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Study on the out-of-plane compression properties of multistage titanium alloy lattice metamaterials at 350℃

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Abstract

Lattice metamaterials can meet the requirements of integrated design of structure and function of future aircraft. However, single-stage lattice metamaterials are prone to buckling at low relative density and thus lose their bearing capacity, while multistage lattice metamaterials can effectively improve the overall mechanical properties of the structure by increasing secondary rods. In this paper, based on single-stage pyramid lattice metamaterials, titanium alloy multistage pyramid lattice metamaterials are designed and fabricated by 3D printing technology. Then, through the out-of-plane compression performance test and numerical simulation of the structure at room temperature (25°C) and high temperature (350°C), the mechanical properties and damage evolution of the structure at different ambient temperatures are obtained. The result shows that compared with the single-stage lattice, the heat exchange area of the multistage pyramid lattice metamaterial designed in this paper increases by 116.51%, the ultimate strength increases by 1.51% at room temperature, and the ultimate strength increases by 12.06% at 350°C. Overall, the multistage lattice can delay the buckling of the structure due to the support of the internal secondary core, moreover increase the heat exchange surface area, so the multistage lattice has excellent bearing/thermal protection integration performance.

Keywords: multistage lattice metamaterials, titanium alloy, high-temperature mechanical property, experimental test, numerical simulation

1. Introduction

With the rapid development of aerospace technology, hypersonic vehicle has become an important direction of future aircraft development, and the thermal protection technology with light weight and high efficiency is one of the technical problems that must be solved in the development of hypersonic vehicles[1][2].

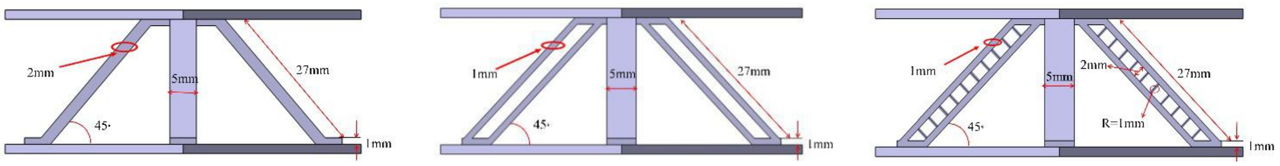
The lattice sandwich structure combines the material design, structural design and functional designorganically, which greatly improves the bearing capacity of the material. At the same time, the interior of the structure has a large porosity, which can realize the forced convection heat transfer, and is conducive to the realization of the integrated structure of light weight, heat prevention and bearing. The lattice sandwich structure has broad application prospects in the field of aerospace[3][4]. Meanwhile, compared with the single-stage lattice, the multistage lattice can effectively improve the buckling resistance and bearing efficiency of the structure, and increase the heat transfer area, which is expected to achieve the goal of thermal resistance-bearing integration in aircraft structure design[5][6].

Previous studies have shown that the single-stage lattice sandwich structure has excellent mechanical properties, but when the relative density is small, the structure is prone to buckling failure[7]. Compared with the single-stage lattice, the multistage lattice metamaterials redesigns the core on the basis of the single-stage lattice metamaterials, which can greatly improve the buckling resistance of the core element and give full play to the maximum potential of each element to withstand the load[8][9]. Kooistra et al [8] analyzed out-of-plane compression and in-plane shear failure mechanism of multistage second-order corrugated plate structure. The result shows that when the relative density is less than 5 %, the compression and shear failure strength of the second-order corrugated plate structure manufactured by aluminum alloy is significantly higher than that of the first-order truss with equivalent mass, and the out-of-plane compression and in-plane shear strength of the second-order structure are 10 times that of the first-order corrugated plate structure with the same relative density. Xiong Jian et al.[10] studied the mechanical properties and failure mechanism of “corrugated plate-pyramid” multistage lattice metamaterial. It is concluded that the buckling resistance of multistage lattice metamaterials is significantly better than that of single-stage pyramid structure under low relative density. Sui et al.[11] studied the mechanical properties of the tensile-dominated multistage triangular grid sandwich panel. Through the calculation theory of equivalent multistage triangular grid sandwich plate, they made theoretical predictions on its modulus and bending strength. They also analyzed the elastic buckling load and strength failure mode of the structure under lateral pressure, drew the failure mode diagram of the structure, and gave the relationship between structural size parameters and structural failure mode. Wu et al.[9][12] conducted out-of-plane compression and shear tests on pyramid-pyramid and pyramid-corrugated plate multistage lattice metamaterials, and analyzed the failure mechanism diagram. The results show that the bearing capacity of corrugated plate multistage metamaterial is four times that of the same primary structure under the same density, and the bearing capacity of pyramid-pyramid multistage lattice metamaterial is more significant than that of other multistage metamaterials.

As is shown in research mentioned above, multistage lattice metamaterials have great application potential. However, the current research mainly focuses on resin matrix composites and room temperature environment, which cannot meet the bearing requirements of hypersonic vehicle leeward structure at 350° ambient temperature. Therefore, in this paper, we study the high-temperature mechanical properties of titanium alloy multistage lattice metamaterials. Through experiments and numerical simulation, we explore the mechanical properties of multistage pyramid lattice metamaterials at room temperature and high temperature, and clarify the influence of temperature, core rod thickness and structural configuration on the bearing performance of pyramid lattice metamaterials. The work mentioned above can provide reference and guidance for the engineering application of multistage lattice metamaterials, and has important significance of engineering application.

2. Specimen

In this paper, a multistage pyramid lattice metamaterial is designed and fabricated based on the single-level pyramid lattice metamaterial. Compared with the single-level lattice, the multistage pyramid lattice increases the internal surface area of the structure by nearly twice, which also improves the buckling resistance of the structure. In the design process mentioned above, the total weight of the structure remains basically unchanged. The size of the test piece fabricated by 3D printing of TC4 titanium alloy is shown in Figure 1.



(a) (b) (c)

Figure 1 Diagram of shape and size of test piece: (a)P-type; (b)MH-type; (c)MP-type;

3. Experiment

The test device is shown in Figure 2. The room temperature test step test reference standard GB/T1454-2005, the high temperature test reference standard GB/T1454-2005 and HB 7571-1997. The test matrix is shown in Table 1.

Table 1 Test matrix

Name	Size	Quantity	Abbreviation	Test contents	Test types
Pyramidal lattice structure	Figure 1(a)	6	P-type	Load-displacement curve, Structural failure mode	Room/high temperature Out-of-plane quasi-static compression test
Multistage Hollow Pyramidal Lattice Metamaterial	Figure 1(b)	6	MH-type		
Multistage Pyramidal lattice Metamaterial	Figure 1(c)	6	MP-type		

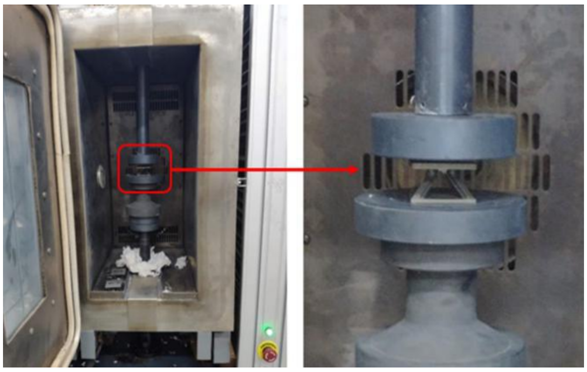


Figure 2 Schematic Diagram of High Temperature Compression Device for Testing Machine

4. Numerical Method

In this paper, the parametric modeling of lattice metamaterials is carried out in ABAQUS using Python language, and Johnson-Cook (hereinafter referred to as J-C) model is used as the material constitutive model. The Young ' s modulus of TC4 titanium alloy is 110MPa and the Poisson ' s ratio is 0.34. The corresponding relation between yield stress and plastic strain at room temperature is shown in Table 2 [13].

Table 2 Plastic stress-strain data of TC4 titanium alloy

True strain	0	0.00072	0.00145	0.00218	0.00291
True stress (MPa)	895.9	903.469	910.48	917.27	923.54
True strain	0.00364	0.00437	0.0051	945.71	
True stress (MPa)	929.47	935.21	940.5	0.00583	

5. Result and Discussions

5.1 Experiment Results and Analysis

The test results are shown in Table 3. It can be seen that for pyramid lattices with the same equivalent core thickness but different configurations, although the MH-type pyramid lattice metamaterial increases the internal surface area of the structure and enhances the heat transfer performance of the lattice metamaterial to a certain extent, it sacrifices the bending stiffness of the core in the structure, so the overall ultimate strength is small, and there is no support between the primary cores, resulting in the lowest carrying capacity compared with other types of structures. Compared with MH-type pyramidal lattice metamaterial, the secondary core in the middle of the primary core of MP-type pyramidal lattice metamaterial can effectively increase the bending stiffness of the primary core and delay the buckling of the primary core. Therefore, the carrying capacity of MP-type lattice metamaterial is higher than that of MH-type lattice metamaterial with the corresponding core thickness. Compared with P and MH pyramid lattice metamaterials, MP pyramid lattice metamaterial increase the weight and also increase a certain out-of-plane compressive ultimate strength. Compared with P-type and MH-type pyramidal lattice metamaterials, MP-type pyramidal lattice metamaterial increase the ultimate strength by 1.51% and 33.29%, respectively. It shows that at room temperature, when the core thickness is small and does not exceed a certain thickness, the secondary core can significantly improve the bearing capacity of the structure.

At the same time, the improvement of load-carrying efficiency of secondary cores in high temperature environment is higher than that in room temperature environment. It indicates that the material performance decreases with the increase of temperature, and it can be judged from the change trend that the improvement of the bearing efficiency of the MP-type pyramidal lattice metamaterial with thicker primary core by the secondary core will be greater. Compared with the P-type pyramid, the strength of the MH-type pyramid lattice metamaterial decreases due to the descent trend of the bending stiffness of the structure core, and the decrease is consistent, which is consistent with the load change trend. The strength of MP-type pyramid lattice metamaterial increases by 12.06%, which is significantly higher than that at room temperature. It shows that for the thicker primary core, the effect of secondary core on improving structural strength at high temperature is greater than that at room temperature. Compared with the P-type pyramidal lattice metamaterial, the strength increase of MP-type pyramidal lattice metamaterial is about six times of the weight increase, and the improvement of the bearing performance of MP-type pyramidal lattice metamaterial is more obvious at high temperature than at room temperature.

Table 3 Comparison of bearing capacity of different pyramid lattice metamaterial configurations

Specimen type	Room temperature test		High temperature test	
	Ultimate strength/kN	Strength reinforcement	Ultimate strength/kN	Strength reinforcement
P-type	27.81	/	18.66	/
MH-type	21.18	-23.84%	13.75	-26.31%
MP-type	28.23	1.51%	20.91	12.06%

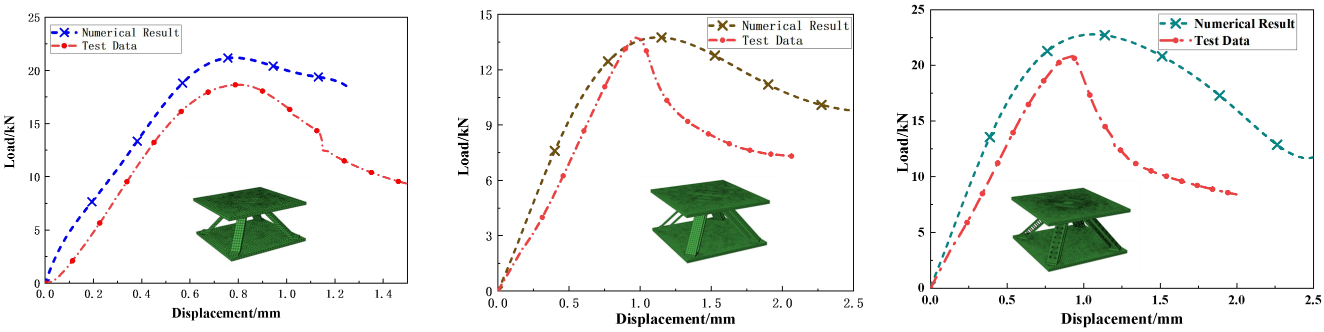
5.2 Numerical Simulation Analysis

The mechanical properties of the material decrease at high temperature, so whether in the test or in the simulation, it will be found that the bearing capacity of the structure decreases at high temperature. The comparison between numerical simulation and experimental data is shown in Table 4.

Table 4 Comparison of ultimate strength between high temperature environment test and simulation

Structure type		Ultimate strength of out-of-plane pressure at high temperature environment (kN)		Error
		Experimentation results（kN）	Numerical results（kN）	
Equivalent core thickness 2mm	P	18.66	21.20	13.6%
	MH	13.75	13.93	1.3%
	MP	20.91	22.70	8.6%

It can be seen from the table that the error between experiment and simulation is small, which verifies the rationality of numerical simulation. Figure 3 shows P-type, MH-type, MP-type pyramid lattice metamaterials numerical simulation and experimental load-displacement curve comparison, can further verify the accuracy of numerical simulation.



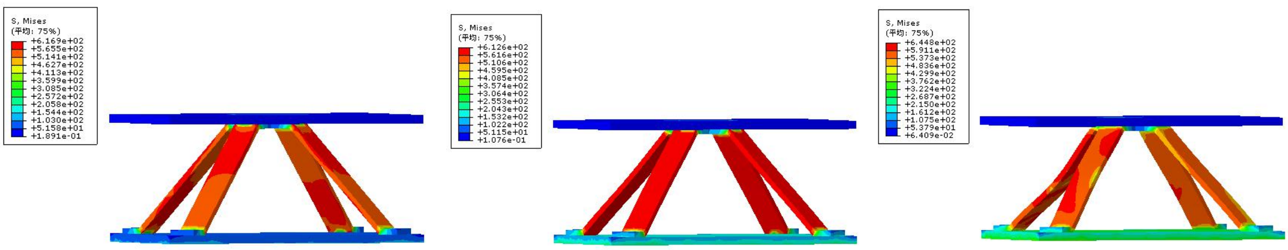
(a)P-type (b) MH-type (c) MP-type

Figure 3 Comparison of test and simulation ultimate strength loads at high temperature

The stress nephogram of high temperature numerical simulation process of three pyramid types is shown in Figure 4~Figure 6. As is shown in Figure 4, at the beginning of compression and subsequent process, the load of P-type core is larger and larger. In Figure 4(b), it can be seen that the core rod has begun to buckling when the load reaches the maximum and then begins to decline on the load displacement curve. With further loading, the core buckling becomes more and more serious, and the structure gradually loses its bearing capacity. The final failure mode of the structure in the simulation results is the severe buckling of two cores and the slight buckling of the other two cores, which is similar to the experimentation results. The high temperature leads to the attenuation of material modulus, resulting in the decrease of the bending stiffness of the core. The stress at the beginning of the core buckling in the high temperature environment is smaller than that in the room temperature environment.

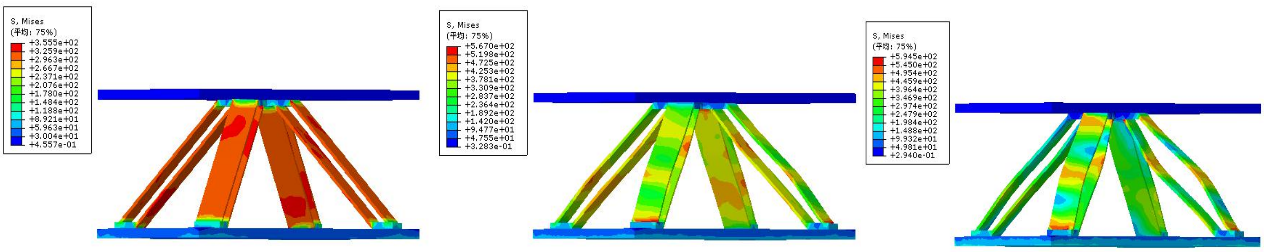
As is shown in Figure 5, similar to the P-type pyramid lattice metamaterial, the carrying capacity of MH-type pyramid lattice metamaterial in high temperature environment is lower than that in room temperature environment and is easy to fail. Due to the decrease of core thickness and the influence of high temperature environment on material properties, the core of MH-type pyramid lattice metamaterial has buckling when compressed to 0.4mm, and the buckling time is further advanced than that of P-type pyramid lattice metamaterial in high temperature environment. From the simulation load-displacement curve, it can be seen that the structure has failed when the load is less than 0.6mm. Displacement loading is adopted in the simulation and test, so the earlier buckling means the worse bearing performance. Before buckling occurs, the stress distribution of the core member is relatively uniform. When buckling occurs, the stress concentration area appears at the buckling position and the connection between the lateral core and the lower panel. With the buckling of the core member, the stress concentration phenomenon is more and more obvious. The ultimate failure mode is similar to that of the test, with two bars severely buckling and the other two slightly buckling.

Figure 6(a), 6(b) and 6(c) represent the stress nephogram of the core bar before, beginning and after buckling, respectively. At the beginning of compression, the stress distribution of the first-order core is ladder-shaped, and the second-order core is subjected to small load. When the primary core begins to buckle, the stress of the secondary core gradually increases to the maximum. Similar to the room temperature load, the second core region where the stress first increases is the buckling position of the first core, which corresponds to the position where the load begins to decrease on the load-displacement curve. The existence of secondary core can largely mitigate the buckling of the primary core, so the structural bearing capacity of MP-type pyramidal lattice metamaterial is better than that of MH-type pyramidal lattice metamaterial at whether room temperature or high temperature, and the buckling displacement will be relatively large. After loading to1.4mm, the maximum stress also appears in the secondary core, and the structure has lost its carrying capacity at that time. Moreover, under the influence of the first-order core, part of the second-order core inclines, resulting in further decrease of the structural bearing capacity. The bearing deformation process of the secondary core is similar to the simulation in the room temperature condition.



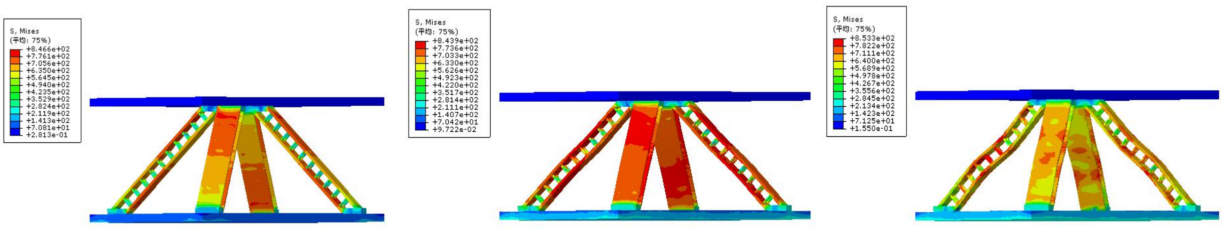
(a) Compress to 0.3mm (b) Compress to 0.6mm (c) Compress to 0.9mm

Figure 4 The stress cloud atlas of P-type pyramid lattice metamaterial at high temperature



(a) Compress to 0.25mm (b) Compress to 0.4mm (c) Compress to 0.5mm

Figure 5 The stress cloud atlas of MH-type pyramid lattice metamaterial at high temperature



(a) Compress to 0.3mm (b) Compress to 0.6mm (c) Compress to 1.4mm

Figure 6 The stress cloud atlas of MP-type pyramid lattice metamaterial at high temperature

6. Conclusion

(1) In room temperature and high temperature environment, the carrying efficiency of MP-type,

P-type and MH-type decreases in turn. For three types of pyramidal lattice configurations, the difference of structural mechanical properties between the same configurations tends to be consistent in high temperature environment. Compared with the increase of the thickness of the pyramid lattice metamaterials core, the increase of the bearing efficiency by adding the secondary core is more obvious.

(2) The failure modes of pyramids at room temperature and high temperature are the buckling failure of the first-order core, and the second-order core of MP-type pyramid lattice is destroyed, indicating that the performance of the second-order core is fully utilized, which verifies the rationality of the structural design. The bearing capacity of three types of pyramid lattice metamaterials at 350 °C decreases by about 30 % compared with that at room temperature.

(3) The numerical simulation results of pyramid lattice metamaterials at room temperature and high temperature show that when P-type and MH-type pyramid lattice metamaterials are subjected to out-of-plane compressive load, there will be stress concentration at the joint of core and panel and core member buckling position. For MP-type pyramid lattice metamaterial, stress concentration also exists in the secondary core at the buckling of the primary core. In the compression process, the secondary core is subjected to the load transmitted by the primary core, which can effectively delay the complete buckling of the primary core of the structure, thus continuing or enhancing the bearing capacity of the structure.

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