FATIGUE THRESHOLD BEHAVIOR OF THIN METALLIC FOILS

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The fatigue crack growth and threshold behavior of Cu foils with thicknesses ranging between 20 and 100 μm was investigated. A special test technique was developed for the determination of fatigue crack growth data. The threshold data were determined by a load shedding technique and found to range between 2.5 and 5 MPa.m1/2 depending on the ratio of grain size to foil thickness. To reveal the global dislocation arrangement near the fatigue crack the electron channeling contrast imaging technique was applied.

INTRODUCTION

Thin foils, sheets or wires of metallic, semiconducting or non-metallic materials resemble essential parts of microelectronic and micro-electro-mechanical systems. These parts are often subjected to cyclic straining due to mechanical vibrations or temperature fluctuations which may cause premature failure of the devices.

Since such failures may result in considerable economic losses, the fatigue behavior of thin foils and wires is of considerable technical interest. Little information on the load response of foils is available. A deduction of properties (elastic constants, monotonic and cyclic loading response) from those of bulk materials appears difficult due to the two-dimensional nature of the parts. Ilschner et al. (1) conducted fatigue life tests of Cu-foils (20 and 100 μm thickness) under tension-tension loading. For these experiments the investigators had designed an elaborate testing system. A significant increase in fatigue life with decreasing thickness was reported. These observations were interpreted by the fact that the thinner specimens were almost free of extrusions and may have lost most of the dislocations due to the short migration distance to the free surface and the effects of

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image forces. In contrast, Hong and Weil (2) investigated the cyclic stress strain behavior under low cycle fatigue conditions of Cu-foils and reported only a minor effect of thickness on fatigue life.

In electro-deposited Cu foils with high dislocation densities the authors found no dislocation cells when the grain size was smaller than 2 µm. Sharpe (3) performed tension-tension fatigue tests with polycrystalline Si of 3.5 µm thickness and reported the absence of plastic deformation up to the breaking load.

No information on fatigue crack growth and threshold behavior in free-standing thin foils are available. Therefore, the objective of present investigation was to develop a suitable testing method to investigate the crack growth behavior of thin Cu foils, and to compare the results with experimental data from bulk material.

EXPERIMENTAL DETAILS

The specimen material consisted of commercial rolled Cu foils in a soft-annealed condition with a nominal purity of 99.9 %, ranging in thickness between 8 and 100 um. For comparison, bulk material in form of rolled strips of 5 mm thickness of commercial E-Cu were used. The materials were tested in the as-received condition and after various recrystallization heat treatments in a vacuum of better than 5.10^{-3} Pa (600°C/3h and 850°C/6h). The grain sizes as determined by the linear intercept method varied between 10 and 200 µm depending on the heat treatment.

The mechanical properties under monotonic loading were determined with a micro-tensile test equipment and a non-contacting laser-speckle strain sensor (4). For the cyclic tests the specimens were attached to a supporting specimen holder and subjected to cyclic loading either in a standard fatigue test equipment or in a resonance fatigue test system. The specimen set up is shown schematically in Fig.1. The end portions of the specimens were attached to a properly shaped supporting holder with a strain-gauge type adhesive, leaving a free-standing middle zone of approximately 4 mm width. The strain of the foil was calibrated with miniature strain gauges against the signal of a strain gauge on the narrow side of the specimen holder. For the reported experiments the specimen holder was excited to longitudinal resonance vibrations in a 20 kHz resonance fatigue test equipment (5). In this testing mode the specimen is subjected to displacement controlled symmetric loading ($R = -1$). A small starting notch was introduced in the mid-section of the foil by electro-discharge machining. The crack growth behavior was monitored and measured continuously with a computer-controlled travelling light microscope and data acquisition system (6). For these tests crack growth rates in the range between 10^{-10} and 10^{-13} m/cycle were evaluated. With this test system the threshold value for fatigue crack growth was determined by a load shedding technique and fatigue crack growth curves as function of loading cycles were obtained for constant-strain amplitude loading. The microstructural changes in the vicinity of the fatigue crack were investigated intermittently in a scanning electron microscope using the electron-channeling contrast method (7) to reveal changes in the global dislocation arrangement.

EXPERIMENTAL RESULTS AND DISCUSSION

Fatigue crack growth (a-N) curves for foil-specimens of three selected thicknesses and one bulk sample are shown in Fig. 2. The grain sizes of the foil specimens as indicated in this figure are comparable with the thickness of the foils. In contrast to the smooth crack growth curve of the bulk material the fatigue crack growth curves in the near-threshold regime of the thin foils is considerably irregular. From these data and da/dN-a curves similar interactions with grain boundaries were observed, as are known for short fatigue cracks in bulk materials (8). The stress values indicated in Fig.2 were computed from the calibrated strain data and the Young's modulus of Cu (assumed to be 126 GPa). The a-N curve of the bulk specimen (5mm thickness) shows the usual crack growth behavior for a center-notched specimen under constant load conditions. In contrast, the a-N curves of the thin-foil specimens appear to approach a saturation value which may be due to the loading condition essentially under displacement control.

TABLE 1 - Summary of fatigue threshold values of Cu foils with various thicknesses (accuracy of ΔK_{th} ± 5%)

Foil thickness (μm)	Heat treatment	Grain size (μm)	ΔK_{th}[MPa.m$^{1/2}$]
20	as received	cold worked	3,8
20	600°/3h	10-20	2,6
20	850°/6h	40	3
50	as received	10-20	2,5
78	as received	10-20	2,9
100	as received	20-30	4,6
100	850°/6h	180	4,8
bulk	annealed	20-30	2,6

A summary of the experimental results is given in Table 1. Threshold values were computed by using the standard LEFM- relations for plane stress conditions for a through crack (9). We consider these values only as a rough approximation, not taking into account the effects of the displacement controlled test procedure. A detailed analysis will be given elsewhere (10). For a foil of 20 μm thickness an increase in grain size (by annealing) resulted in an increase of the threshold value. A similar effect was observed for the 50 and 100 μm foils. The comparatively higher threshold value for the 100 μm foils may be due to an inhomogeneous grain size distribution and texture effects in the as-received material. Furthermore, the threshold value of foils containing grains with a high amount of deformation were higher. In general the results indicate that the threshold values increase when the grain sizes become larger than the thickness, i.e. the foil consisted of single grains across its thickness.

The thin foil specimens were evaluated in the as-received condition, after crack growth experiments, and after a subsquent electropolishing step to remove the topography effects resulting from the cyclic deformation. Typical SEM-ECC micrographs of a coarse grain foil of 100 µm thickness are shown in Fig.3 and Fig.4. These figures can be related to positions on the a-N curve marked in Fig.2. Figure 3 shows the tip of the fatigue crack at the threshold position. The interaction of the strain field at the tip of the crack with a twin boundary can be seen from the change in channeling contrast. The plastic zone around the fatigue crack is small, the adjacent grain contains a typical vein structure with persistent slip bands. At several positions along the crack path locations can be recognized at which the crack growth was considerably retarded, always associated with a plastically deformed region at grain boundaries. The composite Figure 4 is from a region closer to the starting notch as also indicated in Fig.2. This micrograph shows a region around the crack of approximately 20 µm width with a fine cell structure (<1um), further away from the crack most of the grains, exhibit a vein structure with persistent slip bands, frequently ending within the grain. From the observed microstructures the local cyclic plastic strain values may be deduced, i.e. at the edge of the cell region the plastic strain should have reached values of $\varepsilon_{pl} > 6\times10^{-4}$, the region containing persistent slip bands correspond to plastic strains of $6\times10^{-4} > \varepsilon_{pl} > 10^{-5}$ (7).

SUMMARY

A test method was developed which permits measurements of the fatigue crack growth and threshold behavior of thin foil materials. With this test set-up the near-threshold crack growth behavior of Cu foils of thicknesses between 20 and 100 µm was investigated. A characteristic a-N and threshold behavior was found to depend on the ratio foil thickness to grain size. The dislocation arrangements could be related to the crack growth rates and indicated strong interactions of the crack front with grain and twin boundaries. Furthermore, from the observed dislocation arrangement the magnitude of the plastic strain in the vicinity of the crack could be estimated. Based on this preliminary experience we consider the test method suited for the evaluation of various two-dimensional materials systems.

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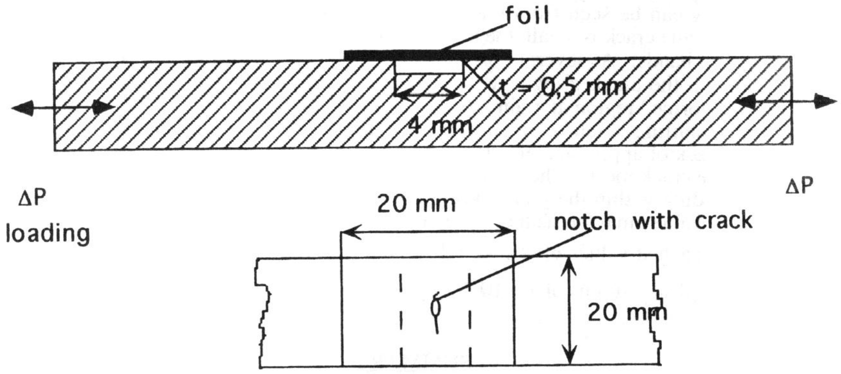

Figure 1 Specimen assembly, thin foil specimen attached to the supporting specimen holder, schematic

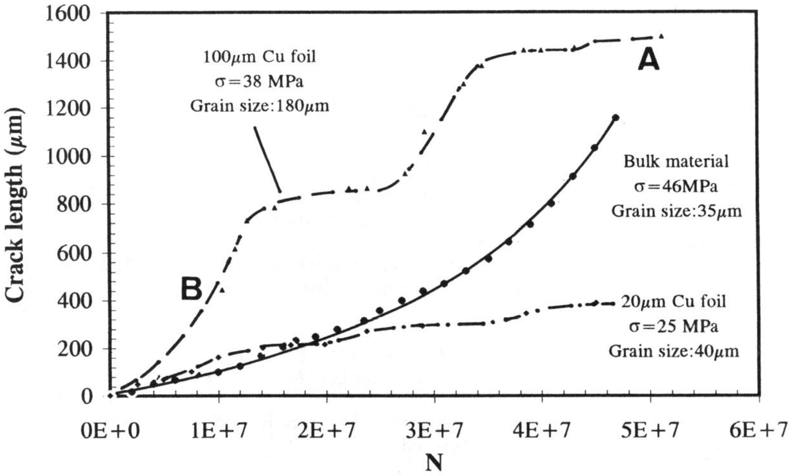

Figure 2 Crack length as function of number of loading cycles, Cu-foils of various thicknesses and grain sizes

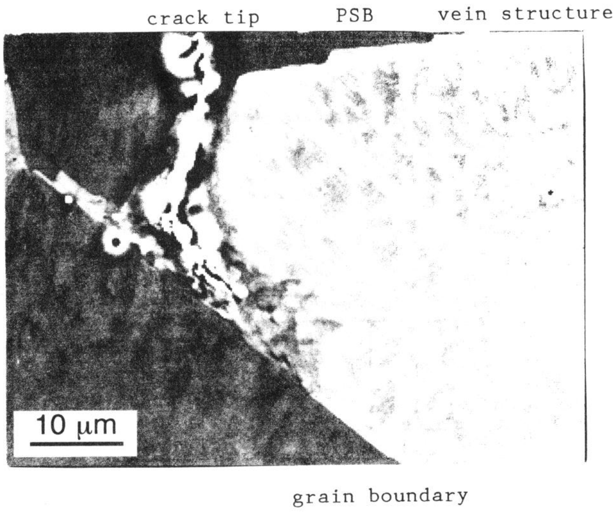

Figure 3 Tip of the fatigue crack at threshold position in Cu-foil of 100 μm thickness (Position A in Fig. 2), SEM-ECC micrograph

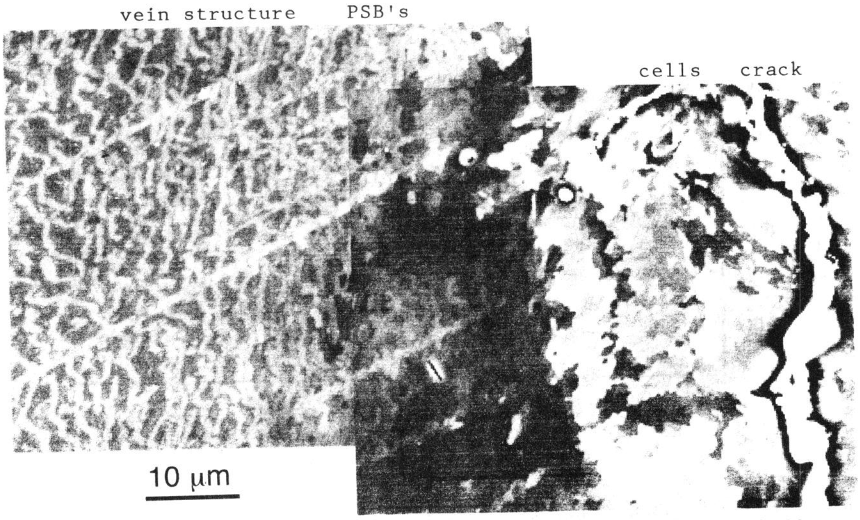

Figure 4 Dislocation arrangement in vicinity of the fatigue crack in Cu-foil of 100 μm thickness (Position B in Fig. 2)