International Journal of Solids and Structures 96 (2016) 400–408

Contents lists available at ScienceDirect

International Journal of Solids and Structures

journal homepage: www.elsevier.com/locate/ijsolstr

Grain boundary compliance and ultrasonic velocities in pure copper undergoing intergranular creep

Colin M. Sayers[a,*], Masahiko Hirao[b], Tomohiro Morishita[c]

[a] Schlumberger, Houston, TX 77077, USA
[b] Graduate School of Engineering Science, Osaka University, Toyonaka, Osaka 560-8531, Japan
[c] Akashi National College of Technology, Akashi, Hyogo 674-8501, Japan

ARTICLE INFO

Article history:
Received 2 August 2015
Revised 18 April 2016
Available online 24 May 2016

Keywords:
Ultrasonics
Wave velocities
Copper
Creep
Damage
Porosity
Grain boundaries

ABSTRACT

Measured ultrasonic velocities decrease in pure copper samples subjected to intergranular creep while their anisotropy increases as creep progresses. Intergranular creep occurs at relatively high temperature and low stress, accompanied by damage caused by the nucleation and growth of voids on the grain boundaries. Subsequent coalescence of these voids leads to microcracking, and eventually macroscopic cracks occur. In this paper, we represent grain boundaries as imperfectly bonded interfaces, across which traction is continuous, but displacement may be discontinuous. We express the elastic anisotropy caused by the nucleation and growth of voids on the grain boundaries in terms of a second-rank and a fourth-rank tensor, which quantify the effect on elastic wave velocities of the orientation distribution as well as the normal and shear compliances of the grain boundaries. As a result, one may invert ultrasonic wave velocity measurements to obtain the components of these tensors. Application of this method to ultrasonic velocity measurements made on pure copper samples subjected to intergranular creep shows that a simple model using only the second-rank tensor reasonably agrees with the data, thus confirming the correctness of the underlying model. One can use deviations between the measurements and predictions of this simplified model to determine the ratio of normal to shear compliance of the grain boundaries, which are found to be more compliant in shear than in tension or compression.

1. Introduction

Creep may lead to fracture of structural materials used in high temperature applications. Nondestructive evaluation methods for assessing the remaining life of such materials are, therefore, of great interest. As creep proceeds, a number of microstructural processes may affect the velocities such as (i) changes in dislocations, (ii) the generation of creep voids (or cavities), (iii) precipitation of second phase particles such as carbides and intermetallic compounds, and (iv) modification of texture due to recrystallization and plastic deformation. A number of authors have used ultrasonics to estimate damage due to creep (Willems et al., 1987; Willems, 1987; Ledbetter et al., 1987; Birring et al., 1989; Hirao et al., 1990; Morishita and Hirao, 1997). These studies show that damage due to creep is characterized by a decrease in the wave velocity and an increase in the attenuation of ultrasonic waves.

In the case of intergranular creep, damage evolves from the nucleation and growth of voids on the grain boundaries (Hirao et al., 1990; Morishita and Hirao, 1997). These voids cause degradation of the material by lowering strength and increasing brittleness. Subsequent coalescence causes microcracking, and eventually macroscopic cracks occur. During this process, the density and effective elastic stiffness coefficients change, leading to a decrease in ultrasonic velocity. This decrease in velocity is observed to depend on the direction of propagation and polarization of the wave, resulting in anisotropy (Hirao et al., 1990). Morishita and Hirao (1997) proposed a damage model in which creep-induced voids are considered spherical and confined within oblate ellipsoidal volume elements. The distribution in orientation of these ellipsoids was represented by an orientation distribution function that was expanded in generalized Legendre polynomials, following Roe (1965). The coefficients in this expansion that yield agreement between the measured and calculated velocities are consistent with an axisymmetrical distribution of the minor axes of the ellipsoids around the stress direction, indicating progressive alignment of the ellipsoids' minor axes with the stress direction as creep progresses. However, photomicrographs shown by Hirao et al., (1990) from creep-damaged copper specimens at 600 °C and 7.4 MPa stress indicate the presence of damage at the grain

* Corresponding author. Tel.: +17136896012.
E-mail address: cmsayers@slb.com (C.M. Sayers).

http://dx.doi.org/10.1016/j.ijsolstr.2016.04.033
0020-7683/

boundaries, rather than in ellipsoidal volume elements as assumed by Morishita and Hirao (1997).

To treat the effects of damage at the grain boundaries on the elastic wave velocities, we present below a model in which the grain boundaries are represented as imperfectly bonded interfaces, across which traction is continuous, but displacement may be discontinuous. We then show that the elastic anisotropy caused by the nucleation and growth of voids at the grain boundaries can be represented in terms of a second-rank and a fourth-rank tensor that quantify the dependence of the elastic stiffness coefficients on the normal and shear compliances of the grain boundaries and their orientation distribution. The model allows ultrasonic wave velocity measurements to be inverted for the components of these tensors. Results from applying this model to the ultrasonic velocity measurements of Hirao et al. (1990) made on pure copper samples undergoing intergranular creep are presented next, followed by the conclusions of this work.

2. Data

The ultrasonic measurements used in this paper are from Morishita and Hirao (1997). These authors used pure copper specimens to avoid precipitation, and applied a stabilization annealing prior to creep tests in order to suppress the change of metallurgical structure. The specimens used were machined from a rolled plate, and are anisotropic in their initial state due to the presence of texture, i.e. preferred orientation of crystallites induced by rolling. In the tests, a tensile stress was applied parallel to the rolling direction. High temperature and low stress test conditions were chosen on the basis of the fracture mechanism map of Ashby et al. (1979) so that intergranular creep fracture occurs. The Cu specimens fractured with no visible evidence of plastic deformation, and contained very low dislocation density because of the annealing at 800°C, higher than the creep temperature, for 3 hours before machining and then further annealing at 550°C for 20 hours before the creep tests. As a result, dislocations and plastic deformation are not expected to contribute to the measured velocities. In general, dislocations have a greater influence on attenuation than on wave velocities. For example, similar pure Cu specimens have been subjected to cyclic loading at room temperature causing fatigue damage in them (Hirao et al., 2000). In these tests, the measured evolution of shear-wave velocity was limited to within 8% of the original velocity despite the quite high dislocation density. However, the attenuation coefficient showed as much as a five times larger value than that measured before being fatigued.

Morishita and Hirao (1997) found that creep voids cause transverse isotropy with the axis of rotational symmetry parallel to the stress axis. To determine the void volume fraction, Morishita and Hirao (1997) used the Archimedes method with 20 mm cubic specimens following Ratclife (1965). The measurement error was estimated to be less than 10^{-4}.

Photomicrographs from creep-damaged copper specimens at 500 °C and 6 MPa stress are shown in Fig. 1. The volume fraction of voids (black areas) caused by creep is 0.00106 for the specimen on the left and 0.020 for the specimen on the right. The damaged grain boundaries are seen to have a preferred orientation with normals in the direction of the applied stress.

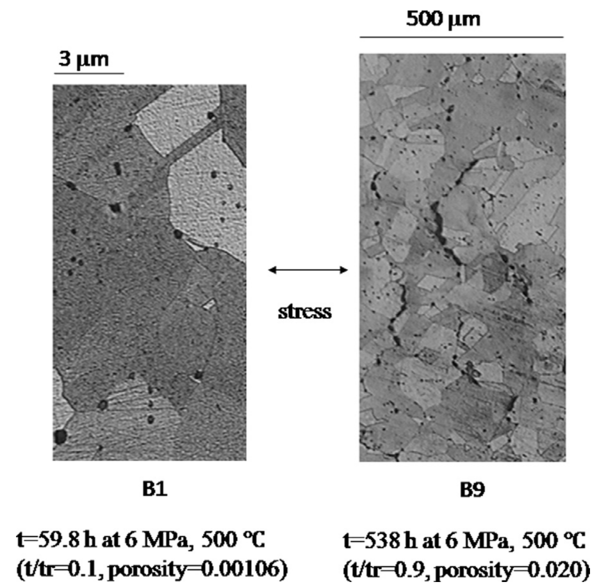

Fig. 1. Photomicrographs from creep-damaged copper specimens at 500 °C and 6 MPa stress. The double-headed arrow shows the direction of the applied stress, chosen as the x_3 direction in this paper. t is the time in hours that the specimen was exposed to stress, while t_r is the lifetime of the specimen at this level of stress. The black areas show the creep-induced voids.

3. Model description

In this section, we investigate the effects of damage at the grain boundaries on ultrasonic velocities by modeling the grain boundaries as imperfectly bonded interfaces, across which traction $\boldsymbol{t}$ is continuous, but displacement $\boldsymbol{u}$ may be discontinuous (Schoenberg 1980). It is convenient to denote the discontinuity in displacement across the grain boundary by $[\boldsymbol{u}]$. Assuming that $[\boldsymbol{u}]$ is linear in the traction, the ith component may be written as

$$[u_i] = B_{ij} t_j, \tag{1}$$

where t_j is the jth component of the traction vector, and B_{ij} is the grain boundary compliance matrix. If there is rotational symmetry around the normal to the grain boundary, it follows from Schoenberg (1980) and Kachanov (1992) that B_{ij} may be represented in terms of a normal compliance B_N and shear compliance B_T as follows:

$$B_{ij} = B_N n_i n_j + B_T \left(\delta_{ij} - n_i n_j\right), \tag{2}$$

where n_i is the ith component of the normal $\boldsymbol{n}$ to the grain boundary. Choosing a reference set of axes X_1, X_2, X_3 with X_3 normal to the grain boundary, Eq. (2) may be written (Schoenberg, 1980; Kachanov, 1992) as:

$$[u_3] = B_N t_3, [u_\alpha] = B_T t_\alpha, \text{ for } \alpha = 1 \text{ or } 2. \tag{3}$$

B_N gives the displacement discontinuity normal to the grain boundary for unit normal traction, while B_T gives the displacement discontinuity parallel to the grain boundary for unit shear traction. The normal and shear grain boundary compliances B_N and B_T will be used below to determine the change in ultrasonic wave velocities due to damage at the grain boundaries.

To treat the effect of the orientation distribution of grain boundaries, we use the Cartesian reference set of axes x_1, x_2, x_3, with axis x_3 in the direction of the applied stress, axis x_1 in the through thickness direction of the sample, and axis x_2 along the transverse direction. We denote the components of the elastic stiffness tensor of the samples by C_{ijkl} ($i, j, k, l = 1, 2, 3$) with units of [Pa], while we will denote the components of the elastic compliance tensor of the samples by S_{ijkl} with units of [Pa^{-1}].

In the presence of an orientation distribution of grain boundaries, the elastic compliance tensor may be written in the form (Sayers and Kachanov, 1991, 1995):

$$S_{ijkl} = S^0_{ijkl} + \Delta S_{ijkl}, \tag{4}$$

where S^0_{ijkl} is the elastic compliance tensor in the absence of creep-induced damage. S^0_{ijkl} is anisotropic for the samples of