Superplastic forming of hemispheres out of AZ61 magnesium alloy

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Abstract. The paper proposes a method for calculating the rheological parameters included in the standard power ratio of superplasticity based on the results of test forming of hemispheres using a cylindrical matrix. The method takes into account the value of the entry radius of the matrix. The analytical model of the process is developed based on the main assumptions of the theory of thin shells, the finite element model is executed using the ANSYS10 ED software package. As compared to the traditional approach, the proposed method allows improving the modeling accuracy with an error less than 1%, not only for the forming time, but also for the thickness at the pole of the dome.

1. Introduction

The increased interest in the superplastic forming (SPF) process in recent years is associated with the possibility of manufacturing hollow structures from difficult-to-machine alloys based on titanium, aluminum and magnesium for the aerospace industry. [1].

Application of computer models makes it possible to replace mechanical experiments with computational ones that leads to savings in time and material costs. In addition, conducting a computational experiment based on a computer model allows visualizing the process of forming. However, to create such a model, it is necessary to know the values of the rheological parameters (material constants) $K$ and $m$, which are included in the constitutive relations. The standard power-law relation for superplasticity is as follows:

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

where $\sigma$ is the flow stress; $\dot{\varepsilon}$ is the deformation rate, $K$ and $m$ are material constants.

Rheological parameters are usually determined from the results of uniaxial tensile tests, however, large differences between the values of numerical calculations and experimental data are often observed. For this reason, the results of biaxial tension tests were used for identification of the material constants that provided acceptable modeling accuracy for engineering calculations [2]. In this paper, not only the rheological parameters were obtained using the test forming of hemispheres, but the entry radius of the cylindrical matrix was also taken into account in the calculations.

The common approach to define the rheological parameters $K$ and $m$ does not consider the dependence of the thickness at the pole of the hemisphere’s dome on the forming time, only the height of the dome is taken into account. Therefore, the problem of developing a method for identification the values of parameters $K$ and $m$, which will increase the accuracy of computer modeling of SPF of hemispheres (dependencies of both the height and the thickness at the pole of the dome on the forming time), is still relevant.

2. Fitting the material constants

The method for calculating the rheological parameters $K$ and $m$ included in the standard power relation (1) consists of three steps and is described in detail in [3].
In this paper, the method was tested using the data obtained from the SPF of hemispheres of the magnesium alloy AZ61 (Mg–6% Al–1% Zn in wt.%) [4]. A sheet perform of AZ61 alloy with a thickness of $s_0=0.7$ mm and a diameter of $d=50$ mm was placed in a cylindrical matrix with an entry radius of $r_0=1$ mm. The SPF temperature was 400°C. The first set of experimental values was received by forming a hemisphere with a height of $H_1=14.94$ mm and a thickness at the pole of the dome $s_1=0.2$ mm during the time $t_1=840$ s under a constant gas pressure $p_1=0.8$ MPa. The second set of experimental values was received by forming a hemisphere with a height of $H_2=15$ mm and a thickness at the pole of the dome $s_2=0.21$ mm during the time $t_2=250$ s under a constant gas pressure $p_2=1.2$ MPa.

Using these data, the rheological parameters were found to be $K_0=166.3$ and $m_0=0.34$. They were used to create a finite element model of the SPF hemisphere. The results of calculations in the ANSYS 10ED software package are presented in table 1.

| Constant pressure, [MPa] | Height of the dome, [mm] | Thickness of the dome, [mm] | Forming time, s |
|-------------------------|--------------------------|-----------------------------|-----------------|
|                         |                          | $s_{\text{Exp}}$ | $s_{\text{Ans}}$ | $\Delta$, % | $t_{\text{Exp}}$ | $t_{\text{Ans}}$ | $\Delta$, % |
| 0.8                     | 14.94                    | 0.2                       | 0.2             | ~0.1        | 840            | 934.03         | ~11.2          |
| 1.2                     | 15                       | 0.21                      | 0.21            | ~0.1        | 250            | 250.12         | ~0.4           |

In accordance with Ref. [5], the accuracy of the method can be improved by adjusting the rheological parameters $K$ and $m$ in such a way as to obtain convergence in values of the forming time and the thickness at the pole of the dome, at least for one of two sets of experimental values. For further calculations, an experimental set of values ($i=1$) was selected, which was obtained as a result of the SPF of hemisphere at a constant gas pressure $p_1=0.8$ MPa. After adjusting the $m$ value, both the calculated thickness at the pole of the dome and the experimental thickness were approximately the same, $s_{\text{Ans}} \approx s_{\text{Exp}}=0.2$ mm. Table 2 presents the results of the ANSYS simulation of SPF of the hemisphere up to a height $H_1=14.94$ mm with a constant pressure $p_1=0.8$ MPa.

| $m$ | $s_{\text{Ans}}$, mm | $s_{\text{Exp}}$, mm | Forming time, s |
|-----|----------------------|----------------------|-----------------|
| 0.32| 0.210                | 0.213                | 875.28          |
| 0.335| 0.216               | 0.219                | 840             |
| 0.34| 0.219                | 0.222                |
| 0.35| 0.219                | 0.222                |
| 0.36| 0.222                |
| 0.4 | 0.246                |

Linear interpolation of the $m$ values from table 2 revealed the value of the adjusted rheological parameter $m^*=0.32$. The calculated values of thickness at the pole of the dome and the forming time were compared with the experimental ones in table 3.

| $m^*$ | $s_{\text{Ans}}$, mm | $s_{\text{Exp}}$, mm | Forming time, s |
|-------|----------------------|----------------------|-----------------|
| 0.32  | 0.21                 | 0.21                 | 875.28          |
| 0.21  | 0.21                 | 840                  |

Table 1. Experimental thickness of the hemisphere at the pole of the dome ($s_{\text{Exp}}$) and forming time ($t_{\text{Exp}}$) vs calculated ones ($s_{\text{Ans}}$, $t_{\text{Ans}}$)

Table 2. Calculated thickness of the hemisphere at the pole of the dome ($s_{\text{Ans}}$) for different values of the rheological parameter $m$

Table 3. Calculated thickness of the hemisphere at the pole of dome ($s_{\text{Ans}}$) and the forming time ($t_{\text{Ans}}$) vs experimental ones ($s_{\text{Exp}}$, $t_{\text{Exp}}$) for the adjusted value of the rheological parameter $m^*$
At the second step of calculations, the calculated thickness at the pole of dome of the hemisphere was equal to the corresponding experimental value, but there was a difference in the forming times. In order to increase the accuracy in simulation of the SPF time, a third calculation step was suggested. At this step, the value of the rheological parameter $K$ was adjusted to match the experimental forming time. The adjusted value of the parameter $K$ was found to be $K^* = 148.256$ MPa·s$^m$.

**Table 4.** Comparison of the results of finite element simulations with experimental values from [4]

| Constant pressure, [MPa] | Thickness of hemisphere at the pole of dome, mm | Forming time, s |
|--------------------------|-----------------------------------------------|-----------------|
|                          | $s_{Exp}$ | $s_{Ans}$ | $\Delta, %$ | $t_{Exp}$ | $t_{Ans}$ | $\Delta, %$ |
| 0.8                      | 0.2      | 0.2       | $\approx 0.1$ | 840       | 839.61   | $\approx 0.4$ |
| 1.2                      | 0.21     | 0.184     | $\approx 12$ | 250       | 246.87   | $\approx 1.3$ |

As can be seen from table 4, the difference between the results of calculations and the first set of experimental values ($i = 1$) is less than 0.5%, while for the second set of values it exceeds 1%. This difference can be explained by the fact that the standard power ratio SPF (1) for the same values of rheological parameters $K$ and $m$ and different values of constant pressure does not allow obtaining correctly similar modeling for such parameters as the forming time and the thickness of hemisphere at the pole of the dome.

3. Conclusions

The use of rheological parameters $K$ and $m$, which are included in the standard power relation and are determined according to the proposed method taking into account the entry radius of the matrix, makes it possible to create an adequate model of the SPF of hemisphere. The difference between the calculated and experimental values of the forming time and the thickness of hemisphere at the pole of the dome does not exceed 1%.

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