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Superplastic forming Ti−6Al−4V titanium alloy cylinder with near uniform thickness distribution

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Abstract: Different shapes of pre-forming die were designed using MSC. MARC. The influence of surface friction of pre-forming die and final forming die on final thickness distribution was analyzed. The results show that the thinning of the blank near the periphery and the bottom of deep cylinder benefits to the uniform thickness. And higher friction coefficient of pre-forming die (0.57) can efficiently reduce the thickness of this regions and result in a more uniform final thickness distribution. Lower friction coefficient of forming die can make the sheet tend to integral formation, also results in uniform thickness distribution. The friction of pre-forming die is increased by machining and the friction of forming die is decreased by spraying BN ceramic powder. The aerospace Ti−6Al−4V deep cylinder with uniform thickness (1.50−1.78 mm) is fabricated successfully by using friction changing and direct-reverse superplastic forming method.

Key words: superplastic forming; Ti−6Al−4V; friction changing; thickness distribution; finite element method (FEM)

1 Introduction

The use of titanium superplastic forming technology of aviation manufacturing structural parts, can improve the anti-fatigue and anti-corrosion properties of the structure, to meet light weight, high strength goals [1−6]. However, superplastically formed part often has a large non-uniform thickness distribution because SPF is primarily a stretch forming process where there is very little or no draw-in of material from the perimeter of the blank during forming [7,8]. This leads to the increase of weight and reduction of the integral property of the parts, and easily causes cracks and decreases the forming limit of materials [9]. Therefore, the non-uniform limits the practical application of superplastic forming. The direct-reverse superplastic forming process was an effective approach to improve the thickness uniformity [10]. It consists of two stages: firstly, the sheet was formed into the pre-forming die to pre-thin material in local regions, and then the pre-formed sheet was blow formed into the forming die to obtain the final shape.

In this work, based on superplastic forming Ti−6Al−4V deep cylinder whose wall thickness accuracy was demanded in the range of (1.6±0.2) mm, different shapes of pre-forming die were designed, the influence of these shapes on the wall thickness distribution of the final piece was studied by FEM and the characteristic of shape was discussed. Meanwhile, the relation between friction of pre-forming die, forming die and final thickness distribution was investigated. Furthermore, the experimental dies were machined in response to the results of numerical simulation, and the experiment of direct-reverse superplastic forming was performed.

2 FEM analysis for friction changing of dies to control thickness distribution

The geometry of Ti−6Al−4V deep cylinder is shown in Fig. 1. The wall demanded the thickness within the limits of (1.6±0.2) mm, while the initial thickness of sheet was 3.3 mm. After the sheet was superplastically formed to be deep cylinder, the flange and bottom would be removed as the useless parts. The higher volume ratio of wall means that it is hard to fabricate the cylinder whose thickness of wall meets the requirements by a single blow forming process. So, the aim points to design the pre-forming die which can not only make the

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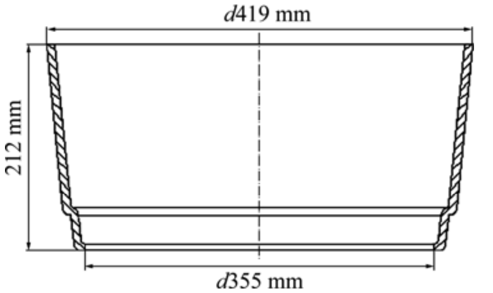

Fig. 1 Geometry of Ti−6Al−4V deep cylinder

thickness tend to be uniform, but increase the volume of the wall as much as possible.

Finite element simulation for sheet metal superplastic forming has been widely used in the aerospace industry to provide direct information and reduce the cost and time of component, even eliminating the need for expensive trial-and-error testing [11−16]. Therefore, FEM method was used to design the dies to avoid wasting the manpower and resources.

Because of its symmetry, only quarter of the dies was modelled. The curves of pre-forming die and forming die were plotted using AutoCAD software and then were imported into MSC.Marc through the interface of METANT. The surfaces of pre-forming die and forming die were generated by rotating and expanding the curves. The initial model of sheet was divided into 360 elements and then the model was remeshed according to the deformation of different regions of the deep cylinder.

In this work, the material properties were set to be rigid-plastic and the flow behavior was described by the Backofen equation as follows:

$$\sigma = K\dot{\varepsilon}^{m} \tag{1}$$

where σ is the flow stress, $\dot{\varepsilon}$ is the strain rate, m is the strain-rate sensitivity exponent and K is a material-related constant. The superplastic forming was performed at 925 °C, K was set to be 1030 and m was 0.65. The FEM process of direct-reverse superplastic forming of Ti−6Al−4V deep cylinder is shown in Fig. 2, in which steps (1)−(3) constitute the reverse forming (pre-forming stage), and steps (4)−(6) constitute the direct forming (forming stage).

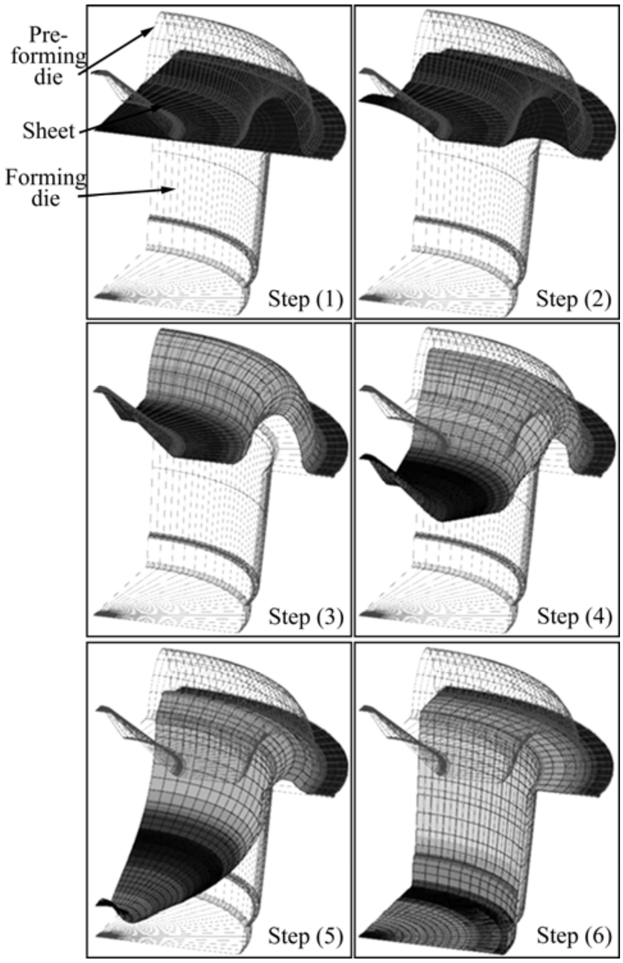

Fig. 2 FEM process of direct-reverse superplastic forming of Ti−6AL−4V deep cylinder

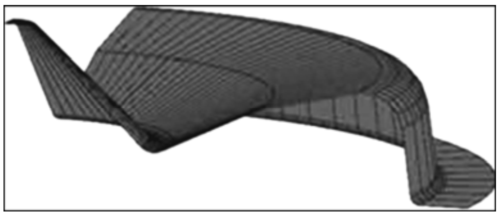
Fig. 3 Shape of pre-forming die

2.1 Influence of friction changing of pre-forming die on thickness distribution of final deep cylinder

Based on the pre-forming die (Fig. 3), the friction of pre-forming die was changed to obtain more uniform thickness of deep cylinder. To obtain the optimal coefficient of friction, the FEM simulation was performed.

The friction coefficient of pre-forming die was set to be 0, 0.3, 0.45, 0.577 and sticking, respectively, and the result of the thickness distribution is shown in Fig. 4. It is obvious that with the coefficient of friction increases from 0 to 0.577, the thickness distribution tends to be more uniform and the deviation between the thinnest and the thickest point turns to be smaller. This is because the coefficient of friction has a great influence on the thickness distribution. As the coefficient of friction increases, the pre-thinning of blank near periphery and the bottom becomes larger by contacting with the surface of the preforming-die. This makes the resistance of deformation of these regions turn to be smaller than that of other regions, thereby the most of the deformation is concentrated in these useless regions during the final forming process. The deformation of sidewall tends to be even because almost no intense local deformation generates in the useful region.

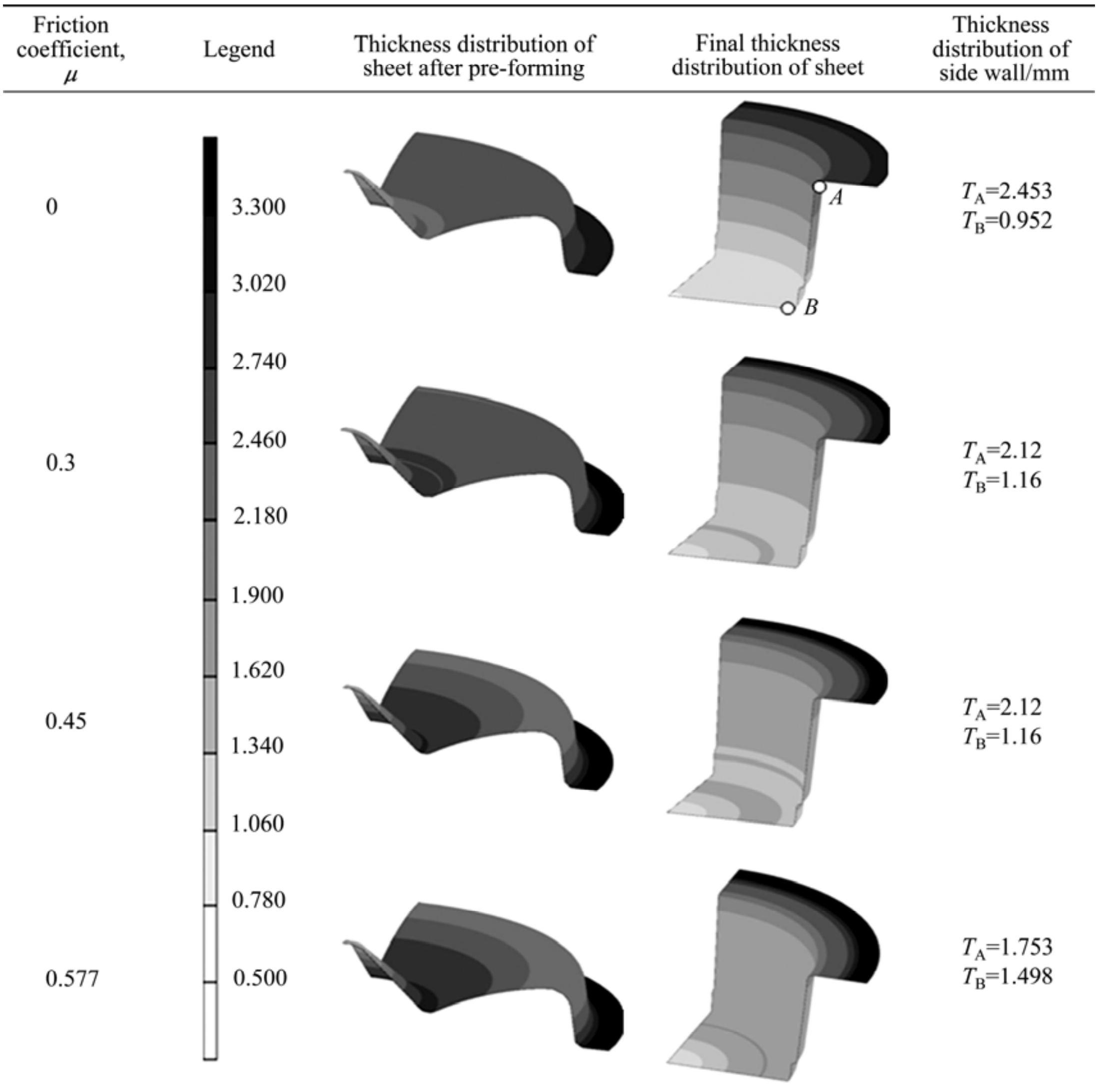

Fig. 4 Final thickness distribution of sidewall of deep cylinder for different friction coefficients of pre-forming die

2.2 Influence of friction changing of forming die on thickness distribution of final deep cylinder

To investigate the influence of friction of forming die on the thickness distribution of deep cylinder, the FEM was also performed. Using the pre-forming die of Design 5, the coefficient of friction of pre-forming die was set to be 0.2, and the coefficient of friction was set to be 0, 0.3 and 0.577, respectively. The results are shown in Fig. 5. Clearly, with the decrease of the coefficient of friction, the thickness tends to be uniform, and when μ is set to be 0, the thickness of sidewall turns to be almost totally even. This indicates that the smaller coefficient of friction makes much advantages of thickness distribution. This is because if the friction is smaller, when the sheet contacts with the die, it is still in a state of free sliding. This means that the flowing of sheet still occurs after the sheet touches the die. The forming sheet tends to be whole stretching, thus the thickness deviation also tends to be more uniform.

2.3 Simulation time—pressure curve

To obtain the time—pressure curve under the condition of the direct-reverse superplastic forming, the pre-forming and final forming were set in two independent load cases, respectively, in one analysis. The superplasticity control module of Marc was utilized to load pressure in accordance with the target strain rate, and the target strain rate was set to be 0.002 s^{-1}. MARC solver calculated the required pressure in each incremental step to make the global maximum strain rate remained within the vicinity of the target strain rate during the direct-reverse superplastic forming process. Figure 6 shows the simulation time—pressure curve at the strain rate of 0.002 s^{-1}. It can be seen that the curve is divided into two parts of the preforming and final forming. During the preforming process, the pressure increases gradually, and reaches its maximum at 500 s of about 2 MPa. In the final forming process, the pressure also increases gradually, and reaches the

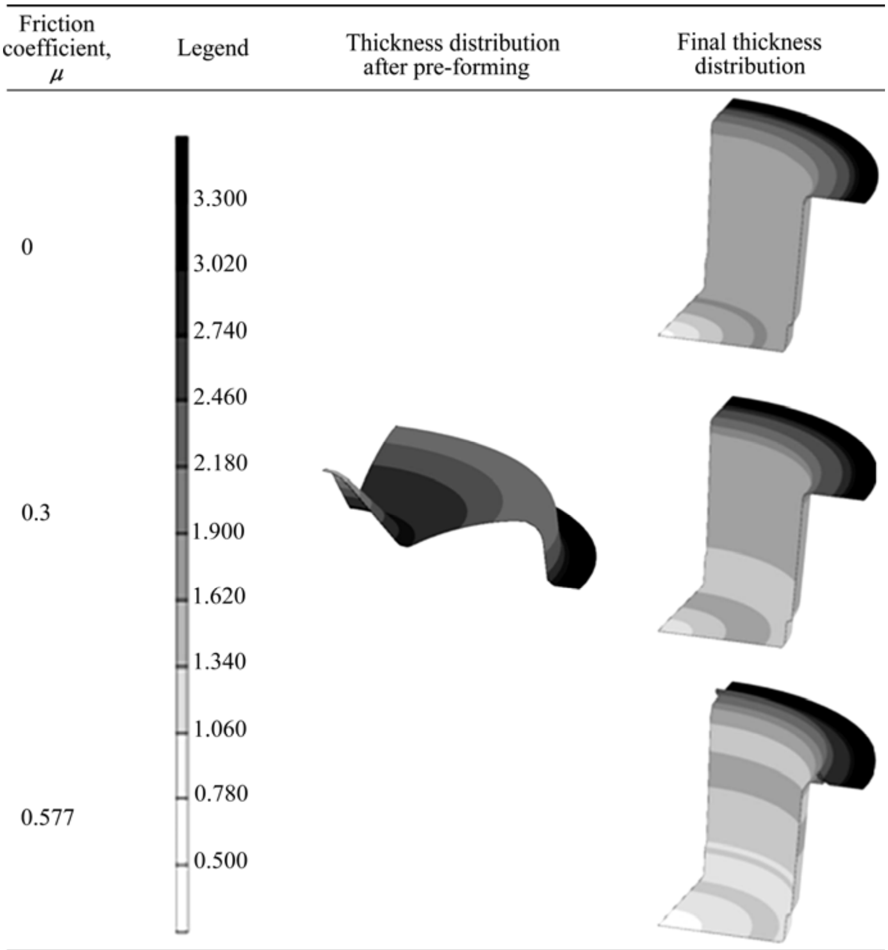

Fig. 5 Final thickness distribution of sidewall of deep cylinder for different friction coefficients of forming die

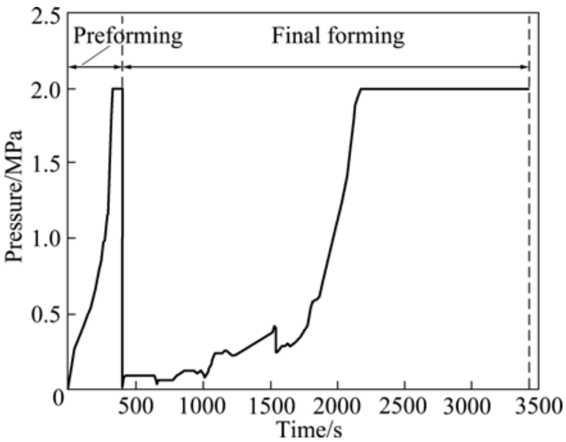

Fig. 6 Time−pressure curve at strain rate of 0.002 s^{-1}

maximum of 2 MPa in about 2000 s, then keeps until 3500 s. This simulation curve with appropriate modifications can be used as a bulging experimental process curve.

3 Experiment of superplastic forming of Ti−6Al−4V deep cylinder

The results of FEM analysis indicate that both the increased friction of pre-forming die and decreased friction of forming die are conducive to the uniform thickness distribution. So, the friction of pre-forming die was increased by mechanical machining and the friction of forming die was decreased by spraying BN powder (Fig. 7). Meanwhile, the friction coefficient was measured in superplastic forming condition by compression ring method. It is shown that the friction coefficient of machining surface can reach 0.55 and the friction coefficient of surface on which the BN coating is sprayed can reach 0.15. The structure of dies used in direct-reverse superplastic forming is shown in Fig. 8, which comprises three parts, including pre-forming die, forming sheet and forming die. Two vent holes were processed on the pre-forming die to prevent that the forming sheet cannot touch the die completely. Also one vent hole was processed at the last contact region of forming die. The Ti−6Al−4V sheet was heated at a rate of 15 °C/min up to 930 °C and held for 60 min before pre-forming. Then, the high pressure nitrogen gas from hole ③ was controlled by using gas-pressure meter to blow the Ti−6Al−4V plate into the pre-forming die. The gas pressure applied to the sheet was increased gradually up to 1.5 MPa. In order to achieve complete adaptation

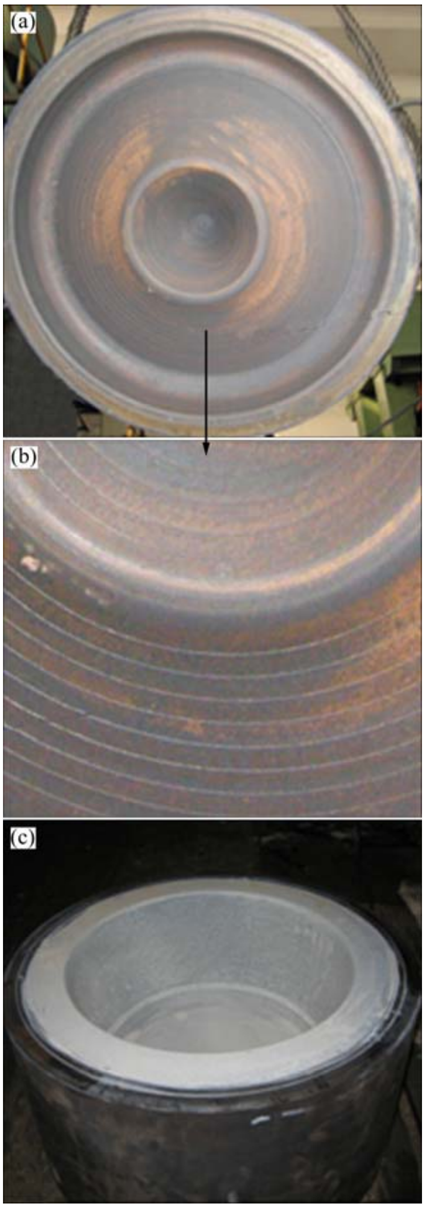

Fig. 7 Surface of pre-forming die and forming die: (a), (b) Pre-forming die and groves on surface; (c) Forming die and BN coating on surface

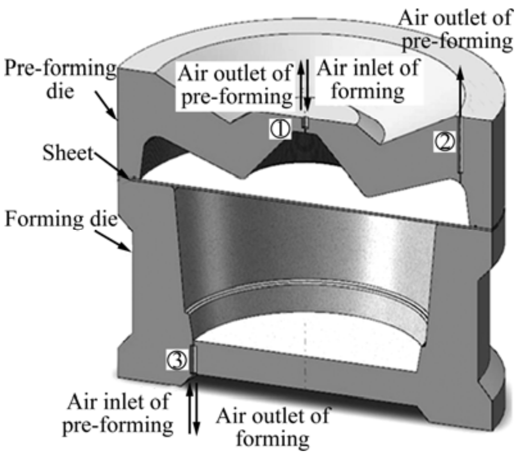

Fig. 8 Structural diagram of dies used for direct-reverse superplastic forming

of the Ti−6Al−4V sheet to the pre-forming die, a holding time of 30 min was used. And then, the gas from vent hole ③ was released gradually to unload the pre-forming pressure. Meanwhile, the gas from vent hole ① was increased to blow the Ti−6Al−4V sheet into forming die.

Experimental loading curve is based on finite element simulation, as shown in Fig. 9. In the pre-forming stage, the gas pressure applied to the sheet gradually increased up to 1.4 MPa within 750 s, and then the pressure was relieved. In the final forming stage, the pressure increased to 1.4 MPa in 1500 s and a dwell time of about 1500 s was used before it was allowed to cool. After cooling in the atmosphere, the Ti−6Al−4V deep cylinder was removed from the forming die.

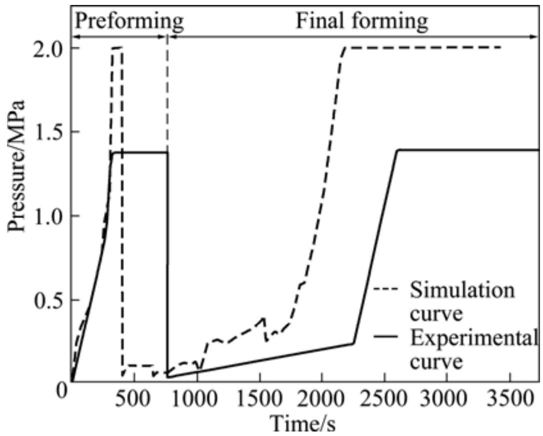

Fig. 9 Experimental time−pressure curves

Figure 10 shows the superplastically formed Ti–6Al–4V deep cylinder. The comparison of a sectional thickness distribution through the experimental sample formed by changing friction direct-reverse superplastic forming and common direct-reverse superplastic forming is shown in Fig. 11. It is clear that, compared with the thickness distribution (1.18−2.24 mm) formed by common direct-reverse superplastic forming, the thickness distribution (1.50−1.78 mm) formed by

Fig. 10 Ti−6Al−4V deep cylinder

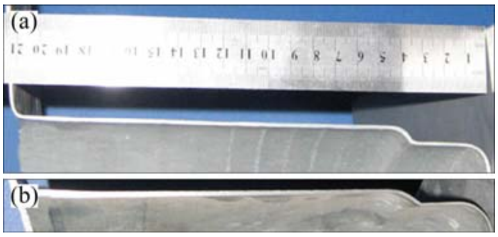

Fig. 11 Comparison of sectional thickness distribution: (a) Formed by changing friction direct-reverse forming; (b) Formed by common direct-reverse superplastic forming

changing friction direct-reverse superplastic forming tends to be more uniform. And the experimental thickness distribution is close to the results of the FEM numerical simulation when the friction coefficients of pre-forming die and forming die are set to be 0.577 and 0.1, respectively. The actual thickness distribution of Ti−6Al−4V deep cylinder was set in the range of (1.6±0.2) mm and fully meets the design requirements.

After removing the flange and bottom of the deep cylinder by using wire-cutting, the aerospace Ti−6Al−4V titanium alloy cylinder was fabricated successfully (Fig. 12). It can be concluded that the friction of dies is an important factor affecting the thickness distribution in superplastic forming process. Using FEM, the thickness distribution of superplastically formed workpiece is forecast and the simulation data are very close to the experimental data. It is an effective way to control the thickness distribution of superplastically formed workpiece by changing the friction of dies.

Fig. 12 Ti−6Al−4V deep cylinder with near uniform thickness distribution

4 Conclusions

1) The thickness distribution of deep cylinder can be controlled effectively by changing friction of dies. As the friction coefficient of performing-die increases, the thickness distribution tends to be more uniform and the deviation between the thinnest and the thickest point turns to be smaller because in the case of larger friction of pre-forming die, the concentration of sheet deformation can be controlled more effectively during pre-forming process.

2) With the decrease of the friction coefficient of forming die, the thickness distribution tends to be more uniform because in the forming process, the forming sheet tends to be whole stretching under the condition of small friction.

3) The experimental result shows the deep cylinder fabricated by the direct-reverse superplastic forming owns near uniform thickness distribution, reaching the ranging of 1.50−1.78 mm, and entirely meets the requirement of (1.6±0.2) mm.

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厚度近均匀分布的 Ti−6Al−4V 钛合金筒形件超塑成形

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摘 要：采用 MSC. MARC 软件设计不同形状的预成形模具，采有限元模拟方法研究预成形模具和终成形模具的表面摩擦因数对筒形件侧壁厚度分布的影响规律。结果表明：对预成形模具压边部分环形带区域和筒形件底部区域进行局部预减薄有利于筒形件厚度的均匀分布。当预成形模具表面的摩擦因数达到 0.57 时，局部减薄效果最明显，有利于最终的厚度分布。终成形模具的表面摩擦因数为 0 时，板料趋于整体变形，厚度分布区域均匀。通过机械加工增加预成形模具的摩擦因数，通过喷涂 BN 陶瓷粉末降低终成形模具的摩擦因数，最终，采用正反向超塑成形成功制得厚度分布为 1.50~1.78 mm 的 TC4 钛合金深筒形件。

关键词：超塑成形；Ti−6Al−4V；变摩擦；厚度分布；有限元法

(Edited by YANG Bing)