Bulge Testing under Constant and Variable Strain Rates of Superplastic Aluminium Alloys

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Abstract
The present paper deals with superplastic forming of aluminium alloy AA5083 sheet metals tested at specific strain rates, temperatures and counter pressures by means of bulge testing using circular and elliptical dies and by the cone-cup testing method. Further, differences from batch to batch can lead to a different strain rates at the maximum m value. It is shown by experimental investigations that pulsating strain rates can lead to higher m values and to increased thickness strains.

Keywords:
Superplasticity, Formability, Sheet Metal Forming, Aluminium Alloys

1 INTRODUCTION

Superplastic sheet metal forming allows the production of complex parts that are not formable under normal conditions or require the assembly of a certain number of parts. Superplastic sheet metal forming processes normally are based on the same common principle: the sheet metal is firmly clamped between the die halves and is blow-formed by means of gas pressure. Superplastic materials are usually characterized by their total elongation at failure in uniaxial tensile testing and by the strain rate sensitivity exponent. Because commercial superplastic forming processes are performed under multiaxial stress conditions, the material data from the uniaxial tensile tests are insufficient to describe the formability. First analytical models for superplastic bulging were developed by Jovane [1], Cornfield [2] and Holt [3]. They were extended by Ghosh [4], Yang [5], Dutta [6], Ding [7] and others. Recently an increasing number of authors are taking into account the cone-cup testing method for testing superplastic materials [8, 9].

2 ANALITICAL MODELS FOR BULGING

2.1 Bulging into circular and elliptical dies

An original theoretical model used for the computation of the pressure-time relationship has been developed by the authors [10, 11]. In order to form the dome with a constant strain rate in the pole, the pressure-time relationship according to this model is:

$$p=2\cdot\frac{1+\alpha\cdot\frac{b_0^2}{a_0^2}}{\sqrt{1-\alpha+\alpha^2}}\cdot\frac{s_0}{b_0}\cdot\left(e^{\frac{2-\alpha}{2\sqrt{1-\alpha+\alpha^2}}\cdot\dot{\varepsilon}_e\cdot t}-1\right)^{\frac{1}{2}}\cdot e^{\frac{3}{2\sqrt{1-\alpha+\alpha^2}}\cdot\dot{\varepsilon}_e\cdot t}\cdot C\cdot\dot{\varepsilon}_e^m \quad (1)$$

where C is a material parameter, s_0 the initial sheet thickness, a_0 the die radius, $\dot{\varepsilon}_e$ the equivalent strain rate, m the strain rate sensitivity exponent and t the time. Further a_0 and b_0 are the major and minor half-axes of the elliptical die. According to this model, α is the ratio of the principal stresses σ_2/σ_1 in the pole:

$$\alpha=\frac{1}{2}\cdot\left(1+e^{1-\frac{a_0}{b_0}}\right) \quad (2)$$

2.2 Bulging into a conical die

The search for an analytical solution requires also some simplifying assumptions [12]:

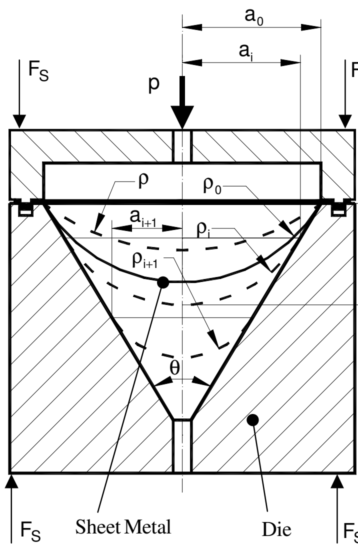

Figure 1 : Geometrical model for superplastic forming sheet metals into a conical die

The sheet is firmly clamped between the two halves of the die and loaded with the pressure p. The superplastic forming of aluminium sheets process into a conical die consists of two stages:

1. A free bulging phase with the initial die radius a_0 until the radius of the curvature of the deformed sheet metal becomes $\rho_0 = a_0/\cos(\theta/2)$
2. A second phase of forming into the conical die which is also assumed to take place as a free bulging for a very

short moment of time dt with no change of the die radius a_i but with an incremental change of the radius of curvature ρ_i and sheet thickness s_i

In the first free bulging stage the pressure-time relationship will be computed using the relationship developed by Dutta and Mukherjee [6].

$$p = C\cdot\frac{4\cdot s_0}{a_0}\cdot\left(1-e^{-\dot{\varepsilon}_e\cdot t}\right)^{\frac{1}{2}}\cdot e^{-\frac{3}{2}\cdot\dot{\varepsilon}_e\cdot t}\cdot\dot{\varepsilon}_e^{m} \quad (3)$$

where C is a material parameter, s_0 the initial sheet thickness, a_0 the cone radius, $\dot{\varepsilon}_e$ the equivalent strain rate, m the strain rate sensitivity exponent and t the time.

An analytical model of the incremental forming process into the conical die has been developed by the authors [12]. According to this model the pressure versus time relationship is:

$$p_{i+1} = 2\cdot\frac{s_i}{\rho_i}|A|\cdot(A\cdot B)^{-\frac{1}{2}}\cdot e^{-\frac{3}{2}\cdot\dot{\varepsilon}_e\cdot dt}\cdot C\cdot\dot{\varepsilon}_e^{m} \quad (4)$$

where

$$A = a_i^2\cdot e^{-\dot{\varepsilon}_e\cdot dt} - 2\cdot\rho_i^2 + 2\cdot\rho_i\cdot\left(\rho_i^2 - a_i^2\right)^{\frac{1}{2}} \quad (5)$$

and

$$B = a_i^2 - 2\cdot\rho_i^2 + 2\cdot\rho_i\cdot\left(\rho_i^2 - a_i^2\right)^{\frac{1}{2}} \quad (6)$$

This pressure-time path can be easily integrated into the control system of a superplastic forming process [12].

The analytically computed pressure-path based on the Equation 4 is in a very good agreement with the FEA done by Hambli [13] for an AA5083 sheet metal, see Figure 2.

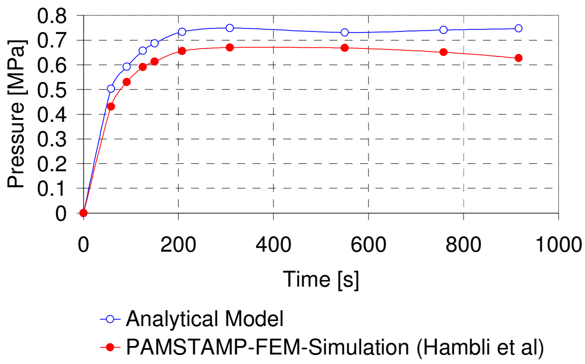

Figure 2 : Comparison between the pressure paths computed analytically and by FEA [13]

The following parameters have been used in the PAMSTAMP finite element code: forming temperature 515 ^{0}C, strain rate $1\text{x}10^{-3}$ s^{-1}, strain rate sensitivity exponent 0.35, initial sheet thickness 3 mm, cone radius 50 mm, die angle 62^0 .

3 EXPERIMENTAL INVESTIGATIONS

3.1 Tested material

A commercial superplastic formable aluminium sheet metal AA5083 with a thickness of 1.6 mm was investigated. This alloy is not age-hardenable. Figure 33 shows an optical micrograph with grain size smaller than 10 μm. The variation of the strain rate sensitivity exponent over the strain rate is shown in Figure 4 [14].

The testing temperature was set to 550 ^{0}C and the strain rate to $1\text{x}3\cdot10^{-3}$ s^{-1}.

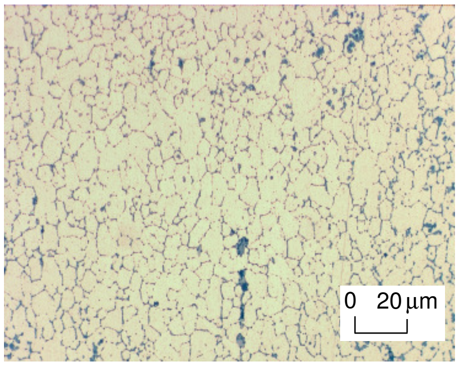

Figure 3 : Optical micrograph of AA5083 alloy after solutionizing at 525 ^{0}C for 15 min followed by water quench and aging at 150 ^{0}C for 24 h.

3.2 Experimental device

Due to the high sensitivity of the forming process with regards to the forming temperature and forming pressure, special care was taken in designing the heating system and the control unit.

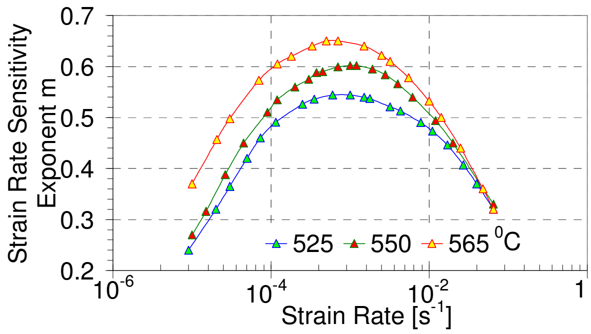

Figure 4 : Strain rate sensitivity exponent versus strain rate and temperatures [14]

The testing equipment was designed and built (at the Institute for Metal Forming Technology from Stuttgart University) for both pneumatic bulging at elevated temperatures of superplastic materials using circular and elliptical draw rings (initial sheet diameter $d_0=2\cdot a_0=100$ mm). Figure 5 shows the device carrying a conical die (radius $a_0=64$ mm; angle of the cone 62^0).

Figure 5 : Experimental device using a conical die

The bulge device consists of two chambers that can be used if necessary as pressure and/or counter pressure chambers. The pressure and/or counter pressure inlet and outlet take place through a drilling in the cylindrical and/or conical part of the die. The heating of the tool consists of band heaters that exhibit a heat flow density of up to 7 W/cm^2. The advantages of using band heaters are their even, task-related heat distribution and their exchangeability. The clamping force is provided by a 1000 kN hydraulic press. Two pneumatic proportional valves are integrated in the tooling to control the pressure over time.

3.3 Experimental procedures

Experiments using a circular draw ring with a radius of 50 mm were carried out in order to verify the analytical model presented above. To determine the strain after the superplastic forming process, circle grids of an average diameter of 4.0 mm were electrically-etched on the outer surface of the sheet metal. The bulge tests were interrupted at specific moments of time in order to measure the hoop and the meridian strain at the bulge apex.

4 RESULTS AND DISCUSSIONS

4.1 Bulging using circular and elliptical dies

Usually, the pressure-height plot is used for the validation of the theoretical model of bulging. Finite elements simulations using the Superplastic Forming code [15] developed at ETH Zurich were further carried out with the analytically computed pressure-time paths. Figure 6 shows the theoretical pressure-height plot versus the experimental results and the FEA. The pressure-height profile is well reproduced with small discrepancies in the model prediction.

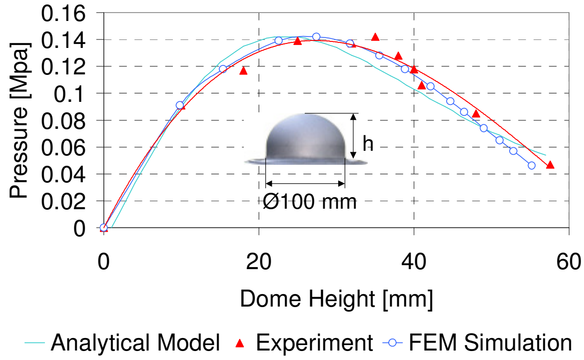

Figure 6 : Validation of the theoretical model for the superplastic bulging with circular die.

For further tests, three elliptical dies with the aspect ratio of 10:7, 10:6 and 10:4 were used. According to Equation 2, the corresponding stress ratio α is 0.8257, 0.7567 and 0.6116, respectively. As shown in Figure 7, Figure 8 and Figure 9, the maximum value of the forming

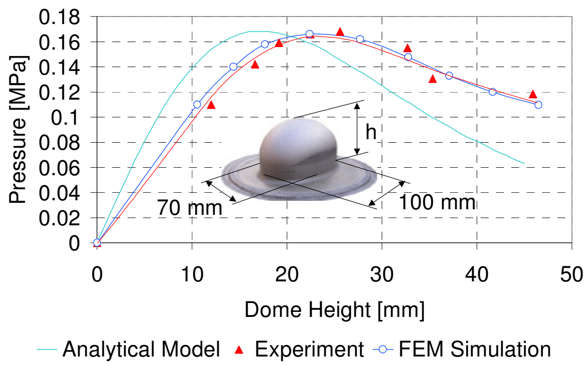

Figure 7 : Validation of the theoretical model for the superplastic bulging using an elliptical die with an aspect ratio of 10 :7

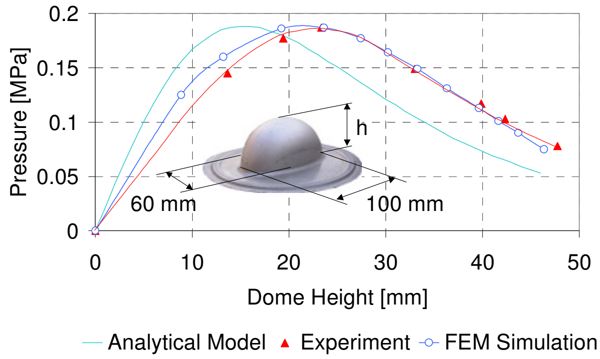

Figure 8 : Validation of the theoretical model for the superplastic bulging using an elliptical die with an aspect ratio of 10 :6.

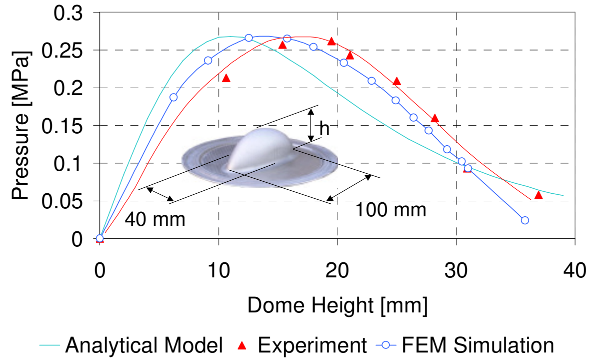

Figure 9 : Validation of the theoretical model for the superplastic bulging using an elliptical die with an aspect ratio of 10:4.

pressure is very well predicted as well as the overall profile. The bulge height is not predicted with a high accuracy. The discrepancy may be caused by the approximate assumptions made on the bulge geometry and by the assumed stress ratio.

4.2 Forming Limit Diagram

The forming limit diagram for this alloy was plotted using the experimental data form the bulge test with circular and elliptical dies, see Figure 10.

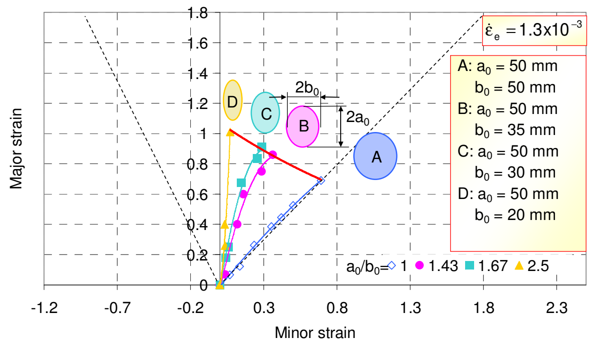

Figure 10 : Forming Limit Diagram of the AA5083 aluminium alloy (T=550 ^{0}C)

The limit strains determined experimentally increase as the strain ratio decreases. The shape of the forming limit curve in the case of superplastic forming is different from that of the conventional forming. A similar curve profile has been determined experimentally by Chan [16], who has reported higher strain values. The discrepancy may be due to the difference in sheet thickness (limit strains increase with thickness) and to the difference in microstructure (e.g. grain size, initial cavitation etc.)

4.3 Influence of a pulsating strain rate on the formability investigated by means of the cone test

Figure 4 shows that the highest m value at the temperature of 550 ^{0}C is reached at a strain rate of about 1.3x10 $^{-3}$ s^{-1}. Differences from batch to batch can lead to a different strain rate at the maximum m value. Experiments at pulsating strain rates can lead to higher m values and to increased thickness strains.

The experiments for the cone test were performed at a mean strain rate of 1.3x10^{-3} s^{-1} with two different strain rate amplitudes of 2x10^{-4} s^{-1} and 1x10^{-4} s^{-1} and for each amplitude, three different frequencies were chosen corresponding to three pulsating periods of 50, 100 and 150 s. The variation of the strain rate has been controlled indirectly, inducing pulsations of the air pressure acting on the specimen. The authors have noticed that the amplitude and the frequency of the strain rate pulsations can be satisfactorily controlled by means of the amplitude and frequency of the pressure variation. As it can be seen in Figure 11, the use of proportional pneumatic valves leads to an almost perfect response of the system to the applied signal.

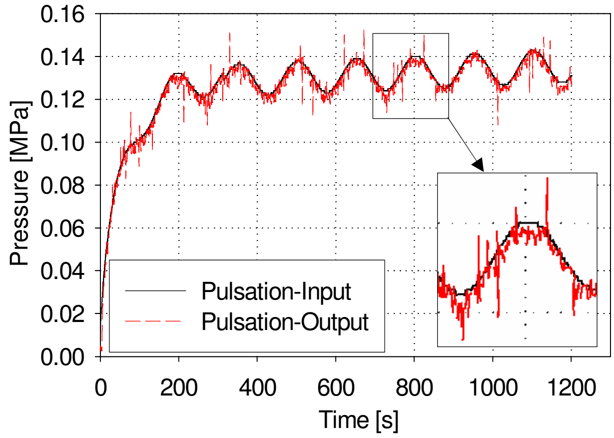

Figure 11 : Pressure-time path for superplastic forming into a conical die (amplitude of the strain rate of 1x10^{-4} s^{-1} and a pulsating period of 150 s)

The experiments were carried out until failure.

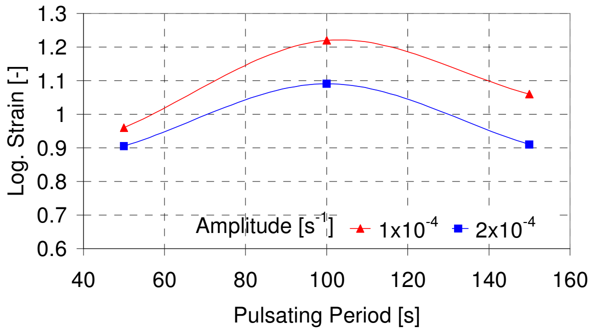

Figure 12 : Thickness strains at failure versus pulsating period for different amplitudes of the strain rate

As shown in Figure 12, the thickness strain at failure can be increased by up to 20 % by applying a pulsating strain rate. Thus, the material will achieve the highest m-value at this temperature when the strain rate is within the range of 1.1x10^{-3} to 1.5x10^{-3} s^{-1}.

5 CONCLUSIONS

The analytical models developed by the authors can be used to predict the pressure profile over time and to study the influence of different parameters on the material formability. It was also demonstrated by the experimental investigations using the cone-cup testing method, that the thickness strain at failure can be increased by applying a pulsating strain rate.

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