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Technical note

Variation of monotonic strain in copper thin films during fatigue testing

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ABSTRACT

The plastic deformation behavior is important to evaluate the fatigue damage of copper thin films. In spite of the importance of the deformation behavior of thin films with load cycling, there is no trial to measure the strain directly on the surface during fatigue testing because of difficulties in measuring the strain.

In this study, the monotonic strain of copper films of 12 μm thickness during fatigue testing was measured by using the DIC method. The DIC method provides full field deformation of the specimen with high precision, and can directly measure the strain of the gauge section without any assumption. With increasing number of cycles, the monotonic strain increases similarly to the conventional creep curve, and the fluctuations of the strain on the specimen surface seriously increases and the increase in the fluctuation range is very large compared to that in the mean strain due to the roughness of the specimen.

1. Introduction

Among various techniques to measure mechanical properties of thin film materials [1–6], tensile testing has the advantage that stress distribution across the cross section of the specimen is uniform so that mechanical properties can be obtained simply without any assumption. One of the most difficult problems in tensile testing of thin film materials is measuring strain because contact measurement methods such as the extenso-meter and strain gauge, which are generally used for bulk materials, cannot be used. Various techniques have been developed and adapted to measure the strain of thin film materials during tensile testing. Optical methods such as laser interferometry strain/displacement gauge (ISDG) [6] and the digital image correlation (DIC) method [7,8] are widely used for thin film materials. The resolution of these methods is so high that precise measurement of strain is possible even for a micro specimen. Another important advantage is that the strain of a specimen can be calculated directly from the deformation of the gauge section.

On the other hand, only a few reports on fatigue properties of thin film materials are available [9–16], mainly due to difficulties in performing fatigue testing and measuring deformation. Recently, Sharpe developed the dynamic ISDG [9,10] which uses a photomultiplier tube instead of linear diode arrays to record the fringe pattern, and used the gauge for very high-cycle fatigue tests at a high frequency (20 kHz) [9] and low-cycle fatigue tests of micro-specimens [10]. The ISDG requires two reflective markers on the specimen surface to reflect laser beam, and the markers are made by micro Vickers or a focused ion beam. The DIC method can measure the full field deformation of the specimen with high precision. However, the frame rate of the CCD camera is generally too low to apply the DIC method to fatigue testing. Accordingly, the DIC method has been widely used for tensile testing, not for fatigue testing.

Hwangbo and Song [11] performed fatigue tests to investigate the effect of mean stress on fatigue life of an electrodeposited copper thin film, and noted that monotonic plastic strain is important in the fatigue life of copper thin film materials. They measured cyclic and monotonic plastic strains during fatigue testing using a capacitance type displacement gauge [11,12]. The capacitance gauge measures the grip-to-grip displacement which involves not only the deformation of the gauge section of the specimen but also that of fillet areas of the specimen, indicating that the strain cannot measure directly on the specimen surface. Thus, a conversion procedure is required to calculate the strain of the specimen from the grip-to-grip displacement.

To enhance understanding of fatigue behaviors of thin film materials, it is important to investigate variations of the strain on the specimen surface by cyclic loading. However, no report on the variations of the strain measured directly on the specimen surface during fatigue testing can be yet found because of difficulties in measuring the strain. In this study, the monotonic strain of copper thin films during fatigue testing was directly measured on the surface of a specimen using the DIC method, and the variation of the monotonic strain with cyclic loading was analyzed.

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2. Tests

2.1. Testing system and specimen

Fatigue tests were performed using an electro-dynamic vertical axial loading testing machine shown in Fig. 1 [11,12]. The load was measured using a commercial load cell (Honeywell Co.) with a capacity of 5 N, and the grip-to-grip displacement was measured with a home-made, capacitive type displacement gauge (sensitivity: 11.3 mV/μm, linearity: 0.13%). A CCD camera (Point Grey Co.) with a strobe light was used to measure the deformation of the specimen during cyclic loading. The camera has a resolution of 2448 × 2048 pixels, where 1 pixel corresponds to 3.225 μm of the specimen. Fatigue tests were stress-controlled at a frequency of 13 Hz, and were automated using LabView. The cyclic load signal was monitored cycle by cycle, and if the maximum and minimum loads of a loading cycle were not within an allowable error band (±0.1%) the command signal to the testing machine was adjusted by a control program. Both the maximum and minimum stresses of a loading cycle were controlled within a maximum error of 0.25%. To reduce the effect of random noise included in signals, 13 continuous cycles were averaged. Then, 1000 load-displacement data pairs and two images of the specimen were collected for a loading cycle. A more detailed schematic diagram of the testing system and experimental procedure can be found in [11,12].

The material used was an electrodeposited copper foil of 12 μm thickness fabricated by Furukawa Circuit Foil Co., Ltd. The schematic configuration of the specimen is shown in Fig. 2 and the specimens were fabricated by etching techniques. The yield and tensile stresses of the copper foil tested are 235 and 317 MPa, respectively [11].

2.2. Strain measurement system

Fig. 3(a) shows variations of the stress versus grip-to-grip displacement S–d_g curves every 500 cycles in the beginning of a constant amplitude loading test of the copper thin films. The test was performed at a maximum stress of S_{max} = 260 MPa and a mean stress of S_{mean} = 190 MPa. With load cycling, the stress versus grip-to-grip displacement curves shifted continuously along the displacement axis, indicating that ratcheting occurs. Additionally, slight hysteresis loops, representing cyclic plastic deformation, can be found in the curves. Fig. 3(b) shows variations of the maximum and minimum grip-to-grip displacement in a loading cycle, d_{max} and d_{min}, with number of cycles, N.

Hwangbo and Song [11] calculated the strain of the specimen from the grip-to-grip displacement curve, shown in Fig. 3(b) by

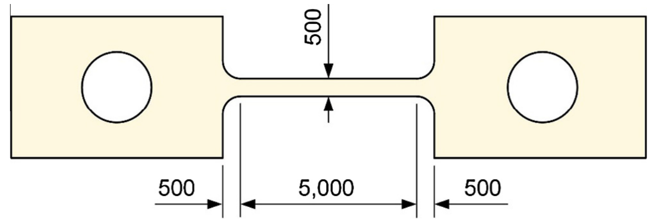

Fig. 2. Schematic configuration of the specimen (unit: μm).

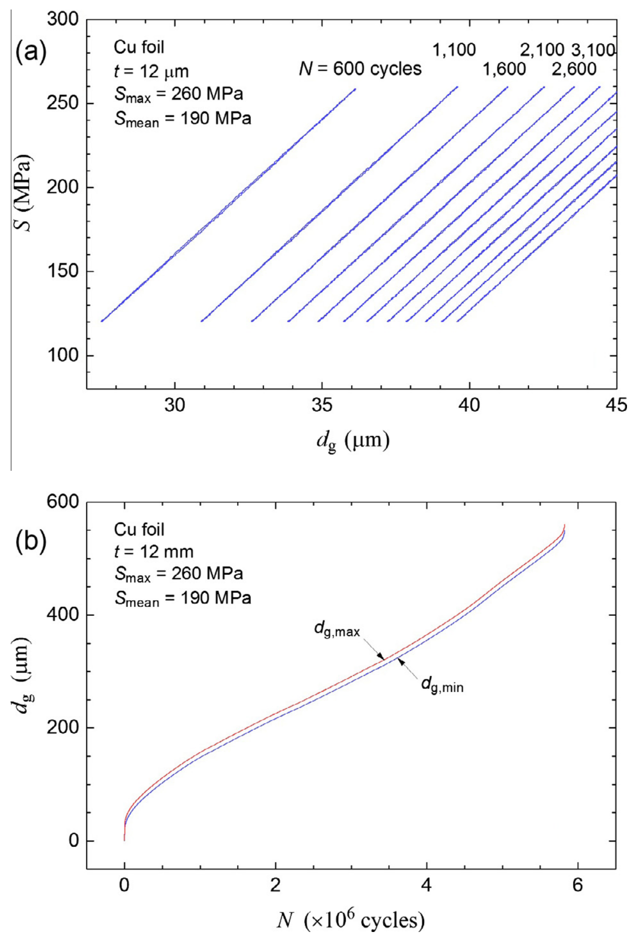

Fig. 3. Variations of (a) S–d_g and (b) d_g–N curves with number of cycles.

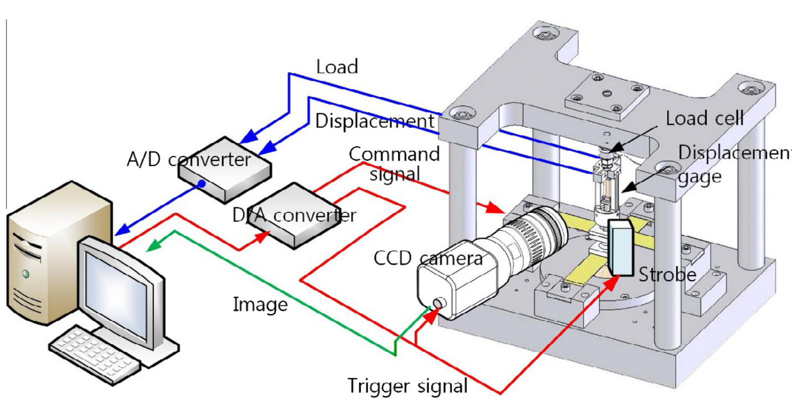

Fig. 1. Testing system.