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Letters

On the constitutive equation of AA2017 aluminium alloy at high temperature

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Abstract

This study describes an original procedure to define the material constants present in the constitutive equation for the aluminium alloy Al 2017. Free bulging forming tests were therefore carried out using pressurised gas and an inverse analysis technique was applied based on minimising the difference between the data obtained from experimental activity and the data that can be obtained from numerical simulation carried out using the finite element method. The free bulging forming tests under pressure were carried out at a constant temperature (sheet metal temperature $T = 438$ °C) and using circular sheets characterised by an initial thickness of 0.55 mm. The constants of the material obtained by means of the proposed procedure allowed a free bulging forming process under pressure to be simulated in order to produce an axisymmetric tray. The results of a comparison between the numerical simulation and the experimental activity corresponded well and this showed that the material constants are reliable.

Keywords: AA2017 aluminium alloy; Gas blow forming test; Constitutive equation; Finite element method

1. Introduction

In general, to carry out a mechanical characterisation of a metallic material one should refer to the tensile test results. Nevertheless, there are limits to tensile tests which has made it necessary to refer to a different test method. The reasons for developing a new test type are: (a) increasing the test speed (preparing the traction test pieces for the tensile test requires too much time), (b) a mono-axial tensile test is not representative of a real forming process using a pressurised gas, and (c) it is necessary to devise a simple test that a company can easily carry out in house.

This test is represented by a free bulging forming test using pressurised gas and is shown schematically in Fig. 1. The technique has already been successfully used by other authors [1–9]. It is carried out at a constant temperature via the action exerted by a gas at constant pressure. Following the action of the gas under pressure, the sheet metal, positioned above a cylindrical die, freely deforms until it ruptures without coming into contact with the die surface. In [4], the authors showed a comparison between the constitutive equations of superplastic alloy PbSn60 obtained by tensile test and free bulging test. Using the equation obtained by the free bulging test the results of forming processes simulation were more accurate.

In this study the free bulging forming test requires the use of a circular test piece characterised by a diameter of 80 mm and a thickness of 0.55 mm. The sheet metal material is 1.0 mm thick and is an aluminium alloy AA2017 (Al-4.5%Cu-1%Mn-1%Mg-0.8%Si-0.7%Fe) bought in T4 conditions. Beginning with the 1.0 mm thick metal sheet, a 0.55 mm thick metal sheet was obtained via a sequence of cold laminations. The AA2017 aluminium alloy exhibit high cold mechanical strength and is generally used for a variety of structural applications. The cold mechanical behaviour of the material is shown in [10–11].

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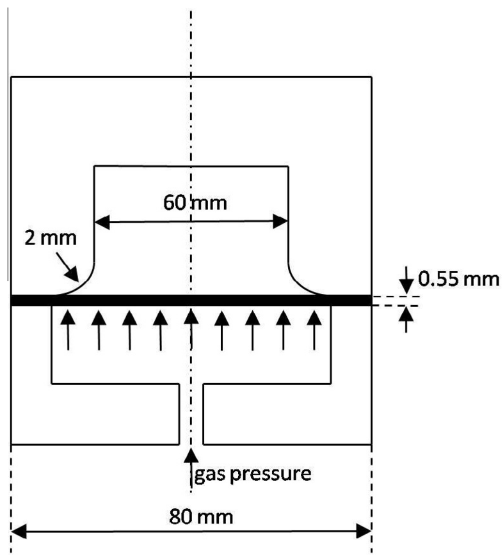

Fig. 1. Schematic illustration of free bulging forming test.

The off-the-shelf program MSC.Marc was used to numerically simulate the free bulging forming process by means of the implicit nonlinear FEA (Finite Element Analysis). The sheet metal was modelled via 64 axisymmetric 4 node elements set out in a single row [12]. Given the symmetry of the problem, the analysis was carried out considering only one half of the sheet metal cross-section. The null movement constraint in the orthogonal direction to the axis itself was applied to the nodes located on the axis of symmetry. In order to simulate the presence of a blank holder, the nodes in the peripheral area of the sheet metal were blocked in an orthogonal direction in relation to the axis whereas the peripheral node shift directly in contact with the die was also blocked in an axial direction. The die was considered as a rigid body characterised by an internal radius of 30.0 mm and a die entry radius of 2.0 mm. A constant uniform pressure was applied on the upper side of the sheet metal (Fig. 1).

Although many forms of yield condition are available in the MSC.Marc code, in this paper the Von Mises criterion and an isotropic yield criterion were used since an anisotropic behavior of the material was not observed at high temperature.

The material behaviour was modelled by means of the following power law [13]:

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

where σ is the flow stress, ε is the strain, $\dot{\varepsilon}$ is the strain rate, m is strain rate sensitivity index, n is the strain hardening index and K is the strength coefficient. Both the constitutive equation for the material and the pressure value applied during the forming process were assigned using a subroutine.

The experimental results used to characterize the material were obtained by a series of pressurised forming tests measuring the height h of the dome apex as the forming time varied. The tests were carried out at the constant pressures of 0.4 MPa and 0.5 MPa and bringing the sheet to a constant temperature of 438 °C via the forming system described in detail in [14].

Unlike what was obtained in [5–7], in this paper the procedure employed was implemented in order to determine the constants of a non superplastic material and in different process conditions.

2. Experimental

The first constant to be identified is the strain rate sensitivity index m. Having set a value for the dome height, h, [7] showed that the forming times are tied to the forming pressure via the following equation:

$$t = a \cdot p^{-b} \tag{2}$$

where a and b are constant with b equal to $1/m$. Therefore, the value of m can be obtained as follows:

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

where t_1 and t_2 are the forming times taken to reach the set value of h respectively at pressures p_1 and p_2.

The experimental tests were carried out at the pressures $p_1 = 0.4$ MPa and $p_2 = 0.5$ MPa. The times taken to reach a dome height of $h = 20$ mm were respectively $t_1 = 474.7$ s and $t_2 = 129.1$ s. A value of $m = 0.171$ was obtained from Eq. (3).

The dimensionless parameter τ introduced in [5] and defined as follows was used to calculate the value of n:

$$\tau = \frac{t_{h=20}}{t_{h=10}} \tag{4}$$

where $t_{\mathrm{h}=20}$ and $t_{\mathrm{h}=10}$ indicate the forming times taken for the test sheet apex to reach respectively the values of $h = 20$ mm and $h = 10$ mm.

In [5], it was shown that the values of n and τ are linked by a linear relationship that is independent of the value of K. Using the value of m previously determined via Eq. (3), and having assigned an arbitrary value to K, for each pressure value adopted two free bulging test simulations were carried out, assigning two arbitrary values to n (e.g. $n = 0$ and $n = 0.1$). Having calculated the values of τ corresponding to the two numerical simulations it was possible to obtain the constants A and B present in the following equations:

$$n = A \cdot \tau + B \tag{5}$$

Hence, with the experimental value of τ being known, then from Eq. (5) one obtains a value of $n = 0.043$.

To determine the value of the constant K, a series of free bulging test numerical simulations were carried out with the values of m and n obtained from Eqs. (3) and (5) being attributed to the sheet metal and attributing a value for K that varies within a suitable range. The appropriate value for K will be the one corresponding to the minimum value of function F: