Mechanisms of fatigue in LIGA Ni MEMS thin films

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Abstract

This paper presents the results of an experimental study of the mechanisms of fatigue in LIGA Ni micro-electro-mechanical systems (MEMS) thin films with micro-scale columnar and nano-scale equiaxed grains. Stress-life behavior is reported for films with thicknesses of 70 and 270 \mu m. The stress-life data are compared with previously reported data for Ni MEMS films and bulk Ni. The films with the nano-scale grains (15 nm average grain size) are shown to have higher strength and fatigue resistance (stress-life data) than those with columnar grain structures. The thicker films (with a columnar microstructure) are also shown to have comparable fatigue life to annealed Ni, while the thinner films (with a columnar microstructure) have comparable fatigue life to wrought Ni. The underlying mechanisms of crack nucleation and growth are elucidated via scanning and transmission electron microscopy. These reveal the formation of slip bands and surface oxides and crystallographic surface/sub-surface crack nucleation and growth in the films with the columnar structures. Surface and corner crack nucleations (from pre-existing defects) are observed in the nanostructured films. The implications of the results are discussed for the analyses of fatigue in nickel MEMS structures.

Keywords: Fatigue; Mechanisms; LIGA Ni; MEMS; Thin films

1. Introduction

In recent years, LIGA (Lithographic, Galvanoformung, Abformung) processing, which is the German acronym for electrodeposition into X-ray etched molds has been used to fabricate Ni micro-electro-mechanical systems (MEMS) thin films [1–34]. These have emerged as candidate materials for applications in larger and thicker MEMS devices (>20 \mu m thick) with high aspect ratios [17]. The potential applications include: microswitches, micro-gears and linkage mechanisms, micromotors and accelerometers for the deployment of airbags [29]. In most of these potential applications, fatigue failure can occur at stress ranges that are significantly below the measured strengths under monotonic loading [30]. However, until recently [31], it has been difficult to diagnose fatigue failure in LIGA Ni MEMS structures, such as Ni MEMS accelerometers [32,33]. This was due largely to the lack of prior fractographic studies of LIGA Ni MEMS thin films/structures.

Prior efforts have been made to study the fatigue behavior of LIGA Ni MEMS thin films [4,5,8,31,34]. The initial work was done by Hemker et al. [8] and Cho et al. [4,5], who measured the stress-life behavior of LIGA Ni MEMS thin films, and compared their results with previously reported data for annealed and wrought bulk Ni. Most recently, Allameh et al. [31] have studied the effects of specimen thickness on the stress-life behavior and the fatigue fracture modes in LIGA Ni MEMS structures. Boyce et al. [34] have also suggested that fatigue cracks nucleate from oxide films that form on the surfaces of slip bands that are induced on the surfaces of cyclically deformed LIGA Ni MEMS thin films. However, an integrated understanding of the mechanisms of fatigue crack nucleation and growth in LIGA Ni MEMS structures is yet to emerge.

In most of the prior work, LIGA Ni MEMS thin films have been studied in columnar microstructural conditions [1–34]. These generally have much lower strengths (300–800 MPa) than competing silicon MEMS thin films (\sim 1–2 GPa) [35–39]. However, in recent years, nanostructured Ni MEMS thin films have been developed with strengths of \sim 1.5–1.9 GPa [40]. However, there have been no prior studies of the micromechanisms of fatigue in such LIGA Ni MEMS thin films. It is also unclear...