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Fatigue crack closure in submicron-thick freestanding copper films

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ABSTRACT

The fatigue crack closure in approximately 500-nm-thick freestanding copper films were investigated by in situ field emission scanning electron microscope (FESEM) observations of the fatigue crack opening/closing behavior at three stress ratios of R=0.1, 0.5, and 0.8 in the low-K_{max} (maximum stress intensity factor) region of K_{max} < 4.5 MPam$^{1/2}$. The direct observation of fatigue cracks clarified that crack closure occurred at R=0.1 and 0.5, while the fatigue crack was always open at R=0.8. Changes in the gage distance across the fatigue crack during a fatigue cycle were measured from the FESEM images, and the crack opening stress intensity factor K_{op} was evaluated on the basis of the stress intensity factor K vs. the gage distance relationship. The effective stress intensity factor range $\Delta K_{eff}=K_{max}-K_{op}$ was then evaluated. The R-dependence of the da/dN vs. ΔK_{eff} relationship was smaller than that of the da/dN vs. ΔK relationship. This suggests that ΔK_{eff} is a dominating parameter rather than ΔK in the fatigue crack propagation in the films. This paper is the first report on the presence of the fatigue crack closure in submicron-thick freestanding metallic films.

1. Introduction

The fatigue crack propagation rate (da/dN) in bulk metals is generally characterized by the stress intensity factor range ΔK. In most metallic materials, however, the fatigue crack propagation properties (da/dN vs. ΔK relation) depend on the stress ratio (R) particularly in the near-threshold region. A contributory cause of the R-dependence is considered to be crack closure [1,2]. The existence of crack closure has been clarified experimentally [3–14] and numerically [15–21] by many researchers. Proposed possible mechanisms of crack closure include plasticity-induced crack closure [1,2,15,19,20], roughness-induced crack closure [6,12,14,21], and oxide-induced crack closure, including corrosion product-induced crack closure [4,5,7,9,11]. The R-dependence in fatigue crack propagation has been reasonably explained by using the effective stress intensity factor range ΔK_{eff} that takes the crack closure into account: i.e., da/dN in the materials with the same Young's modulus uniquely correlates with ΔK_{eff} regardless of R [2,3,8–14,22–24].

On the other hand, the fatigue of submicron-thick metallic films has not yet been fully clarified. Although several studies have been conducted on the fatigue in metallic thin films fixed on substrates [25–32] and freestanding films [33–36], fatigue crack propagation of freestanding submicron-thick films have rarely been studied [37–39]. Thin films have a structure with a large surface area to volume ratio, and those formed by physical vapor deposition generally consist of fine columnar grains. Due to these structural differences, the fatigue crack propagation properties of submicron-thick films differ from those of their bulk counterparts.

In a previous study, the authors investigated the fatigue crack propagation properties of approximately 500-nm-thick freestanding copper (Cu) films [39]. In the high-K_{max} region (maximum stress intensity factor $K_{max} \geq 4.5$ MPam$^{1/2}$), the fatigue crack propagated by tensile fracture mode accompanied by a necking deformation in the thickness direction irrespective of R, and da/dN was dominated by K_{max}. In contrast, in the low-K_{max} region (K_{max} < 4.5 MPam$^{1/2}$), we identified a characteristic mechanism of fatigue crack propagation at stress ratios of R=0.1 and 0.5: intrusions and extrusions projecting in the out-of-plane directions formed ahead of the crack tip, and the fatigue crack then propagated preferentially through these intrusions/extrusions. This result suggests that the formation of intrusions/extrusions plays a major role in fatigue crack propagation in submicron-thick films. This is due to the geometric structure of the films: once intrusions/extrusions are formed on the surface, a fracture readily occurs in the thickness direction due to the thinness of the film. At a higher stress ratio of R=0.8 in the low-K_{max} region, the fatigue crack propagated in the tensile fracture mode similar in the high-K_{max} region. It is notable that although the fatigue crack propagated by the same mechanism at R=0.1 and 0.5 in the low-K_{max} region, da/dN against ΔK at R=0.5 was higher than that at R=0.1. This R-

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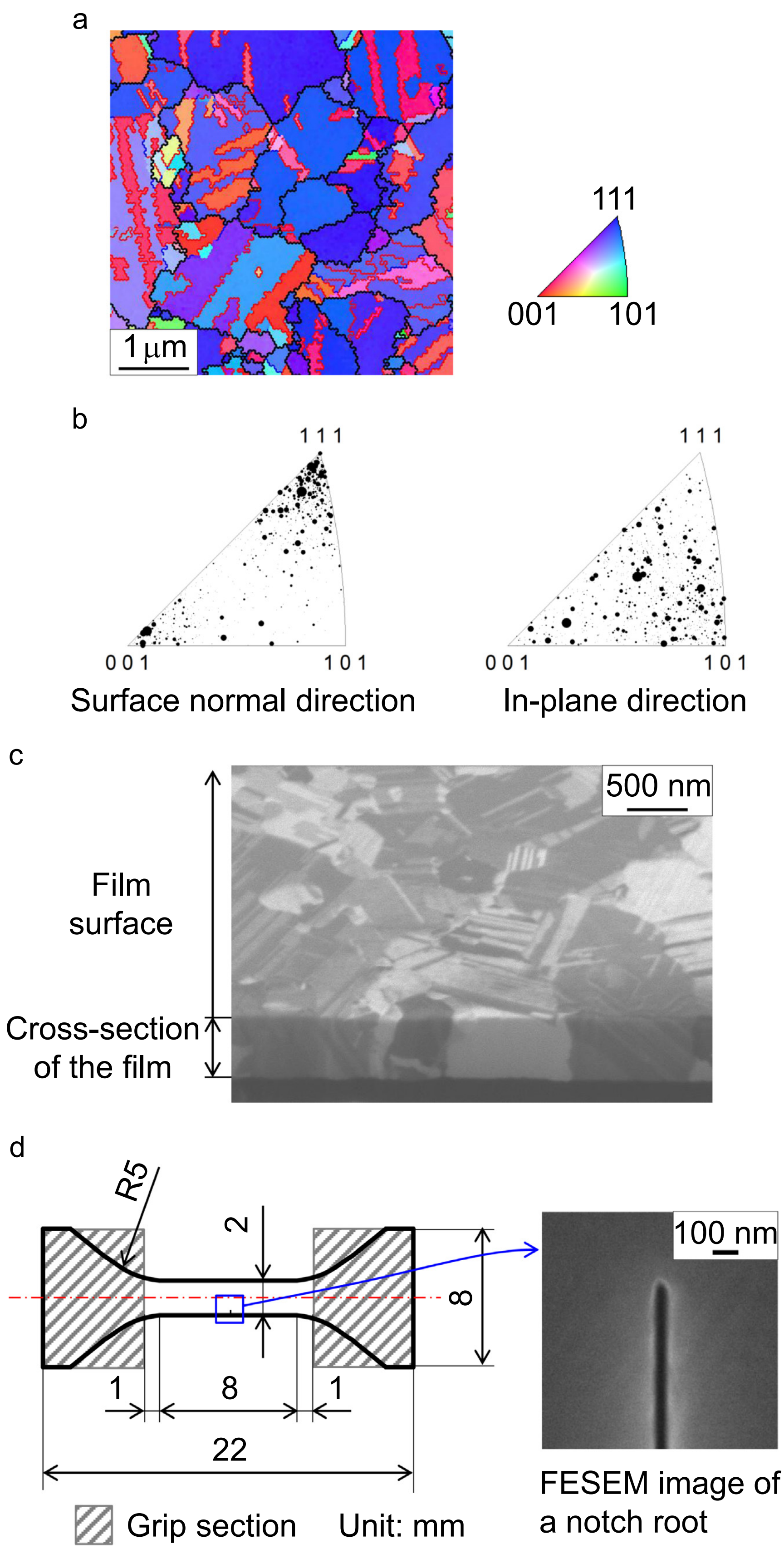

Fig. 1. Microstructure of a tested Cu film and specimen shape used in fatigue crack propagation experiments. (a) Microstructure of a film surface (black lines: grain boundaries, red lines: Σ3 twin boundaries, blue lines: Σ9 twin boundaries). (b) Crystal orientation distribution in a surface normal direction and an in-plane direction of the film. Size of the black dots is proportional to the grain size. (c) Scanning ion microscope image of the cross-section and film surface of the Cu film observed at an angle of 52° from the surface normal direction. (d) Shape and dimensions of specimens.