SUPERPLASTIC DEFORMATION BEHAVIOR AND SUPERPLASTIC FORMING
OF Pb-Sn EUTECTIC ALLOY

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ABSTRACT

A series of load relaxation and tensile tests were conducted on Pb-62%Sn eutectic alloy at room temperature. The internal variable theory of structural superplasticity proposed recently was employed to analyze the results. The flow curves were shown to consist of the contributions from GBS and the plastic deformation. A new attempt to deduce the superplastic forming parameters from this theory has also been made, which makes it possible to introduce the nature of grain boundary sliding into the consideration of superplastic forming process quantitatively.

1. INTRODUCTION

Superplasticity is the deformation process that produces large, essentially neck-free, elongation of many hundred percents in crystalline materials usually deformed in tension at very low level of stress. Superplastic forming (SPF) process is widely accepted as an advanced manufacturing method in the aerospace industry. In general, superplastic properties are exhibited in materials having a stable, equiaxed, and extremely fine microstructure only under a very narrow range of strain rate and temperature normally above 0.5T_M, where T_M is absolute melting point. In this respect, the pressure-time loading cycle is one of the most important parameters in the SPF process to maintain the forming rate within the narrow strain rate range to assure superplastic deformation during the process. To construct a proper pressure-time cycle which can reduce the forming time to take a full advantage of superplastic forming process, it is necessary to determine the optimum value of strain rate \( \dot{\varepsilon} = \dot{\varepsilon}_{opt} \), which can be regarded as the upper limit of strain rates during the forming process\[1\]. The optimum strain rate \( \dot{\varepsilon}_{opt} \) has mostly been determined from the log \( \sigma \) vs. log \( \dot{\varepsilon} \) curves, obtained by conducting several step strain rate tests or a series of uniaxial tensile tests under a various strain rates on superplastic materials. It has been the general practice to select the optimum strain rate corresponding to the maximum value of strain rate sensitivity parameter \( m \).

This strain rate sensitivity parameter \( m \), the slope of the log \( \sigma \) vs. log \( \dot{\varepsilon} \) curve, has widely been used as one of the most important parameters characterizing superplastic deformation behavior. There is, however, no critical value of \( m \), above which superplastic deformation can be predicted\[2\]. This seems to originate from the fact that classical strain rate sensitivity parameter \( m \), is defined by using the two external variables, viz., the flow stress \( \sigma \) and strain rate \( \dot{\varepsilon} \). It is believed that a proper description of inelastic deformation is not possible only with the external variables\[3\]. A new
approach for inelastic deformation was, in this regard, made by utilizing internal deformation variables derived directly from a simple consideration of dislocation dynamics[3]. An extension of the theory to a structural superplasticity has also been made recently by taking the dislocation glide mechanism as the major accommodation process for GBS instead of the generally accepted high temperature diffusion process[4].

A series of load relaxation tests has been conducted at room temperature in this study. The load relaxation test provides the flow data in a much wider range of strain rates with minimal microstructural change to insure a constant microstructure during the test. The flow curves obtained from the load relaxation test results have consequently been analyzed for the flow behavior of Pb-Sn eutectic alloy based on the internal deformation theory described in detail elsewhere[3]. A new attempt to determine the optimum strain rate has also been made by the quantitative consideration of GBS and its accommodation process. Additional tensile tests were performed to verify the results of analysis.

2. INTERNAL DEFORMATION THEORY

A simple rheological model used in this analysis is given in Fig. 1 showing that the GBS is mainly accommodated by a dislocation process giving rise to an internal strain(\(\dot{\varepsilon}\)) and plastic strain rate(\(\dot{\varepsilon}\)). A more detailed description of \(\dot{\varepsilon}\) and \(\dot{\varepsilon}\) is given in the reference [3].

![Figure 1 - A rheological model representing the grain boundary sliding accommodated by grain matrix deformation.](image)

For the model given in Fig. 1, we have the following stress relation and kinematic relation among the deformation rate variables \(\dot{\varepsilon}\), \(\dot{\varepsilon}\), and the GBS rate \(\dot{\varepsilon}\).

\[
\varepsilon = \varepsilon^I + \varepsilon^F \\
\dot{\varepsilon} = \dot{\varepsilon} + \dot{\varepsilon} + \dot{\varepsilon}
\]

The internal stress variables \(\varepsilon^I\) and \(\varepsilon^F\) represent the internal stress required to overcome a long range interaction force among glide dislocations and the friction stress to surmount a short range interaction force between dislocations and lattices, respectively[5]. The time rate \(\dot{\varepsilon}\) denotes the materials time rate of change of internal strain tensor similar to that prescribed by Hart[5].

Since the room temperature test of Pb-Sn eutectic alloy corresponds to a high homologous temperature of about 0.65Tm, \(\varepsilon^F\) is in general very small compared to \(\varepsilon^I\) and \(\dot{\varepsilon}\) can be neglected if the relaxation test is performed uniaxially at a steady state. It is therefore sufficient to describe the constitutive relations for \(\dot{\varepsilon}\) and \(\dot{\varepsilon}\) elements of Fig. 1 at high temperatures. The constitutive relation between \(\varepsilon^I\) and \(\dot{\varepsilon}\) can be expressed in a form similar to that of Hart[5] as

\[
(\varepsilon^I/\dot{\varepsilon}) = \exp\left(\alpha^* \dot{\varepsilon}\right)
\]

\[
\dot{\varepsilon}^* = \frac{\mu}{\dot{\varepsilon}} \exp\left(-\frac{Q^I}{RT}\right)
\]

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