Research of Superplastic Forming, Mechanical Properties, and Thermal Insulation Performance of Titanium Alloy 3D Lattice Structure

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Abstract. A physically constitutive model based on microstructure evolution was constructed to describe the coupling relationship between various macro and micro variations of TA32 titanium alloy in superplastic deformation. Then, a finite element analysis model was established to simulate and analyse the superplastic forming process of titanium alloy based on the physically constitutive model. The deformation characteristics, mechanical properties and thermal insulation performance of the three dimensional lattice structure were analysed and tested. The results show that the three-dimensional lattice structure of titanium alloy has good formability, excellent mechanical properties, and good thermal insulation performance, indicating that it is a promising load-bearing functional integrated structure.

1 Introduction

Titanium alloy three-dimensional lattice structure of is a load-bearing functional structure that has excellent mechanical properties and can integrate multiple functions, such as insulation, heat dissipation, impact resistance, pipeline layout, fuel storage, etc [1-3]. However, the plastic forming of titanium alloys are difficult and costly to manufacture. Superplastic Forming/Diffusion Bonding (SPF/DB) technology can produce complex multifunctional structures with a near net shape, making it an effective method for fabricating titanium three-dimensional lattice structure, especially for high-temperature titanium alloys [4-6]. In this paper, the microstructure evolution of TA32 alloy during superplastic deformation was explored, and a unified constitutive model for titanium alloy superplasticity based on microstructure evolution was established. The titanium alloy three-dimensional lattice structure superplastic forming process was analyzed, and the simulation results were verified through experiments. Furthermore, load-bearing and thermal insulation properties of TA32 alloy three-dimensional lattice structures are discussed.

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2 Unified superplastic constitutive relationships based on microstructure evolution

Fig. 1 shows the different micro deformation phenomenon during the superplastic deformation of TA32 alloy. The main mechanism is the relative sliding of grains along high-angle grain boundaries (HAGBs), and the coordinated mechanisms are dislocation motion, grain rotation, dynamic recrystallization (DRX), etc. However, in the middle and late stages of deformation, the dislocation annihilation and the weaker DRX effect make the grain rotation play a more important role in the coordination mechanism, and the low texture strength and the coexistence of multiple slips with high critical resolved shear stress (CRSS) values indicate the continuous enhancement of grain rotation.

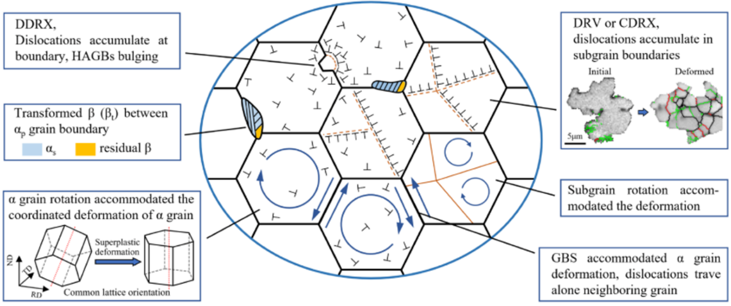
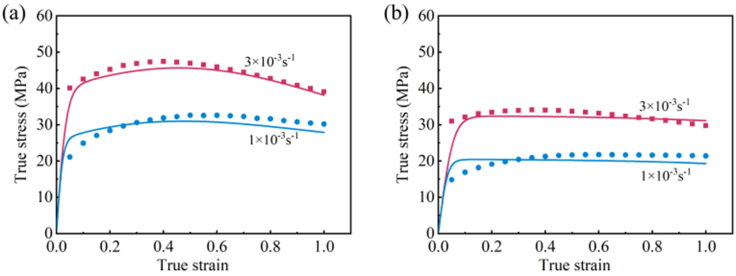


Fig.1. The micro deformation phenomenon in TA32 alloy

Based on the macro and micro deformation characteristics of TA32 alloy superplastic deformation, key internal variables such as grain size were introduced into the existing unified constitutive model [7], then a unified constitutive relationship for superplastic deformation of TA32 alloy was established. Fig.2(a) ~ Fig.2(c) show the comparison between predicted stress of unified constitutive model and experimental results. The predicted values generally fit experimental values well. However, the prediction accuracy decreases in the low strains (0.05~0.4) as the temperature increases. Fig.2(d) shows the correlation between predicted and experimental stress values. These results suggest that the unified constitutive model has high prediction accuracy and can effectively describe the TA32 alloy behavior under superplastic deformation conditions.



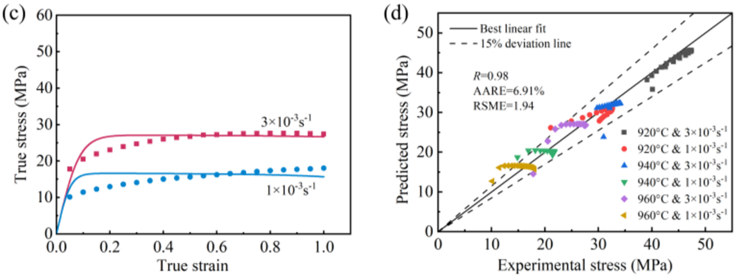
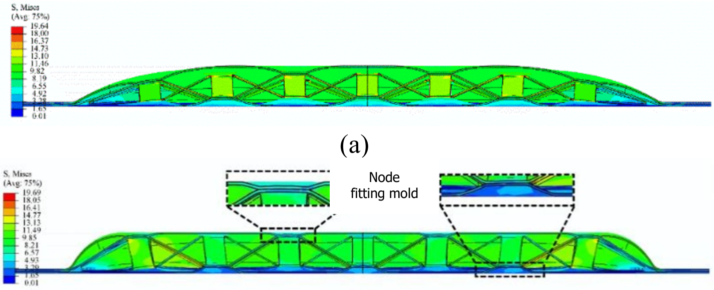


Fig.2. Comparison between predicted stress values (curves) of constitutive model and experimental results (points): (a) 920 °C, (b) 940 °C and (c) 960 °C; (d) correlation between predicted and experimental values.

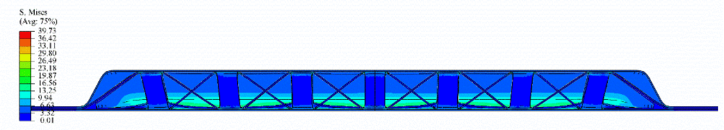
3 Forming and properties of lattice structure

3.1 Lattice structure forming

The TA32 alloy superplastic unified constitutive model is used to simulate the superplastic forming process of three-dimensional lattice structure. The results are shown in Fig.3, the upper panel bulges upwards towards the mold and gradually adheres to the inner wall of the mold, under the action of air pressure, while the lower panel always adheres to the lower mold. At the same time, the continuous movement of the core sheet through the nodes tied causes the ribs to stretch, ultimately forming a pyramid configuration three-dimensional lattice structure. The deformation area of the lower panel is concentrated in the node area under the tension of the ribs. The main deformation areas of the core sheet are the ribs and the joints between the ribs and nodes. The deformation of the upper panel is relative complex, with the non-nodal area forming an arc and being bulging, and the nodal area forming a 2mm deep groove. The stress distribution between the ribs and the upper panel is relatively uniform, the stress concentration occurs at the right angles where the ribs intersect. A lattice structure sample was formed by SPF/DB process, as shown in Fig.4. It can be seen from that the rib shape of the lattice core is relatively consistent, with good deformation, and there is no desoldering at each node. The cell structure symmetry in the center of the lattice structure is good, which is close to the shape of the standard single cell. The single cell structure in the edge skin area tilts and twists towards the border of the lattice structure, which is consistent with the simulation results. The forming situation of TA32 alloy lattice structure at different positions is shown Fig.5, the grain growth at the rib position is not obvious, and keeps as equiaxed grains. The diffusion bonding interface at the node has not any void defects, achieving complete metallurgical bonding.



(a)



(c)

Fig.3. SPF/DB simulation results of lattice structure: (a) 368.7s (b) 752.5s (c) 1543s

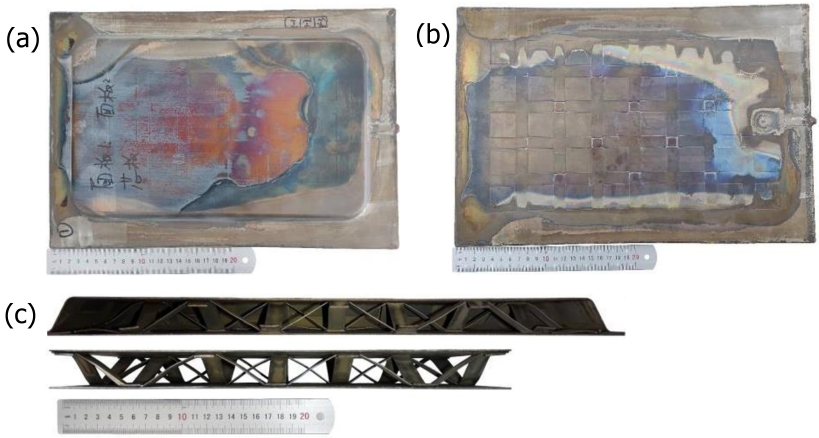
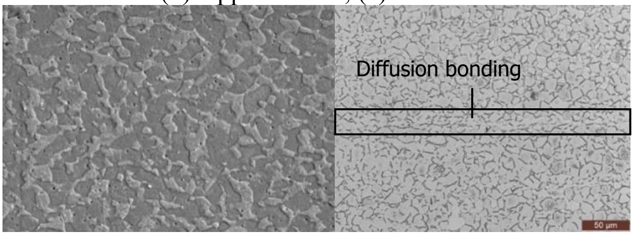


Fig.4. TA32 titanium alloy lattice structure formed by SPF/DB process: (a) Positive side; (b) Opposite side; (c) Section



(a) (b)

Fig.5. Microstructure at different positions: (a) Rib; (b) Node

3.2 Lattice structure mechanical properties

Fig.6 (a) ~ Fig.6 (f) show the room temperature flat compression results of the lattice structure. It is known that the main deformation characteristics during the compression deformation process are the continuous buckling deformation of the ribs and the formation of supports. As the length of the supporting ribs decreases, the load-bearing capacity of the lattice structure increases. During the continuous buckling deformation process of the ribs, there is a relative displacement along the OX axis between the upper panel and the upper rigid body plane, causing the upper panel to drive the core to undergo shear deformation. The shear deformation affects the buckling process of the ribs, causing them to undergo curling deformation along the width direction during the bending process along their length direction. Fig.6 (g) shows the compression results of the lattice structure, it is shown that the side skin undergoes bending and fracture under the combined action of shear deformation and flat compression load, thereby slowing down the shear deformation. The ribs at the central position experience fracture during the secondary plastic buckling process, while some ribs take on a straight shape due to tensile deformation. This indicates that the shear deformation of the lattice structure is more significant in the early deformation stage, and the buckling of the ribs is the main deformation in the later stage.

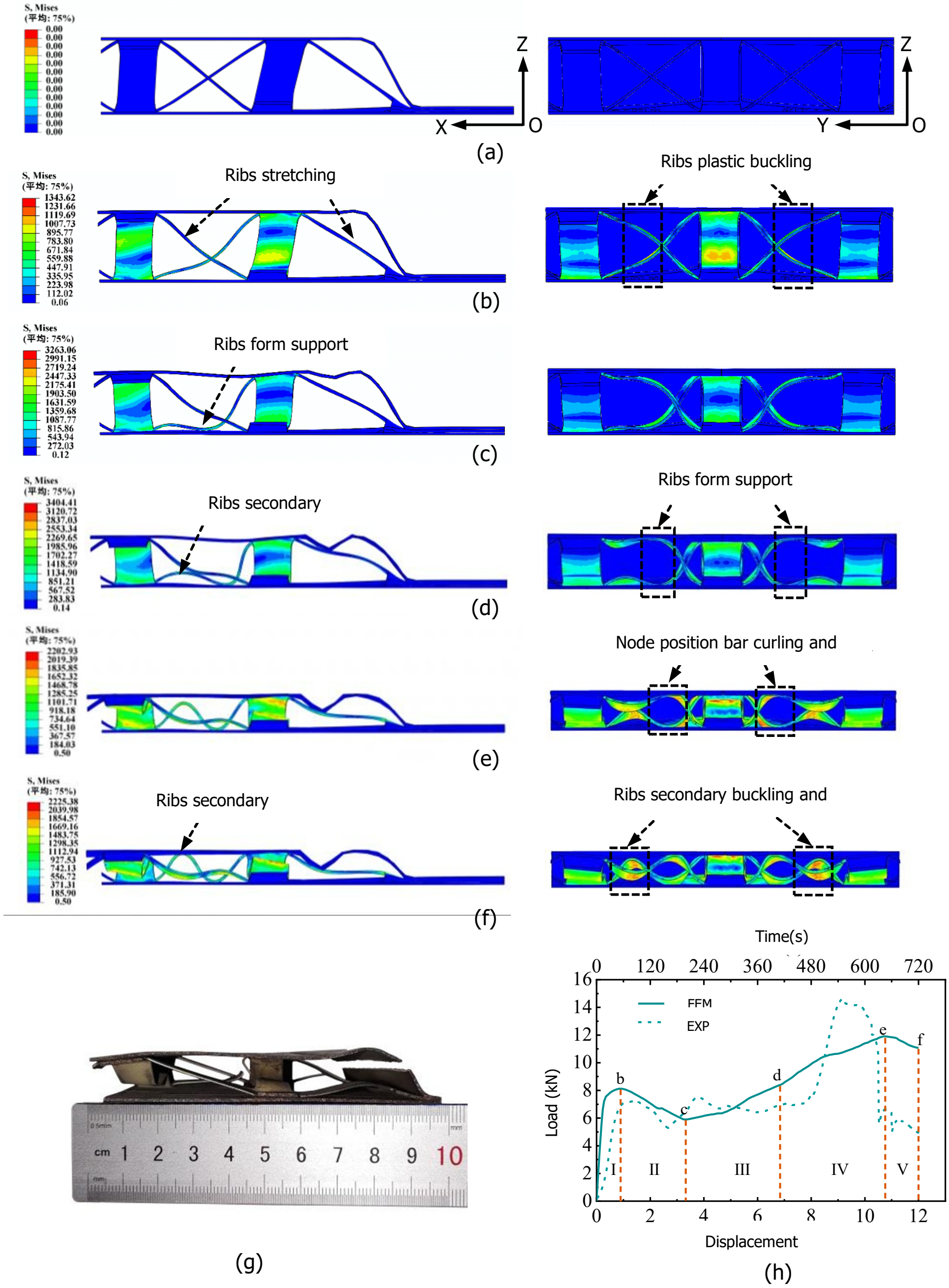


Fig.6 Results of compression deformation of lattice structure : (a)0s;(b)56.1s; (c)201.2s; (d)411.4s; (e)646.4s; (f)720s; (g)experiment result;(h)load-displacement curves.

3.3 Lattice structure thermal insulation performance

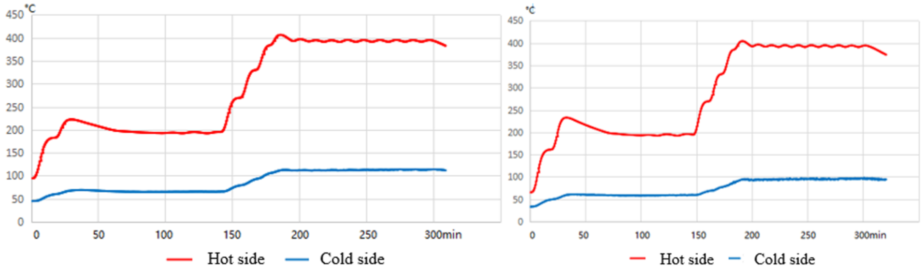
Aerogel is a kind of lightweight material with good thermal insulation performance [8-9], in this paper, the supercritical drying process is used to prepare silica based aerogel [10-11]. The drying process includes two stages, and the parameters are: 50 ℃ drying 1h+90 ℃ drying 1h, 50 ℃ drying 2h+90 ℃ drying 2h. Then, the dried aerogel block is broken into powder and poured into the titanium alloy hollow lattice. The filling process is vibrated at the same time, finally, the filling compactness reaches 88.14%.The thermal insulation performance of different test pieces was tested. The effective size of test pieces was 326mm × 200mm × 30mm. Test piece A was not filled with aerogel powder, B and C were filled with aerogel powder. The environmental temperature includes two situations, one is the insulation space environment, where the hot side is heated to the set temperature on one side, while the cold side is located in a closed air environment, the cold side of the other is in an open air environment. Table 1 shows the stable temperature values after high-temperature heating for 2 hours. The insulation temperature difference in the insulation cavity environment is 115 ℃~200 ℃, and the insulation temperature difference in the natural air environment is 277 ℃~310 ℃. After filling aerogel, the insulation temperature difference has increased by 30 ℃~80 ℃.

Table 1 Thermal insulation performance of titanium lattice structure at different conditions

Num	A		B		C	
	Hot face	Cold face	Hot face	Cold face	Hot face	Cold face
Insulation environment	403.2℃	287℃	400℃	208.2℃	400℃	202.7℃
Air environment	400℃	123.7℃	400℃	92.2℃	400℃	90℃

The thermal insulation performance of the titanium lattice structure with thermal barrier coating is also tested, as shown in Fig.7 (a). The spraying method is plasma spraying, and the coating is a mixture of $ZrO_2+Y_2O_3$, two coating thicknesses of 0.3mm and 0.5mm were selected. Heat the coating surface to 400 ℃ in an insulation environment. The temperature change of cold side is shown in Fig.7 (b) ~ Fig.7 (c), after 300 minutes, the maximum temperature of the cold surface reaches 113.7℃ with a 0.3mm thickness coating. However, the maximum temperature of the cold surface reaches 96.7 ℃ with a 0.5mm thickness coating. When the coating thickness increases from 0.3mm to 0.5mm, the plasma spraying coating is not damaged, and the thermal insulation temperature difference is increased by 17 ℃.

(a)



(b) (c)

Fig.7. Thermal insulation performance of titanium alloy lattice structure with spray coating: (a) Test piece of sprayed thermal insulation coating; (b) Temperature curve when the coating thickness is 0.3mm; (c) Temperature curve when the coating thickness is 0.5mm

4 Conclusions

(1) GBS dominates the superplastic deformation in TA32 alloy, accompanied by mechanisms such as intragranular dislocation motion, many grains with moderate rotation, the DRX with active dislocation motion to promote the increase of HAGBs.

(2) A unified constitutive model is constructed established with the grain size evolution, this superplastic model is applied to simulate the superplastic forming of TA32 three-dimensional lattice structure. The results show that the stress distribution of the lattice structure's ribs and the upper panel is relatively uniform, and stress concentration occurred at the right angle where the ribs intersected. After the deformation of the upper panel, a 2mm deep groove is generated on the surface of the node position.

(3) The main characteristics of flat compression in lattice structure are the simultaneous occurrence of plastic buckling of ribs and shear deformation of the structure.

(4) The thermal insulation performance test showed that the lattice structure filled with aerogel powder has good thermal insulation performance. When the hot surface temperature is 400℃, the thermal insulation temperature difference reached 277℃~310℃. Spraying a 0.5mm thick coating of $Zr_2O+Y_2O_3$ on the titanium alloy three-dimensional lattice structure resulted in a maximum insulation temperature difference of 303.3℃ at a hot surface temperature of 400℃, showing excellent insulation performance.

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