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Short Communication

Simulation of instability during superplastic deformation using finite element method

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Abstract

In this paper, the instability of superplastic deformation was examined under uniaxial tension by using the finite element technique. Tensile tests have been conducted using a fine-grained Pb–Sn alloy that presents superplastic properties at room temperature. The elongation to failure predicted by numerical analysis was found to be in reasonable agreement with the experimental findings.

Keywords: A Non-ferrous metals and alloy; F Plastic behaviour; H Failure analysis

1. Introduction

Aeronautical and aerospace industries utilize the exceptional ductility of superplastic alloys, such as aluminium and titanium, in the forming of parts with complex shapes by gas pressure forming techniques similar to the techniques used in the glass and plastic industries. The tensile ductility of superplastic materials is typically in the range of 200–1000% elongation. However, the superplastic forming is dependent on high temperature (greater than about half the absolute melting point), narrow range of strain rates (in the range 10^{-4}–10^{-2} s^{-1}) and very fine grain size (of the order of 10 μm) [1]. Most recently, some methods have been examined to further reduce the grain size of superplastic materials so as to achieve high strain rate and low processing temperature [2,3].

The finite element technique has been successfully used to simulate superplastic forming processes [3–13] and optimize the forming parameters, such as the strain rate and the final thickness [14]. It has been observed that the value of the strain rate sensitivity index has a strong effect on the ductility of superplastic materials. In general, the higher the m value, the greater the elongation to failure [1].

A significant problem is the failure mode of sheet metals during superplastic forming process. Chung [15] has showed that, in some superplastic materials, the fracture mode is dominated by unstable plastic flow. The instability of superplastic deformation has been studied by several investigators by analytical approaches. Pearce [16] showed that in the tensile test the shrinkage rate is inversely proportional to the cross section of the specimen and highly sensitive to the strain rate sensitivity index. Thus, the deformation process is predominately post-uniform, in contrast to conventional ductile metal behaviour. The thinning in the tensile specimen can be assumed to be the result of a pre-existing geometrical or structural non-homogeneity which can grow under the imposed deformation. This non-homogeneity may be associated to a variation of the sheet thickness or some defects of the lattice. The rate of thinning in the tensile specimen is therefore determined by the size of the non-homogeneity, but also the strain rate sensitivity index value. This has been shown analytically [17] for an idealized tensile specimen containing a geometric non-homogeneity. In [1], Pilling observed that if the initial non-homogeneity is small then there is a very strong dependence of the elongation

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to failure on the strain rate sensitivity index. The strain to failure is given by:

$$\varepsilon_u = -m \ln\left(1 - f^{1/m}\right), \tag{1}$$

where m is the strain rate sensitivity index and f is the pre-existing non-homogeneity.

In this work, using the finite element technique, the tensile test of superplastic metal sheet was simulated numerically. The analyses showed that the elongation to failure depends on the initial non-homogeneity, strain hardening exponent, and strain rate sensitivity index.

2. Numerical model

The analysis of the tensile test has been performed assuming a geometrical non-homogeneity in the form of a thickness variation [18]. Therefore, the specimen has two regions: region "A" having an initial uniform thickness t_0^A, and region "B" having the initial thickness t_0^B (Fig. 1). The model is based on the growth of the geometrical non-homogeneity. The initial value of the geometrical defect is characterized by the ratio $f = t_0^B/t_0^A$. This two-zone material is subjected to superplastic deformation applying a constant velocity at the region "A" of the specimen. During superplastic flow, the evolution of strain rates is different in the two zones. If ε_1^A and ε_1^B are the principal strains in the two regions, when the ratio $\varepsilon_1^B/\varepsilon_1^A$ becomes too high (infinite in theory, above 10 in practice), the limiting strain of the sheet is reached. The principal strain ε_1^A in region A represents the limit strain.

The finite element calculations were performed using commercial software. Rigid plasticity and the plane stress condition are assumed. Due to the symmetry of the loading and the geometry, only a quarter of the specimen is analyzed. The element mesh is refined near the centre of the specimen because strain localization phenomenon is expected to occur in that region. The bottom and the left edges of the specimen were clamped by symmetry boundary condition. At the top edge of the specimen, constant velocity was applied. To facilitate the analysis, a power law form of the constitutive relationship is assumed:

$$\bar{\sigma} = K\bar{\varepsilon}^n\dot{\bar{\varepsilon}}^m, \tag{2}$$

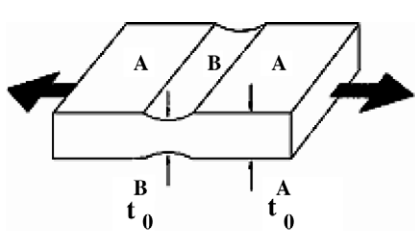

Fig. 1. Geometrical model of metal sheet.

where $\bar{\sigma}$ is the effective stress, $\bar{\varepsilon}$ the effective strain, $\dot{\bar{\varepsilon}}$ the strain rate, K a constant, n the strain hardening exponent and m the strain rate sensitivity index.

3. Experimental activity

The experiments were conducted using a commercial PbSn60 alloy constituted by Pb 60% and Sn 40%, which is known to exhibit superplastic properties at room temperature. The PbSn60 alloy presents a high specific weight, good resistance to the corrosive agent, good deformability and low cost. A small-sized rolling mill was used to prepare the superplastic material, obtaining the necessary fine and equiaxed microstructure [19].

The tensile tests were carried out using an Instron testing machine at constant crosshead velocity to establish the limit strain. The uniaxial tension specimens were machined with a gage length of 40 mm and width 10 mm. The testing machine was designed to operate at crosshead velocity in the range from 20 to 150 mm/min.

The constitutive equation of the material was obtained using a special apparatus, realized for superplastic testing [20]. It was composed of a conical die, a compressor, a proportional valve and a pressure transducer. The forming experiments were carried out at a constant pressure. The starting material was in the form of sheets 0.3 mm thick. The sheet evolution was analyzed using a video camera. The total number of experiments at constant pressure has been equal to 20. During each forming test the polar heights of the deformed specimens have been measured as a function of the processing time. As reported in [20] the experiments provide the stress versus strain rate. Fig. 2 show the constitutive equation obtained.

4. Results and discussions

In the numerical analysis, f varies from 0.999 to 0.99 and the predictions obtained at $f = 1$ are also considered. The effects of material parameters (K, m and n) and the specimen geometry were analyzed. The m value has been varied from 0.3 to 0.9 and n had the following values: 0, 0.05 and 0.1. The numerical results have shown that the strain localization phenomenon is independent from the K value and dependent from geometry of specimen. Fig. 3(a–c) shows the predicted limit strains at different m and $f (n = 0)$. It is shown that in both initial non-homogeneity factors, the predicted strain increases with increasing m. If a small value of initial non-homogeneity factor is assumed, the predicted limit strain decreases. The calculated limit strain–strain rate sensitivity index curves are listed in Table 1. This table show that the predicted strain increases with increasing n. Fig. 3(d) show the results extrapolated at $f = 1$.