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Constitutive Modelling of Superplastic AA-5083

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In this study a fast procedure for determining the constants of superplastic 5083 Al alloy at 723 K is analyzed. To evaluate the displacement and the thickness evolutions at the dome apex of the metal sheet bulge forming experiments at constant pressure are performed. The displacement-time curves at the constant pressures of 0.30, 0.35, 0.40, 0.45 and 0.50 MPa are obtained by laser measurements whereas many bulging tests at the same gas pressures stopped up at prefixed intervals of time were carried out to evaluate the thickness at the dome apex. Direct measurements of the thickness were obtained using a centesimal micrometer. It is known that an equibiaxial stress state is present at the dome apex of the metal sheet. In contrast, at other locations, a nonequibiaxial stress state prevails. Due to the nonequibiaxial stress state, the thickest location occurs at the sheet periphery and the thinnest location at the dome apex. Therefore, by using the finite element method, it is possible to accurately analyse the superplastic forming process in the real stress state conditions. The material behaviour is modelled by the power law relationship between the effective flow stress, the effective strain and the effective strain-rate. In the power law relationship the strain-rate sensitivity index, m, is a constant, n and K are variables that are functions of the effective strain-rate. Experimental results allowed to easily determine the value of m. Moreover, by means of some numerical simulations it was possible to determine the values of n and K and associate them with specific strain-rates. The results of comparison of the numerical simulations of a bulge forming process with the experimental tests have shown good agreement and they indicate that the material constants are reliable.

1 Introduction

This paper describes the characterization of AA5083 aluminium sheet by using an inverse analysis technique in order to minimize the difference between numerical data and experimental measurements. Using the commercial finite element software MSC.Marc®, the bulging process at constant pressure is simulated. A rigid-plastic flow formulation is applied to the superplastic forming analysis (Zienkiewicz, 1984). The mesh is composed of four-node, isoparametric elements used for axisymmetric applications. As this element uses bilinear interpolation functions, the strains tend to be constant throughout the element. The stiffness of this element is formed using four-point Gaussian integration. The element has two coordinates in the global z- and r-direction and two degrees of freedom for node (Msc.Marc, 2005). An integration scheme which imposes a constant dilatational strain constraint on the element is used. The deformable body corresponding to the metal sheet is discretized with two layers of 128 continuum elements with 4 nodes. The die is considered as a perfectly rigid body. Constant pressure is applied as a distributed load. Because of the symmetry of the geometry, the load and the constraint conditions, half of the cross-section of the sheet metal is analysed. It is necessary to lock the movement of the nodes along the axis of symmetry in a direction that is orthogonal of the axis of symmetry, to avoid penetration of the adjacent elements. Moreover, it is necessary to impose constraint conditions on the periphery of the sheet in order to simulate the action of a blank holder.

Figure 1a shows the shape of the die, the finite element mesh of the sheet and the distributed load over the edges of the sheet.

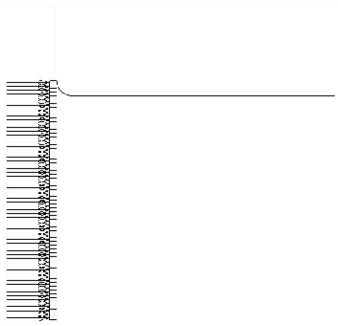
The material behaviour is modelled by the power law relationship between the effective flow stress, $\bar{\sigma}$, the effective strain, $\bar{\varepsilon}$, and the effective strain-rate, $\dot{\bar{\varepsilon}}$, by using the following equation

$$\bar{\sigma} = K\bar{\varepsilon}^n\dot{\bar{\varepsilon}}^m \tag{1}$$

where the strain-rate sensitivity index, m, is a constant, n and K are variables that are functions of the effective strain-rate. The properties of the material and the pressure value, applied to the top part of the sheet metal, are included using a subroutine.

2 Material and Forming Tests

Aluminium alloy, AA5083 in the form of a 1mm thick sheet is characterized by using bulge forming tests at the constant pressures of 0.30, 0.35, 0.40, 0.45 and 0.50 MPa. The bulging tests are carried out at temperature of 723 K (450°C).
A circular 79-mm-diameter specimen is interposed between two heated steel dies. The upper die has a circular geometry with an aperture radius of 30.0mm and a die entry radius of 2.0mm. The lower die works as a blankholder. From the lower die a pressure gas acts on one side of the sheet forcing it to expand into the upper die cavity. The air pressure is obtained by a compressor and it is regulated by a proportional valve. A pressure transducer is inserted on the air injection line to ensure that the pressure inside the die is equal to the one set for the bulging test. The specimen temperature is indirectly controlled through the temperature of the heating bands wrapped around the dies and connected to an electrical feeder. The temperature of the bands is measured and checked by a LabVIEW program. Figure 1b shows the heating bands wrapped around the dies. Further details about the forming system are reported in (Giovinco, Giuliano and Testa, 2010).



(a)

(b)

Figure 1: a) Schematic view of the die and sheet mesh and b) forming dies for bulging test

The objects of the experimental activity are to evaluate the displacement and the thickness evolutions at the dome apex of the metal sheet. The displacement-time curves are obtained by laser measurements whereas many bulging tests at the same gas pressures stopped up at prefixed intervals of time were carried out to evaluate the thickness at the dome apex as showed in (Giuliano, 2010) for a magnesium-based alloy. Direct measurements of the thickness are obtained using a centesimal micrometer.

forming pressure (MPa)	forming time to H=1 (s)	average strain-rate (s^{-1})
0.30	2545	4.12×10^{-4}
0.35	1732	6.13×10^{-4}
0.40	1226	8.83×10^{-4}
0.45	896	1.23×10^{-3}
0.50	671	1.66×10^{-3}

Table 1: Experimental data

Figure 2 shows the experimental trends of the displacement-time curves for constant gas pressures of 0.30, 0.35, 0.40, 0.45 and 0.50 MPa, respectively. Figure 3 shows the dome apex thickness evolution at the same pressures considered in Fig.2: it is possible to consider the relationship $[1-(s/s_0)]$ versus $[H^2/(1+H^2)]$ as linear. In this figure H is the normalized polar displacement (defined as the ratio of the displacement and the die radius), s_0 and s are the initial and the current thickness at the dome apex.
Table 1 summarizes data from the experimental tests. The average strain-rate is $\bar{\varepsilon}/t$, where $\bar{\varepsilon}$ is the effective strain at the dome apex for H=1 and t is the forming time.

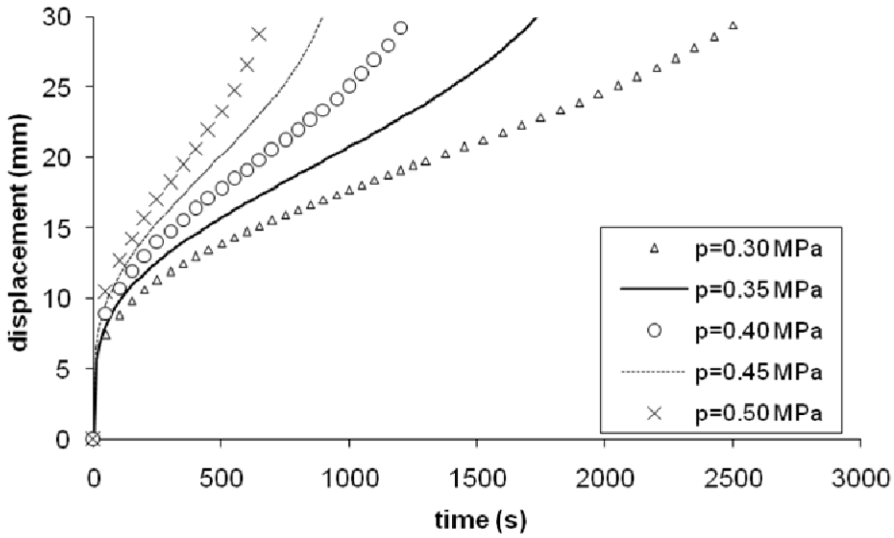


Figure 2: Displacement-time curves in superplastic forming process at constant pressure

3 Characterization of the Superplastic 5083 Al Alloy

The model proposed to describe the behaviour of the 5083 Al alloy, relates the flow stress to the strain and the strain rate, according to the equation (1). The material constants were obtained by using the experimental bulging tests at constant pressure and different numerical simulations. Under a given constant pressure, the displacements at the dome apex are measured by a laser device and recorded as a function of time. In order to obtain material constants, the bulging test data at five different pressure values were used: for each single pressure value, the time step taken for the sheet to pass through the normalized polar displacement H=0 to H=1 was measured.

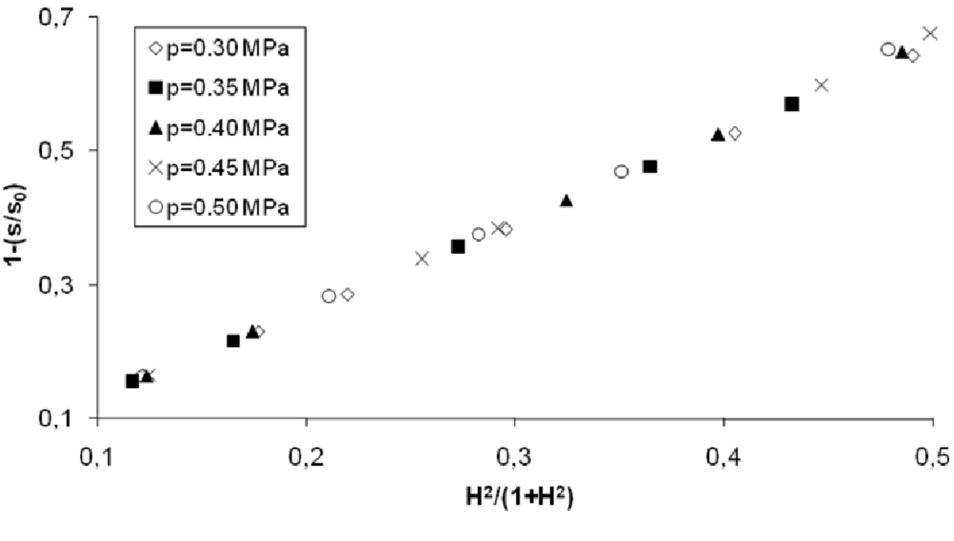


Figure 3: Dome apex thickness evolution in superplastic forming process at constant pressure

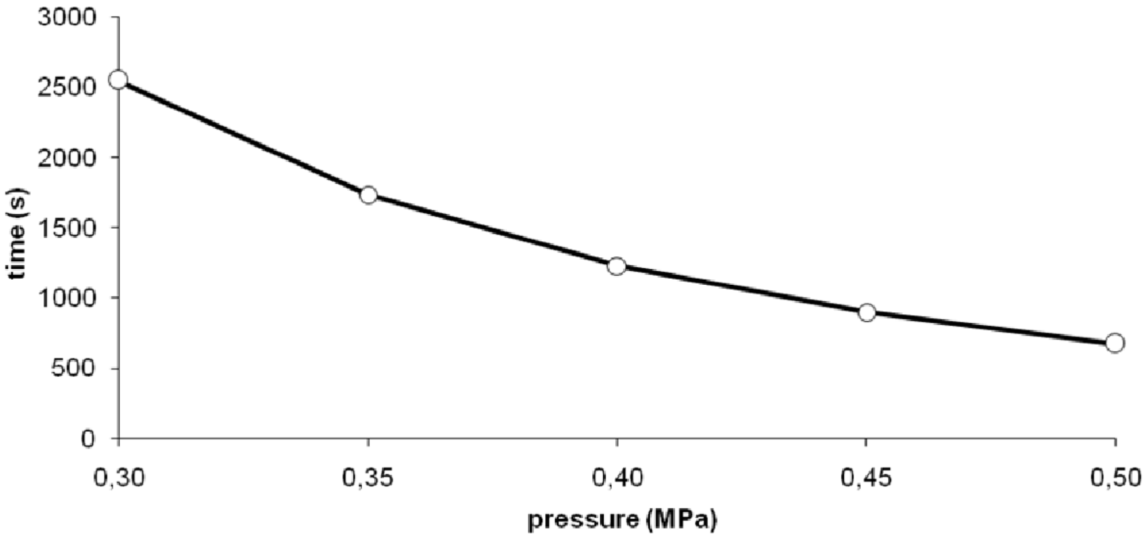


Figure 4: Pressure-time experimental data at H=1

Figure 4 shows the pressure-time experimental data at H=1. It is possible to note that

$$t = ap^{-b} \tag{2}$$

where t is the forming time at the polar displacement H=1, p is the pressure and a and b are constants.
Therefore, the strain rate sensitivity index, m, can be determined by adopting the expression presented in (Giuliano, Franchitti, 2007; Enikeev, Kruglov, 1995; Giuliano, 2009)

$$m = \frac{\ln(p_1/p_2)}{\ln(t_2/t_1)} \tag{3}$$

where t_1 and t_2 are forming times at constant pressures p_1 and p_2, respectively. In this paper, from t-p experimental relationship eq. (2), m may be defined from the following expression

$$m = -\frac{\partial(\ln p)}{\partial(\ln t)} \tag{4}$$

Then, from eq. (2), one can obtain that

$$m = \frac{1}{b} \tag{5}$$

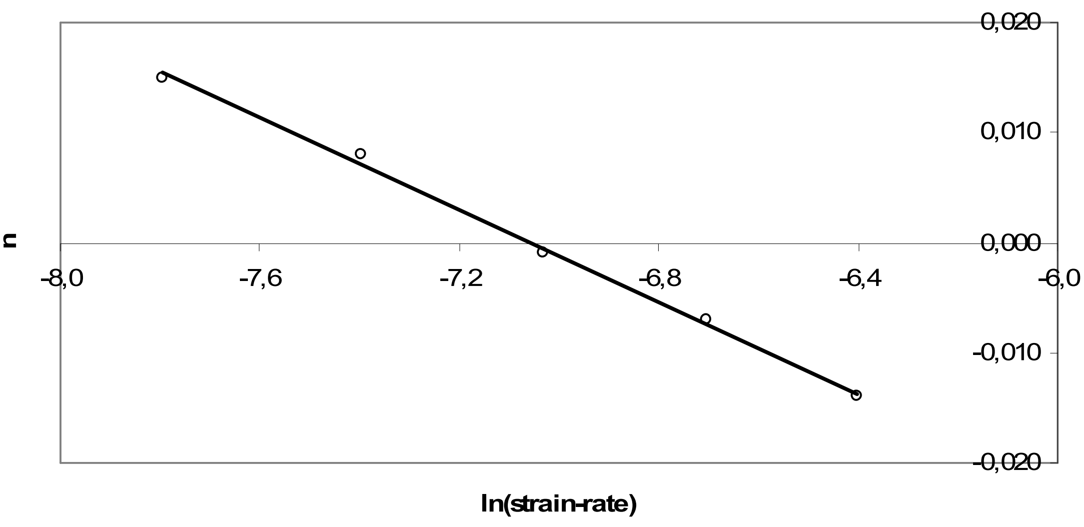


Figure 5: Relationship between n and the strain-rate

Moreover, by means of some numerical simulations it was possible to determine the values of n and K and associate them with specific strain-rates. The first numerical phase requires the bulge forming simulations at the same pressure considered in the experimental activity: m is well-known through eq. (5), to K is assigned an arbitrary value and n is made to vary in a suitable range.
The numerical value of n is calculated minimizing the function Q by

$$Q(n_i)=\left(\frac{(\ln\tau)_i^N-(\ln\tau)^{EXP}}{(\ln\tau)^{EXP}}\right)^2+\left(\frac{(\varepsilon)_i^N-(\varepsilon)^{EXP}}{(\varepsilon)^{EXP}}\right)^2 \tag{6}$$

where $(\ln\tau)_i^N$ and $(\varepsilon)_i^N$ represent the values of the normalized time and the equivalent strain obtained from the numerical simulation for a fixed value of n whereas $(\ln\tau)^{EXP}$ and $(\varepsilon)^{EXP}$, instead, are the normalized time and the equivalent strain obtained experimentally.
The parameter τ or normalized time to be defined as follows

$$\tau = t_{H=1}/t_{H=0.5} \tag{7}$$

where $t_{H=1}$ and $t_{H=0.5}$ are, respectively, the forming times taken to reach the configurations H=1 and H=0.5 in a constant pressure-forming process.
Figure 5 shows that it is possible to consider the relationship $n = \ln(\dot{\varepsilon})$ as linear.
The last phase of the procedure to determine the material constants requires the value of the constant K to be determined: for each single pressure value, m is well-known through eq. (5), n is known by minimizing the function Q(n), and K is made to vary in a suitable range. The numerical value of K is calculated by minimizing the function F given by

$$F(K_i)=\left(\frac{(t_{H=1})_i^N-(t_{H=1})^{EXP}}{(t_{H=1})^{EXP}}\right)^2 \tag{8}$$

where $(t_{H=1})_i^N$ and $(t_{H=1})^{EXP}$ are the forming times necessary to obtain the same dome geometry at constant pressure (H=1) from the numerical simulation and from the experimental tests, respectively.
Figure 6 shows that a third-order polynomial function can give an adequate relationship between $K-\ln(\dot{\varepsilon})$.

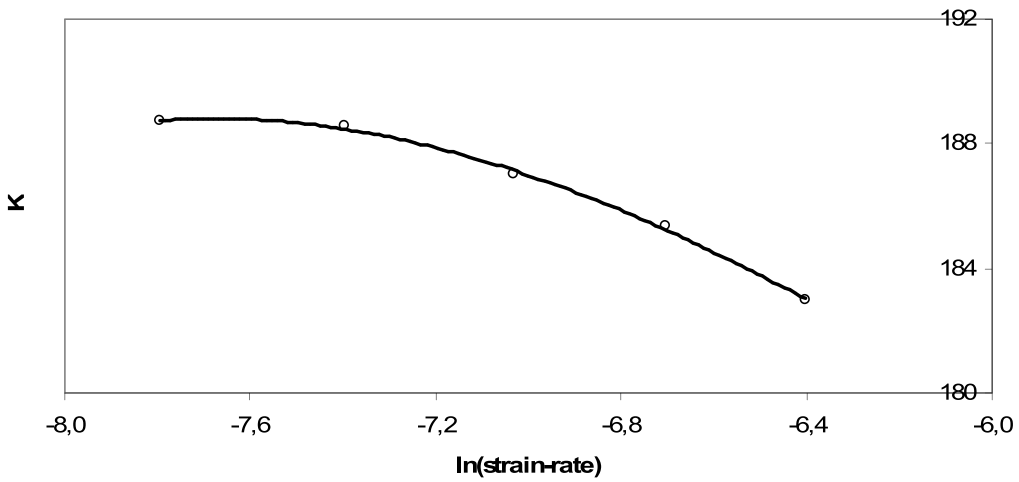


Figure 6: Relationship between K and the strain-rate

4 FEM Results and Discussions

Using the commercial finite element software MSC.Marc®, the bulging process at the constant pressures of 0.30, 0.35, 0.40, 0.45 and 0.50 MPa has been simulated.
The material behaviour is modelled by the power law relationship between the effective flow stress, the effective strain and the effective strain-rate according to eq. (1).

In the strain rate interval of 4.12×10^{-4} - 1.66×10^{-3} s^{-1} which corresponds to the region of the superplastic behaviour for aluminium alloy AA5083, it is assumed in FEM calculations that

$$n = A \ln(\dot{\varepsilon}) + B \tag{9}$$

$$K = C_0 + C_1 \ln(\dot{\varepsilon}) + C_2 [\ln(\dot{\varepsilon})]^2 + C_3 [\ln(\dot{\varepsilon})]^3 \tag{10}$$

where A, B, C_i are constants. The values for the constants are: A=-0.021, B=-0.148, C_0=236.820, C_1=52.816, C_2=11.317 and C_3=0.684.

For each single numerical simulation, the displacement-time curve and the $[1-(s/s_0)]-[H^2/(1+H^2)]$ curve have been obtained. All the numerical analyses show that it is possible to consider the relationship $[1-(s/s_0)]$ versus $[H^2/(1+H^2)]$ as linear.

In the range $0 \leq H \leq 1$, the distance between numerical calculations and experimental measurements was evaluated. This distance is expressed as

$$t\% = \left| (t_{num} - t_{\exp}) / t_{\exp} \right| \cdot 100 \tag{11}$$

$$s\% = \left| (s_{num} - s_{\exp}) / s_{\exp} \right| \cdot 100 \tag{12}$$

where t is the forming time, s is the current thickness at the dome apex and the subscripts num and exp indicate the numerical and experimental values, respectively. In all the bulging tests, t% and s% were found to be less than 10%.

5 Conclusions

Constant pressure superplastic bulging tests of AA5083 aluminium sheet at 723 K are considered in the present paper. The displacement-time curve and the thickness evolution at the dome apex of the metal sheet are evaluated. Commercial finite element software is used to determine the constants of superplastic alloy. The results of comparison between the numerical simulations of bulge forming process and the experimental tests show good agreement and they indicate that the material constants are reliable.

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