RESEARCH ARTICLE | APRIL 19 2018

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AIP Conf. Proc. 1957, 050006 (2018)
https://doi.org/10.1063/1.5034336

Stability Analysis and Finite Element Simulations of Superplastic Forming in the Presence of Hydrostatic Pressure

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Abstract. It is established that some superplastic materials undergo significant cavitation during deformation. In this work, stability analysis for the superplastic copper based alloy Coronze-638 at 550 °C based on Hart's definition of stable plastic deformation and finite element simulations for the balanced biaxial loading case are carried out to study the effects of hydrostatic pressure on cavitation evolution during superplastic forming. The finite element results show that imposing hydrostatic pressure yields to a reduction in cavitation growth.

INTRODUCTION

Superplastic materials are a unique class of polycrystalline solids that have the ability to undergo very large uniform tensile ductility under certain operating conditions. Superplastic forming (SPF) is a metal forming technique that utilizes a certain class of alloys; mainly titanium, aluminum and magnesium alloys, to form components for different applications. Gas forming technique is considered the most common practice employed in forming superplastic materials where a sheet is formed onto a female die using an inert gas that is regulated at high pressure. Several researchers [1-8] investigated different aspects of the SPF process using computer simulations and experiments.

SPF offers many advantages over conventional forming operations, for example: low forming pressure, lower die cost, and greater design flexibility. However, the industrial use of SPF is still limited because of a number of issues such as low production rates and the limited understanding of the phenomenon of superplasticity. In addition, some superplastic materials such as Al 5083, Mg AZ31, Coronze-638 alloys exhibit significant amounts of cavities when deformed to large strains. Cavitation is the phenomenon of internal void formation, which generally occurs within metallic materials during secondary working and deformation. Cavitation growth is affected mainly by strain rate, temperature, and stress state. Varloteaux and Surey [9] have investigated the effects of annealing and hot isostatic hipping on components that already have internal voids. They have shown that annealing is effective in eliminating small voids only. In addition, hot isostatic hipping is expensive and there is a high possibility that voids reappear if heat treatment is conducted after isostatic hipping [10]. An effective method to restrict voids evolution during SPF is the application of hydrostatic pressure that superimposes compressive flow during deformation. This compressive flow is believed to restrict void growth.

Several researchers investigated the effect of superimposing hydrostatic pressure on cavitation evolution during SPF [11-14]. Pilling and Ridley [14] conducted a thorough investigation to examine the effects of hydrostatic pressure on the size of cavities and volume fraction of voids for three aluminum alloys. They concluded that cavitation growth highly depends on the biaxial stress ratio and superimposing hydrostatic pressure is effective in preventing void growth.

2018 6th International Conference on Nano and Materials Science
AIP Conf. Proc. 1957, 050006-1–050006-6; https://doi.org/10.1063/1.5034336
Published by AIP Publishing. 978-0-7354-1658-1/$30.00

The impact of varying hydrostatic pressure on cavitation evolution during deformation is studied in this paper. Stability analysis and finite element simulations are performed under various conditions in order to arrive at the hydrostatic pressure that guarantees minimal cavitation growth.

CONSTITUTIVE MODEL

For superplastic materials, the constitutive behaviour can be represented as follows [15-20]:

$$\dot{\varepsilon} = \frac{k}{d^p}\left[\frac{\sigma}{(1-f_a)}\right]^{1/m} \tag{1}$$

$$d = d_\circ + c\bar{\varepsilon} \tag{2}$$

$$f_a = f_{ao}\exp(\psi\bar{\varepsilon}) \tag{3}$$

$$\psi = \frac{3}{2}\left(\frac{m+1}{m}\right)\sinh\left[2\left(\frac{2-m}{2+m}\right)\left(\frac{\sigma_m}{\sigma}\right)\right] \tag{4}$$

where $\dot{\varepsilon}$ is the strain rate, σ is the flow stress, m is the strain rate sensitivity index, f_a is the area fraction of voids, d is the grain size, p is the grain size exponent and k and c are constants, $d_\circ$ is the initial grain size, $\bar{\varepsilon}$ is the strain, f_{ao} is the initial area fraction of voids, ψ is the void growth parameter, and σ_m is the mean stress.

The alloy used in this work is the copper based alloy Coronze CDA 638, with a composition of Cu-2.8%Al-1.8%Si-0.4%Co. The parameters used in the constitutive equations were determined by fitting the constitutive model to the experimental data obtained at a temperature of 550 °C by Caceres and Wilkinson [20]. Figure 1 [21] shows the stress strain rate curve for the fitted model versus the experimental data.

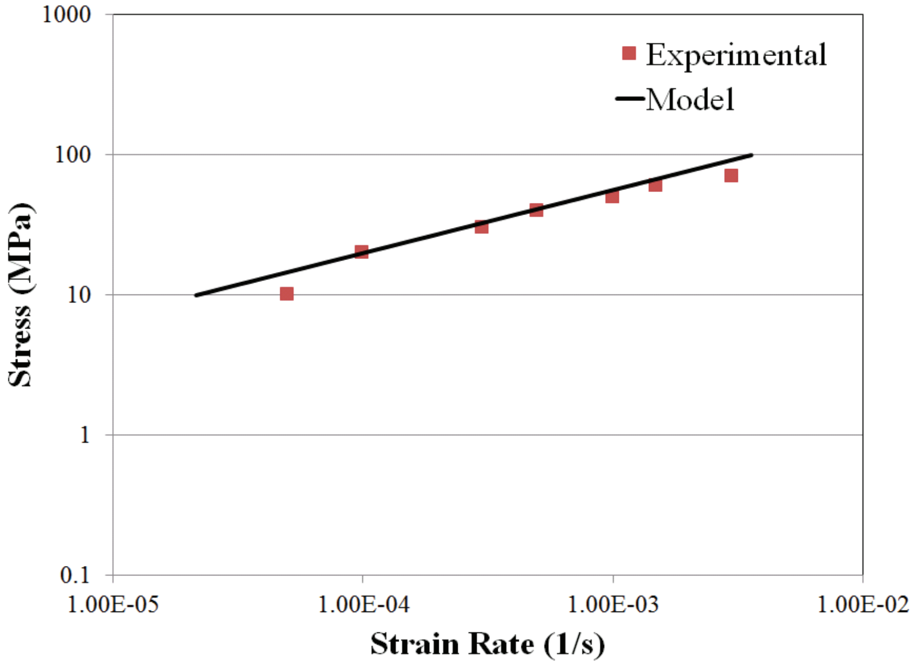

FIGURE 1. Model versus experimental stress strain rate curve for Coronze-638; experimental data was obtained from Caceres and Wilkinson [20].

STABILITY ANALYSIS

Thuramalla and Kharisheh [22] developed a stability criterion for biaxial loading taking into account microstructural evolution, strain rate sensitivity and cavitation. This stability criterion is based on the framework of Hart stability analysis for uniaxial loading. Hart defined the condition for stable deformation in a tensile test as follows [23]:

$$\frac{d\dot{A}}{dA} \leq 0 \tag{5}$$

where $d\dot{A}$ is the variation of the area increment rate and dA is the variation in cross sectional area of the tensile specimen. Note that Hart assumed stress as a function of strain and strain rate only in his work. The stability criterion devised by Hart for uniaxial loading is:

$$\gamma + m \geq 1 \tag{6}$$

where γ is the strain hardening exponent and m is the strain rate sensitivity index. The modified criterion by Thuramlla and Khraisheh has the following form [22]:

$$a\gamma' + m' + a\zeta = 1 \tag{7}$$

$$\gamma' = \frac{\dot{d}}{\dot{\bar{\varepsilon}}^{2}} \left(\frac{\partial \dot{\bar{\varepsilon}}}{\partial d} \right)_{\bar{\sigma}, f_a} \tag{8}$$

$$m' = \frac{\bar{\sigma}}{\dot{\bar{\varepsilon}}} \left(\frac{\partial \dot{\bar{\varepsilon}}}{\partial \bar{\sigma}} \right)_{d, f_a} \tag{9}$$

$$\zeta = \frac{\psi\, f_a}{\dot{\bar{\varepsilon}}} \left(\frac{\partial \dot{\bar{\varepsilon}}}{\partial f_a} \right)_{\bar{\sigma}, d} \tag{10}$$

$$a = \sqrt{\frac{4}{3}(1 + \rho + \rho^{2})} \tag{11}$$

$$\rho = \frac{\varepsilon_2}{\varepsilon_1} = \frac{\dot{\varepsilon}_2}{\dot{\varepsilon}_1} \tag{12}$$

The contribution of strain hardening, strain rate sensitivity, and cavitation are accounted for in the first, second and third term in equation (7); respectively. Note that ρ row is the biaxial ratio, ε_1 and ε_2 are the strains in two orthogonal directions.

DISCUSSION AND RESULTS

Based on a previous study by the author [21], it was shown that the cavitation evolution rate increases rapidly as the biaxial ratio increases. The balanced biaxial loading case ρ = 1.0 is studied in this work since it represents the worst case scenario. To study the effects of hydrostatic pressure on deformation stability, the term Normalized hydrostatic Pressure (NP) is introduced as: hydrostatic pressure /overall effective flow stress. Different values of NP are applied. These amounts are as follows: 0.0, 0.4, and 0.8.

Figure 2 shows the critical strain at different strain rates and NP values. Critical strain are calculated by solving numerically the stability equation (equation 7) after coupling it with the constitutive model (equations 1-4). It is concluded from this figure that as the normalized hydrostatic pressure increases, the critical strains increase as well. A value of (NP=0.8) yields to the maximum critical strain. This can be explained by examining equation 4. In this equation, it is seen that the void growth parameter depends on the ratio between the mean stress and effective stress. As hydrostatic pressure is applied, the mean stress decreases which yields to a low value for the void growth parameter.

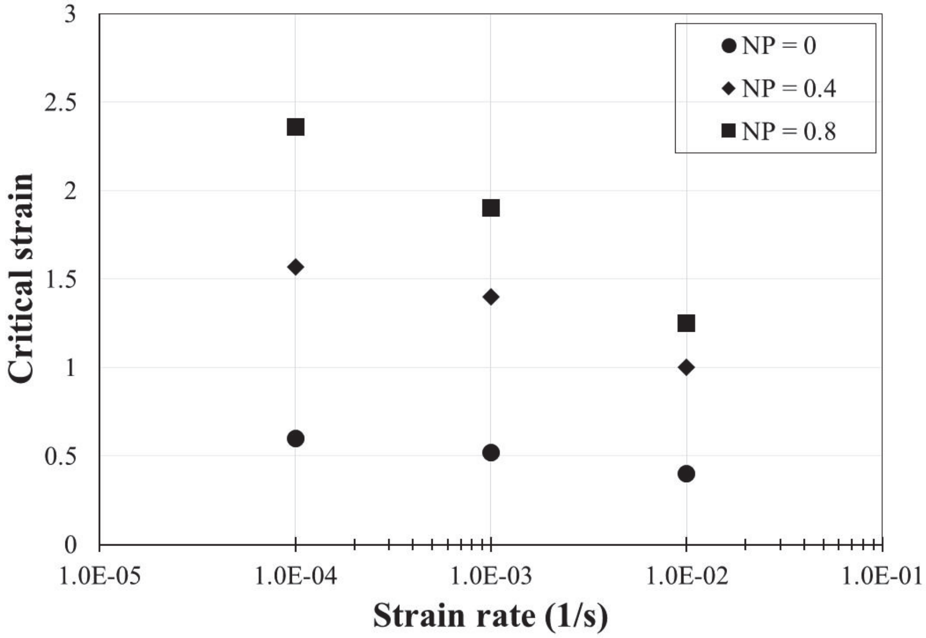

FIGURE 2. Critical strains for different strain rates at NP=0, NP=0.4, NP=0.8

Finite Element simulations for the free bulge forming of a dome (figure 3) made of Coronze-638 at 550 °C are conducted using the commercial FE code ABAQUS [24]. The free forming region of the die is 22 cm in diameter, and the initial sheet thickness is 1.8 mm. Due to symmetry, an axisymmetric FE model is used as shown in figure 3. Axisymmetric four-node bilinear continuum elements that can handle complex non-linear analysis are used to model the sheet. The die is modeled as a rigid body. The initial area fraction of voids is set to 0.01. For all simulations, the analysis is stopped when the dome height reaches 10 cm. A special user subroutine was composed using Fortran to implement the constitutive model in the FE code.

The loading pressure profile is generated using a built in algorithm [24] that adjusts the forming pressure based on the maximum strain rate in the formed sheet. In this case, the maximum strain rate is set to 0.0005 /s. The pressure profile for of NP=0.8 is shown in figure 4.

Figure 5 shows the final area fraction of voids distribution for two values of normalized hydrostatic pressure; NP=0.0, NP=0.8. It is concluded from this figure that a normalized hydrostatic pressure value of NP=0.8 is capable of preventing cavitation growth.

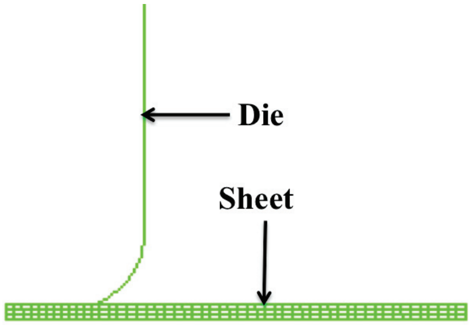

FIGURE 3. Finite Element model for the bulge forming process.

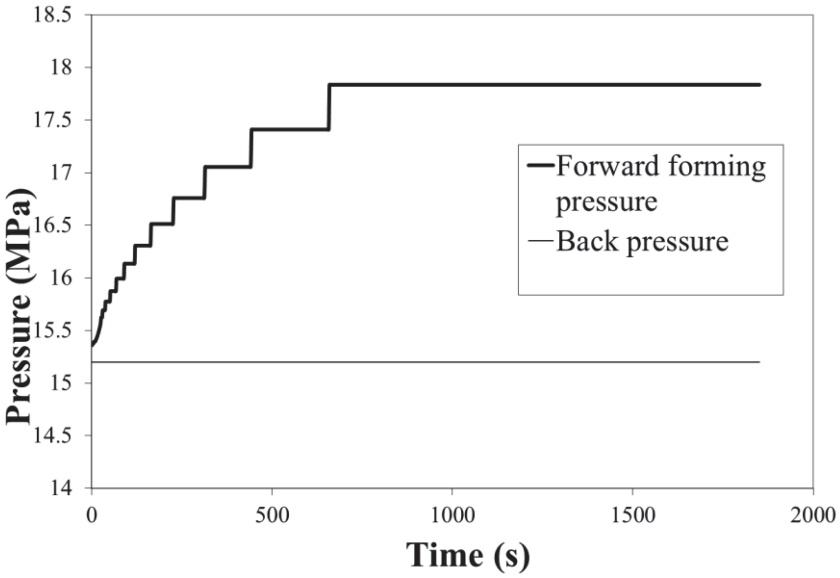

FIGURE 4. Forming pressure schedule for a normalized back pressure of NP = 0.8

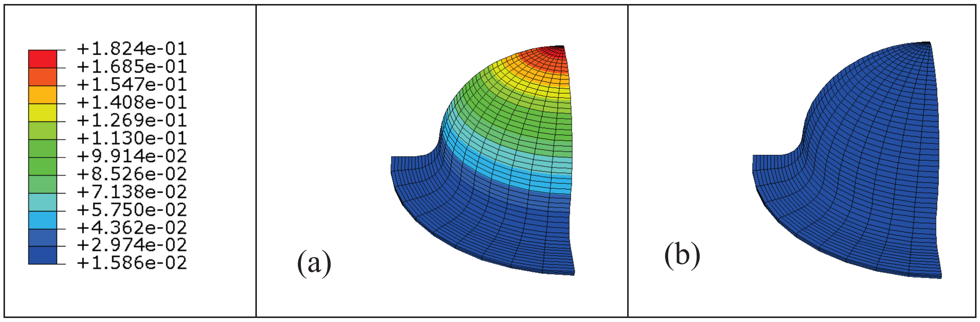

FIGURE 5. Final area fraction of voids for different values of normalized hydrostatic pressure. (a) Legend (a) NP=0.0, (b) NP=0.8

CONCLUSIONS

Stability analysis and FE simulations are conducted to study the effects of superimposing hydrostatic pressure on cavitation damage evolution during superplastic deformation. The stability and FE results demonstrate the effectiveness of hydrostatic pressure in preventing cavitation growth; which agree with the experimental results obtained in other investigations. The model will be extended to account for nucleation of cavities and mechanical contact conditions

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