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Modeling of the process of superplastic forming of hemispherical shells from blanks of different profiles

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In the present work, the process of superplastic forming of hemispherical shells from blanks of different profiles on the basis of computer modeling is considered. A relevant task in superplastic forming of shells is to reduce the thickness difference, which will significantly improve the quality of their geometric characteristics with a general reduction in the cost of production. It is shown that the forming of a hemispherical shell from a billet of constant thickness with a fixed flange leads to an inevitable appearance of thickness differenses. It has been shown in a number of works that, in the case of superplastic forming of hemispherical shells from blanks of constant thickness made of titanium alloys, the difference in thickness exceeds 50%. Various methods have been tried to solve this problem. From the analysis of published works, it follows that the solution to this problem lies in the use of a profiled blank. Traditionally, it is suggested to use a blank with a spherical profile. In the present work, a blank with a conical profile was used, since such a shape of the blank is easier both in manufacture and in calculations compared to a spherical one. The superplastic forming process was simulated using the ANSYS 10ED software package. Using the example of the formation of a hemispherical shell made of titanium alloy Ti-6Al-4V, it was found that the use of a blank with a conical profile makes it possible to reduce the thickness difference down to 7%.

Keywords: blank shape, hemisphere, modeling, superplastic forming, titanium alloy.

1. Introduction

Spherical containers of spherical tank type are used in aerospace equipment [1]. The industrial technology for manufacturing spherical tanks includes the use of two hemispherical shells and their welding with each other [2]. Superplastic forming (SPF) is recognized as one of the most effective methods of manufacturing hemispherical shells from titanium alloys. By the traditional method of manufacturing hemispheres from a blank of constant thickness, there is inevitably a difference in thickness. By forming a hemispherical shell, the thickness of the blank changes from the pole of the dome to its fixation zone.

The problem of thickness difference has been considered in many works [3–12]. Various methods to reduce the thickness differences were proposed such as reverse forming, forming using friction forces, forming in an uneven temperature field, forming of a profiled blank, etc.

By implementing the first three methods, a blank of constant thickness is used. For example, the use of a reverse forming scheme provides a thickness difference of no more than 14% as shown in [10]. In this case, Eq. (1) is used to calculate the thickness difference:

$$\left(1-\frac{s_{\min}}{s_{\max}}\right)\cdot 100\%. \qquad (1)$$

The authors of [11] proposed to reduce the value of the wall thickness difference during reverse forming of a blank with a fixed flange due to the redistribution of deformation using brake elements. The essence of the method consists in preliminary forming along the punch at the first transition and subsequent turning to obtain the final shape in the same die at the second transition.

In [12] the temperature field of the blank is changed. Suggestion is based on the dependencies of the metal flow stress on temperature.

In the method where a profiled blank of variable thickness is used, the thickness of the blank is larger at the place where maximum thinning occurs during SPF, i.e. in the pole of dome of the formed hemisphere, which leads to reduction of the thickness difference. Using an initial blank of a variable thickness so that after the SPF the thickness of the hemisphere becomes almost homogeneous, it would be possible to significantly reduce the cost of processing of finished products.

In order to solve the problem of thickness difference, spherical blank profile was proposed in [13]. The results of [13] lead to reduction in the thickness difference down to 8%. However, it is quite labor-consuming to get a spherical blank profile. To show the possibility of reducing the thickness difference by using a conical blank is the purpose of this work. This is less labor-intensive both in calculations and in manufacturing. For a comparison of the results, the process of SPF of a hemispherical shell from a blank of constant thickness is also considered.

2. Materials and methods

The process of forming a hemisphere from sheet blanks of Ti-6Al-4V titanium alloy was modeled. This alloy is widely used for the manufacture of spherical pressure vessels for aircraft [1,2]. Blanks of constant and variable thicknesses were considered. The variable thickness was set in the form of a conical profile. Computer modeling was carried out in the ANSYS 10ED software package.

Pressure time cycle included two stages. At the initial stage, the pressure was increased from to 1 MPa for 30 seconds (Ramped mode). At the second stage, the exposure was held at constant pressure (Stepped mode).

When modeling the SPF process of a shell from a blank of constant thickness, the blank thickness s_0 and its radius R_0 were set at the input. In all considered cases, the gas pressure was constant and equal to 1 MPa. Standard power law [14] of superplastic flow was used:

$$\sigma = K\xi^m, \tag{2}$$

where σ is the flow stress, ξ is the strain rate, m and K are the material constants.

The values of K and m have been chosen as follows: $m=0.43$, $K=410$ MPa$\cdot s^m$ [15]. These values have been tested in modeling the SPF processes in [16–18]. The problem was solved in a 2D setting, since the hemisphere is an axisymmetric figure. Due to the symmetry of the blank, half of the shell was considered in the modeling.

The scheme of deformation of a blank of constant thickness with the initial grid of finite elements is shown in Fig. 1. The scheme of deformation of the blank of a conical shape is shown in Fig. 2. The current thickness of the blank s_g is a segment MN, which after deformation passes into the segment M_1N_1.

When modeling the SPF process of a shell from a conical blank, the following blank geometry was set at the input: the radius of the matrix R_0; the minimum thickness at the periphery of the initial blank s_{min}; the maximum thickness of the initial blank in the center (the future pole of the dome) s_{max}, which were calculated according to the algorithm described below.

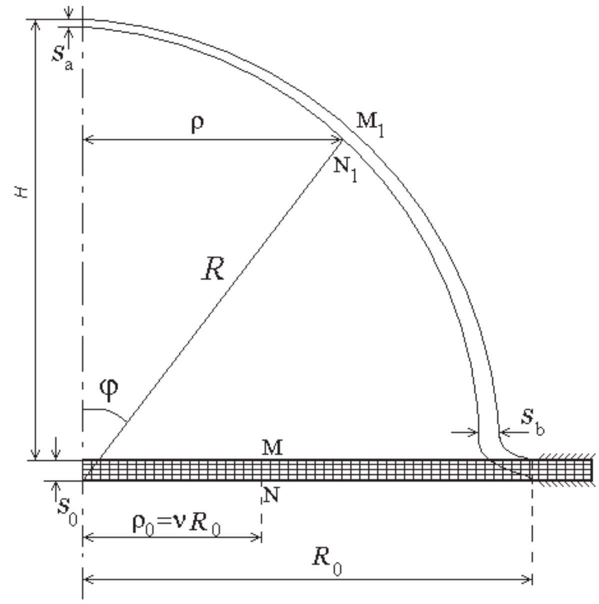

Fig. 1. The scheme of deformation of a hemispherical shell from the blank of constant thickness (the radius of the dome R; the initial thickness of the blank s_0; the thickness at the pole of the dome s_a; the thickness at the edge of the fixing zone s_b; the height of the dome H).

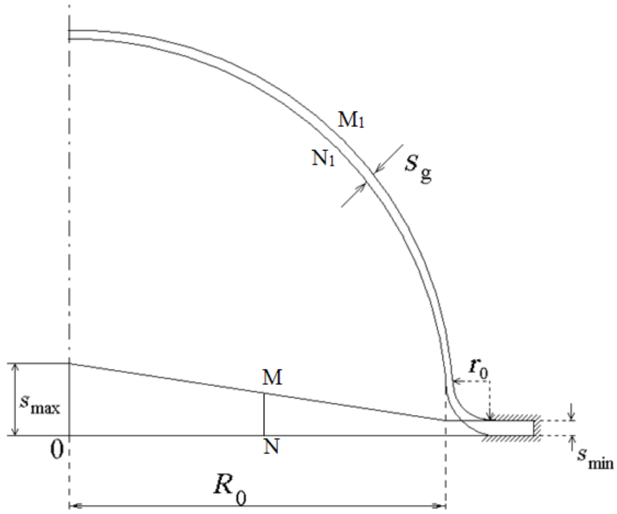

Fig. 2. Scheme of deformation of a hemispherical shell from a conical blank.

The thickness of the initial blank in this case depends on the distance from the axis.

Two geometric parameters, s_{max} and s_{min}, are tied together through the thickness of the hemisphere s_g. To express this relation mathematically, it is necessary to calculate the volume of the blank and equate it to the volume of the metal in the hemisphere. To avoid dangerous thinning in the clamping zone of the blank, the entrance radius was increased by 3 times.

In this case, the thickness of the initial blank depends on the distance from the axis of symmetry, i.e. $s_0=s_0(\nu)$, where $\nu=\rho_0/R_0$ is the Lagrangian coordinate of the considered point M. The task is to calculate such an initial profile of the blank $s_0=s_0(\nu)$, the forming of which will allow one to obtain a product of a given thickness.

The distribution of thickness along the profile of the dome is described by an expression of the form $s(\varphi,\alpha)=s_0(\sin\alpha/\alpha)^2\varphi/\sin\varphi$,

$$s(\varphi,\alpha) = s_0\left(\frac{\sin\alpha}{\alpha}\right)^2 \frac{\varphi}{\sin\varphi}, \tag{3}$$

and does not depend on the rheological properties of material K and m within the geometric model. Therefore, in order to obtain an equidistant hemisphere of a given thickness $s_g=\text{const}$, the profile of the initial blank must satisfy the condition $s_0(\nu)=s_g$.

$$s_0(\nu) = s_g\left(\frac{\alpha}{\sin\alpha}\right)^2 \frac{\sin\varphi}{\varphi}, \tag{4}$$

or, taking into account the ratio $\varphi=\nu\alpha$ coming from the hypothesis of equal stretching of the meridian,

$$s_0(\nu) = s_g\left(\frac{\alpha}{\sin\alpha}\right)^2 \frac{\sin\nu\alpha}{\nu\alpha}, \tag{5}$$

where the value of α determines the final configuration of the dome.

In particular, to obtain a hemisphere of constant thickness, the initial thickness distribution over the profile of the blank must satisfy the ratio

$$s_0(\nu) = s_g\left(\frac{\pi}{2}\right)\cdot\frac{\sin(\nu\pi/2)}{\nu}. \quad (6)$$

To calculate the volume of the blank V, calculate

$$V = \int 2\pi s_0(\rho_0)\rho_0 d\rho_0, \quad (7)$$

with limits of integration from 0 to R_0, as a result we get

$$V = \left(\frac{2\pi}{3}\right)\left\{R_p^2 - \left(R_p^2 - R_0^2\right)^{3/2}\right\} - \pi y_p R_0^2 = 2\pi s_g R_0^2. \quad (8)$$

In this case, the volume of the metal of the finished hemisphere is equal to

$$V_g = \pi R_0^2 s_g, \quad (9)$$

and the volume of the blank V_0 consists of two parts: cilinidric V_1 and conical V_2, where height $h = s_{max} - s_{min}$.

$$V_0 = V_1 + V_2 = \pi R_0^2 s_{min} + \frac{1}{3}\pi R_0^2\left(s_{max} - s_{min}\right) = = V_{g1} = 2\pi R_0^2 s_g. \quad (10)$$

3. Results and discussion

The results of modeling of the formation of a hemisphere from a blank of constant thickness are shown in Fig. 3, where the diagram of the distribution of the third principal strain over the cross section of the shell is depicted. The choice of the third principal strain is due to the fact that its value is closest to the natural logarithm of the ratio of the initial thickness s_0 to the current thickness s_g. The thickness of the blank was equal to 1 mm and the radius to 35 mm. The entry radius of the die was chosen equal to zero.

As can be seen from the figure, the maximum thinning occurs at the pole of the dome. The non-uniformity of the thickness is equal to 59%. The simulation results are consistent with the well-known data of [10,19 – 23].

The results of modeling of a blank with variable thickness are shown in Fig. 4. The blank had a conical profile, which was set by the values s_{min} = 0.91 mm, s_{max} =1.18 mm. The values were calculated analytically using the volume (Eq. (7–10)). The radius of this blank was also equal to 35 mm. In contrast to the modeling of a blank of constant thickness, non-zero entry radius was set, since, as a result of modeling, it was revealed that dangerous thinning occured in the area of the entry radius, which can lead to rupture of the shell. To avoid breaking the shell, the entry radius was set at least $3s_{min}$. This value was determined from the results of modeling of the shell formation at several values of the entry radius. The same loading mode as during the modeling of a shell from a blank of constant thickness was used.

As can be seen from Fig. 4, the deformation is localized in the contact zone of the shell with the entry radius of the die, and not at the pole of the dome, as in the formation of a hemisphere from a blank of constant thickness. This feature must be taken into account and the input radius of the die must be increased, as mentioned above.

In the modeled hemisphere, the thickness non-uniformity did not exceed 7%. This result was obtained with the coefficient of thickness difference of the conical blank s_{max}/s_{min} =1.3. Calculations have shown that a change in the values of s_{max} and s_{min} increases the thickness difference in the hemispherical shell. The result obtained indicates that there should probably be an optimal coefficient of thickness variation of a blank with a conical profile in order to obtain

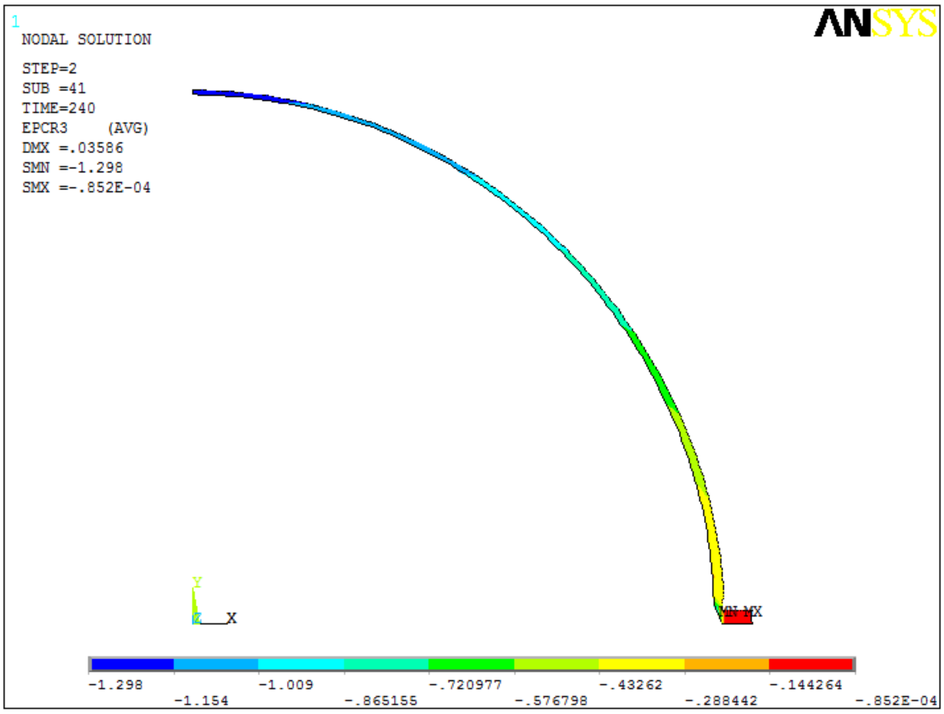

Fig. 3. (Color online) Distribution of the third main deformation in the hemispherical shell from a blank of constant thickness.

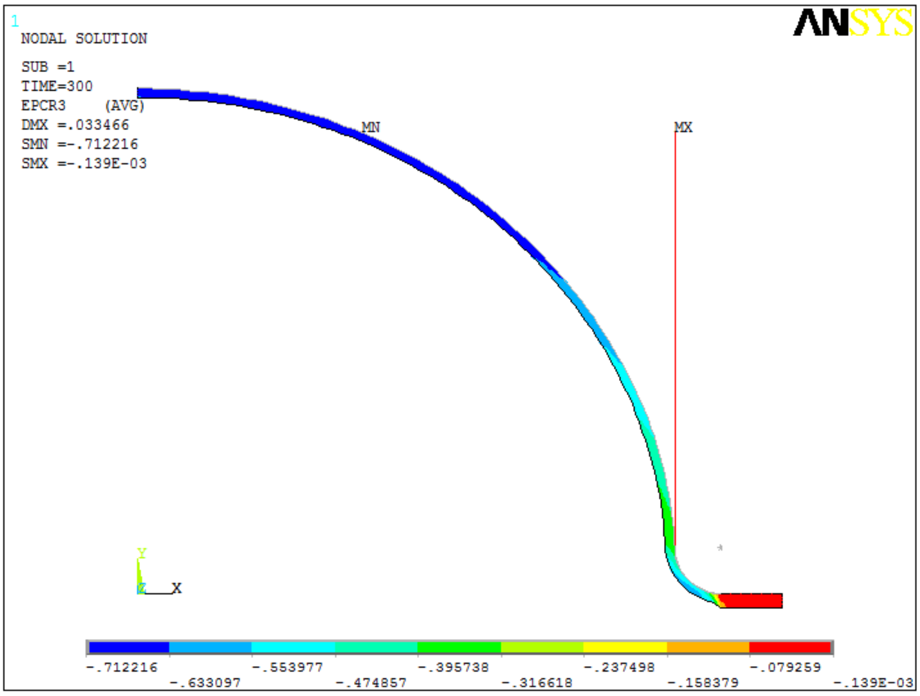

Fig. 4. (Color online) Distribution of the third main deformation in the hemispherical shell from a conical blank.

shells of different diameters and thicknesses, which would provide a minimum thickness variation in them.

One can evaluate the result according to data from well-known works. In [10], the thickness difference was 14%, and in [13] approximately 8%. In [10], to obtain a hemisphere, reverse forming was used, and in [13] the blank was of a spherical profile.

4. Conclusions

Computer modeling of the process of superplastic forming of hemispheres from a blank of constant thickness and a blank of conical profile has been carried out using the example of titanium alloy Ti-6Al-4V. The distributions of thickness in hemispherical shells obtained from these blanks were compared. When forming a blank of constant thickness, significant thinning occurs in the pole of the hemisphere, while when forming a blank of conical profile, localization of deformation occurs in the area of the entry radius of the die. It has been shown that when using a conical blank it is possible to achieve a thickness difference of no more than 7%. The result can be explained by the fact that the deformation is distributed more evenly in comparison with the known shaping schemes, where a blank of constant thickness is used.

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