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A finite element analysis of the superplastic forming of an aluminum alloy processed by ECAP

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Abstract

Finite element analysis (FEA) was used to simulate a superplastic forming operation for an aluminum alloy processed by equal-channel angular pressing (ECAP). An earlier report described the processing of an Al–3% Mg–0.2% Sc alloy by ECAP and the subsequent gas-forming of the as-pressed alloy into domes at 673 K using an unconstrained bulge test. The experiments provided detailed information on the uniaxial tensile behavior over a range of strain rates at 673 K and these stress–strain curves are now used to develop a constitutive relationship based on a strain hardening form of the power-law creep model. The FEA was performed by representing the aluminum disk as linear reduced integration continuum elements and incorporating adaptive remeshing. It is shown that, by assuming a reasonable value of 0.5 for the coefficient of friction between the disk and the clamps, the predicted superplastic forming of the disks is in good agreement with the experimental data for forming times of 30 and 60 s.

Keywords: Equal-channel angular pressing (ECAP); Finite element analysis (FEA); Forming; Modeling; Superplasticity

1. Introduction

Superplastic forming is a net-shape manufacturing process permitting the fabrication of complex shapes and curved surfaces using thin metal sheets. In practice, the sheet is heated to a temperature where diffusion becomes reasonably rapid and a gas pressure is applied so that the sheet is strained under conditions of superplastic flow. If the temperature and strain rate are selected for an optimum forming operation, the imposed strains may exceed 1000%. In practice, however, it is generally recognized that tensile strains up to ∼400% are sufficient for use in commercial superplastic forming operations [1,2].

There are several recent reports where finite element analysis (FEA) was used to simulate superplastic forming and to predict both the final shape of the product and any sheet thinning that may be caused by deviations from the optimal strain rate [3–11]. Many of these efforts are directed towards predicting the optimum forming conditions and using data from experiments to validate the accuracy of the FEA. However, all of these studies have simulated the forming in a die where the deformation is naturally constrained by an outer dome. Furthermore, although the finite element formulations are usually sophisticated, the constitutive models are generally rather simplistic because they are based on simple creep laws having single-value parameters which cannot successfully capture either the total evolution of strain and strain rate, or the gradients in strain and strain rate, during the deformation process. These limitations are inherent in the errors reported between the experimental data and the finite element predictions. In practice, these errors are typically ∼20% and they are often higher in the early stages of forming before the sheet reaches the point of contact with the constraining die.

The present approach was motivated by a recent demonstration of superplastic forming in an Al–3% Mg–0.2% Sc alloy after processing by equal-channel angular pressing (ECAP) [12]. The

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principles of ECAP are now well-established and the technique has become an accepted procedure for producing bulk materials with submicrometer grain sizes [13]. In the earlier work, a cast and solution-treated alloy was processed by ECAP and then small disks were cut from the as-pressed rods and inserted into a biaxial gas-pressure forming facility, heated to 673 K, and rapidly blow-formed into domes using an argon gas. This forming was undertaken as a free expansion without the use of a constraining die in the procedure often termed the bulge test [14]. These earlier experiments are unique in two respects. First, they provide the only direct evidence to date of the development of a superplastic forming capability through processing by ECAP. Second, the experimental results are fully documented and they provide detailed constitutive data in terms of the associated stress–strain behavior in tensile testing of the alloy at the forming temperature of 673 K.

The present research was motivated by the possibility of using these extensive results to develop a constitutive relationship defining the deformation of the alloy and to make use of this relationship in implementing a finite element model to simulate the experimental forming operation. Thus, rather than relying on single-valued parameters as in conventional FEA of superplastic forming, the constitutive model was designed to incorporate the entire strain hardening response of the alloy over the complete range of strain rates experienced during forming. The FEA was conducted using ABAQUS version 6.3 (ABAQUS Inc., Pawtucket, RI) and it is shown that the analytical predictions are in very good agreement with the experimental results. In addition, the analysis permits an examination of the influence of the value incorporated for the coefficient of friction between the disk and the clamps of the gas-forming facility.

2. Procedure

2.1. Superplastic forming of the Al–Mg–Sc alloy

A detailed description of the experiments on the Al–3 wt% Mg–0.2 wt% Sc alloy was given earlier [12]. Briefly, the alloy was produced by casting using high purity materials (99.99% Al, 99.9% Mg and 99.999% Sc), it was homogenized for 24 h at 753 K, cut into bars and swaged into rods with diameters of 10 mm, cut into billets having lengths of ∼60 mm and solution-treated for 1 h at 883 K. The initial grain size after solution treatment was ∼200 μm. The ECAP was conducted at room temperature using a die with an internal channel bent abruptly through an angle of 90° and with an angle of 45° at the outer arc of curvature where the two parts of the channel intersect. Each billet was pressed for a total of 8 passes, equivalent to an imposed strain of ∼8 [15], using processing route B_C where the billets are rotated about their longitudinal axes by 90° in the same sense between each pass [16]. Following ECAP, the microstructure consisted of a reasonably homogeneous array of equiaxed grains separated by boundaries having high angles of misorientation and with a measured grain size of ∼0.2 μm. Several investigations have demonstrated this alloy exhibits excellent superplastic properties in the as-pressed condition when testing in tension at high strain rates ($\geq 10^{-2}$ s^{-1}) [17–20].

Disks were cut from the billets perpendicular to their longitudinal axes with thicknesses of ∼0.3 mm. These disks were clamped around their peripheries in a steel die, heated to 673 K and then subjected to an argon gas pressure of 10 atmospheres for various times up to a maximum of 60 s. By statically annealing for 10 min at 673 K, it was shown that the grain size increases to an average size of ∼1.1 μm. Thus, these results demonstrate that, at a temperature of 673 K, the grain size of the alloy remains within the range generally associated with superplastic flow. The stress–strain behavior was examined by cutting tensile specimens oriented parallel to the pressing direction with gauge lengths of 5 mm and cross-sectional areas of 2 mm × 3 mm. These specimens were heated to 673 K, held at temperature for 10 min and then pulled to failure over a range of strain rates from 1.0×10^{-4} to 3.3 s^{-1}.

2.2. Procedure for the finite element analysis

The FEA was conducted by meshing one-half of the disk using an axisymmetric model with the plane of symmetry lying across the center of the disk. Linear reduced integration continuum elements were used to represent the aluminum disk and the upper and lower steel clamps of the die were represented as rigid surfaces. Sliding surfaces were introduced between the aluminum disk and the upper and lower clamps and these surfaces were modeled using an appropriate coefficient of friction. The experimental condition was matched by setting the outer diameter of the aluminum disc at 10 mm and the unrestricted and unclamped inner diameter at 7.0 mm: thus, this inner section was available for the forming operation. The sharp corners of the rigid surfaces of the clamps were given a very small radius of curvature, equal to 0.025 mm, to avoid any potential non-physical numerical difficulties in the contact algorithm: in practice, this radius of curvature was approximately equal to the radius of the experimental fixture. It should be noted that calculations showed the numerical solution was independent of this radius over a span of radii up to 2 times larger or smaller. A total of 1670 mesh elements was used in the calculation: a mesh sensitivity test indicated this mesh choice was conservative. To resolve the intense deformation occurring at the corners of the die caused by the sliding contact, a more refined mesh was established initially in the section in contact with, and in the immediate vicinity of, the die as shown in the view of the undeformed mesh in Fig. 1(a).

The simulation proceeded in two distinct steps.

In the first step, which simulated the initial room temperature clamping of the disc within the die, the lower die was raised until the gap between the two dies was equal to the initial disk thickness of 0.3 mm. It was found that the numerical solution at the end of this simulation was independent of the gap size over a span of gap sizes between 0.3 and 0.6 mm. The first step was solved using the explicit integration technique [21] with the incorporation of adaptive remeshing to capture the deformation in the region around the corners of the clamps. Because the clamping operation was quasi-static, successive trials were used to select a conservative speed for the lower die at which the inertial effects become negligible. In practical terms, the