Improving the accuracy of finite element modeling of superplastic hemisphere forming

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Abstract. A novel procedure to determine the values of the material constants $K$ and $m$ for the standard power superplastic law from the results of the bulge tests of the hemispheres is suggested. Unlike other approaches known in the literature, the involved procedure requires only two experimental measurements of the time of forming under constant pressure, with the thickness at the pole being used to refine the values $K$ and $m$. Experimental justification of the developed techniques was fulfilled on the example of aluminum alloy AA5083. The validity of the suggested approach is confirmed by comparing the experimental data with the corresponding finite element solutions of the boundary value problem in the theory of creep production using the ANSYS software. It is found that the maximum deviation of experimental records from the corresponding finite element solutions does not exceed 1% both for the time of formation and for the thickness at the pole.

1. Introduction

Hemispheres are widely used in various industries to produce spherical pressure vessels by welding two hemispheres. For such vessels, high demands are placed on the reliability and the structural strength; therefore, they are made of titanium alloys and stainless steel. The most promising method for the manufacture of hemispherical products is superplastic forming (SPF) of sheet metals. Instead of labor-intensive, full-scale experiments on the study of the formation of hemispheres, mathematical modeling, in particular, computer models based on the finite element method, is effectively used. The degree of adequacy of the computer model depends on the accuracy of determining the values of the constants of the material included in the determining ratio. The most commonly used in practice is the standard power law of superplasticity [1]:

\[ \sigma = K \xi^m \]  \hspace{1cm} (1)

where $\sigma$ is the flow stress, $\xi$ is the strain rate, $K$ and $m$ are the material constants to be determined experimentally.

In [2], we proposed an approach that enables determining the height of the dome at two experimental points of length forming the hemispheres with elevated gas pressure values. In [3], the well-known technique was modified and made it possible to determine the height of the dome thickness at the pole dome for two experimental points at the same time depending on the duration of the hemisphere formation.

According to the method proposed in [2], the material constants $K$ and $m$ included in (1) are determined by the results of two technological experiments, which are a set of experimental data: \{${t_i, p_i, h_i, s_i}$\}, $i=1, 2$, where $t_i$ is the duration of the hemisphere forming at constant pressure $p_i=const$ to the height of the dome $h_i=const$ and the thickness at the pole $s_i$.

2. Fitting of the material constants

The method of three stages presented in [2] is a reverse analysis with a consistent refinement of the material constants $K$ and $m$. To improve the estimation of $K$ and $m$ in the second and third stages, one
experimental data set is selected from the two available (i.e. \(i=1\) or \(i=2\)). The application of finite element modeling in the ANSYS 10ED software with the subsequent comparison of the obtained numerical results with a set of experimental data allowed us to confirm the reliability of the obtained calculations.

The presented method was tested in experiments on SPF hemispheres of sheet blanks of aluminum alloy AA5083 with a thickness of 1.2 mm in a cylindrical matrix with a diameter of 100 mm with an input radius of 5 mm at a molding temperature of 450 °C (table 1).

| Pressure, [MPa] | Forming time of the hemisphere, [sec] | Height of the hemisphere, [mm] | Thickness at the pole, [mm] |
|----------------|--------------------------------------|-------------------------------|---------------------------|
| 0.29           | 1080                                 | 46.5                          | ≈-0.48                    |
| 0.56           | 120                                  | 43.2                          | ≈-0.51                    |

The results of the finite element modeling using the material constants \(K\) and \(m\), calculated using the set of the experimental data on the hemisphere obtained at SPF with a constant gas pressure \(p_1=0.29\) MPa (table 2) and \(p_2=0.56\) MPa (table 3) are presented below.

| Pressure, [MPa] | Thickness of the dome at the pole, [mm] | Forming time of the hemisphere, [sec] |
|----------------|-----------------------------------------|--------------------------------------|
| 0.29           | \(s_{\text{Exp}}\) \(s_{\text{ANS}}\) \(\Delta\), % | \(t_{\text{Exp}}\) \(t_{\text{ANS}}\) \(\Delta\), % |
| 0.56           | 0.48 0.481 ≈0.23 1080 1076.83 ≈0.37 | 120 194.58 ≈62 |

| Pressure, [MPa] | Thickness of the dome at the pole, [mm] | Forming time of the hemisphere, [sec] |
|----------------|-----------------------------------------|--------------------------------------|
| 0.29           | \(s_{\text{Exp}}\) \(s_{\text{ANS}}\) \(\Delta\), % | \(t_{\text{Exp}}\) \(t_{\text{ANS}}\) \(\Delta\), % |
| 0.56           | 0.48 0.464 ≈3.3 1080 770.02 ≈28.7 | 120 120.23 ≈0.19 |

From the comparison of the numerical values with the corresponding experimental data presented in tables 1 to 3, it can be seen that an error of no more than 1% is observed with the set, which was chosen to improve the estimation of the material constants \(K\) and \(m\) at the second and third stage of the calculations according to the method proposed in [2].

This is due to the fact that the standard model of the SP material (1) does not allow achieving the same accuracy of the simulation, both in the duration of molding and the thickness of the dome at the pole at different values of constant pressure with the same values of the constants \(K\) and \(m\).

Time dependence of the dome height \(H_t\), mm (figure 1) and the thickness of the pole \(s\), mm (figure 2), calculated with the help of the ANSYS software complex is compared with corresponding experimental data. Finite element models of the SPF of the hemisphere in ANSYS were constructed using the constant material \(m=0.563\) and \(K=1128.4\) MPa-s\(^m\), obtained by selecting the first
experimental data set \( (i=1) \) for calculations at the second and third stages of the method (a) and \( m=0.53, K=810.9 \text{ MPa} \cdot \text{s}^m \) when choosing the second experimental data set \( (i=2) \) for calculations (b).

**Figure 1.** Time dependencies of the dome height, \( H \) (mm), obtained as a result of the finite element modeling with ANSYS software (solid line). Markers present the experimental data.

**Figure 2.** Time dependencies of the thickness at the pole, \( s \) (mm), obtained as a result of the finite element modeling with ANSYS software (solid line). Markers present the experimental data.

It is known from [5] that the phenomenon of SP manifests itself in a narrow range of deformation rates, and therefore it is necessary to regulate the gas pressure supply for the process of forming with a constant deformation rate at the pole of the dome. To ensure this mode, it is necessary to change the value of the gas pressure, according to the calculation formulas (2) and (3),

\[
p(\alpha) = 2 \cdot \sigma_{opt} \cdot \left[ \frac{s_0}{(R_0 + r_0)} \right] \cdot \left[ \frac{\sin^3 \alpha}{\alpha^2} \cdot \frac{1}{1 - r_0 \sin \alpha} \right]
\]

\[
t(\alpha) = \frac{1}{\xi_{opt}} \cdot 2 \cdot \ln \left( \frac{\alpha}{\sin \alpha} \right)
\]

where \( p \) is the gas pressure, \( t \) is the forming time, \( \alpha \) is the angle between the symmetry axis and the current dome radius passing through the center of curvature of the input radius of the matrix from the work [3], \( s_0 \) is the initial thickness of the sheet; \( R_0 \) is the die radius; \( r_0 \) is the matrix input radius; \( \sigma_{opt} \) is the optimal flow stress, \( \xi_{opt} \) is the optimal strain rate.
An example of the application of the suggested algorithm is presented in figure 3.

![Figure 3](image.png)

**Figure 3.** Time dependence of the Mises equivalent stress at the dome apex, $\sigma_e$, MPa, calculated by means of the finite element method with the target stress $\sigma_{opt} = 21.5$ MPa.

As seen in figure 3, the flow stress goes to the steady-state stage in the SPF time interval from 20 to 80 sec, after that a slight increase is observed.

3. Conclusions
The method presented in [2] allows one to calculate the values of the material constants $K$ and $m$ included in the standard model SP, the use of which allows building a finite element model of the SPF process of the hemisphere with engineering accuracy (the error does not exceed 1%).

The practical application of the proposed algorithm makes it possible to avoid rupture of the sheet preform and to increase the uniformity of thickness in the product.

References
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