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Research Article

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Posted Date: December 28th, 2021

DOI: <https://doi.org/10.21203/rs.3.rs-1180054/v1>

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Adaptive Honeycomb Based on Additive Manufacturing: Research on Rapid Generation Algorithm, Manufacturing Process, and Mechanical Characteristics

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Abstract:

In order to solve the problems of low efficiency and complex process in the current generation algorithm and process verification of hexagonal honeycomb structures for complex spatial shapes and arbitrarily curved surfaces, this paper proposes an adaptive hexagonal grid calculation method based on the intracellular splitting iteration method for the first time. This method can better adapt to the complex spatial shape and arbitrary curved surface structure in the three-dimensional space, and it can also achieve the purpose of enhancing the mechanical performance while maintaining the lightweight structure. According to the principle of the above algorithm, different structural models including honeycomb cells are calculated and generated. 316L Stainless Steel material and Selective Laser Melting additive manufacturing processes are also used for printing actual samples. The printed samples are mechanically compressed. According to the results of the compression curve, the critical yield force of the honeycomb grid parts with iteration is higher than that of the homogeneous honeycomb grid parts, and the value is basically greater than 30%-40%. Finally, the energy absorption efficiency can be increased by more than 20% according to the compression characteristics of the adaptive iterative honeycomb analyzed.

Keywords: selective laser melting; hexagonal honeycomb structure; additive manufacturing; 316L stainless steel; energy-absorbing structure

1 Introduction

The hexagonal honeycomb structure has many advantages such as perfect geometry, high strength, lightweight, and large specific surface area, and so on. It is widely used in building structures, mechanical structures, bionic structures, heat exchanger structures, microreactor structures, etc. Because of its good application prospects, honeycomb structure generation and design technology has become a hot research topic at home and abroad[1-4]. For the potential applications of the honeycomb structure, from energy-absorbing structures, thermal insulation materials, sound-absorbing materials to biomedical engineering scaffold, etc., people have carried out extensive research on it[5-8]. However, the existing design methods often rely on mathematical principles and formulas to realize the construction of the model at one time. In terms of overall performance, the realized construction of the model cannot be as simple in structure and superior in performance as natural honeycombs. In order to realize the customization of the performance of the honeycomb structure, Amin Ajdari et al. [9,10] proposed a two-dimensional layered honeycomb structure, which repeatedly replaced each vertex of the regular hexagonal cell with a smaller hexagonal to achieve different orders of two-dimensional layered honeycomb, and then calculated and verified by analytical, numerical and experimental methods. The results show that the hardness of the two-dimensional layered honeycomb is 2.0 and 3.5 times higher than that of the ordinary honeycomb under the same mass, which provides a new idea for the role of structural organization and hierarchical structure in adjusting the mechanical behavior of materials. However, the author only studied the two-dimensional honeycomb structure perpendicular to the z-direction and could not cut it according to the surface shape of the model. In order to study the performance of the honeycomb structure in three-dimensional space, Thomas Tancogne-Dejean et al. [11-13] proposed a method for generating three-dimensional flat plate lattice. On the basis of theoretical analysis, the overall structural diagram of cubic symmetrical elastic isotropic plate lattice was established. The most notable feature of the flat plate lattice is that its stiffness and yield strength are less than a few percentage points from the theoretical limit of the isotropic porous structure. Its lattice stiffness is three times higher than the lattice stiffness of an equal mass truss, and the results have been verified by experiments. The results show that this new type of metamaterial can not only achieve lightweight structure, but also can be used in heat exchange,

heat preservation, acoustics and biomedical engineering.

Due to the unique characteristics of the honeycomb structure, many organisms in nature have natural honeycomb structure morphology, and the meso or micro cell structures such as trabecular bone, wood, shells, and sea urchins can have a higher load-bearing capacity. The shape, morphology, and structure of these cellular structures are divided into open cell and closed cell cellular structures. Fabrication of a compact lattice structure is still considered difficult due to the support structure within the lattice. Ajeet Kumar et al. [14] proposed a new method for manufacturing dense cell structures by using AM extrusion process, a shell-shaped closed lattice structure simulating the shape of a sea urchin is manufactured by using a PLA process without a supporting structure and a post-treatment removal process. Through experiments and finite element analysis of physical properties, deformation behavior and compression performance, the structure has good damping characteristics. Hedayati R. et al. [15] studied the in-plane mechanical behavior of hexagonal honeycombs made by fused deposition of polylactic acid.

Honeycomb structure can not only improve the stiffness and strength, but also realize the energy absorption, but how to realize the energy absorption of the honeycomb structure and how to improve the efficiency of energy absorption under the condition of reducing the weight of the structure is a key problem. In order to solve this problem, Shanmugam Kumar et al. [16] Proposed a honeycomb structure with tunable energy absorption characteristics. By changing the cell wall thickness gradient of the honeycomb, the energy absorption characteristics of the honeycomb were experimentally and numerically calculated, and the three-dimensional honeycomb structure design with local buckling (wrinkling) and progressive failure as the response characteristics was realized, and the analytical calculation formula was given. The experimental results show that the specific energy absorption (SEA) of the honeycomb structure increased by more than 110% , and the energy absorption efficiency increased by 65% . If the global buckling and collapse mechanism is adopted, the energy absorption efficiency of the honeycomb structure can reach 90% . The energy-absorbing lattice structure can be used for manufacturing human body protection structures such as helmets and so on, which has the advantage of lightweight and suitability for complex adaptive curved surfaces. S. Farajzadeh Khosroshahi et al. [17] used gradient-graded honeycombs in helmets, and the results showed that the use of gradient grid serifs had the potential to significantly reduce the risk of brain injury. According to the influence of geometric

precision on mechanical properties of honeycomb structure, Davis J. McGregor et al.[18] studied the mechanical properties of hexagonal honeycomb structure manufactured by CLIP process for the first time. By designing different relative density, honeycomb aspect ratio, wall thickness and other parameters, the difference between the geometric precision and theory of the manufactured parts were evaluated, and the influence of geometric deviation on mechanical properties was studied, and the factors of affecting the failure mode of honeycomb structure were also studied. The honeycomb structure is usually sandwiched between two layers of skin, resulting in poor sound absorption. The acoustic performance of such a sandwich plate can be improved by perforating the surface layer or replacing it with a perforated plate, the honeycomb structure behind the perforated plate not only providing structural support for the face layer, but also improving the absorption coefficient [19,20]. Deepak C. Akiwatt et al.[21] studied the acoustic characteristics of periodic honeycomb micro-perforated plates based on additive manufacturing, and proposed a generalized analytical formula for the absorption coefficient applicable to various perforation cross-sections, which incorporated the shape-dependent viscous effect into the honeycomb perforation. The effects of pore size and cell length on absorption coefficient and peak frequency were investigated by the parametric study. The results show that the structure can be tuned to the desired frequency range by changing the geometric parameters of the perforation unit, such as the length, shape, and hole size.

As mentioned above, honeycombs have in-depth applications in many fields such as mechanical structure manufacturing, bionic structure manufacturing, heat exchanger structure manufacturing, etc. The design methods and simulations of honeycombs have also been extensively studied, and the calculation and analysis of the honeycombs with simple spatial shapes have been realized. However, there are few reports about algorithms for complex spatial shapes, especially for arbitrarily curved surfaces. The SLM additive manufacturing technology has high processing flexibility and can form lattice structures with a high surface-to-volume ratio for boiling heat transfer[22]. Yadroitsev et al. [23] used the SLM technology to accurately reproduce the geometry of microporous heat transfer structures and manufacture thin-wall 3-D filters and custom filters with micron-level channels. Wong and Leong [24] studied the saturated pool boiling performance of a porous lattice structure prepared by L-PBF. In this paper, an adaptive hexagonal cell computing method based on the cell splitting iteration method is proposed for the first time to

adapt to the complex spatial shape and arbitrary curved surface structure in 3D space, so as to enhance the mechanical properties and maintain the lightweight structure. And, the SLM forming method is combined with the requirements of the honeycomb grid, using the advantages of the honeycomb structure, a new structure controllable and efficient forming method with an adaptive hexagonal grid structure is proposed, and the forming method of the honeycomb structure is explored. And the forming process, analyzed the influence of different honeycomb iteration distance and iteration number on compression characteristics, and then explained the difference in energy absorption efficiency of different honeycomb distance and iteration number.

2 Design of adaptive hexagonal honeycomb structure

Fig. 1 shows the design structure of a hexagonal honeycomb part and the coordinate system used to describe the orientation of the part during printing and testing. The hexagonal honeycomb is composed of a series of hexagonal cells with the same shape, and the geometric shape of each cell is defined by the wall thickness t , the side length l , the h height and the included angle of the hexagon θ respectively. In this paper, regular hexagons with $h/L = \sqrt{3}$ and $\theta=60$ degrees are used, so that the geometry of the element is simply described by t and l . This edge length and angle definition allows you to customize the mechanical properties of the part by selecting these parameters and the materials used.

Figure 1 Design structure of regular hexagonal honeycomb part

3 Adaptive hexagonal cell computing method

Algorithm principle: In order to achieve the optimal material distribution and optimal strength distribution of the hexagonal honeycomb structure, this algorithm uses the variable density honeycomb grid topology optimization design to drive the grid material to reconstruct the distribution inside the 3D model. Under the constraints of the same material weight and the same structure configuration, for any 3D structure and any 2D outline shape, this paper proposed an

adaptive hexagon automatic calculation method based on the intracellular iterative method. Adapt to the three-dimensional shape of different models and different two-dimensional outline cross-sectional shapes, the adaptive iterative hexagonal honeycomb structure and scanning path are automatically calculated through the program to ensure that the density of the hexagonal cell increases at the edge of the outline and the area of the contacted hexagonal sidewall is enlarged to increase the deformation resistance at the edge of the outline. (as shown in Fig. 2)

3.1 Concept definition and basic calculation formula:

- 1) Calculation: hexagon height: $H_i = \sqrt{3}l_i - 2t_i$ -- (1).
- 2) calculation: total volume of hexagon: $V_b = \frac{3}{2}\sqrt{3}l_i^2 l_x$ --(2), l_x is the height of the honeycomb structure.
- 3) calculation: hexagonal unit cell wall volume: $V_s = \left(\frac{3}{2}\sqrt{3}l_i^2 - \frac{3}{2}\sqrt{3}a_i^2 \right) l_x$ -- (3).
- 4) calculation: relative density of hexagonal honeycomb: $\rho_i = 1 - \left(1 - \frac{2\sqrt{3}}{3} \frac{t_i}{l_i} \right)^2$ -- (4).
- 5) calculation: six endpoints of hexagonal unit cell:

$$\left\{ \begin{array}{l} X_{A(i,j)} = X_{O(i,j)} - L, Y_{A(i,j)} = Y_{O(i,j)} \\ X_{B(i,j)} = X_{O(i,j)} - \frac{1}{2}L, Y_{B(i,j)} = Y_{O(i,j)} + \frac{\sqrt{3}}{2}L \\ X_{C(i,j)} = X_{O(i,j)} + \frac{1}{2}L, Y_{C(i,j)} = Y_{O(i,j)} + \frac{\sqrt{3}}{2}L \\ X_{D(i,j)} = X_{O(i,j)} + L, Y_{D(i,j)} = Y_{O(i,j)} \\ X_{E(i,j)} = X_{O(i,j)} + \frac{1}{2}L, Y_{E(i,j)} = Y_{O(i,j)} - \frac{\sqrt{3}}{2}L \\ X_{F(i,j)} = X_{O(i,j)} - \frac{1}{2}L, Y_{F(i,j)} = Y_{O(i,j)} - \frac{\sqrt{3}}{2}L \end{array} \right\} \text{--(5)}$$

Figure 2 Distribution of vertices and center points of the hexagon

6) calculation: center point of hexagonal unit cell: $X_{O(i,j)} = X_{\min} + i \frac{3}{2} L$ --(6),

$Y_{O(i,j)} = Y_{\min} + j \sqrt{3} L$ --(7), wherein, $j \in \left[0, \frac{Y_{\max} - Y_{\min}}{\sqrt{3} L} \right]$, j , is a positive integer in the

interval, $i \in \left[0, \frac{X_{\max} - X_{\min}}{1.5 L} \right]$, i is a positive integer in the interval

7) calculation: center points of three sub-hexagons in hexagonal unit cell:

$$\left\{ \begin{array}{l} O'_1(X, Y) = \left(X_{O(i,j)} - \frac{1}{4} L, Y_{O(i,j)} + \frac{\sqrt{3}}{4} L \right) \\ O'_2(X, Y) = \left(X_{O(i,j)} + \frac{1}{2} L, Y_{O(i,j)} \right) \\ O'_3(X, Y) = \left(X_{O(i,j)} - \frac{1}{4} L, Y_{O(i,j)} - \frac{\sqrt{3}}{4} L \right) \end{array} \right\} \text{--(8)}$$

8) calculation: intersection point of two edges in the plane $P = \text{Intersect}(L_1, L_2)$:

The first edge is $L_1 : A + \overbrace{(B-A)}^{m} m$, wherein, A is the start point, B is the endpoint, and the

second edge $L_2 : C + \overbrace{(D-C)}^{n} n$, wherein, C is the start point, D is the endpoint, then the

formula for calculating the intersection of the two edges is:

$$\left\{ \begin{array}{l} vt = \frac{X_C Y_{(D-C)} + Y_A X_{(D-C)} - Y_C X_{(D-C)} - X_A Y_{(D-C)}}{X_{(B-A)} Y_{(D-C)} - Y_{(B-A)} X_{(D-C)}} \\ vs = \frac{X_A Y_{(B-A)} + Y_C X_{(B-A)} - Y_A X_{(B-A)} - X_C Y_{(B-A)}}{X_{(D-C)} Y_{(B-A)} - Y_{(D-C)} X_{(B-A)}} \\ P = A + vt(B-A) : 0 < vt < 1, 0 < vs < 1 \end{array} \right\} \text{--(9)},$$

In this formula, only the two edges under case $0 < vt < 1, 0 < vs < 1$ have a point of intersection.

9) Definition1: Two-dimensional outline ring $C_{\text{contour}} = \sum V_{\text{Vertex}}$: A outline ring consists of a series of points V_{Vertex} arranged in sequence. Generally, if the points of the ring are sorted counterclockwise, they are considered as outer rings and clockwise as inner rings.

10) Definition2: Two-dimensional section (slice) $S_{slice} = \sum C_{contour}$: A closed area where a two-dimensional section is surrounded by one or more outline rings.

11) Definition3: The boundary of a two-dimensional outline ring $LC : LC_{start} = Vertex_i, LC_{end} = Vertex_{i+1}$ is an outline ring boundary composed of two adjacent vertices in front of and behind any outline ring. On this basis, it can also be considered that the two-dimensional outline ring is a ring border surrounded by a series of boundaries.

12) Definition4: Slice rectangular bounding box $S_Cube : \{(X_{min}, Y_{min}), (X_{max}, Y_{max})\}$: where

$$X_{min} = Min(\sum_0^M X_{vertex}) \quad , \quad Y_{min} = Min(\sum_0^M Y_{vertex}) \quad , \quad X_{max} = Max(\sum_0^M X_{vertex}) \quad ,$$

$$Y_{max} = Max(\sum_0^M Y_{vertex}), \quad M, \quad \text{are all the numbers of the vertices of the slice.}$$

13) Calculation: determine whether the point is in the section $B_{inner}(P, S_{slice})$: in order to judge whether all hexagonal cells in the two-dimensional section are in the two-dimensional section (slice) or intersect with the outline, it is necessary to calculate whether all hexagonal boundaries are in or out of the section:

$$\left\{ \begin{array}{l} \vec{V}_{Hor} = V_{normal}(x=1, y=0), \\ Ray_R = P + vt\vec{V}_{Hor}, Ray_L = P - vt\vec{V}_{Hor}, \\ Count_R = \sum Intersect(Ray_R, S_{slice}), \\ Count_L = \sum Intersect(Ray_L, S_{slice}), \\ B_{inner} = Count_R \% 2 == 1 \& \& Count_L \% 2 == 1, \end{array} \right\} \quad --(10)$$

Where $\vec{V}_{Hor}$ is the unit vector in the direction of X-axis, Ray_R is the ray starting from point P to the direction of X-axis, Ray_L is the ray starting from point P to the negative direction of X-axis, $Count_R$ is the number of points of intersection between Ray_R and all outline rings in two-dimensional section, $Count_L$ is the number of points of intersection between Ray_L and all outline rings. When both numbers are odd, this point is considered in the section, otherwise, it is out of the section. To simplify the calculation of the intersection point, the boundary of the outline ring can be projected to the Y-axis first. If Y_p the value is within this

projection interval, it can be preliminarily judged that there may be an intersection point, otherwise, it is directly considered that there is no intersection. If an intersection is possible, the ray can be converted to a ray segment (i.e., The end of the segment is at S_Cube the maximum /minimum boundary $X_B = X_{max}$) and the intersection of the ray and the boundary can be calculated using equation (9).

3.2 Adaptive hexagonal honeycomb calculation steps

In this paper, the adaptive hexagonal honeycomb is calculated for each layer of the slice. The hexagonal honeycomb is calculated for each layer of slice and the boundary path of the hexagonal cell is generated, and then the laser melting scanning is carried out with the boundary path to form the solid part of the honeycomb grid. The calculation steps are as follows:

- 1) Definition of slice, outline and bounding box data: slice is a two-dimensional outline boundary at a certain height of the model, which is represented by a closed outline boundary. The outline is a closed boundary formed by a series of continuous points, and the bounding box is a rectangular structure surrounded by slices.
- 2) Gets a rectangular bounding box of the slice of the current layer;
- 3) Data structure definition and hexagonal honeycomb definition: define the regular hexagonal data structure HoneycombCell, which stores the center point of the Cell, the Cell side length Lcell, and the starting point and endpoint of six equilateral edges, etc.
- 4) Data initialization of hexagonal structure: calculate the hexagonal cell array along X and Y directions with fixed side lengths within the scope of the rectangular bounding box, and store the center point of each cell and the starting point and endpoint of six equilateral segments, etc., and encapsulate the data in the Cell structure in the form of structure.
- 5) Calculate each cell in the hexagonal cell array in the previous step, as follows: Each equilateral in the Cell grid is intersected with the slice outline. When the Cell equilateral is within the slice region, this edge is directly retained; when the Cell equilateral is outside the slice region, this edge is deleted from the Cell data structure; when it intersects the slice outline, this equilateral is truncated, and the truncated part in the slice is retained.
- 6) Cell attribute calculation: calculate the length LReserve of the reserved six equal sides after the six sides of the Cell are calculated. When the length L is equal to 6 times LCell, it can be

known that the Cell is in the region and the next iteration is not carried out, but the Cell is kept in the Cell array. When the length is less than 6 times LCell and greater than 1 time LCell, it can be known that this Cell is located on the slice boundary, partly within the slice region, and partly outside the slice region. In this case, the next iteration is carried out. When the remaining length is less than 1 LCell, it is known that most of the cells are outside the slice region or all of them are outside the slice region, and the Cell is removed from the Cell array without further iteration.

7) Sub-cell iterative calculation:

① Definition of sub-cell structure: The sub-cell structure of the next step is determined according to the center point and side length data of the parent Cell in the previous step. The sub-cell structure is the three lower-level HoneycombCell located on the upper left, lower left and right side of the parent Cell grid, whose side length is half of that of the parent Cell, and whose center point is located on the upper left, lower left and right side of the parent Cell.

② According to the center point and side length of the sub-cell structure determined in the previous step, the Cell attributes of the three sub-cell structures in the sixth step are judged in turn, and the first item in the seventh step is iterated according to the attribute results.

③ Iteration end condition: when the child Cell's side length is less than $1/8$ of the original parent Cell's side length, that is, the iteration will end after 3 iterations.

8) According to the above steps 6 and 7, the boundaries of all parent and child cells located in the area are generated and output to the path file. The specific flow block diagram is shown in Fig. 3 below:

Figure 3 iterative calculation process of adaptive hexagonal grid

4 Algorithm test:

According to the above algorithm flow and time complexity analysis, this paper selected three typical sections to test and count their computation time, as follows:

1) Cuboid part (Fig. 4), the size of which is 50mm*50mm*10mm. For convenience of comparison, this paper calculated three sizes of hexagonal cells with side lengths of 3mm, 4mm and 5mm, and the path spacing is 0.1mm. The calculation results are shown in Fig. 5 and 6:

Figure 4 cuboid model (50mm*50mm*10mm) and lightweight structural model after cell calculation

(a) side length 3mm, spacing 0.1mm (b) side length 4mm, spacing 0.1mm (c) side length 5mm, spacing 0.1mm

Figure 5 calculation results of the regular hexagonal honeycomb of cuboid model

(a) side length 3mm, spacing 0.1mm (b) side length 4mm, spacing 0.1mm (c) side length 5mm, spacing 0.1mm

Figure 6 calculation results of the adaptive iterative honeycomb of cuboid model

2) Square fillet parts (Fig. 7): in order to test the continuity of hexagonal honeycomb grid in fillet transition, this paper calculated hexagonal cell for square with fillet transition to test the computational efficiency. Two types of cell calculations were performed at a slice height of 1 mm, and the results are as follows shown in Fig. 8 and 9:

Figure 7 cuboid model with rounded corners (50mm*50mm*10mm, R=20mm) and lightweight structural model after calculation

(a) side length 3mm, spacing 0.1mm (b) side length 4mm, spacing 0.1mm (c) side length 5mm, spacing 0.1mm

Figure 8 calculation results of hexagonal honeycomb without iteration of rounded cuboid model

(a) side length 3mm, spacing 0.1mm (b) side length 4mm, spacing 0.1mm (c) side length 5mm, spacing 0.1mm

Figure 9 calculation results of the adaptive iterative honeycomb of rounded cuboid model

Through the above calculation, it can be clearly found that for the calculation of hexagonal honeycomb cell with single structure, the intracell iterative honeycomb cell calculation method can automatically generate finer hexagonal honeycomb in the arc transition, increase the support points of the arc transition, improve the number and density of supports in the arc transition area, and help to improve the support strength in theory.

5 Algorithm verification and process experiment:

In order to verify the above simulation results, in this paper, the process experiments of different edge lengths of honeycomb cells are carried out for the above-mentioned rectangular, rectangular with circular arc and semicircular plate models respectively. The parts are printed by adopting the selective laser melting additive manufacturing process. The printing material is 316L and the printing equipment is SLM M150. The printing material parameters and printing process parameters are shown in the following table respectively:

5.1 Experimental materials and process parameters

The metal powder used in the experiment was 316L Stainless Steel, as shown in Fig. 10, and the powder particle size range was: 15-53 μm , and the particle size distribution was $D_{10}=21.9\mu\text{m}$, $D_{50}=33.0\mu\text{m}$, $D_{90}=49.6\mu\text{m}$. The particle size distribution is shown in Fig. 11, the hall flow rate is 17.0 s/50 g, and the apparent density is 4.10 g /cm³. The 316L stainless steel powder contains the following elements: Ni, Cr, Fe, Mo, C, Si, Mn, S, P. The proportions are shown in Table 1.

Figure 10 SEM morphology of powder

Figure 11 Size distribution of powder particles

Table1 Chemical composition of the 316L powder

Element	Fe	Cr	Mo	S	P	C	Mn	Si	Ni
/wt%	Bal	16.79	2.53	0.0056	0.022	0.027	0.68	0.64	11.07

The process parameters of this experiment are shown in Table 2:

Table 2 Table of experimental process parameters

Process parameters	Value
Laser power (P)	200W
Scanning speed (v)	1000mm/s
Scanning interval (m)	0.06mm
Thickness of powder layer (h)	0.035mm
Scanning mode (T)	Oblique partition
the side length of the cell (L)	3mm /4mm/5mm

5.2 Experimental platform

The schematic diagram of the host is shown in Fig. 12(a). The SLM host constituted a working platform, a powder feeding system, and a laser scanning system. The experimental platform could be vacuumed or filled with a protective gas according to materials and processing requirements to prevent the oxidation or burning of metal powders during melting and solidification processes[25]. The SLM experimental facility constituted a host, a laser system, a cooling system, a control system, and a gas protection system (Fig. 12(b)). The laser was an RFL-C300L continuous-wave fibre laser. The laser parameters are presented in Table 3. The printer had a formation size of 150 mm × 150 mm × 120 mm and fed powders through a cylinder.

(a) Schematic diagram of the SLM forming (b) Actual SLM equipment

Fig. 12 Schematic of the SLM equipment and experimental facility[25]

Table 3 Primary working parameters of the laser

Parameter	Setting
Rated output power/W	250
Working mode	Continuous/Modulated
Centre wavelength/nm	1080
Output power fluctuation	<3%
Minimum spot diameter/mm	0.06

5.3 Experimental results and discussion

Using the above materials and printing process parameters, the selective laser melting printing with arc rectangle, square rectangle and semicircle plate was carried out in this article. The printed samples were cleaned by an ultrasonic cleaning machine with industrial alcohol for 10 minutes, and the bonded powder and stains left by wire cutting on the surface of the samples were cleaned. The corresponding experiments were carried out on the printed samples respectively. To be more specific:

5.2.1) The printed results of the right-angled rectangular model and its compression curve

In order to compare the compression difference of the square model, the author fabricated by the SLM M150 the parts of the non-iterative honeycomb grid model and the parts with the iterative honeycomb grid of the right-angled rectangular structure respectively, and the side lengths of the honeycomb cell are respectively from 3mm, 4mm to 5mm, as shown in Fig. 13(a) and (b). Then

the quasi-static compression performance of the six parts was measured. The stress-displacement curve is obtained, and the results are shown in the Fig. 14 and Fig. 15:

(a) the right-angled rectangular printed parts of non-iterative honeycomb grid (b) right-angled rectangular model part with honeycomb cell after 2 iterations

Figure 13 right-angled rectangular honeycomb grid sample after fabricated

(a) 3 mm side length honeycomb cell morphology (b) 4 mm side length honeycomb cell morphology (c) 5 mm side length honeycomb cell morphology

Figure 14 Compression deformation morphology of right-angled rectangular parts with homogeneous honeycomb cells

(a) 3 mm side length honeycomb cell morphology (b) 4 mm side length honeycomb cell morphology (c) 5 mm side length honeycomb cell morphology

Figure 15 compression deformation morphology of right-angled rectangular part with iterative honeycomb cells

Through the above compression experiments, it can be found that:

(1) the smaller the edge length of the honeycomb cell is, the greater the pressure entering the critical yield of compression is, that is, the crushing point force of the small grid is larger. With the decrease of the edge length of honeycomb cell, the compression critical yield force of right-angled rectangular homogeneous honeycomb cell decreases from 5400 N (Fig. 14(a)) to 3300 N (Fig.

14(c)), and the compression critical yield force of right-angled rectangle with iteration decreases from 7200 N (Fig. 15(a)) to 5400 N (Fig. 15(c)), and the edge length of 4mm (Fig. 15(b)) and 5mm are basically the same (Fig. 15(c)).

(2): the compression curve of the homogeneous honeycomb grid part does not decrease smoothly after passing through the critical yield point, but passes through more than three times of compression force fluctuation, and this fluctuation point is called the crushing point (Fig. 14(a)). Compared with the solid part, this crushing point is the inherent characteristic of the honeycomb grid part due to the force transmission characteristic of the honeycomb. However, the crushing curve of the homogeneous honeycomb grid is relatively smooth, while the crushing curve of the iterative honeycomb grid fluctuates violently, and the pressure fluctuation range exceeds 1000n (Fig. 15(a));

(3) the critical yield force of the honeycomb grid parts with iteration is higher than that of the homogeneous honeycomb grid parts without iteration, and the value is basically greater than 30%-40%;

(4) for the honeycomb part with iteration, the pressure can expand to both sides in the compression process (Fig. 15(c)). The reason is that there are many small cells filling in the outline boundary of the right-angled rectangular part to disperse the pressure to both sides, which can significantly improve the deformation resistance.

5.2.2) Fabricated results and compression curves of rectangular model with arc

For the rectangular model with arc, the parts without iterative honeycomb grid model and the parts with iterative honeycomb grid are printed respectively, and the side lengths of the honeycomb grid are respectively from 3mm, 4mm to 5mm, as shown in Fig. 16(a) and (b). Then the quasi-static compression performance of the six parts was measured. The stress-displacement curve is obtained, and the results are shown in the Fig. 17 and Fig. 18:

(a) fabricated rectangular non-iterative honeycomb grid sample with arc (b) printed rectangular honeycomb grid sample with arc after 2 iterations

Figure 16 fabricated rectangular honeycomb grid sample with arc

(a) 3 mm side length honeycomb cell morphology (b) 4 mm side length honeycomb cell morphology (c) 5mm side length honeycomb cell morphology

Figure 17 compression deformation morphology of rectangular homogeneous honeycomb grid parts with arc

(a) 3 mm side length honeycomb cell morphology (b) 4 mm side length honeycomb cell morphology (c) 5mm side length honeycomb cell morphology

Figure 18 compression deformation morphology of rectangular iterative honeycomb grid with arc

Through the above compression experiment and its curve diagram, compared with the right-angled rectangular model, it can be found that its characteristics are:

(1): the smaller the edge length of the honeycomb cell is, the greater the pressure entering the critical yield of compression is, that is, the crushing point force of the small cell is larger. With the decrease of the edge length of honeycomb cell, the compression critical yield force of right-angled rectangular homogeneous honeycomb cell decreases from 2250 N (Fig. 17(a)) to 250 N (Fig. 17(c)), and the compression critical yield force of right-angled rectangle with iteration decreases from 3200 N (Fig. 18(a)) to 400 N (Fig. 18(c)). Compared with the compression of the right-angled rectangle, the yield force decreases obviously. The reason is that the stress area of the rectangle with arc is only the middle area of the upper plane, and the arc area is not contacted with the compression mold (Fig. 18(b)), which is equivalent to the concentrated stress process in compression.

(2): the compression curve of the homogeneous honeycomb grid part rises slowly and smoothly after passing through the critical yield point, and the smaller the honeycomb side length is, the more obvious the rising trend is. This phenomenon is different from that of the right-angled rectangle in detail. The reason is the same as the above analysis. As the arcs on both sides of the rectangle with arc gradually contact during compression, the purpose of gradually increasing the deformation resistance is achieved in macro. However, once that right-angle rectangle exceeds the critical yield point during compression, the whole structure shows an obvious collapse process, and the macro-resistance can not be improved only by the honeycomb structure of the structure itself;

(3) similar to the compression results of right-angle rectangular honeycomb grid, the critical yield force of honeycomb grid parts with iteration (Fig. 18) is higher than that of honeycomb grid parts without iteration (Fig. 17), and its value is basically greater than 30%-40%.

(4) for the honeycomb part with iteration, the pressure can expand to both sides in the compression process (Fig. 18(b)), because there are many small cells filling in the outline boundary of the rectangular part to disperse the pressure to both sides, which can significantly improve the deformation resistance;

(5): however, the crushing process is different from the compression crushing of a right-angled rectangle in detail. The iterative honeycomb cell of the model only has about 2 crushing points, but the resistance of each crushing point increases greatly compared with the yield force, and the pressure of the secondary crushing point as shown in Fig. 18(b) increases by more than 2 times compared with the critical yield force to 5500N, and the crushing force is the largest when the side length is 4mm, which is also its particularity.

5.2.3) Printed results of semicircular plate model and its compression curve

In order to make a simple comparison with the compression simulation results of the semicircular plate model, the part of the circular plate model without iterative honeycomb grid model and the part with iterative honeycomb cell are printed respectively, and the side length of the honeycomb cell is 5mm, as shown in Fig. 19. The quasi-static compression performance of the two parts was then measured. The stress-displacement curve is obtained, and the results are shown in the following figure:

(a) compression morphology of honeycomb grid parts without iteration (b) compression morphology of honeycomb grid parts with two iterations

Figure 19 deformation morphology of compression curve of the part of the semicircular plate model with 5mm honeycomb cell edge length

Through the compression experiment and its curve diagram of the semicircular plate model, it can be found that its characteristics are:

(1): under the condition of the same side length, the compression curve of the homogeneous honeycomb grid part rises smoothly after passing through the critical yield point and approaches the crushing point after a large compression displacement (10mm) (Fig. 19(a)), which is different from the compression curve of the two structures mentioned above in detail. The reason is that the mold gradually contacts the arc surface when the semicircular plate model is compressed, and the arc surface and the internal honeycomb cell gradually participate in the compression resistance, which plays the purpose of gradually increasing the deformation resistance on the macro level, so there is no obvious yield point for the critical yield of the part with gradually increasing the compression contact area, and only one crushing point. However, when compressed, the whole structure shows an obvious collapse process once the compression vertex is exceeded, and the collapse point similar to the compression process of a right-angled rectangle does not appear, so the macroscopic structure can be considered to have been completely destroyed, and the macroscopic compression resistance can not be realized any more;

(2): however, the compression process of the semicircular plate model of the iterative honeycomb grid structure presents a high frequency of crushing (Fig. 19(b)), and the compression force distribution at the crushing point is basically located in a pressure interval, which is similar to the continuous cyclic loading and unloading process. The reasons are as follows: A large number of secondary and final honeycombs are distributed along the boundary of the semicircular arc outline. These micro-honeycombs continuously contact during compression, and continuously transfer

compression force to all the cell wall surfaces of the structure, forming a hierarchical resistance process. In the process of compression, the honeycomb cells can achieve the multistage compression effect of continuously replenishing, rupturing, replenishing, and rupturing, so it shows the result of the high-frequency collapse in terms of pressure.

5.2.4) comparison of compression results of two models. In order to visually compare the compression characteristics of iterative honeycomb grid parts with homogeneous honeycomb grid parts, the compression results are compared in this section, and the results are as Fig. 20:

(a) comparison of critical yield between homogeneous honeycomb and iterative honeycomb with right-angled rectangle (b) comparison of critical yield between homogeneous honeycomb and iterative honeycomb with the rectangle with arc

Figure 20 comparison of compressive yield forces of model parts with different structural types

5.2.5) analysis of commonness and characteristics of compression results of the three models. Based on the comparative analysis of the above compression results, the following commonness laws can be found:

- (1) the smaller the spacing of honeycomb cells, the greater the pressure to enter the critical yield of compression, that is, the larger the crushing point force of small cells (Fig. 20(a));
- (2) when the compression passes the critical yield point, the cell will slip and break, and the slip line is about 30°. When the slip occurs, the honeycomb will quickly produce large dislocation, and the ability of resisting deformation will drop sharply. After the critical point, the compression resistance will decrease.
- (3) for the honeycomb part with iteration, the pressure can expand to both sides in the compression process. The reason is that the pressure can be dispersed to both sides due to the filling of many small cells in the outline boundary of the part, which can significantly improve the deformation resistance.

(4) the critical yield force of the honeycomb grid parts with iteration is higher than that of the homogeneous honeycomb grid parts, and the value is basically greater than 30%-40% (Fig. 20(b));

(5): the honeycomb grid with iteration can obviously collapse during compression, and the compression resistance increases in a large range with the increase of compression displacement (Fig. 15(c), Fig. 18(b) and Fig. 19(b)). The large fluctuation of the compression resistance and the increase of the compression frequency during compression help to significantly improve the energy absorption performance of the parts in a high-speed collision. This high-performance energy absorption characteristic has a good application prospect in many safety protection fields.

However, for the different contact conditions between the part and the mold during compression, the compression results will also produce great differences:

- (1) for the parts with constant contact area, there are more crushing points, but the pressure at the subsequent crushing points shows a gradual downward trend;
- (2) for the initial state of partial contact, when the contact area increases gradually with the increase of compression displacement, the compression curve also moves upward gradually, and the deformation resistance increases gradually after reaching the critical yield point. The subsequent crushing points were less, and the pressure showed a gradual upward trend.
- (3) In the case of no contact in the initial state and the contact area gradually increasing with the increase of compression displacement, the homogeneous grid compression curve has no crushing point, and the crushing frequency of the iterative grid curve increases significantly with fine fluctuation.

In particular, for the iterative honeycomb grid structure with small grid length, as shown in Fig. 15(a), Fig. 18(a) and Fig. 19(b), the sample exhibits multiple "reciprocating instability" during the stress-displacement platform stage under compression, and the occurrence of such intermittent instability or relaxation phenomenon has obvious periodic characteristics. Combined with the deformation observation of the sample with different compression displacements, it is considered that when the cell side length is small, the iterative honeycomb grid structure will undergo periodic evolution process of "elastic deformation-plastic instability - fracture failure - continuous plastic deformation - deformation strengthening" layer by layer during compression. For this structure, there is no layer by layer fracture phenomenon of the homogeneous honeycomb cell, but a layer by layer evolution process of "elastic deformation-plastic

deformation-deformation strengthening". Therefore, the compression curve of the iterative honeycomb grid structure shows a "wave-like" shape, and the evolution of this shape is very conducive to the energy absorption under the instantaneous impact state.

5.3 Analysis of energy absorption characteristics of honeycomb with different iterative edge lengths

Through the analysis of the crushing and energy absorption results of the iterative honeycomb grid, it can be found that there is a gentle and long plastic stage shown by the static quasi-state compression curve of the iterative honeycomb grid, which reflects a good energy absorption characteristic. When subjected to an external load, the flow stress level is low through large deformation. The impact energy is transformed into the energy of deformation and cracking of hexagonal holes in the iterative honeycomb grid structure, so the iterative honeycomb grid is a good energy absorption structure. Therefore, in order to further analyze the energy absorption characteristics of honeycomb cells with different wall thicknesses, this paper analyzed the mechanical characteristics of the influence of the wall thickness on energy absorption to find the optimal wall thickness for energy absorption. In this paper, a rectangular structure with iterative honeycomb cells is used as a model, and the energy absorption efficiency η is taken as an evaluation means: energy absorption capacity E equation, as shown in the formula of 11, energy absorption efficiency η equation [26], as shown in the formula of 12. In this equation, the overall stress and strain of the model can be calculated using the equivalent density, equivalent elastic modulus and equivalent yield strength derived.

$$E = \int_0^{\varepsilon_m} \sigma d\varepsilon \quad (11)$$

$$\eta = \frac{E}{\sigma_m} = \frac{1}{\sigma_m} \int_0^{\varepsilon_m} \sigma d\varepsilon \quad (12)$$

Where: ε_m is the strain at a certain moment; σ_m is the stress at the corresponding time;

ε And σ are the compression stress and compression strain, respectively;

According to equation 12, the curve calculation is carried out for a typical right-angled rectangular honeycomb cell (Fig. 13), and the energy absorption efficiency curve obtained is shown in Fig. 21. With the reduction of the cell side length, the compressive strain increases, and the energy absorption efficiency of the iterative honeycomb grid structure also increases. The higher the energy absorption efficiency, the energy absorption efficiency can be increased by more than 20% at the compressive displacement of 4mm, the more gentle the plastic platform stage of the compression curve, and the better the energy absorption characteristic.

Figure 21 energy absorption efficiency curve of the right-angled rectangular honeycomb structure with different honeycomb cell side lengths

6 Conclusions

In this paper, according to that characteristic of adaptive hexagonal honeycomb structure, the calculation method of the adaptive iterative honeycomb grid was studied, the corresponding algorithm was developed. The proposed algorithm was used to generate a variety of structural models containing honeycomb cells. After the structural models are generated, actual samples were printed by adopting the 316L Stainless Steel material and the selective laser melting additive manufacturing process. Mechanical compression was carried out on the printed samples, and comparative analysis was conducted on different models and different honeycomb types according to the compression curve results. Finally, the energy absorption efficiency curve was analyzed according to the compression characteristics of the iterative honeycomb grid. Through the above work, this paper draws the following conclusions:

- (1) the critical yield force of the honeycomb grid parts with iteration is higher than that of the homogeneous honeycomb grid parts, and the value is basically greater than 30%-40% ; the honeycomb grid with iteration can obviously collapse during compression, and the compression resistance increases in a large range with the increase of compression displacement. The large fluctuation of the compression resistance and the increase of the compression frequency during compression help to significantly improve the energy absorption performance of the parts in a high-speed collision.
- (2) Combined with the deformation observation of the sample with different compression displacements, it is considered that when the cell side length is small, the iterative honeycomb grid structure will undergo periodic evolution process of "elastic deformation-plastic instability - fracture failure - continuous plastic deformation - deformation strengthening" layer by layer

during compression. For this structure, there is no layer by layer fracture phenomenon of the homogeneous honeycomb cell, but a layer by layer evolution process of "elastic deformation-plastic deformation-deformation strengthening".

(3) with the decrease of the edge length of the iterative honeycomb cell, the compressive strain increases, and the energy absorption efficiency of the iterative honeycomb grid structure also increases, the energy absorption efficiency can be increased by more than 20% at the compressive displacement of 4mm. The higher the energy absorption efficiency is, the more gentle the plastic plateau stage of the compression curve is, and the better the energy absorption performance is. In this paper, a lightweight structure with iterative honeycomb grids is proposed for the most homogeneous honeycomb grids currently in use, which has a good application prospect in many safety protection fields due to its high performance of energy absorption characteristics.

Declarations

Funding: This paper was funded by the Key Project of Chinese National Programs for Fundamental Research and Development- Model Processing and Process Planning Software Project for Additive Manufacturing (2018YFB1105300)-Universal Full-dimension Digital Model Project (2018YFB1105301) and National Natural Science Foundation of China(51705307), Open Project Program of the State Key Lab of CAD&CG(Grant No. A2015), Zhejiang University.

Conflicts of interest/Competing interests: The authors have declared that no conflict of interest exists.

Availability of data and material: Not applicable

Code availability: Not applicable

Ethics approval: Not applicable

Consent to participate: Not applicable

Consent for publication: the publication has been approved by the authors

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