CRACK NUCLEATION AND PROPAGATION DURING FATIGUE OF THIN METAL FILMS

O.Kraft[1,2], R. Schwaiger[1], G.P. Zhang[3], C.A. Volkert[1]
[1]Forschungszentrum Karlsruhe, Institut für Materialforschung II, Karlsruhe, Germany
[2]Universität Karlsruhe (TH), Institut für Zuverlässigkeit von Bauteilen und Systemen, Karlsruhe, Germany
[3]Shenyang National Laboratory for Materials Science, Institute of Metals Research, Shenyang, PR China

ABSTRACT

We have studied the fatigue behavior of pure Cu films with thicknesses between 200 nm and 3 µm. The fatigue damage has been investigated using scanning and transmission electron microscopy as well as focused ion beam microscopy, and consists of extrusions, voids, and cracks in the plane of the film. It has been found that the details of the damage behavior depend sensitively on film thickness and grain size. Delamination of the films has not been observed. At the end of the fatigue experiments, intergranular cracks are found, which form a network over the entire film area. Particular attention has been paid to the mechanism that leads to the formation of the cracks. With the exception of the thinnest films, voids are found near to or at the interface to the substrate. These voids are usually related to extrusions, which form at the surface of the films right above the void. It is believed that cracking occurs when these voids have grown to a critical size.

1 INTRODUCTION

It is well known that large residual stresses in thin films may lead to crack formation, so-called channel cracks, in the plane of a film, and/or to delamination of the film from its substrate. These phenomena are particularly important for brittle films, for which fracture mechanics treatments have been developed over the past decade (for review, see e.g. [1]). For ductile metal films on stiff substrates, channel cracking is typically not observed since growth or thermal strains are usually not large enough to reach the threshold stress required for crack formation. More recently, it has been shown that cracking of metal films on compliant substrates only occurs, when large strains (> 10%) are reached, and the film delaminates locally from the substrate. In our work, we have concentrated on damage formation in metal films on compliant substrates under cyclic loading conditions with typical strain ranges between 0.1% (high cycle fatigue HCF) and 1% (low cycle fatigue LCF). In contrast to monotonic loading, these cyclical strains are large enough to produce cracking.

2 EXPERIMENTS

We have developed a method to characterize the fatigue behavior of thin metal films on an elastic substrate [2]. During loading cycles of the film/substrate composite, the substrate material is deformed elastically while the film may undergo plastic deformation in both tension and compression. Owing to this sample structure, the film stress cannot be determined from the externally applied load. However, the stress-strain behavior of the films has been analyzed for several samples using in-situ X-ray diffraction during straining of the samples [3]. The fatigue tests were analyzed in terms of lifetime by recording the mechanical energy loss per cycle, which is associated to the work of plastic deformation in the thin film and decreases significantly when the film is fatigued. Details of the sample preparation have been described elsewhere [4, 5]. After testing, the samples were investigated using various techniques, including optical microscopy, scanning, and transmission electron microscopy (SEM, TEM) as well as focused ion beam microscopy (FIB) [5, 6].

3 RESULTS AND DISCUSSION

As a typical example, Fig. 1 shows fatigue damage in a 3 µm thick Cu film with a mean grain size of approximately 1 µm. It is observed that particular grains, which are larger than the average grain size, form extrusions (marked by A) growing out of the plane of the film during cyclic loading. Cracks have also formed in the film (B), which are primarily located at grain boundaries and form a network over the entire film area.

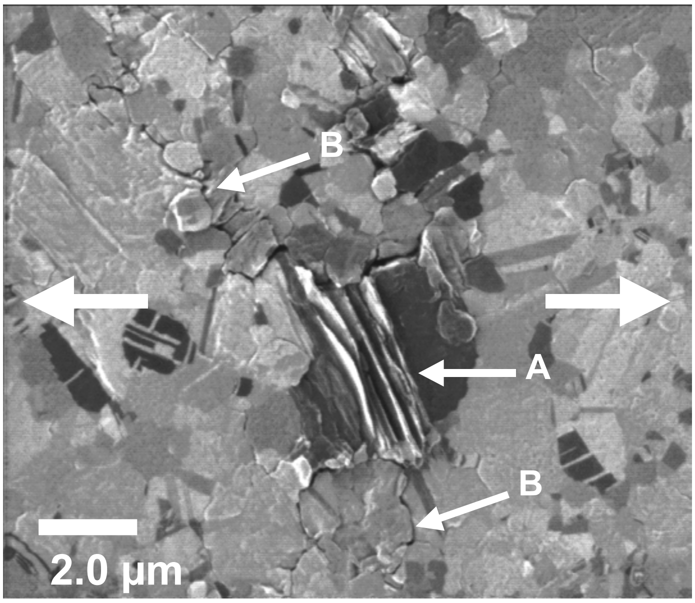

Fig. 1: FIB planview micrograph of a 3 µm thick Cu film after a fatigue experiment with a total strain range of about 1% showing an extrusion (A) and cracks (B). The loading direction was horizontal.

Figure 2 shows a cross-section prepared by FIB through an extrusion. It is seen that the typical extrusion height is of the order of the film thickness, in this example, about 1 µm height in a 3 µm thick film. Opposite to the extrusion at the surface, voids have been formed at the interface to substrate. It has been argued that the damage sequence includes voiding at the interface, crack nucleation from these voids, and crack extension towards the film surface and across the grain [4, 5]. The voids are believed to form from the accumulation of vacancies that are created by dislocation interactions.

Quite recently, a study on the effect of length scale (both film thickness and grain size) on fatigue-induced damage morphology in Cu films revealed that the dimensions of the fatigue extrusions decreased with decreasing film thickness from 3.0 µm to 400 nm and that the characteristic dislocation structures, such as those found in bulk fatigued metals, were only found in the largest grains of the 3.0 µm thick film [5, 6]. In contrast, only individual dislocations were observed in films thinner than 1 µm. This is illustrated in Fig. 3, which shows a plan-view micrograph of a damaged grain in a 400 nm thick film.

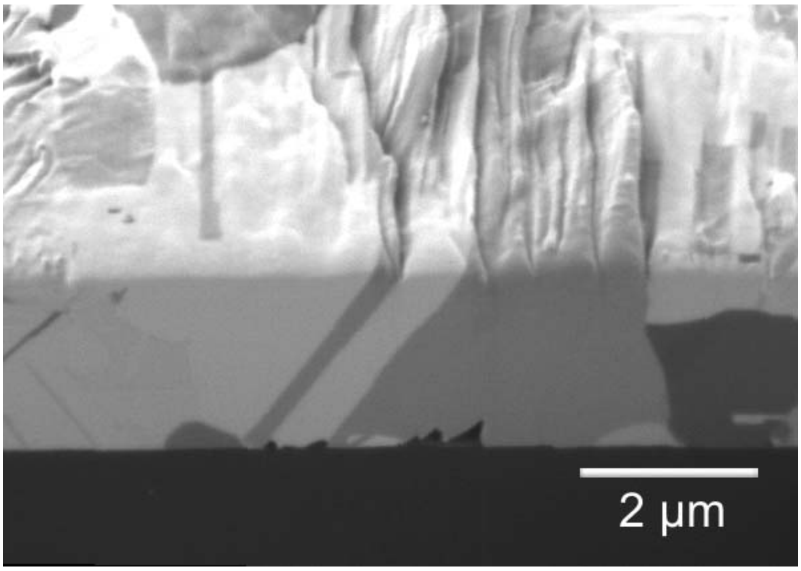

Fig. 2: FIB cross-sectional micrograph of a 3 µm thick Cu film after a fatigue experiment with a total strain range of about 1% showing an extrusion at the surface and voiding near the interface. The loading direction was horizontal.

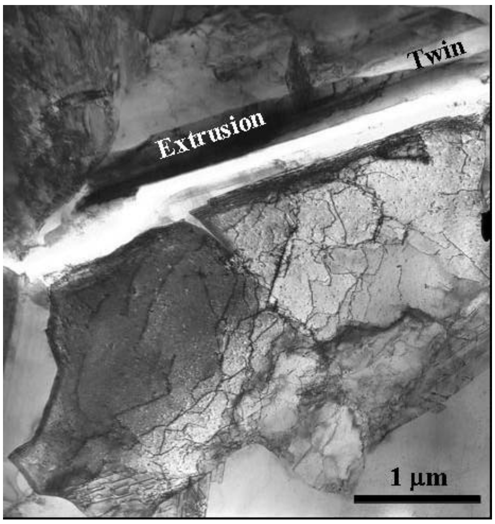

Fig. 3: TEM micrograph of a 400 nm thick Cu film after a fatigue experiment with a total strain range of about 1% showing an extrusion at the surface and crack extending across the entire grain (from [6]).

For geometrical reasons, decreased film thickness makes the interaction of dislocations less likely. In addition, the formation of characteristic dislocation structures is suppressed by the fact that the length scales in the 400 nm thick film are smaller than the characteristic spacing in typical dislocation structures in Cu, such as persistent slip bands (1.3 µm [7]) or dislocation cells (500 nm [8]). Current work addresses a better understanding of the voiding process, which is likely to be related to the annihilation of dislocation dipoles. Instead of forming heterogeneous dislocation structures, a more homogenous dislocation distribution is observed in the thinner films. It can be argued that a smaller number of dislocation dipoles with sufficiently small spacing for annihilation are formed in small dimensions. As a result, less point defects are expected to be created per cycle and smaller and fewer extrusions are formed in the thin films. Instead, the dislocations interact directly with the boundaries. As a result of the increased dislocation interactions with boundaries, and possible elastic incompatibilities between grains, the boundaries become the preferred sites for damage processes in thin films [9]. For a deeper understanding of these mechanisms, a more detailed investigation of the influence of film thickness in the regime of 50 to 500 nm on the fatigue mechanisms is currently being performed.

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