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Formation mechanism and elimination method for surface groove of the hollow lattice structure by superplastic forming

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Abstract. The titanium alloy hollow lattice structures can be widely applied on the advanced aircrafts due to their excellent mechanical properties and light weight. Superplastic forming and diffusion bonding (SPF/DB) process is an advanced process to manufacture these hollow lattice structures with two outer plates and one inner hollow plate. To further decrease the weight of the structures, thinner outer plate is preferred when compared with the inner plate, however, it would result in the occurrence of surface groove at the intersects between the outer plate and the hollow stiffener during superplastic forming process, leading to the failure of the structures. In this paper, the formation characteristics of the surface groove and the influence of the outer/inner sheet thicknesses on the occurrence of surface grooves was investigated through a well-developed finite element model. Furthermore, an innovative method was presented to eliminate the surface groove during SPF/DB, which makes use of double-sided dynamically adjusted gas pressure on the inner and outer of the plate during superplastic forming process. Based on the developed numerical models, the effects of assistant outer gas pressure parameters on groove formation have been investigated. The effectiveness of the proposed new forming method and the optimized parameters have been validated by performing a SPF/DB forming tests of a typical lattice structures. The method developed in this study provides a new way to improve the forming quality and accuracy of hollow parts by SPF/DB.

Introduction

The titanium alloy hollow lattice structure is a typical ordered topological structure [1-2], with the characteristics of lightweight, high strength and excellent load-bearing performance [3-4]. Meanwhile, the internal connected cavity can also be utilized to integrate multiple functions [5], for example, cooling function with active cooling medium flow through [6], insulation function with filled insulation materials [7], and bulletproof function with filled bulletproof ceramics [8]. Therefore, as a typical load-function integrated structure, titanium alloy hollow lattice structure has broad application prospects in future hypersonic aircraft and helicopters, representing an important direction for the development of aircraft structures.

Superplastic forming/diffusion bonding (SPF/DB) process is an advanced technology to manufacture the titanium alloy hollow lattice structures, which can enable a well metallurgical connection between the face sheet and core sheet through diffusion bonding, and form the hollow structure from bonded plates by superplasticity. Compared with other fabrication methods, it has significant advantages [9]. The use of SPF/DB technology can efficiently manufacture large and complex titanium alloy hollow structures with low cost [10]. One of the most commonly used titanium alloy hollow lattice structure is a three-layer superplastic forming structure, with two outer plates and one inner hollow plate. During SPF/DB, when the layer thickness is small (similar to rib thickness) and the rib angle is large, it is easy to form surface grooves on the formed face sheet [11]. To further decrease the weight of the structures, thinner outer plate is generally preferred when compared with the inner plate, however, it would lead to more significant grooves at the intersects between the outer plate and the hollow stiffener during superplastic forming process. The formation of surface grooves can deteriorate the aerodynamic and load-bearing performance of parts.

In this paper, an SPD/DB finite element model of TC4 alloy hollow lattice structure was established, and the influence of out/inner sheet thickness ratios on the groove was explored through finite element simulation. An innovative method of using double-sided adjusted gas pressure on the panel and assisted sheets was proposed to eliminate the groove during the forming process.

Simulation and experimental method

Numerical modelling

The lattice structure is a complex hollow topological structure, and in order to improve the efficiency of simulation, the cell structure was selected for finite element modelling. Fig. 1(a) shows a schematic diagram of the lattice structure, composed with two panels and truss structure, which is obtained through SPF/DB process. Fig. 1(b) shows a finite element model of superplastic forming with the lattice structure, whose size is 110 * 110mm and the size of connection node is 10 * 10mm. The blanks were set as a deformed body, consisting of upper and lower panels (1mm) and hollow core plates (0.8mm). The tie constraints were applied in the diffusion bonding areas. The upper and lower molds were set as rigid bodies, and the height of two molds was 38mm. The friction coefficient between the molds and blanks was set as 0.1.

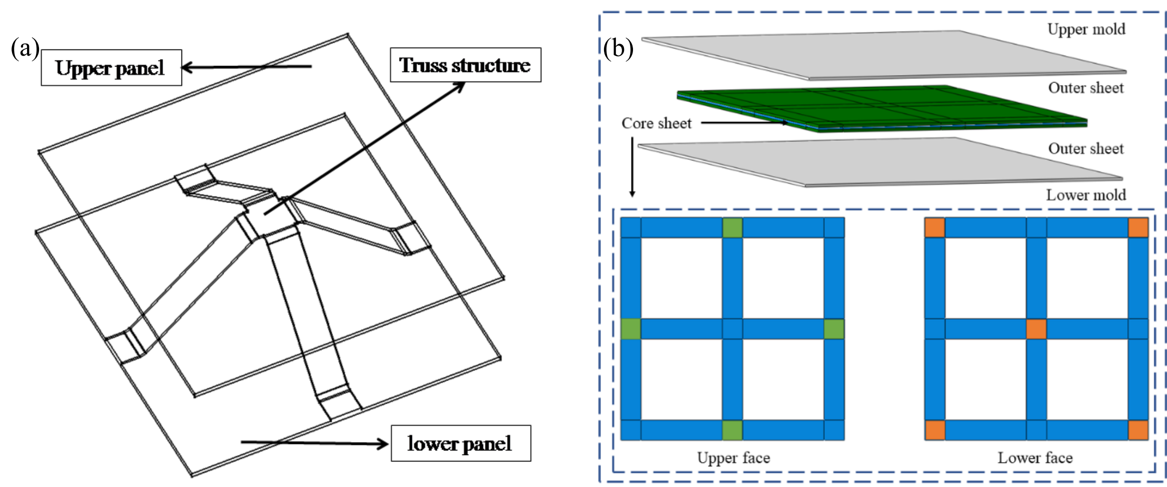

Fig.1 The schematic diagram of cell lattice (a) and finite element model of the superplastic forming (b)

The material of blanks is Ti6Al4V, whose superplastic deformation behaviour was described using the viscoplastic constitutive model: $\sigma = K\dot{\varepsilon}^m\varepsilon^n$

where K is the material constant, m is the strain rate sensitivity index, and n is the strain hardening index. The values of these constants were calculated according to the true stress-strain curves obtained at different strain rates (5×10^{-4}/s、1×10^{-3}/s、3×10^{-3}/s and 1×10^{-2}/s) at 920ºC, as: K=591.61, m-0.469 and n=0.177. Fig. 2(a) compares the experimental data with simulation results with the material model, both results are in good agreement with each other. During the SPF/DB process, the gas pressure was set on each surface of the internal cavity, which varied with time, th detailed values are shown in Fig. 2(b).

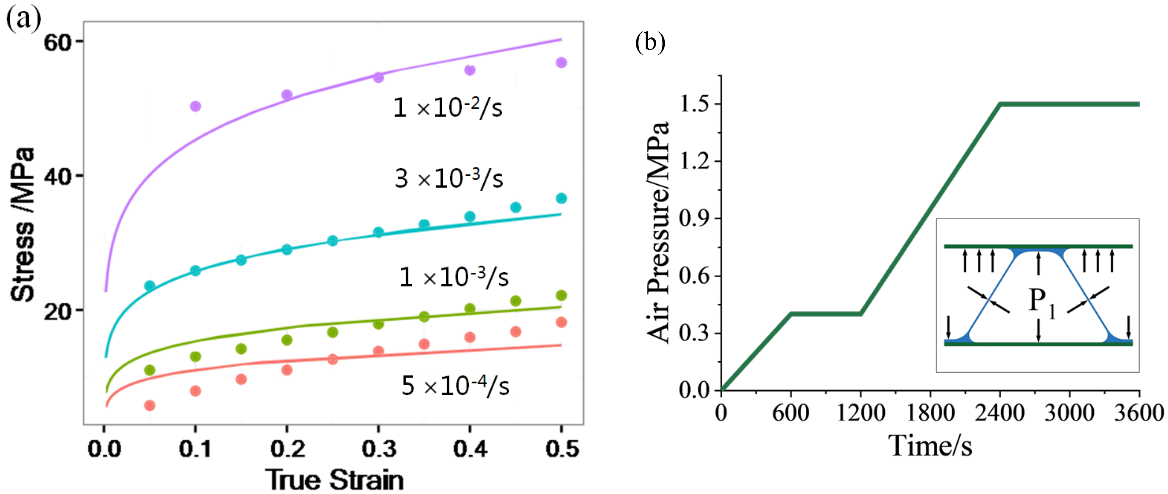

Fig. 2 The true stress-strain curves of Ti6Al4V at 920°C (a) and gas pressure loading curves (b)

SPF/DB tests

A typical lattice structure sample with the size of 420 * 380mm was selected for SPF/DB tests: First of all, the core plate was processed into the hollow shape according to the position of nodes, as shown in Fig. 3(a); Secondly, the stop-off coating was applied at the designated position of the upper and lower panels, so that the corresponding node positions were connected with the core plate by diffusion bonding; Finally, through the superplastic forming process, the upper and lower panels slowly move upwards and downwards to the molds surface, driving the core sheet undergo uniform plastic deformation, until to the formation the three-dimensional lattice structure. The formed lattice structure is shown in the fig. 3(b), and it can be seen that the forming quality of the ribs is intact, and no rupture occurs on the panels, but there are obvious grooves at the nodes.

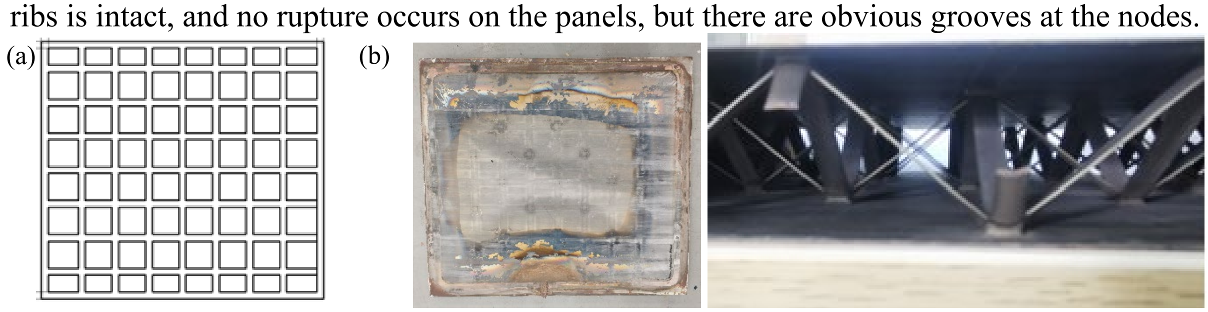

Fig. 3 The processed core sheet (a) and formed lattice structure (b)

Results and discussion

Formation mechanism and influence factor of the groove

Fig. 4 shows the forming process of the lattice structure by simulation, which can illustrate the formation mechanism of the groove. At the intermediate stage of forming as shown in Fig. 4 (a), the deformation rates in DB zone and non-DB zone are different. In non-DB zone, the inner pressure is directly worked on the outer plate, while in DB zones, multi-layers of plates with truss structures has a much larger stiffness than non-DB zone, and thus would deform slower than the non-DB zones with the same inner pressure. With the progress of the forming process, the layer in non-DB zone would firstly contact with the mold, making it difficult for the layer in DB-zone to fully fit the mold due to the significant changes in stiffness in the connection area and the serious storage of material near the DB zone, as illustrated by the final stage of forming as shown in Fig. 4(b). The grooves then would occur at the connection area between DB and non-DB zones.

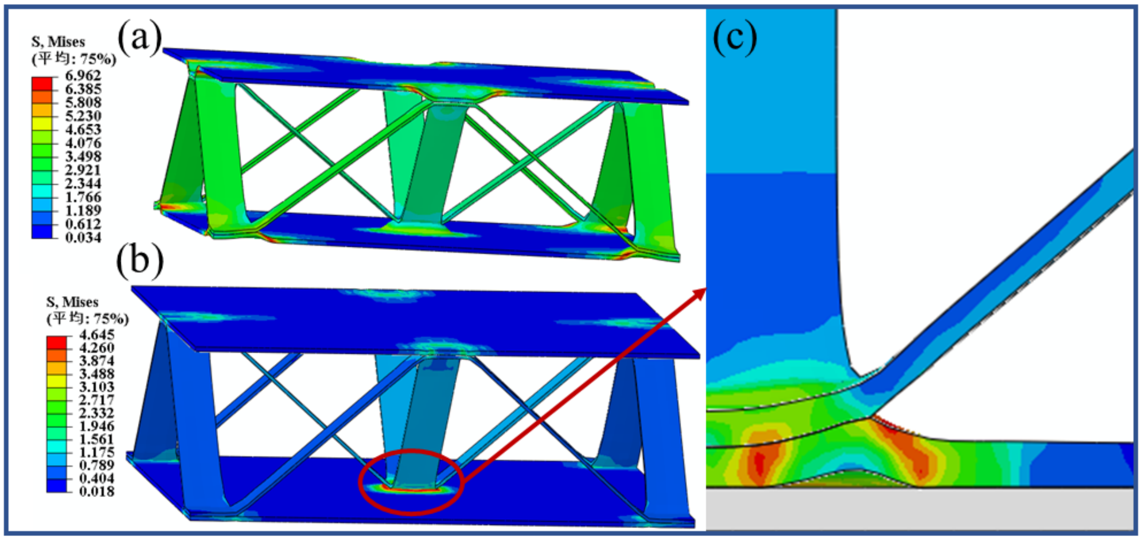

Fig. 4 The simulated forming process of the lattice structure: intermediate stage (a) and final stage (b)

As the occurrence of groove is related to the stiffness changes of the structure, the influence of the outer/inner sheet thickness on the formation of groove was further investigated. The outer/inner sheet thickness ratio (T1/T2) was defined to characterise the thickness effects. Different ratio, 0.75, 1, 1.25, 1.5 and 1.75, have been selected to perform the simulation, based on simulation results, the groove defects was investigated using the maximum groove depth as an evaluation indicator. Fig. 5 shows the maximum groove depths of the panel after forming at the thickness ratios of 0.75, 1, 1.25, 1.5 and 1.75. It can be seen that the groove depth decreases with the increasing outer/inner sheet thickness ratio. When the thickness ratio is 0.75, 1 and 1.25, the groove depth respectively reaches up to 1.566, 1.244 and 0.395mm, which can basically not be eliminated. When the thickness ratio increases to 1.5, the groove depth is 0.126mm, which is possible to be eliminated when continuously increasing the holding pressure and time. At the thickness ratio of 1.75, the groove depth approaches zero. With a thicker outer layer, the difference in stiffness in DB zone and non-DB zone becomes smaller, which could be the reason of the smaller groove being generated.

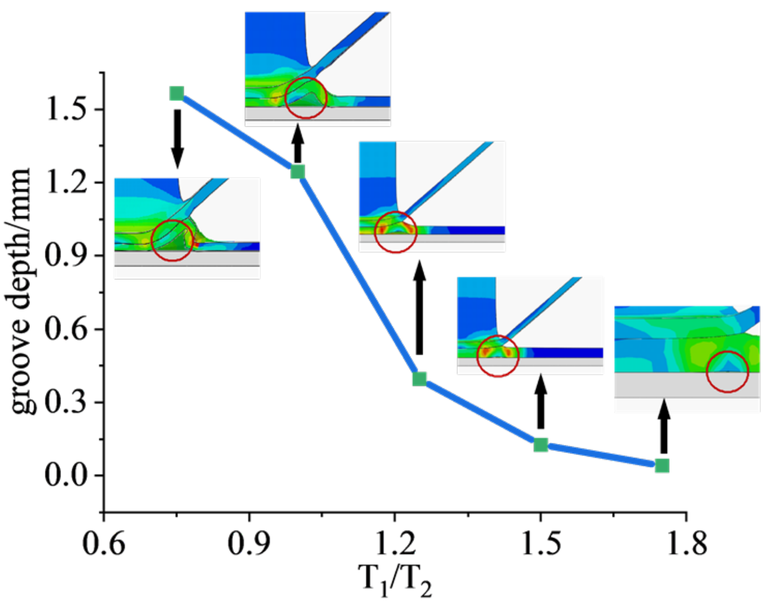

Fig. 5 The maximum groove depths at different outer/inner sheet thickness ratio

It can be concluded that it is a good method to eliminate groove defects by increasing the panels thickness when the thickness of the core sheet is constant. However, in order to achieve weight reduction of the structure, the panel is often designed to be close to the thickness of the core sheet. If thick panels are used for forming, it is still necessary to remove excess materials through chemical milling or mechanical processing, resulting in the increase of manufacturing costs. Therefore, it is still necessary to explore a new forming method for groove suppression when the thickness ratio is not big enough.

Eliminate method on the groove by double gas pressure

Except for changing the thickness of the structures to eliminate groove, another factor that could affect the deformation state in both DB and non-DB zones is the pressure. To further eliminate the strain rate differences in both zones during forming, adjusting the pressure dynamically is another possible way. Hence, an innovative method was presented here to makes use of double-sided dynamically adjusted gas pressure on the panel and assisted sheets to attain the proper thickness ratio during SPF/DB process. The finite element model of the new strategy of SPF/DB with the lattice structure by double gas pressure is shown in Fig. 6 (a), whose difference is that two assisted steel sheets with the thickness of 1.5mm are added contact with panels, and another gas pressure is applied on the surface of the assisted sheets. To verify the effectiveness of the method in this study, a constant out air pressure (1 MPa) was adopted. The outer and inner air pressure loading curves are shown in Fig. 6(b). Corresponding experiments have also been performed based on the method in section 2.2.

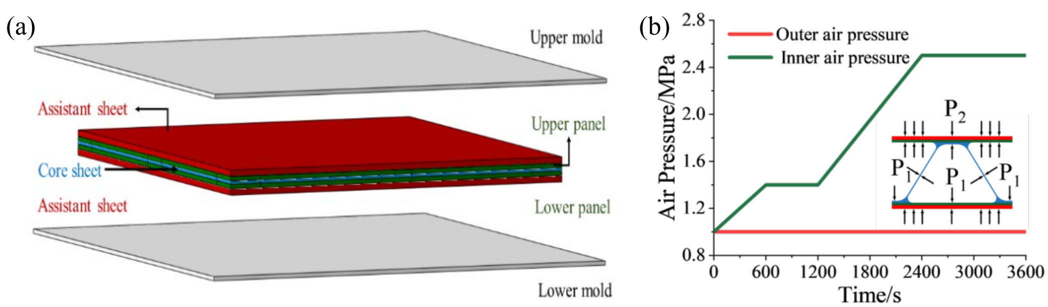

Fig. 6 The finite element model of super-plastic forming with double gas pressure (a) and outer and inner air pressure loading curves (b)

The simulated and experimental results of the lattice structure super-plastic formed using these two methods (single side pressure and double-side pressure) are shown in Fig. 7. At the intermediate stage, the gap between the bonding zone and the mold when formed using double side gas pressure is much smaller than that formed using single side gas pressure. This is because that the assisted sheets are tightly attached to the panels due to the outer gas pressure, which reduces the effect of the “pull” force on the DB zone from the increase of sheet thickness and friction force. At the final stage, the groove does not appear when formed using double side gas pressure, but the groove is obvious when formed using single side gas pressure. The experimental results of typical lattice structure super-plastic forming demonstrate the accuracy of simulation and the effectiveness of groove elimination using double side gas pressure method with assisted sheet.

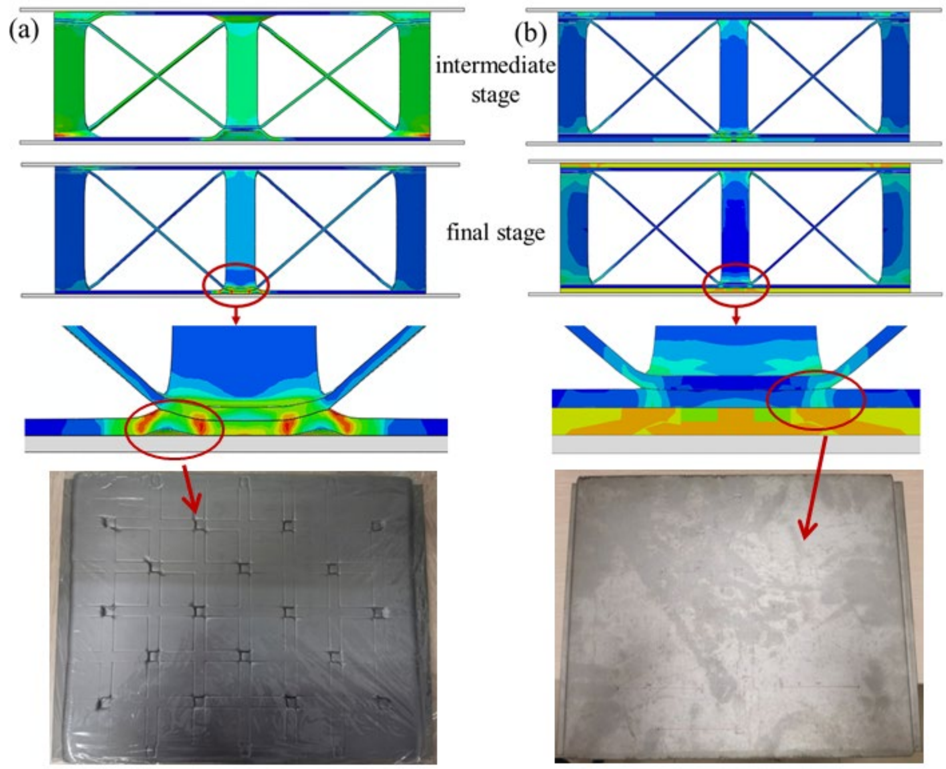

Fig.7 The simulated and experimental results of the lattice structure super-plastic formed using these two methods: single gas pressure (a) and double gas pressure (b)

Furthermore, the effect of different levels of outer gas pressure on groove formation was investigated by simulations. Fig. 8 shows the maximum groove depths of the panel after forming at the different outer gas pressure of 0, 0.2, 0.5 and 1 MPa. The inner gas pressure was adjusted according to the outer gas pressure in order to maintain the consistency of the pressure differences. It can be seen that the groove depth decreases with the increase of the assistant gas pressure. When the assistant gas pressure is 0, 0.2 and 0.5 MPa, the groove depth is respectively 0.395, 0.144 and 0.034mm. with the assistant gas pressure of 1 MPa, the groove depth was eliminated in a well condition.

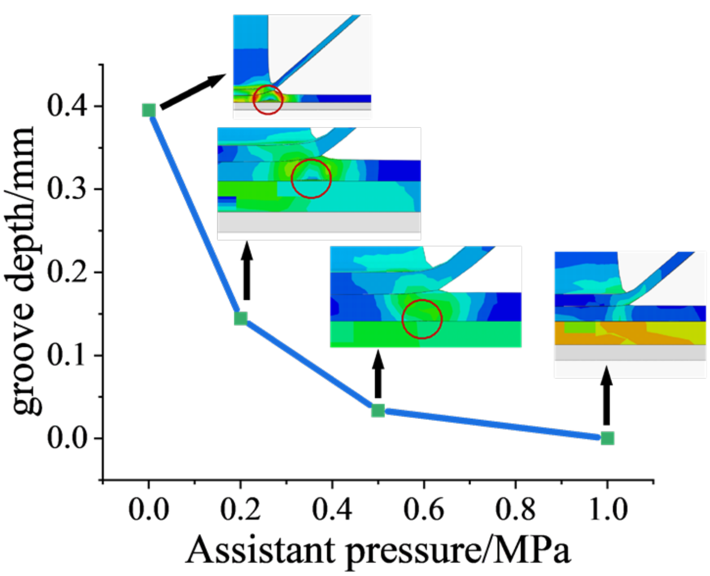

Fig. The maximum groove depths at different assistant gas pressure

Conclusions

(1) The groove would occur during SPF/DB due to the significant stiffness difference between the DB zone and non-DB zone in the hollow structure. The groove depth decreases with the increasing outer/inner sheet thickness ratio, and the groove defects can be eliminated when the thickness ratio reaches to 1.75.
(2) A new method to utilise double-sided adjusted gas pressure (inner gas pressure + assistant outer gas pressure) on the panel and assisted sheets to decrease the stiffness differences has been proposed, both simulation and experiments indicate that it is an effective method to eliminate the surface groove of the lattice structure.
(3) The groove depth decreases with the increase of the assistant outer gas pressure, and the groove depth reaches to zero with the assistant gas pressure of 1 MPa.

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