FATIGUE DAMAGE ACCUMULATION MECHANISMS IN STRUCTURAL FILMS

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ABSTRACT

The maturation of thin film processing technologies has made it possible to manufacture micron-scale structures such as microelectromechanical systems (MEMS) from a variety of ductile and brittle materials. In contrast to conventional applications, these micron-scale structures and components are almost immediately employed in safety critical applications with little regard for crack initiation and growth phenomena such as fatigue. Furthermore, these components routinely accumulate large numbers of fatigue cycles because they often experience loading frequencies in excess of 50 kHz. In order to insure the reliability of these tiny mechanical components we must have a clear understanding of how fatigue damage accumulates in these materials. While the mechanisms of fatigue damage accumulation in ductile and brittle structural films can be similar to their bulk counterparts, some mechanisms unique to thin films have been observed. Fatigue damage accumulation in structural films can be intimately linked to processes that occur on the surface of the material and are only relevant in thin film forms. In this presentation we will explore the differences between fatigue damage accumulation in bulk and thin film silicon, nickel, and silicon carbide. Results from room temperature fatigue testing of thin film silicon, nickel, and silicon carbide using electrostatically-actuated, micromachined fatigue characterization structures and miniature tensile and fracture mechanics geometries will be discussed. The mechanistic origins of fatigue degradation of these materials will be established using electron microscopy, surface analysis techniques, and numerical modeling.

1 INTRODUCTION

Over the past 30 years, there has been a dramatic improvement in the understanding of degradation mechanisms that can limit the useful lifetimes of structural materials. This mechanistic understanding of fracture and fatigue, together with the use of damage/fracture mechanics, has allowed for the reliable design and operation of innumerable *macroscale* structures such as aircraft airframes and engine components. While the bulk forms of many of the materials used in micro- and nanoscale applications are understood, we have only recently begun to appreciate the fact that mechanical behavior and durability of small volumes of materials may differ from that observed for bulk specimens.

Structural materials can degrade through a variety of processes, but the accumulation of damage during cyclic loading conditions, or fatigue, is one of the most commonly encountered modes of failure. In many cases of cyclic fatigue, materials unexpectedly fail at stresses below their ultimate strength. Different fatigue mechanisms are observed in bulk forms of ductile (metallic) and brittle (ceramic) solids [1]. The fatigue of ductile materials is usually attributed to cyclic plasticity involving dislocation motion that causes alternating blunting and resharpening of a pre-existing crack tip as it advances [2]. In contrast, brittle materials invariably lack dislocation mobility at ambient temperatures, such that fatigue occurs by cycle-dependent degradation of the (extrinsic) toughness of the material in the wake of the crack tip that developed from preexisting material inhomogeneities [2]. Recent studies on small-scale specimens, including research by the author, suggest that structural films used in microelectromechanical systems (MEMS) and other nanomaterials are susceptible to unique fatigue degradation mechanisms and that in some cases their fatigue resistance is significantly less than the bulk forms of the material [3-8].

2 STRESS-LIFE FATIGUE OF SILICON-BASED FILMS

Si is a prime example of a material system that has shown different fatigue behavior in bulk and small-scale forms. Si can be regarded as an inherently brittle material at low temperatures, since there is no evidence for dislocation activity or extrinsic toughening. Moreover, bulk specimens of Si are not susceptible to environmentally-induced or fatigue cracking in moist air or water at measurable growth rates [9-11]. However, studies have now confirmed that *micron*-scale mono and polycrystalline Si structural films, as used in microelectromechanical systems (MEMS), are susceptible to premature failure by cyclic fatigue in ambient atmospheres [4, 5, 7, 8, 12-23]. The author's research (Fig. 1) has revealed that in room-temperature air, thin-film Si (~2 to 20 μm thick) can exhibit "metal-like" stress-life fatigue behavior (i.e., reducing the applied stress amplitude increases specimen life). High-voltage transmission electron microscopy coupled with *in situ* monitoring of the compliance of test structures has provided evidence that the fatigue susceptibility of micron-scale samples of Si arises from degradation of the nanoscale SiO_2 reaction layer that naturally forms on the surface of the material upon exposure to air [5]. In this process of "reaction-layer fatigue", initiation, subcritical growth and catastrophic failure of nanoscale cracks occur within the oxide layer (Fig. 2) [3, 5]. Materials other than Si may also be prone to reaction-layer fatigue if they form a surface reaction-layer that is susceptible to environmental- or cycle-dependent cracking. Thus, the reaction-layer fatigue mechanism can lead to delayed failure of thin films of materials that are ostensibly immune to stress-corrosion cracking and fatigue in their bulk form.

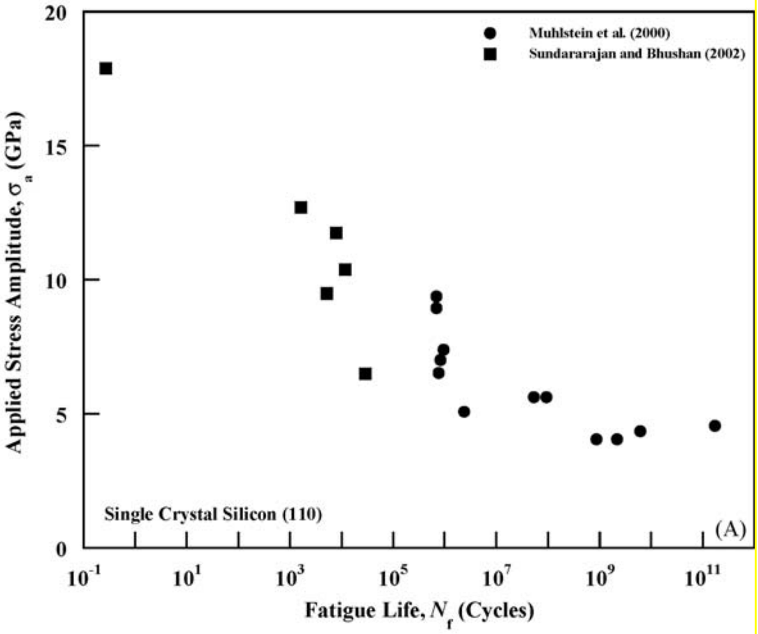

Fig. 1 Stress-life fatigue behavior of single crystal silicon thin films at room temperature.

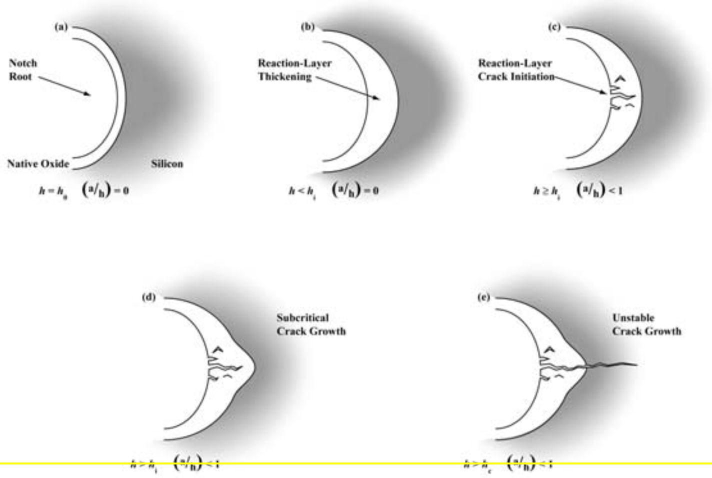

Fig. 2. Schematic illustrations of the reaction-layer fatigue mechanism at the notch of the polycrystalline silicon cantilever beam. (a) Reaction layer (native oxide) on surface of the silicon. (b) Localized oxide thickening at the notch root. (c) environmentally-assisted crack initiation in the native oxide at the notch root. (d) Additional thickening and cracking of reaction layer. (e) Unstable crack growth in the silicon film. The thickness of the oxide, *h*, and relative crack size (*a*/*h*) at each stage of the reaction are shown.

3 STRESS-LIFE FATIGUE OF METALLIC THIN FILMS

As with bulk specimens, different mechanisms must account for fatigue in ductile, as opposed to brittle, nanomaterials. Plastic deformation of metallic materials is generally associated with the motion of dislocations. Increases in fatigue resistance and ultimate strength are typically observed in nanostructured, face-centered cubic (FCC) metals, such as Ni, as the grain size is reduced (Fig. 3) [24-27]. However, once the grain (or wire) size becomes very small (typically ~10 nm), it appears that dislocations cannot remain in the material and alternative deformation mechanisms may become important; a breakdown in strengthening by grain refinement (i.e., inverse Hall-Petch behavior) is observed [24-26, 28, 29]. Furthermore, in small volumes of material, the length scale of plastic deformation becomes very fine, and unusual behavior is predicted (i.e., strain gradient plasticity) [30, 31]. The breakdown of the Hall-Petch relationship and the prediction of strain gradient plasticity raise questions about the mechanisms underlying plastic deformation and fatigue degradation in ductile nanomaterials. During fatigue loading in bulk metals, dislocations generally organize themselves into cell structures within the grains [2]. However, metals with nanoscale grain morphologies that fail in fatigue do not develop these cell structures [32]. This result suggests that a fundamentally different mechanism likely accounts for the fatigue of nanostructured metals. While fracture and fatigue surfaces in nanocrystalline Ni films are easy to differentiate (Fig. 4) [27], how the damage accumulates and creates these unique fracture surfaces is not yet understood. The question remains of how fatigue damage accumulates in metallic nanomaterials when dislocation-based plasticity may not be dominant.

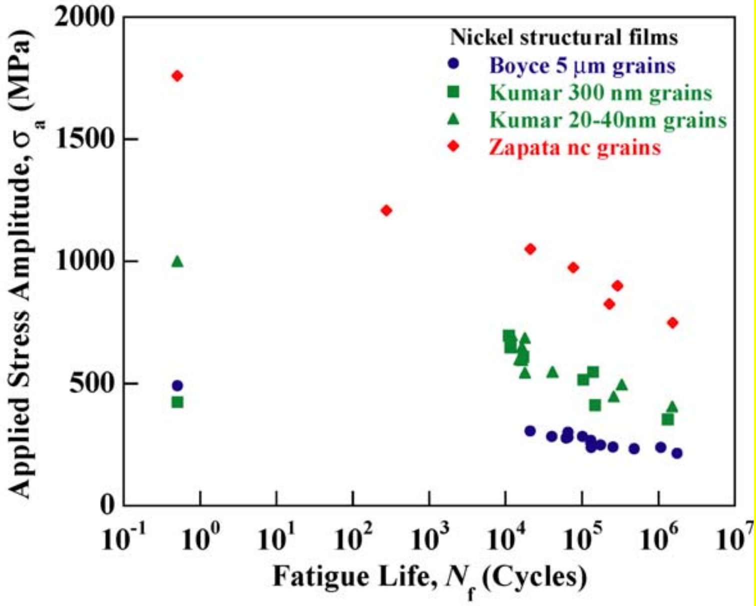

Fig. 3. Stress-life fatigue behavior of nanocrystalline Ni tested in the author’s laboratory (Zapata) and by other investigators.

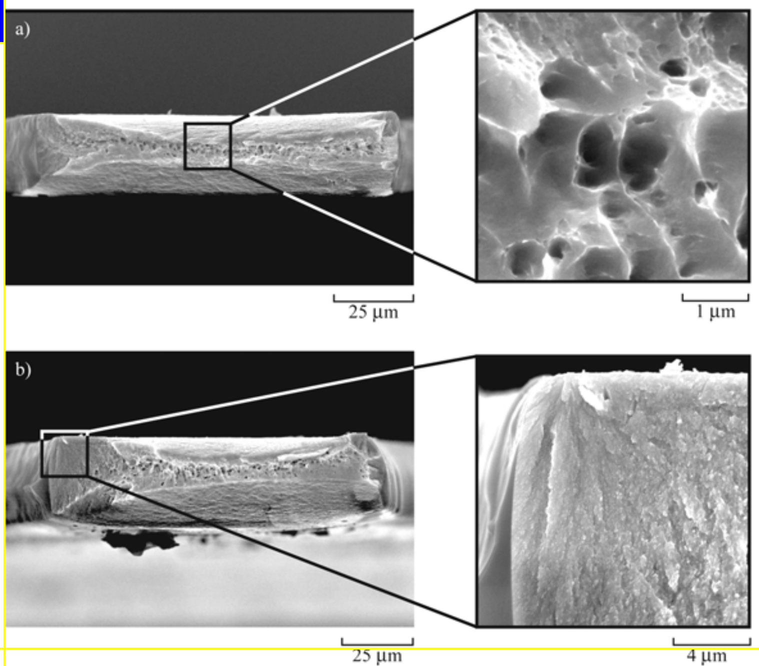

Fig. 4. Scanning electron micrographs of subsized nanocrystalline Ni specimens a) failed in tension (σ_{ult}=1 GPa), inset of void rupture and b) failed after 3452 cycles at a stress amplitude of 800 MPa (R=0.1), inset of fatigue crack initiation region.

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