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Superplastic forming gas pressure of titanium alloy bellows①

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Abstract: The complex superplastic forming (SPF) technology applying gas pressure and compressive axial load is an advanced forming method for titanium alloy bellows, whose forming process consists of the three main forming phases namely bulging, clamping and calibrating phase. The influence of forming gas pressure in various phases on the forming process was analyzed and the models of forming gas pressure for bellows were derived according to the thin shell theory and the plasticity deformation theory. Using the model values, taking a two-convolution DN250 Ti-6Al-4V titanium alloy bellows as an example, a series of superplastic forming tests were performed to evaluate the influence of the variation of forming gas pressure on the forming process. According to the experimental results these models were corrected to make the forming gas pressures prediction more accurate.

Key words: superplastic forming; bellows; Ti-6Al-4V; pressure
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1 INTRODUCTION

The forming technology for titanium bellows includes hydro-forming, roll-forming, welding forming, etc[1-4]. However, the fabrication of titanium alloy bellows using these methods is complicated and expensive due to their large deformation resistance, severe springback, poor plasticity and formability at room temperature[5-7]. As some titanium alloys have superplasticity on commercial condition and their weld metal by high energy beam welding methods have also superplasticity[8-10], an advanced complex superplastic forming (SPF) technology was developed, applying gas pressure and compressive axial load to fabricate titanium alloy bellows. Welded tubes by laser beam welding are used as the forming tubular blank of titanium alloy bellows.

The forming technologies account mainly for the formability and uniformity of wall thickness distribution. If only gas pressure load is applied during the SPF process, it may produce a large amount of deformation of the plate material to form convolutions and result in severe wall-thickness thinning of as-formed bellows. So the complex SPF method applying gas pressure load and compressive axial load is adapted to overcome the disadvantages mentioned above, because the metal can be pushed into a deformation zone during forming. The forming schematic diagram is shown in Fig. 1. In order to obtain uniform thickness distribution, the SPF procedure is designed as follows. (1) Bulging phase: the gas pressure is imposed into the tubular blank to cause suitable plastic deformation, in other words, the generatrix of the formed component should be slightly shorter than that of the bellows. (2) Clamping phase: the punch is operated downward to close upper, middle and lower dies together. While the internal gas pressure p is maintained constant, the axial force is applied along the longitudinal direction of the bulged tube. (3) Calibrating phase: the gas pressure is increased gradually until the whole cylinder wall sticks to the dies in order to complete the final shape of the titanium alloy bellows.

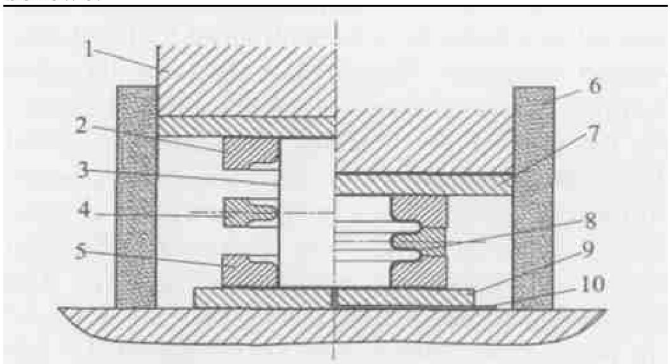

Fig. 1 Schematic diagram of bellows SPF process (left: initial state; right: final state)
1—Punch; 2—Upper die; 3—Tubular blank; 4—Middle die; 5—Lower die; 6—Furnace; 7—Top plate; 8—Bellows; 9—Bottom plate; 10—Inlet pipe

Although there are many factors influencing the quality of titanium alloy bellows like forming gas pressure, duration, SPF temperature, material used, wall thickness and radius of the tube, the forming gas pressure is the most critical factor. For a specific titanium alloy, the superplastic temperature maintain

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constant during forming process, and the duration may vary in some extent. So the gas pressure decides the results of deformation and the quality of formed bellows.

In this paper, the forming gas pressure for SPF process of bellows is analyzed according to the plasticity theory and thin shell theory in order to predict reasonable forming parameters. The predicted values are compared with the experimental values, and as necessary, the suitable modification is incorporated in the available formula to make the forming gas pressures prediction more accurate.

2 ANALYSES

2.1 Bulging phase

A schematic view of the bulging phase is represented in Fig. 2. For simplifying the analysis, the following assumptions are used due to the little amount of deformation of tubular blank: (1) The bulged profile is regarded as a part of a circular arc due to the small amount of deformation; (2) The meridional strain ε_m is equal to the circumferential strain ε_c.

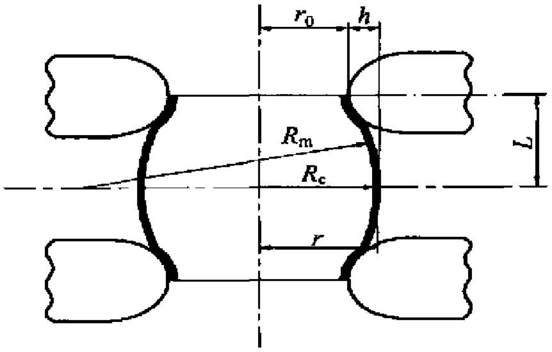

Fig. 2 Schematic diagram in bulging phase

During the bulging phase, at the contact parts constrained by the plate dies the tubular blank is locked to deform so that the bulged tube with many small convolutions is obtained. The gas pressure in bulging phase should be large enough to yield the tubular blank material and be adequate to control the bulge height of crown. Lower forming pressure may result in a smaller deformation degree of the tubular blank, so the crown of convolutions may produce extra deformation during calibrating phase, causing larger local thinning rates and non-uniform wall thickness distribution. On the contrary, the higher forming pressure may lead to excessive deformation of the tubular blank, so wrinkle defect would be produced during clamping phase.

According to the plastic deformation theory and the model of bulging phase, during this phase, the meridional stress, σ_m, and the circumferential stress, σ_c, are related by a well known equation[11-13].

$$\frac{\sigma_c}{R_c}+\frac{\sigma_m}{R_m}=\frac{p}{t} \tag{1}$$

where R_c is the radius of curvature in circumferential direction, R_m is the radius of curvature in meridional direction, p is the forming pressure, t is the thickness of the blank.

The effective flow stress, σ_e, at the apex of the dome can be calculated using the membrane theory, in which the radial stress can be ignored[14, 15]:

$$\sigma_e=(1-\alpha+\alpha^2)^{1/2}\sigma_c \tag{2}$$

and

$$\varepsilon_e=[4(1+\beta+\beta^2)/3]^{1/2}\varepsilon_c \tag{3}$$

where

$$\alpha=\sigma_m/\sigma_c \tag{4}$$

and

$$\beta=\varepsilon_m/\varepsilon_c \tag{5}$$

The circumferential and radial strains ε_c, ε_t can be denoted as:

$$\varepsilon_c=\ln\frac{r}{r_0} \tag{6}$$

$$\varepsilon_t=\ln\frac{t}{t_0} \tag{7}$$

where r_0 is the initial tube radius, r is the instantaneous tube radius, t_0 is the initial wall thickness and t is the instantaneous tube wall thickness.

The Levy-Mises flow rule yields (assuming volume constancy)[10, 11]:

$$\alpha=(2\beta+1)/(2+\beta) \tag{8}$$

or

$$\beta=(2\alpha-1)/(2-\alpha) \tag{9}$$

Combining Eqns. (1), (2), and (4), one can write

$$p=\frac{\sigma_e t}{(1-\alpha+\alpha^2)^{1/2}}\left[\frac{1}{R_c}+\frac{\alpha}{R_m}\right] \tag{10}$$

From the geometry of the tube forming, at the apex of dome, R_m and R_c are calculated from the following equations:

$$R_m=\frac{L^2+h^2}{2h} \tag{11}$$

$$R_c=r_0+h \tag{12}$$

$$\sigma_e=\sigma_s \tag{13}$$

where L is the half-length of deformed part, and h is the bulging height.

Based on the assumptions above and volume constancy, the instantaneous tube wall thickness t can be expressed as follows:

$$t=\frac{t_0 r_0^2}{(r_0+h)^2} \tag{14}$$

Instituting Eqns. (11), (12), (13) and (14) into Eqn. (10), respectively, the following expression is written:

$$p=\frac{\sigma_s t_0 r_0^2}{(r_0+h)^2(1-\alpha+\alpha^2)^{1/2}}\left[\frac{1}{r_0}+\frac{2\alpha h}{L^2+h^2}\right] \tag{15}$$

2.2 Clamping phase

During clamping phase, an axial compressive load is applied to close all of die blocks together. The bellows is subjected to internal pressure load together with compressive axial load. As the stroke increases, the height of tubular blank becomes smaller and the bulge height h is bigger. So the stress yielding the tubular blank increases gradually. However deformation can be performed fluently while the forming gas pressure maintains constant because the major forming force is axial compress force. So the forming gas pressure need not be changed during clamping phase. The schematic diagram is shown in Fig. 3. The gas pressure in the cavity of tube will increase to approximately 1.5 times higher than that of bulging phase.

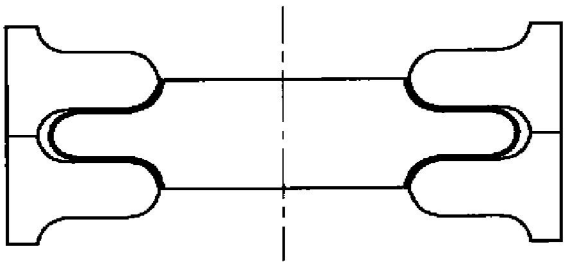

Fig. 3 Schematic diagram in clamping phase

2.3 Calibrating phase

The final convolution shape of the bellows is determined just after the calibrating phase. In calibrating phase, the forming gas pressure should be increased to force the tubular blank deformation continuously in order to fill-in the corner radii of dies and to form the final convolution shape of bellows. The primary problem in this phase is that non-uniform deformation exists between weld metal and base metal because of the difference of flow stress. So during calibrating phase, the gas pressure applied should be appropriate. On one hand, lower gas pressure may cause the crowns of convolutions not to contact on the surface of dies, especially at the high-strength welded seam. On the other hand, higher gas pressure may force the dies apart from, which will influence the accuracy of the formed bellows. Fig. 4 illustrates the schematic diagram of calibrating phase.

The forming gas pressure can be calculated according to Eqn. (10). The corresponding values of various parameters are as follows:

$$R_c \approx D_0/2 \tag{16}$$

$$R_m = R \tag{17}$$

$$\sigma_e = \sigma_w \tag{18}$$

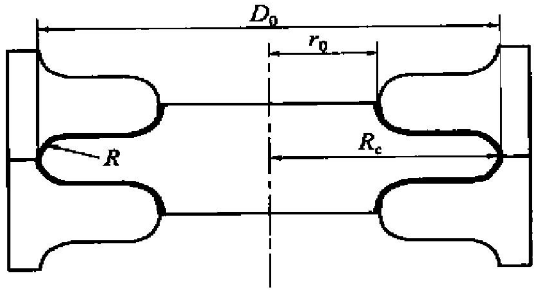

Fig. 4 Schematic diagram in calibrating phase

where R is the curvature radius of convolution, D_0 is the external diameter of crown and σ_w is the yield stress of weld metal at the superplastic temperature.

During calibrating phase, the meridional strain is neglected because of the little elongation of generatrix of bellows, so the instantaneous tube wall thickness t can be denoted as follows:

$$t=\frac{2t_0 r_0}{D_0} \tag{19}$$

Instituting Eqns. (16), (17), (18) and (19) into Eqn. (10), respectively, the following expression is written.

$$p=\frac{2\sigma_w t_0 r_0}{D_0(1-\alpha+\alpha^2)^{1/2}}\left[\frac{2}{D_0}+\frac{\alpha}{R}\right] \tag{20}$$

3 SPF EXPERIMENTS

A series of experiments were carried out to evaluate the influence of the variation of forming gas pressure on the forming process result.

SPF experiments were conducted for a two-convolution bellows made of Ti-6Al-4V titanium alloy, the dimensions of formed bellows are depicted in Fig. 5. A laser welded tube, which is 1.28 mm in wall thickness, 256mm in height and 272 mm in external diameter, was used as tubular blank of SPF process. The corresponding values of parameters are as follows: h= 4 mm, σ_s= 15 MPa, σ_w= 28 MPa.

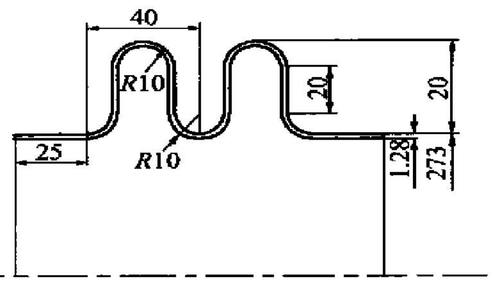

Fig. 5 Cross section of bellows (Unit: mm)

The material used was commercial mill-annealed Ti-6Al-4V alloy thin plate of 1.28 mm thickness.

The SPF experiment procedures are as follows.

Firstly, the forming apparatus is placed into a furnace and heated to 925 ℃ for 30 min. Then the internal gas pressure p is increased up to a proper value to bulge the tube. At the clamping process, while the internal oil pressure p is maintained constant, the axial force is applied along the longitudinal direction of the bulged tube. Finally, the internal gas pressure is increased dramatically in order to complete the final shape of the metal bellows. After removing internal gas pressure, the punch is operated upward to its initial position and the die block assembly is moved from furnace cooling to room temperature. The experimental parameters are listed in Table 1. The experimental results are as follows.

When all the experimental parameters are the calculated values according to the above models, the experimental process could be carried out. However the formed bellows exists two defects. One is that the thickness thinning rate at the apex of bellows increases dramatically. This indicates that crowns are far from the die surface after the bulging is finished. Another is that the weld metal is un-filling, as shown in Fig. 6 (a). This is because the lower forming gas pressure in calibrating phase can not yield the high-strength weld metal. The above defects display that the formulas exist a little error, which may be contributed to those assumptions used.

Table 1 Superplastic forming parameters

Test No.	Bulging phase		Clamping phase		Calibrating phase	
	Gas pressure/MPa	Duration/min	Gas pressure/MPa	Duration/min	Gas pressure/MPa	Duration/min
Calculated value	0.17	–	0.26	–	2.0	–
1	0.17	10	0.26	1	2.0	45
2	0.18	10	0.28	1	2.1	45
3	0.19	10	0.30	1	2.2	45
4	0.20	10	0.33	1	2.3	45
5	0.21	10	0.35	1	2.4	45

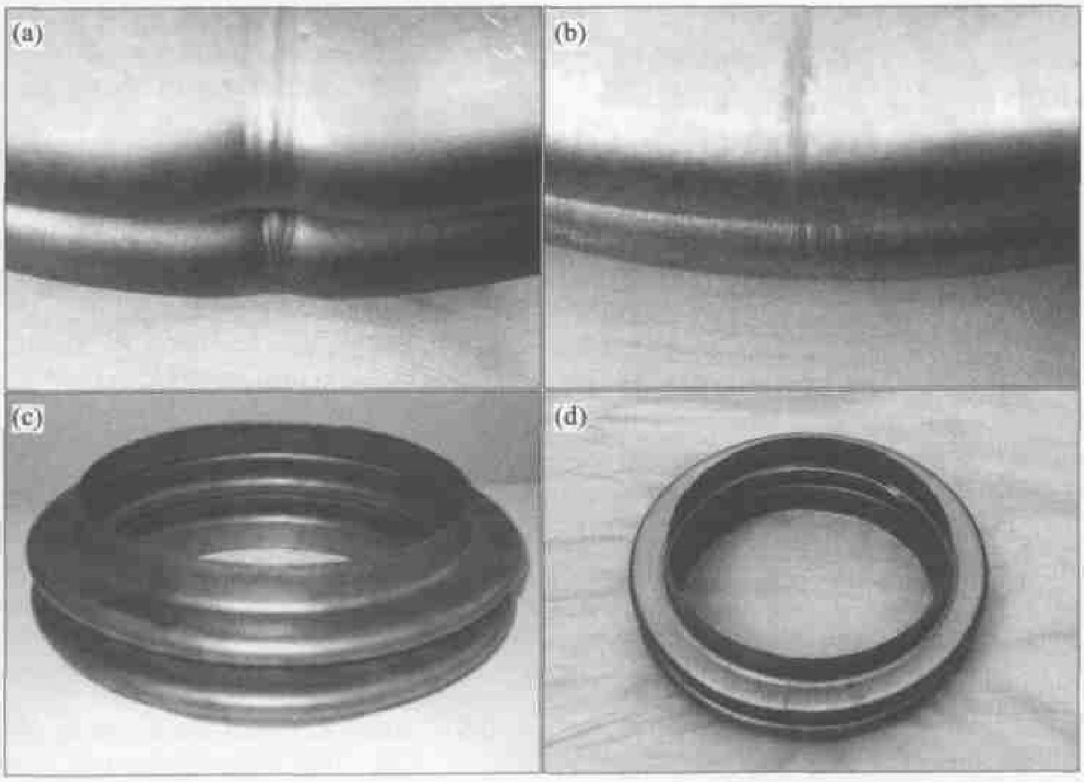

Fig. 6 Bellows photos under various forming pressures
(a) —Un-filling weld metal; (b) —Filling weld metal; (c) —As-formed bellows; (d) —Wrinkling bellows

When the forming gas pressure is 11% greater than the calculated value from bulging model and is 15% greater than the calculated value from calibrating model, the formed bellows possesses proper thickness distribution and dimension clearance. After SPF process the weld metal has smooth surface and no deformation defect, as shown in Fig. 6 (b). The as-formed bellows is shown as Fig. 6 (c).

When the forming gas pressure in calibrating phase is 11% greater than the calculated value, the formed bellows appears wrinkle near the convolution root of bellows although the forming process could be carried out, as shown in Fig. 6(d). The reason is that the excessive gas pressure causes extra deformation of tubular blank. As a result, the generatrix of the deformed welded tube becomes longer than that of the bellows, so the bellows produces wrinkle defect after clamping.

The forming gas pressure in calibrating phase may be 15% greater than the model value. Under the condition of this paper, it may be 50% greater than the model value.

The experimental results represent that the model values of gas pressures are smaller than the forming needs, so the original formulas for predicting gas pressure should be modified by multiplying the right-hand side of Eqns. (15) and (20) by a factor, herein after denoted by A, which is equal to 1.11 in bulging phase and is equal to 1.15 - 1.50 in calibrating phase.

4 CONCLUSIONS

1) The analytical models for forming gas pressure of titanium alloy bellows in SPF process are derived according to the plastic deformation theory and thin shell theory. They consist of bulging, clamping and calibrating phase models.

2) The superpalstic forming experiments are performed to fabricate a DN250 two-convolution Ti-6Al-4V bellows using a laser welded tube in order to evaluate the accuracy of models. The experimental results indicate that the model values are smaller than the practice and the model should be corrected. The proper forming gas pressures may be determined by following rules: it should be 11% greater than the model value in bulging phase and should be 15% - 50% greater than the model value in calibrating phase.

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