Interaction of High-Temperature Deformation Mechanisms in a Magnesium Alloy with Mixed Fine and Coarse Grains

M.G. ZELIN, H.S. YANG, R.Z. VALIEV, and A.K. MUKHERJEE

High-temperature tensile tests have been conducted on a magnesium alloy (Mg-1.5 pct Mn-0.3 pct Ce) with randomly mixed fine and coarse grains. The microstructural examinations clearly show that different mechanisms operate in the regions of coarse and fine grains. The coarse grains deform by dislocation slip, while grain boundary sliding occurs in the fine grains. The influence of these mechanisms on each other has also been observed in terms of dislocation density, intragranular slip lines, and grain boundary sliding. The analytical equations describing the interaction of two deformation mechanisms operative in materials with regions of fine and coarse grains were derived. The analysis is applicable for determining the controlling mechanism of two interacting mechanisms. It is predicted that at a critical volume fraction of fine grains of approximately 40 pct, a transition from superplastic to nonsuperplastic behavior occurs.

I. INTRODUCTION

SUPERPLASTICITY (SP) of metallic materials requires a fine-grained structure (usually on the order of less than 10 μm) and deformation temperatures higher than 0.5Tm (Tm is the absolute melting point). However, the grain structure of commercial superplastic materials is usually nonuniform. The inhomogeneity of grain structure can be (1) of the scale of specimen dimensions, e.g., laminated composites, and (2) in the range of grain size, e.g., bands of fine and coarse grains, clusters of fine and coarse grains. It has been reported that regions of fine and coarse grains coexist, and the distributions of the grain size may change during superplastic deformation. However, it is difficult to describe the deformation behavior of such materials, although the deformation characteristics of materials with either fine-grained structure or coarse-grained structure have been well studied.

In this study, the deformation behavior of a magnesium alloy with randomly mixed fine- and coarse-grained structure was experimentally investigated and theoretically modeled. Besides the commercial significance of superplastically forming structural components, such an investigation is also important from the viewpoint of the interaction of deformation mechanisms operative within the fine- and coarse-grained regions.

II. EXPERIMENTAL PROCEDURE

A magnesium alloy with a composition of Mg-1.5 pct Mn-0.3 pct Ce (in weight percent) was used for this investigation. In the first step of specimen preparation, a fine-grained structure with a grain size of 10 ± 1.5 μm was produced by cold rolling, with a thickness reduction of 20 pct and subsequent annealing at 670 K for 40 minutes. Such fine-grained material showed SP at 670 K and a strain rate of 4 × 10⁻⁴ s⁻¹. The 100 pct coarse-grained structure with a grain size of 100 ± 8 μm could be obtained by cold prestraining a tensile specimen with the fine-grained structure up to a critical recrystallization strain of 3 pct and sequential annealing at 670 K for 40 minutes. The specimens tested in this investigation had a randomly mixed fine- and coarse-grained structure with varying volume fractions of the coarse grains (Vc/V = 0.0 to 1.0). This type of structure was produced by cold prestraining of the fine-grained material (~10 μm) up to 1.8 to 3 pct elongation and subsequent annealing at 670 K for 40 minutes. The higher the prestrain (up to 3 pct), the higher was the volume fraction of the coarse grains.

Mechanical tests were conducted on an Instron machine under conditions which are optimal for SP of the fine-grained material, i.e., a temperature of 670 K and a strain rate of 4 × 10⁻⁴ s⁻¹. Some specimens were electrolytically polished before testing for the study of deformation relief after testing. The polishing procedure has been given previously. Optical microstructural investigations were performed on the as-deformed specimens by using optical microscopy and a two-beam interferometer. Thin foils for use in the transmission electron microscope (TEM) were prepared by electropolishing with a solution of 30 pct orthophosphoric acid and 70 pct ethyl alcohol. The TEM study was carried out at an acceleration voltage of 120 KV.

III. RESULTS AND DISCUSSION

In this section, the result from the microstructural study is first presented and discussed with respect to deformation mechanisms. An analysis of the interaction between the deformation mechanisms operative in regions of fine and coarse grains is given subsequently.

A. Microstructural Study of the Deformed Samples

The grain rearrangements of the magnesium alloy with 50 pct coarse grains (Vc/V = 0.5) after tensile elongations of 5, 20, 40, and 60 pct are shown in Figure 1.

M.G. ZELIN, Postdoctoral Research Fellow, formerly Associate Professor with the Ufa Aviation Institute, H.S. YANG, Postdoctoral Research Fellow, and A.K. MUKHERJEE, Professor, are with the Department of Mechanical, Aeronautical and Materials Engineering, University of California–Davis, Davis, CA 95616-5294. R.Z. VALIEV, Professor, is with the Ufa Aviation Institute, Ufa 450025, Russia.

Several grains are numbered, as shown in Figure 1, for reference purposes. Fine grains (~10 µm) remained equiaxed after deformation. Grain boundary sliding is the main mechanism of deformation in fine-grained regions under optimum superplastic condition. The coarse grains deform by dislocation slip, as can be seen from the slip lines and the increase in the spacing measured in the tensile direction between the twins which are also present in microstructure. Interaction of the operative deformation mechanisms (grain boundary sliding and intragranular dislocation slip in the fine- and coarse-grained regions, respectively) occurred, which is discussed in detail as follows.

When fine grains and coarse grains coexist, the grain boundary sliding of fine grains can be affected by the presence of coarse grains. The deformation of the fine