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The Influence of Pulsating Strain Rates on the Superplastic Deformation Behaviour of Al-Alloy AA5083 Investigated by Means of Cone Test

Mihai Vulcan[1], Klaus Siegert[1], Dorel Banabic[2]

[1]Institute for Metal Forming Technology, Holzgartenstrasse 17, 70174 Stuttgart, Germany
vulcan@ifu.uni-stuttgart.de , siegert@ifu.uni-stuttgart.de

[2]Technical University of Cluj-Napoca, B-dul. Muncii 103-105, 3400 Cluj-Napoca, Romania
Dorel.Banabic@tcm.utcluj.ro

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Abstract. The superplastically formable aluminium alloy AA5083 has good weldability, reasonable corrosion resistance and strength. In order to test the formability of this alloy, blanks were formed by pressurised gas into cones at constant strain rates. For this, a new analytical model was developed. The cone-cup testing method has been used to study the influence of a pulsating strain rate on the formability of this aluminium alloy. The forming operations were performed using an in-house designed and built equipment for superplastic matrices forming. The process was also modelled using a finite element code. Preliminary results are presented.

Introduction

Superplasticity is the capability of certain fine-grained polycrystalline materials to undergo extensive tensile plastic deformation under specific temperature and load conditions without the formation of a neck prior to failure.

Superplastic materials are usually characterised by total elongation at failure, achieved in the tensile test and by the strain rate sensitivity exponent, m. Commercial superplastic forming processes use mainly the following three techniques: matrice forming, bubble forming and diaphragm forming. These techniques have the same common principle: the superplastic sheet metal is usually blow-formed in a die by a gas pressure. Since these applications are performed by multiaxial stress conditions, the material data obtained from the uniaxial tensile test are insufficient to describe the formability. Multiaxial stress conditions can be achieved for instance by performing a pneumatic bulge test. In order to perform such tests, first a pressure-time relationship has to be realized to form the dome at a constant strain rate. This can be done by computing the pressure-time relationship analytically or by FEM simulations. The first analytical models for superplastic bulging were developed in the late 1960's by Jovane [1]. They were completed by Dutta and Mukherjee [2] and others.

Forming superplastic sheet metal into a cone is another possibility to test the formability of such materials. In the last years, several studies concerning superplastic forming into cones have been reported [3,4].

Theoretical Approach

The basics of the analytical model describing the superplastic cone forming process have been taken from the analytical model for superplastic bulging, using a circular diaphragm, developed by Dutta and Mukherjee [2]. It is one of the simplest models found in the literature and it is very easy to understand and to implement in a control unit of a testing equipment. The authors have preliminary tested this analytical model using the superplastic formable aluminium alloy AA5083, for which the experimental and theoretical results were found to be in good agreement [5].

According to the model of Dutta and Mukherjee, the pressure p over the time t can be described by:

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

where C is a material constant, s_0 the initial sheet thickness, a_0 the die radius, $\dot{\varepsilon}_e$ the equivalent strain rate, m the strain rate sensitivity. The model uses the von Mises yield criterion. Based on this model, a new analytical model for the superplastic forming into a cone is proposed. The blanks to be bulged to spherical membranes have uniform thickness and no friction between the sheet metal and the die is taken into account.

The forming process into the conical die consists of two phases:

1. a free bulging phase with the initial die radius a_0 until the radius of the curvature of the deformed membrane becomes ρ_0 and
2. a second phase of forming into the conical die which is also assumed to take place as free bulging for a very short moment of time dt with an incremental change of the die radius a_i, radius of curvature ρ_i and sheet thickness s_i.

As shown in the analytical model of Dutta-Mukherjee, the area A_i of the deformed membrane with a radius of curvature ρ_i at any instant can be calculated as:

$$A_i = 2 \cdot \pi \cdot \rho_i \cdot \left[\rho_i - \left(\rho_i^2 - a_i^2\right)^{\frac{1}{2}}\right] \qquad (2)$$

where a_i is the die radius.

After a very short period of time dt, we assume to have another free bulging process with a smaller die radius $a_{i+1} < a_i$ and a smaller radius of curvature $\rho_{i+1} < \rho_i$. Starting from the geometrical model presented in Fig.1, it can be shown that the die radius a_{i+1} is a function of the radius of curvature ρ_{i+1} and the apex angle θ. It follows:

$$a_{i+1} = \rho_{i+1} \cdot \cos\frac{\theta}{2} \qquad (3)$$

Taking the balanced biaxial stress condition existing at the apex of the dome and the fact that the thickness stress $\sigma_3 = 0$ and using von Mises equivalent stress criterion, it can be shown that

$$\sigma_e = \sigma_1 \qquad (4)$$

where σ_e is the equivalent stress. Furthermore, it can be demonstrated that by substituting the hoop strain ε_1 and the longitudinal strain ε_2 in terms of the thickness strain ε_3 in the expression of the von Mises equivalent strain ε_e, $\varepsilon_e = \varepsilon_3$. Hence, it can be written that

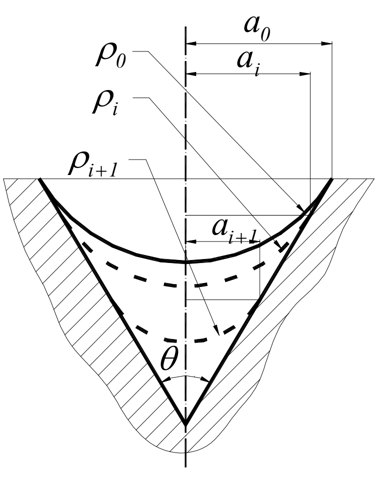

Fig.1 Geometrical model for superplastic forming into a conical die.

$$\dot{\varepsilon}_e = \dot{\varepsilon}_3 \tag{5}$$

The thickness s_{i+1} at the apex of the cone at the moment of time $t_{i+1} = t_i + dt$ can be calculated from the definition of the thickness strain rate $\dot{\varepsilon}_3$:

$$s_{i+1} = s_i \cdot e^{-\dot{\varepsilon}_3 \cdot dt} \tag{6}$$

Combining Eq. 5 and Eq. 6 we obtain:

$$s_{i+1} = s_i \cdot e^{-\dot{\varepsilon}_e \cdot dt} \tag{7}$$

From the constancy of volume, we have the following relationship:

$$A_{i+1} \cdot s_{i+1} = A_i \cdot s_i \tag{8}$$

where A_i and A_{i+1} are the instantaneous areas at the moment of time t_i and t_{i+1}, respectively.
Solving Eq. 8 with the help of *Maple* in terms of ρ_{i+1}, the instantaneous radius of curvature at the moment of time $t_{i+1} = t_i + dt$ becomes:

$$\rho_{i+1} = \left(a_i^2 \cdot e^{-\dot{\varepsilon}_e \cdot dt} - 2 \cdot \rho_i \cdot \left(\rho_i^2 - a_i^2\right)^{\frac{1}{2}} \right)^{-\frac{1}{2}} \cdot \left(2 \cdot \rho_i^2 - a_i^2 - 2 \cdot \rho_i \cdot \left(\rho_i^2 - a_i^2\right)^{\frac{1}{2}} \right) \cdot \rho_i \cdot e^{\frac{1}{2} \cdot \dot{\varepsilon}_e \cdot dt} \tag{9}$$

According to the expression of the hydrostatic pressure from the membrane theory and the Eq. 4, the following expression becomes:

$$p = 2 \cdot \frac{s_{i+1}}{\rho_{i+1}} \cdot \sigma_e \tag{10}$$

By substituting Eq 7. and Eq. 9 into Eq. 10 and using the well-known relationship for superplastic materials

$$\sigma_e = C \cdot \dot{\varepsilon}_e^m , \tag{11}$$

the pressure-time relationship for superplastic forming into cones becomes

$$p = 2 \cdot \frac{s_i}{\rho_i} \cdot \left(a_i^2 \cdot e^{-\dot{\varepsilon}_e \cdot dt} - 2 \cdot \rho_i^2 + 2 \cdot \rho_i \cdot \left(\rho_i^2 - a_i^2\right)^{\frac{1}{2}} \right)^{\frac{1}{2}} \cdot \left(2 \cdot \rho_i^2 - a_i^2 - 2 \cdot \rho_i \cdot \left(\rho_i^2 - a_i^2\right)^{\frac{1}{2}} \right) \cdot e^{\frac{1}{2} \cdot \dot{\varepsilon}_e \cdot dt} \cdot C \cdot \dot{\varepsilon}_e^m \tag{12}$$

In the first phase of the forming process, when the sheet metal has still not touched the inner wall of the die, the pressure-time path can be computed analytically as shown in [2] using Eq. 1.
For the second phase of the forming process, after the sheet metal touches the inner side of the die, the pressure-time path has to be computed incrementally using Eq. 12. Figure 2 shows the pressure paths for different die angles calculated using the iterative procedure outlined above.

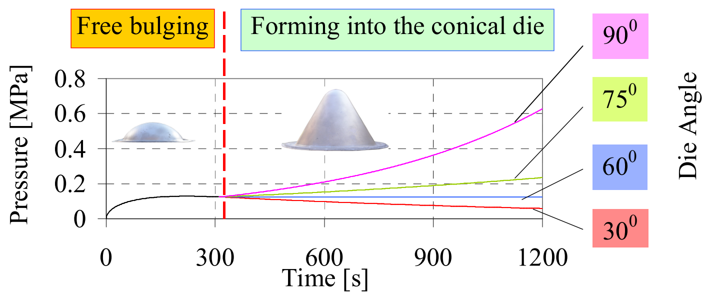

Fig. 2 Calculated pressure path over the time using (12) for different apex angles. Material: Formall®545, forming temperature 550 ^{0}C, strain rate 1.3x10^{-3} s^{-1}, strain rate sensitivity exponent 0,58. Initial sheet thickness 1.6 mm, cone radius 64 mm.

For the first phase of the free bulging, the radius of curvature can be expressed in terms of the cone radius a_0 by resolving Eq. 9, as follow:

$$\rho = \frac{a_0}{2} \cdot e^{\dot{\varepsilon}_e \cdot t} \cdot \left(1 - e^{-\dot{\varepsilon}_e \cdot t}\right)^{-\frac{1}{2}} \quad (13)$$

According to the geometrical model, the free bulging process will take place until the radius of curvature becomes

$$\rho = \rho_0 = 2 \cdot a_0 \cdot tg\frac{\theta}{2} \quad (14)$$

The moment the sheet metal touches the inner wall of the conical die, the solution with respect to t becomes:

$$\frac{a_0}{2} \cdot e^{\dot{\varepsilon}_e \cdot t} \cdot \left(1 - e^{-\dot{\varepsilon}_e \cdot t}\right)^{-\frac{1}{2}} - 2 \cdot a_0 \cdot tg\frac{\theta}{2} = 0 \quad (15)$$

The conical die which has been used for the experimental investigations has a radius $a_0 = 64\,mm$ and an apex angle $\theta = 62^0$. If the superplastic forming process is conducted at a strain rate of $\dot{\varepsilon}_e = 1.3 x 10^{-3}\, s^{-1}$, the sheet metal will touch the inner wall of the conical die after approximately 312 seconds.

Experimental Results and Discussions

A commercial superplastic aluminium AA5083 alloy sheet named Formall®545 with a thickness of 1.6 mm was investigated. For this a new tooling was developed and built up at the *Institute for Metal Forming Technology (IFU) of the University of Stuttgart, Germany*. 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. The pressure and counter pressure chambers were heated up by band heaters, as shown in Fig. 3.

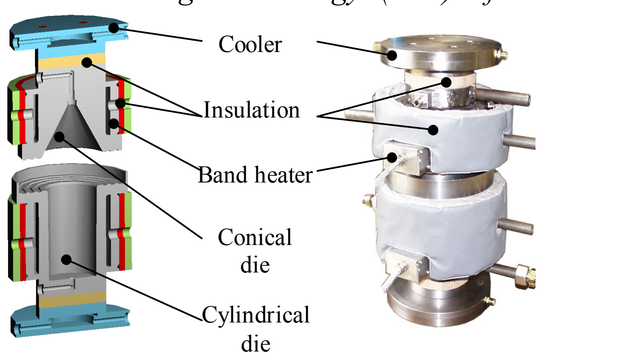

Fig. 3 Tooling assembly for superplastic forming die using gas pressure

The clamping force is provided by a hydraulic press. Two pneumatic proportional valves are integrated in the tooling to control the pressure versus time. Modelling the forming process has been performed using a finite element code *SPForm* [6]. There are two possibilities to execute the code: either the pressure-time path is given, or it can be automatically computed by the program.

The analytically computed pressure-time path as shown in Fig. 2 for a die angle of 62^{0} has been applied to this finite element code and the thickness over the cone height has been calculated. The comparison between the computed and the experimental data are shown in Fig. 4. There are small differences between the experimental results and the FEM simulations.

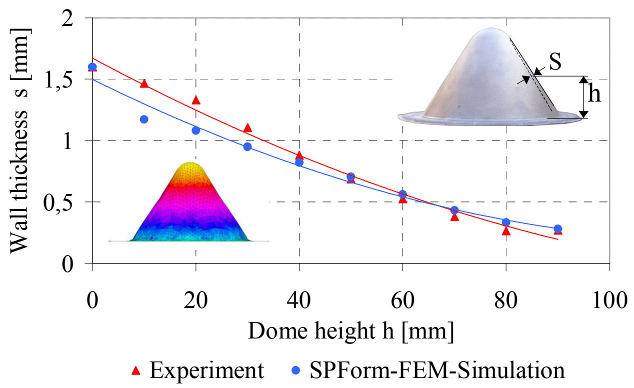

Fig. 4 Wall thickness over the formed part. Material: Formall®545, forming temperature 550 ^{0}C, strain rate 1.3x10^{-3} s^{-1}, strain rate sensitivity exponent 0,58. Initial sheet thickness 1.6 mm, cone radius 64 mm, die angle 62^0.

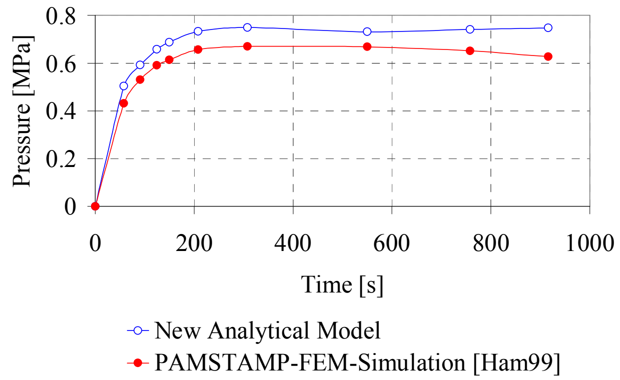

Fig. 5 Comparison between the pressure paths computed analytically by using Eq. 12 and by the FEM simulations using the *PAMSTAMP* code. Material: Formall®545, forming temperature 515 ^{0}C, strain rate 1x10^{-3} s^{-1}, strain rate sensitivity exponent 0.35. Initial sheet thickness 3 mm, cone radius 50 mm, die angle 62^0.

These can be explained by the simplifications made for the analytical model (see *Theoretical Approach*). Furthermore, for the analytical approach, there was made the assumption of a constant equivalent strain rate at the apex and the deformation behaviour of the other regions were not taken into consideration. If the FEM code is applied, different strain rates and stresses will occur over the part. Furthermore, the FEM code can better predict the superplastic behaviour of the material, because the stress-strain rate diagram is divided into three regions in order to accurately compute the stress at different strain rates.

The analytically computed pressure path was also found to be in good agreement with the FEM simulations done by Hambli et al for an AC 5083 sheet metal (see Fig. 5). A pressure-cycle control algorithm was incorporated in *PAMSTAMP* finite element code to regulate the pressure resulting in achieving a specified strain rate once is reached in a part of the sheet metal [7].

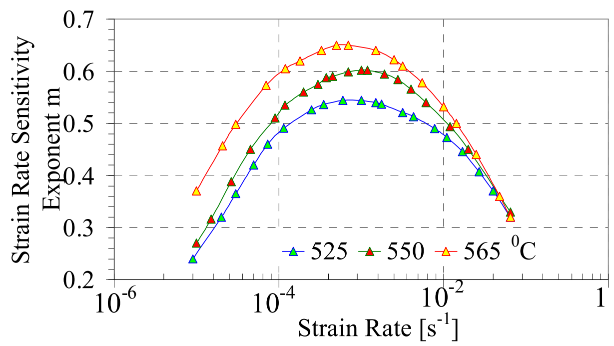

Fig. 6 Strain rate sensitivity exponent versus strain rate and temperatures. Material: Formall®545 [8].

The strain rate sensitivity exponent, m, an important parameter in superplasticity, describes the capacity of the material to resist necking. The m-values shown by Fig. 6 were obtained at a constant true strain rate using the uniaxial tensile test. There are several methods by means of which the m-value can be determined from the uniaxial tensile test. Though, it is well known that the results can slightly differ from method to method and also from batch to batch of the materials.

Fig. 6 for instance, 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 so to more stability against necking. The experiments for the cone test were performed at a mean strain rate of 1.3 x 10^{-3} s^{-1} with two different strain rate amplitudes of 2 x 10^{-4} s^{-1} and 1 x 10^{-4} s^{-1} and for each amplitude, three pulsating frequencies were chosen corresponding to three pulsating periods of 50, 100 and 150 s. As it can be seen in Fig. 7, the use of proportional pneumatic valves leads to an almost perfect response of the system to the applied signal.

The experiments were carried out until failure. Fig. 8 shows significant differences between the achieved strains at failure with respect to pulsating strain rates. Experiments carried out at a constant strain rate of 1.3 x 10^{-3} s^{-1} lead to a maximum thickness strain of 1. It can be seen in Fig. 8 that the thickness strain at failure can be increased by up to 20 % by applying a pulsating strain rate

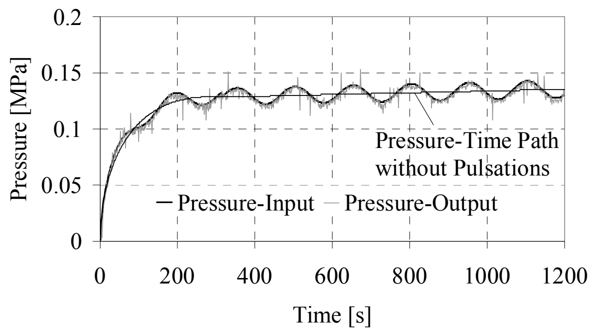

Fig. 7 Pressure-time path for superplastic forming into a conical die with an amplitude of the strain rate of 1 x 10^{-4} s^{-1} and a pulsating period of 150 s.

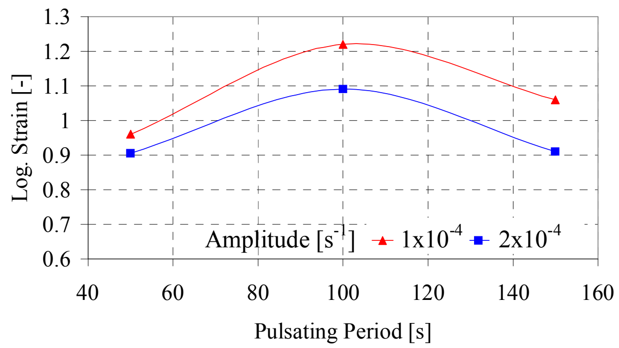

Fig. 8 Logarithmic strain to failure versus pulsating period and amplitude of the strain rate

Summary

In this paper, has been made an attempt to develop a simple relation between pressure and time for superplastic forming of aluminium sheets into cones, using the uniaxial tensile test parameters such as stress, strain rate and strain rate sensitivity exponent. The presented analytical model can still be used to predict the pressure profile over the 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 at failure can be increased by applying a pulsating strain rate.

References

[1] F. Jovane: Int. J. Mech. Sci. Vol. 5 (1968), p. 505-519

[2] A. Dutta and A.K. Mukherjee: Mat. Sci. Eng. Vol. A137 (1992), p. 9-13

[3] K.C. Chan and K.K. Chow: Int. J. Mech. Sci. Vol. 44 (2002), p. 1467-1478

[4] C.K. Syn, M.J. O'Brien, D.R. Lesuer and O.D. Sherby: *Modeling the Peformance of Engineering Structural Materials II* (The Minerals, Metals & Materials Society, USA 2001).

[5] K. Siegert: *New Development in Sheet Metal Forming* (MAT INFO Werkstoff-Informationsgesellschaft mbH, Germany 2002).

[6] Superplastic Forming: *Software Manual SPF* (Swiss Federal Institute of Technology Zürich, Switzerland 1996).

[7] J.C. Gelin, P. Picart: *Numisheet'99: Numerical Simulations of 3-D Sheet Metal Forming Processes* (Impr. BURS, Besancon, France 1999), 581-586.

[8] R. Verma et al: Mat. Sci. Eng. Vol. A191 (1995), p. 143-150.