THE FORMULA OF MEASURING *m* VALUE IN SUPERPLASTIC BULGING BY MEANS OF JUMP PRESSURE*

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I. INTRODUCTION

The index *m* value of strain rate sensitivity is an important mechanical factor for evaluating superplasticity. The authors have established the analytically mechanical theories of *m* value on the basis of many formulae for measuring *m* value by means of tension and have given out a unified measuring method[1]. *m* value is affected by stress status because of the strong structural sensitivity of superplasticity. LUO Zi-jian et al.[2] have experimentally proved that the *m* value under bidirectional tension does not coincide with that under one-directional tension. So it is unsuitable to take the *m* value measured by tension as that of bulging. It is a pity that very few reports about the *m* value of superplastic bulging can be found. Refs. [2 — 6] contribute to this project, but none of them theoretically gives a measuring formula and all of them apply the contact method to experiment. However, the uneven temperature in the contact zone and the additional stress cannot be overcome.

In recent years, the application of superplastic bulging to the study field of space travel has proposed a series of problems which require the mechanical theory to guide regularly and to answer in common. The study on the pattern of bulging deformation is good for us to understand the deformation pattern under more complex stress status. So it is unavoidable to establish the formula of measuring bulging *m* value and the effective measuring method. The authors have designed an apparatus for superplastic bulging on the basis of the photoelectronic theory[7] and have derived the analytical expressions of stress field and strain rate field under free bulging[8], which proves the basic condition for solving the above problem.

II. FORMULA DERIVATION

Hypothesis 1. *The material cannot be pressed, it is totally in plastic state and its anisotropy*

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only exists in the thickness direction of sheet metal.

Hypothesis 2. *The thickness is much smaller than diameter and the effect of bending can be neglected.*

Hypothesis 3. *The pressure-pad is fixed. At any instant during bulging, the medial face of sheet metal is a part of ball surface.*

Hypothesis 4. *The increment theory of plastic mechanics is valid.*

Basing on the above hypotheses, the authors derive the analytical expressions of the equivalent stress $\bar{\sigma}$ and the equivalent strain rate $\bar{\dot{\varepsilon}}$ at the culminating point of free bulging of the round sheet metal:

$$\begin{cases} \bar{\sigma} = \sqrt{\dfrac{2}{1+R}}\ \dfrac{P(r^2+H^2)^3}{4S_0 r_0^4 H}, \\ \bar{\dot{\varepsilon}} = \sqrt{2(1+R)}\ \dfrac{2HV}{r_0^2+H^2}, \end{cases} \tag{1}$$

where S_0 and r_0 are the original thickness of sheet metal and the radius of pressure-pad respectively; H and V are the bulging height and the speed at bulging part culminating point respectively; P is the internal pressure of bulging and R is the anisotropic coefficient in thickness direction of sheet metal.

For universal purpose, M is defined as the universal index of strain rate sensitivity:

$$M = \frac{d \log \bar{\sigma}}{d \log \bar{\dot{\varepsilon}}}. \tag{2}$$

Substituting Eq.(1) into Eq.(2), we have

$$M = \frac{d \log P + 3d \log(r_0^2+H^2) - d \log H}{d \log V - d \log (r_0^2+H^2) + d \log H}. \tag{3}$$

If bulging pressure jumps from P_1 to P_2, then bulging height and speed accordingly change from H_1 and V_1 to H_2 and V_2. Then Eq.(3) becomes

$$M \approx \frac{\log\left(\dfrac{P_2}{P_1}\right) + 3\log\left(\dfrac{r_0^2+H_2^2}{r_0^2+H_1^2}\right) - \log\left(\dfrac{H_2}{H_1}\right)}{\log\left(\dfrac{V_2}{V_1}\right) - \log\left(\dfrac{r_0^2+H_2^2}{r_0^2+H_1^2}\right) + \log\left(\dfrac{H_2}{H_1}\right)} \tag{4}$$

Let $H_1 = H_2$, then Eq.(4) becomes

$$m=\frac{d\log\left(\frac{P_2}{P_1}\right)}{d\log\left(\frac{V_2}{V_1}\right)}\,. \tag{5}$$

This is the formula of measuring superplastic bulging m value under fixed bulging height by means of jump pressure.

III. Measuring Method

The measuring apparatus designed by the authors, as shown in Fig. 1[7], has the following advantages: the parallel light beam goes over the top of specimen through the window of the heating furnace and the silex window on the pressure-pad cylinder, then is by lens focused on photocell, thus the relation curve between bulging height and time t is recorded by a function plotter. The mechanism of this apparatus is first to turn the height change to the light energy change, then to turn the light energy change to the electric energy change. So the additional stress and uneven temperature can be totally avoided, which exist in the previous contact measuring method.

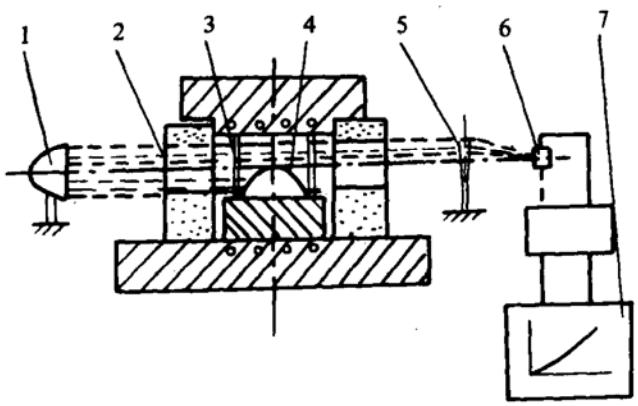

Fig. 1. Photoelectronic experimental apparatus for superplastic bulging.
1. Collimated light; 2, silex window; 3. pressure-pad cylinder; 4. specimen; 5. lens; 6. photocell; 7. X-Y function plotter.

Let the equivalent height $h=\frac{H}{r_0}$, and substituting it into Eq.(1), we have

$$\frac{\frac{dh}{dt}}{\bar{\dot{\varepsilon}}}=\frac{1}{\sqrt{2(1+R)}}\,\frac{1+h^2}{2h}\,. \tag{6}$$

Let $R=1$, and from $\frac{dh}{dt}\Big/\bar{\dot{\varepsilon}}$ in Eq.(6) and the h relation curve, we know that when h is smaller than 0.44, bulging lies in static state. So the measuring points of m value should be selected during this period.

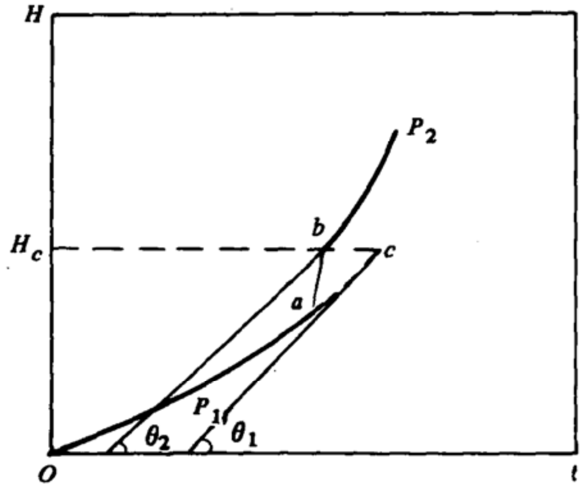

Fig. 2. Schematic diagram of measuring m value by means of jump pressure and expolating.

The typical jump pressure curve of H-t relation for superplastic materials under constant temperature is shown in Fig. 2. Bulge from the pressure P_1 to the static point a, then jump to P_2 to reach the static point b, finally bulge again along P_2. To meet $H_1=H_2$, expolate P_1 line to c. The slope at point c is $\tan\theta_1=V_1$, at point b is $\tan\theta_2=V_2$. Substituting V_1, V_2 and P_1, P_2 into Eq. (5), then m value related to V_1 can be got. For the same reason, the inverse expolating method can be used, but the m value measured is related to V_2. The m values from the two methods have a little difference.

IV. Experimental Results

The tested materials were $ZnAl_4Cu$ and $ZnAl_{22}$ superplastic sheet metals. The temperatures were 320°C and 250°C. The dimensions of the specimen were 200 × 200 × 2 mm, the radius of pressure-pad $r_0=50$ mm, the time for holding temperature $t=10$ min.

By the mentioned formula and method, the measured m values are listed in Tables 1 and 2, and the corresponding m-log $\bar{\dot{\varepsilon}}$ curves are shown in Figs. 3 and 4 respectively.

Table 1

Tested Superplastic Bulging m Values for $ZnAl_4Cu$

P_1(MPa)	P_2(MPa)	V_1(mm/s)	V_2(mm/s)	H(mm)	$\bar{\dot{\varepsilon}}$ (s^{-1})	m
0.05	0.075	0.011	0.059	34.28	4.1×10^{-4}	0.242
0.075	0.1	0.059	0.099	34.28	2.2×10^{-3}	0.55
0.1	0.15	0.099	0.21	34.28	3.69×10^{-3}	0.54
0.15	0.2	0.17	0.27	34.28	6.3×10^{-3}	0.62
0.2	0.3	0.21	0.35	34.28	7.8×10^{-3}	0.793
0.3	0.4	0.35	0.602	34.28	1.3×10^{-2}	0.413
0.4	0.5	0.502	0.932	34.28	2.2×10^{-2}	0.36
0.5	0.6	0.732	1.746	34.28	2.7×10^{-2}	0.21

Table 2

Tested Superplastic Bulging m Values for $ZnAl_{22}$

P_1(MPa)	P_2(MPa)	V_1(mm/s)	V_2(mm/s)	H(mm)	$\bar{\dot{\varepsilon}}(s^{-1})$	m
0.1	0.2	0.006	0.078	34.28	2.24×10^{-4}	0.271
0.2	0.3	0.078	0.209	34.28	2.91×10^{-3}	0.441
0.3	0.4	0.209	0.340	34.28	7.8×10^{-3}	0.589
0.4	0.5	0.340	0.440	34.28	1.27×10^{-2}	0.875
0.5	0.6	0.440	0.560	34.28	1.64×10^{-2}	0.754
0.6	0.7	0.560	0.823	34.28	2.09×10^{-2}	0.403
0.7	0.8	0.823	1.833	34.28	2.58×10^{-2}	0.166

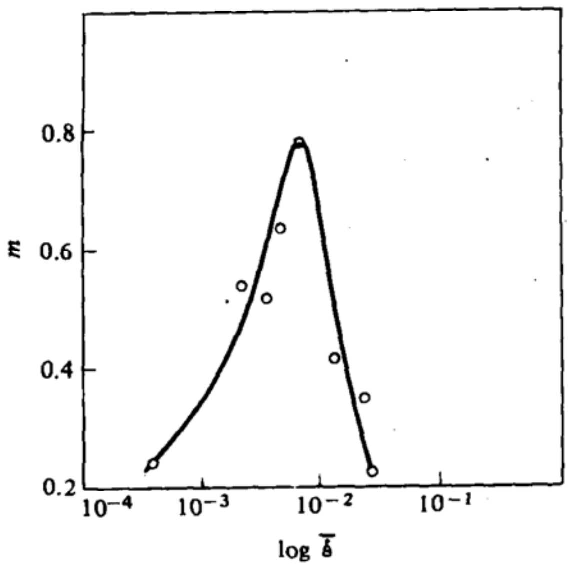

Fig. 3. m-log $\bar{\dot{\varepsilon}}$ relation of $ZnAl_4Cu$.

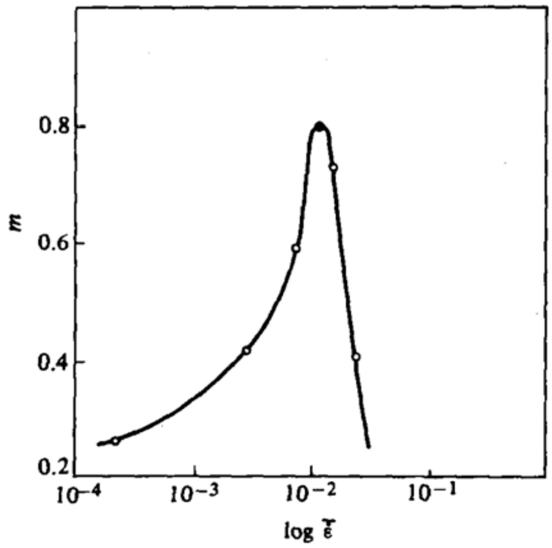

Fig. 4. m-log $\bar{\dot{\varepsilon}}$ relation of $ZnAl_{22}$.

From the above we know that the formula has obvious physical meaning and is easy to measure and calculate. It is similar to the jump tension speed proposed by Backofen for measuring m value[9]. Both can artificially create error when we expolate the experimental curves

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