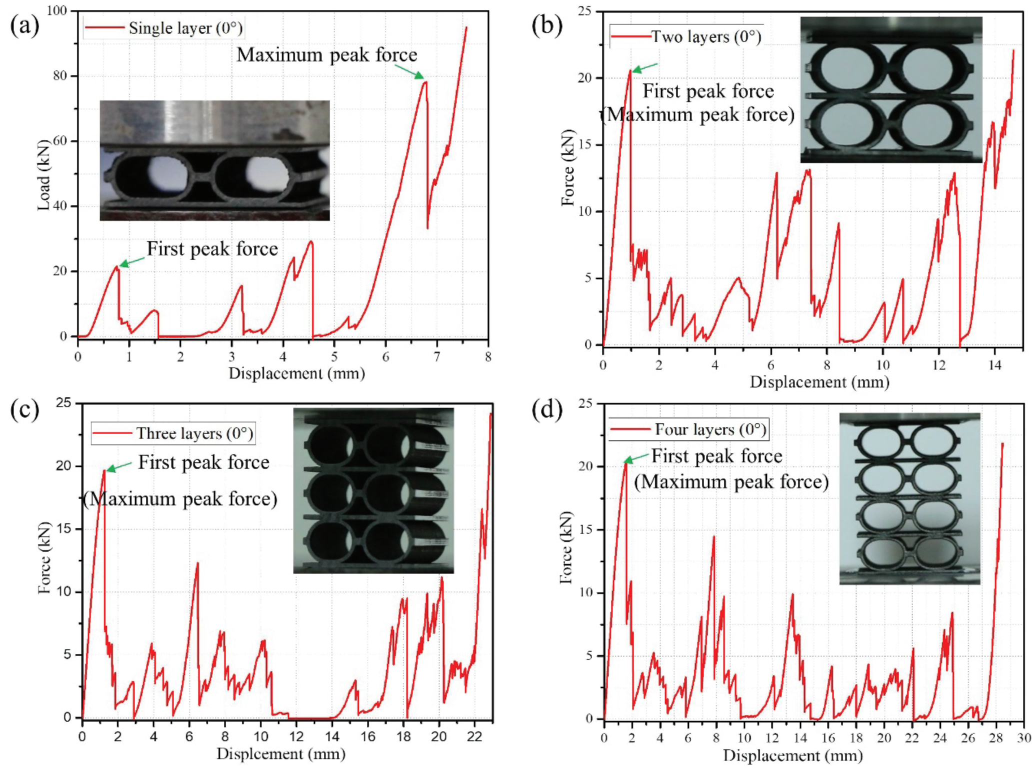


Fig. 6. Force-displacement experimental curves of bio-inspired structure with parallel-arranged configurations: (a) single layer, (b) two layers, (c) three layers and four layers (d).

curves almost had no peaks. The reason may be related to the intrinsic properties of materials. It should be noted that core breaking is the core material occurs to be yield and fractured when the material stress reaches to maximum stress, which belongs to material failure. Comparatively, the core buckling is the structures occur to be instability before the material stress reaches to maximum stress, which belongs to structural failure. Thus, the compressive force of core breaking is greater than that of core buckling. It also seems that the first peak forces are all about 20 kN with the increase of layer numbers, which indicates that increasing the layer number will have no influence on the first peak force. However, the maximum peak force firstly decreases to the first peak force and then keeps constant. It is because that the stability of whole bio-inspired structures decreases when the layer number increases. The maximum peak force is equal to the first peak force in the curves when the layer number is two. With the further increase of the layer number, the maximum peak force will keep constant and be equal to the first peak force.

The damage photographic images of two-layered bio-inspired structures with parallel-arranged configurations are shown in **Fig. 7**. Under the compressive loading, the bottom layer of multilayer bio-inspired structures is firstly damaged and crushed. Then, the middle panel occurs to be fractured. Next, the upper layer of multilayer bio-inspired structures also occurs to be crushed owing to that the core has been fractured in several regions. Finally, the whole bio-inspired structure is compacted completely. During compression, all cores and panels have been damaged. It is summarized that the core fracture is the main failure mode of bio-inspired structures under the compressive loading. The damage pictures also showed that several areas of core structures have been fractured, which also explains why the force-displacement curves have many peak forces.

Energy absorption properties of multi-layered structures are shown in **Fig. 8**. It can be seen that with the increase of the layer number, the bio-inspired structures can absorb the same amount of energy (~ 80 J). The reason is that the force has dropped drastically even though the displacement increases. The SEA decreases gradually due to the weight of bio-inspired structures increases. It is also demonstrated that increasing the layer number cannot improve the structural crashworthiness for multi-layered bio-inspired structures with parallel-arranged configurations.

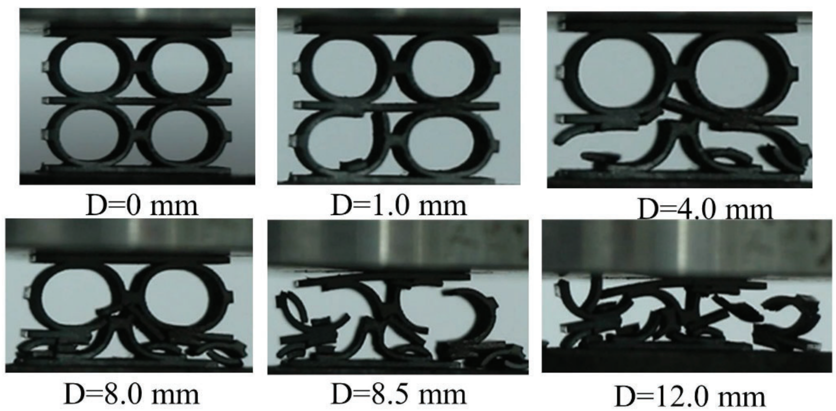


Fig.7. Damage photographic images of two-layered bio-inspired sandwich structures

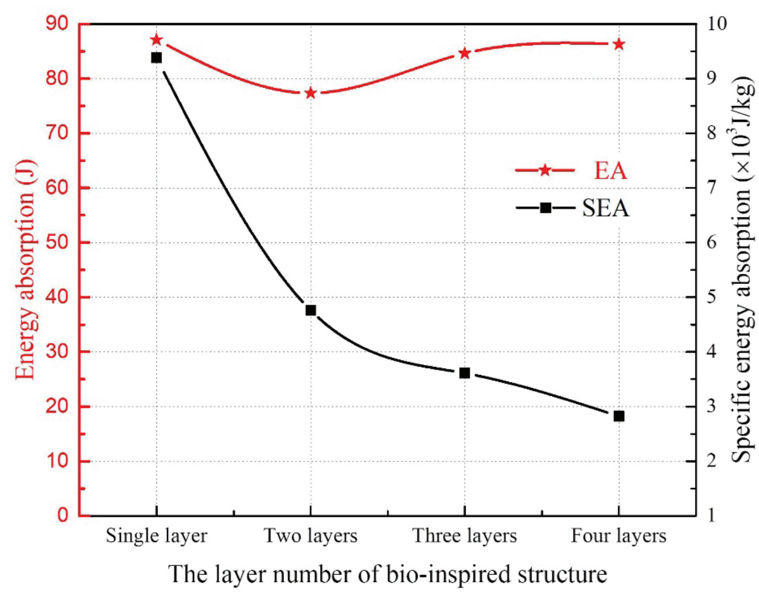
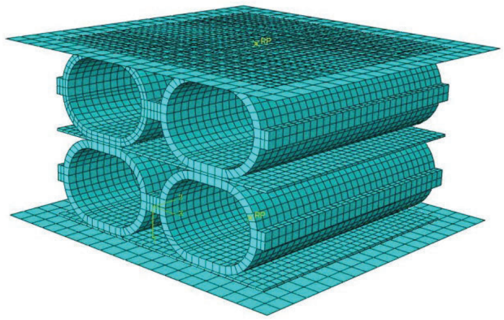


Fig. 8. Energy absorption and specific energy absorption of multi-layered structures with parallel-arranged configurations

4.4. The simulation results of multi-layered sandwich structures

The ABAQUS software was used to simulate compression tests of bio-inspired sandwich structures, and the C3D8R element is selected. And the CAD model is the same as that of the bio-inspired structure. And the simulation model is shown in Fig. **9**(a). The pressing plate is set as a rigid body. The contacts between the rigid body and structure are set as the surface to surface contact. Ti6Al4V alloy acts as the simulation material, whose physical parameters are given in Table **4** and the stress-strain curve is shown in Fig. **9**(b).



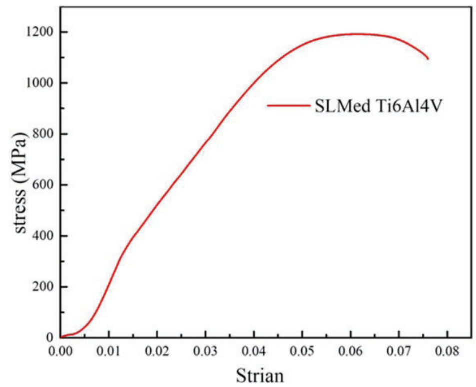


Fig. **9**. The simulation model of compressive tests (a) and the stress-strain curve of Ti6Al4V (b)

Table **4** The physical parameters of Ti6Al4V alloy

Parameters	Density (g/cm^3)	Elastic modulus (MPa)	Poisson's ratio
Value	1.52	110000	0.34

The FEM and experimental results of multi-layered bio-inspired sandwich structures are shown in Fig. **10**. It can be seen that the load-displacement curves of FEM result are consistent with that of experimental results basically. The difference is that the load-displacement curves of compression experiments have many zones which their load is close to zero. The reason is that the Ti6Al4V alloy was brittle fractured on the compressive tests and the velocity of the compressive head is 1mm/min. Therefore, the load will decrease rapidly to zero when the sandwich structures break. However, in the FE simulation, the whole compressive time is set as 0.1s, and the time is so short that the load cannot decrease to zero. The damage process of two-layered sandwich structures is shown in Fig. **11,** and the results indicated that the FEM is consistent with the experiments. Moreover, the fracture zones and stress concentration locations in FEM also are consistent with the experimental results, which declare that the finite element model is accurate.

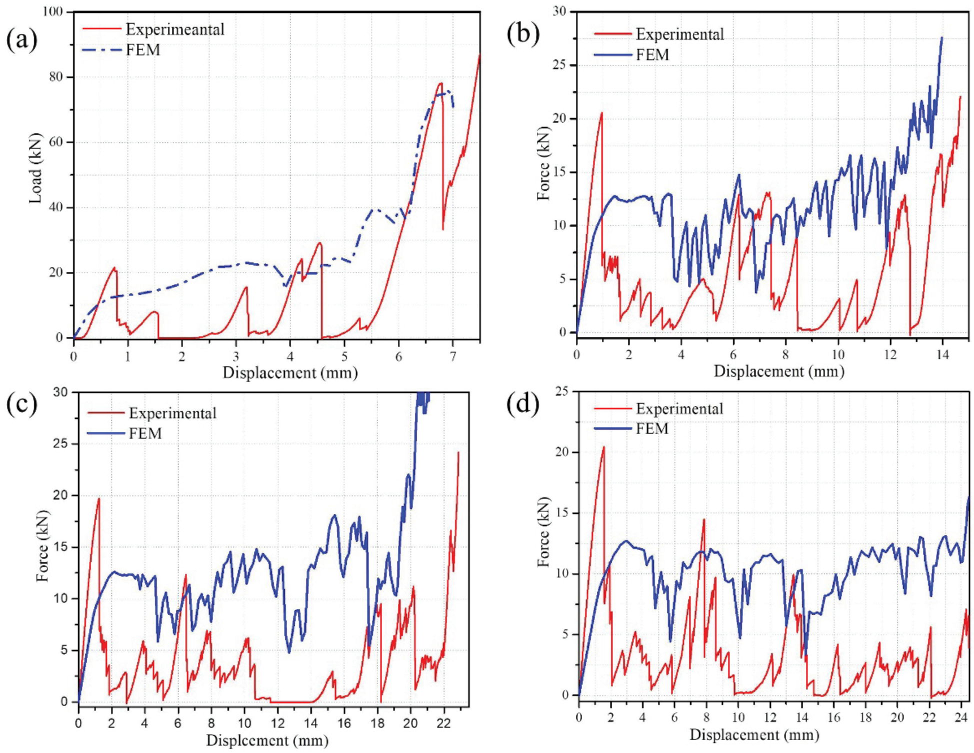


Fig. 10. The FEM and experimental results of sandwich structures with a single layer (a), two-layered (b), three-layered (c) and four-layered (d) core.

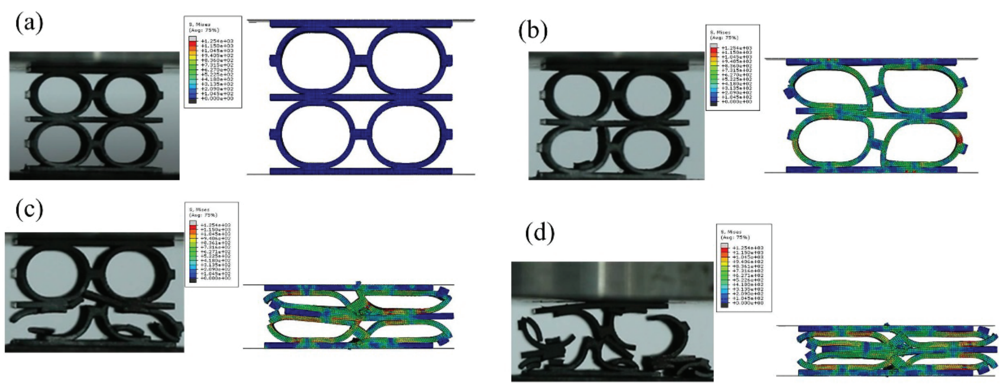


Fig. **11**. The damage process of two-layered sandwich structures: D=0mm (a), D=1mm (b), D=1.50mm (c) and D=8.50mm (d).

Conclusions

The compressive properties optimization of bio-inspired structures via RSM and NSGA-II has been carried out in this work. Moreover, multi-layered bio-inspired structures of Ti–6Al–4V alloy are designed, fabricated by SLM and analyzed in detail. The conclusions are as follows:

(1) Response surface methodology (RSM) and non-dominated sorting genetic algorithm II (NSGA-II) can be applied to better optimize the compressive properties of bio-inspired structures fabricated by SLM.

(2) Increasing the layer number cannot improve the EA and SEA of multi-layered bio-inspired structures with parallel-arranged configurations. The damage process of bio-inspired structures with different core-arranged configurations fails layer by layer.

(3) The load-displacement curves and damage process of FE simulations are consistent with the experimental results.

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References

[1] L. Murr, S. Quinones, S. Gaytan, M. Lopez, A. Rodela, E. Martinez, D. Hernandez, E. Martinez, F. Medina, R. Wicker, Microstructure and mechanical behavior of Ti–6Al–4V produced by rapid-layer manufacturing, for biomedical applications, J. Mech. Behav. Biomed. mater. 2 (2009) 20-32.

[2] C. Guo, D. Li, Z. Lu, Mechanical properties of a novel, lightweight structure inspired by beetle elytra, Chin. Sci. Bull. 26 (2014) 3341-3347.

[3] V. Pandyaraj, A. Rajadurai, G. Anand, Experimental investigation of compression strength in a novel sandwich structure, Mater. Tod. Proceedings. 5 (2018) 8625-8630.

[4] M. Eichenhofer, J. Wong, P. Ermanni, Continuous lattice fabrication of ultra-lightweight composite structures, Addit. Manuf., 18 (2017) 48-57.

[5] C. Li, H. Lei, Y. Liu, X. Zhang, J. Xiong, H. Zhou, D. Fang, Crushing behavior of multi-layer metal lattice panel fabricated by selective laser melting, Inter. Mech. Sci. 145 (2018) 389-399.

[6] L. Ballere, P. Viot, J. Lataillade, L. Guillaumat S. Cloutet, Damage tolerance of impacted curved panels, Int. J. Impact. Eng. 2 (2009) 243-250.

[7] M. Meyers, P. Chen, M. Albert Yu, Biological materials: structure and mechanical properties, Prog. Mater. Sci. 53 (2008) 1-206.

[8] A. Studart, Additive manufacturing of biologically-inspired materials, Chem. Soc. Rev. 45 (2016) 359–376.

[9] Q. Zhang, X. Yang, P. Li, G. Huang, S. Feng, C. Shen, B. Han, X. Zhang, F. Jin, F. Xu, T. Lu, Bio-inspired engineering of honeycomb structure-using nature to inspire human innovation, Pro. Mater. Sci. 74 (2015) 332–400.

[10] Z. Yang, Z. Dai, C. Guo, Morphology and mechanical properties of Cybister elytra, Chin. Sci. Bull. 55 (2010) 771–776.

[11] J. Sun, C. Liu, H. Du, Design of a bionic aviation material based on the microstructure of beetle's elytra, Int. J. Heat. Mass. Tran. 114 (2017) 62-72.

[12] P. Hao, J. Du, Energy absorption characteristics of bio-inspired honeycomb

column thin-walled structure under axial impact loading, J. Mech. Behav. Biomed. 79 (2018) 301-308.
[13]J. Xiang, J. Du, Energy absorption characteristics of bio-inspired honeycomb structure under axial impact loading, Mater. Sci. Eng. A. 696 (2017) 283-289.
[14]B. Chen, M. Zou, G. Liu, J. Song, H. Wang, Experimental study on energy absorption of bionic tubes inspired by bamboo structures under axial crushing, Int. J. Impact. Eng. 115 (2018) 48-57.
[15] Y. Wu, Q. Liu, J. Fu, Q. Li, D. Hui, Dynamic crash responses of bio-inspired aluminum honeycomb sandwich structures with CFRP panels, Comp. Part. B. 121 (2017) 122-133.
[16]Q. Gao, X. Zhao, C. Wang, L. Wang, Z. Ma, Multi-objective crashworthiness optimization for an auxetic cylindrical structure under axial impact loading, Mater. Des. 143 (2018) 120-130.
[17]M. Bezerra, R. Santelli, E. Oliveira, L. Villar, L. Escaleira, Response surface methodology (RSM) as a tool for optimization in analytical chemistry, 76 (2008) 965-977.
[18] J. Eusebio, A. Jose, M. Valentin, T. Carlos, L. Jose, Optimization of geometric parameters in a welded joint through response surface methodology, Constr. Build. Mater. 154 (2017) 105-114.
[19] N. Lgnacio, Y. Brenda, E. Susana, A. Guillermo, Natural astaxanthin encapsulation: Use of response surface methodology for the design of alginate beads. Int. J. Biol. Macromol. 121 (2019) 601-608.
[20] T. Abhishek, M. Amitava, K. Kaushik, Multi-objective optimization of electrochemical machining by non-dominated sorting genetic algorithm, Mater. Today. 2 (2015) 2569-2575.
[21] H. Yin, G. Wen, Z. Liu, et al. Crashworthiness optimization design for foam-filled multi-cell thin-walled structures, Thin.Wall. Struct. 75 (2018) 8-17.
[22] C. Wang, Y. Li, W. Zhao, S. Zou, G. Zhou, Y. Wang, Structure design and multi-objective optimization of a novel crash box based on biomimetic structure, Inter. J. Mech. Sci. 138 (2018) 489-501.
[23] X. Yang, Y. Sun, J. Yang, Q. Pan, Out-of-plane crashworthiness analysis of bio-inspired aluminum honeycomb patterned with horseshoe mesostructure, Thin. Wall. Struct. 125 (2018) 1-11.
[24] D. Zhang, Z. Gao, Forward kinematics, performance analysis, and multi-objective optimization of a bio-inspired parallel manipulator, Robot. Cim-int. Manuf. 28 (2012) 484-492.
[25] K. Dharmasena, D. Queheillalt, H. Wadley, Y. Chen, P. Dudt, D. Knight, Z. Wei, A. Evans, Dynamic response of a multilayer prismatic structure to impulsive loadsincident from water, Int. J. Impact. Eng. 36 (2009) 632-643.
[26] S. Hou, C. Shu, S. Zhao, T. Liu, X. Han, Q. Li, Experimental and numerical studies on multi-layered corrugated sandwich panels under crushing loading, Comp. Struct. 126 (2015) 371-385.
[27] C. Liang, M. Yang, P. Wu, Optimum design of metallic corrugated core sandwich panels subjected to blast loads, Ocean. Eng. 28 (2001) 825-861.

[28] L. Meng, H. Liang, H. Yu, J. Yang, F. Li, Z. Wang, X. Zeng, The energy absorption and bearing capacity of light-weight bio-inspired structures produced by selective laser melting, J. Mech. Behav. Biomed. Mater., 93 (2019) 170-182.

[29] R. Rajpal, L. K.P, K. Gangadharan, Parametric studies on bending stiffness and damping ratio of Sandwich structures, Addit. Manuf., 22 (2018) 583-591.

[30] X. Yang, J. Ma, Y. Shi, Crashworthiness investigation of the bio-inspired bi-directionally corrugated core sandwich panel under quasi-static crushing load, Mater. Des. 135 (2017) 275-290.

[31] N. Uzan, R. Shneck, O. Yeheskel, N. Frage, High-temperature mechanical properties of AlSi10Mg specimens fabricated by additive manufacturing using selective laser melting technologies (AM-SLM), Addit. Manuf., 24 (2018) 257-263.

[32] V. Bey, T. Lore, K. Jean -Pierre, V. Jan, Heat treatment of Ti6Al4V produced by Selective Laser Melting: Microstructure and mechanical properties, J. Alloy. Compd. 541(2012) 177-185.

[33] K. Dehghani, A. Nekahi, M. Ali Mohammad Mirzaie, Using response surface methodology to optimize the strain aging response of AA5052, Mater. Sci. Eng. A. 527 (2010) 7442-7451.

[34] O. Sadoun, F. Rezgui, C. G'Sell, Optimization of valsartan encapsulation in biodegradables polyesters using Box-Behnken design, Mater. Sci. Eng. C. 90 (2018) 189-197.

[35] G. Sun, G. Li, S. Zhou, H. Li, S. Hou, Q. Li, Crashworthiness design of vehicle by using multi-objective robust optimization, Struct. Multidisc. Optim. 44 (2011) 99-110.

[36] T. Vo-Duy, D. Duong-Gia, V. Ho-Huu, H. Vu-Do, T. Nguyen-Thoi, Multi-objective optimization of laminated composite beam structures using NSGA-II algorithm, Comp. Struct. 168 (2017) 498-509.

[37] J. Yang, H. Yu, J. Yin, Z. Wang, X. Zeng, Formation and control of martensite in Ti-6Al-4V alloy produced by selective laser melting, Mater. Des. 108 (2016) 308-318.

[38] R. Audysho, R. Smith, W. Altenhof, Mechanical assessment and deformation mechanisms of aluminum foam filled stainless steel braided tubes subjected to transverse loading, Thin. Wall. Struct. 79 (2014) 95-107.

[39] Z. Xiao, J. Fang, G. Sun, Q. Li, Crashworthiness design for functionally graded foam-filled bumper beam, Adv. Eng. Software. 85 (2015) 81-95.

[40] L. Zhang, S. Zhang, H. Zhu, Z. Hu, G. Wang, X.Y, Zeng, Horizontal dimensional accuracy prediction of selective laser melting, Mater. Des. 160 (2018) 9-20.

[41] J. Liu, J. Liu, J. Me, W. Huang, Investigation on manufacturing and mechanical behavior of all-composite sandwich structure with Y-shaped cores, Comp. Sci. Tech. 159(2018) 87-102.

[42] S. Hou, S. Zhao, L. Ren, X. Han, Q. L, Crashworthiness optimization of corrugated sandwich panels, Mater. Des. 51 (2013) 1071-1084.

[43] Y. Sun, Y. Li, Prediction and experiment on the compressive property of the sandwich structure with a chevron carbon-fiber-reinforced composite folded core,

Comp. Sci. 150 (2017) 95-101.