Engineering Fracture Mechanics 168 (2016) 1–10

Contents lists available at ScienceDirect

Engineering Fracture Mechanics

journal homepage: www.elsevier.com/locate/engfracmech

Cyclic magnetic actuation technique for thin film interfacial fatigue crack propagation

Gregory T. Ostrowicki *, Suresh K. Sitaraman

George W. Woodruff School of Mechanical Engineering, Georgia Institute of Technology, 813 Ferst Drive, Atlanta, GA 30332, United States

ARTICLE INFO

Article history:
Received 21 May 2016
Received in revised form 14 September 2016
Accepted 16 September 2016
Available online 20 September 2016

Keywords:
Cu thin film
Interfacial delamination propagation
Cyclic fatigue
Magnetic actuation

ABSTRACT

Interfacial fatigue crack characterization is challenging for as-deposited thin films due to issues with fixturing and precision application of cyclic loading. A fixtureless and microfabricated test technique is presented to characterize delamination propagation rate as a function of constant amplitude fatigue loading using a novel peel test configuration and magnetic actuation. The test was demonstrated for 1.6 μm thick Cu films on a Si substrate, where interfacial fatigue crack propagation was observed to follow Paris Law behavior.

1. Introduction

Thin film delamination is often responsible for device failure, and is a major reliability concern in applications such as microelectronics, solar cells, flexible displays, microelectromechanical systems (MEMS), and many others. For example, sudden catastrophic delamination can occur due an unforgiving fabrication process or an overload in the field. Interfacial cracks can also nucleate and grow incrementally over many subcritical loading cycles, causing premature device failure. Current experimental test techniques are mainly suited to characterize thin film interfacial fracture toughness under monotonic loading. In other words, these techniques determine the critical load at which fracture occurs, however they are generally ill-suited to provide rapid and precise cyclic loading for a fatigue crack propagation (FCP) study. Consequently, there is a general lack of data in the literature concerning interfacial delamination under cyclic fatigue loading for virtually all thin film material systems.

For characterization of thin film adhesion, it is important for test specimens to have both process conditions and film thickness that is representative of the target material system and interface. Sputtering, electroplating, electroless plating, evaporation, atomic layer deposition, etc. are some of the techniques used for depositing thin metal films, and the type of process chosen is dependent on the substrate on which deposition is done, the final thickness of the deposited metal, other materials in the specimen, etc. Thus, the resulting interfacial property is dependent on the process which is governed by, amongst other factors, the thickness of the film. The grain size, orientation, and how they grow from the substrate are also dependent mostly on the process parameters and on the final thickness of the film. In addition, when the film thickness is of the same order as the surface roughness of the substrate, the mechanical interlocking can play a more significant role in the measured interfacial fracture energy.

* Corresponding author.
E-mail addresses: gtostrowicki@gatech.edu (G.T. Ostrowicki), suresh.sitaraman@me.gatech.edu (S.K. Sitaraman).

http://dx.doi.org/10.1016/j.engfracmech.2016.09.007
0013-7944/

Nomenclature

a	crack length
A	crack area
b	film strip width
C	Paris law constant
E	elastic modulus
F	peel force
G	strain energy release rate
h	film strip thickness
K	power law hardening constant
m	Paris law constant
n	power law hardening constant
N	number of cycles
P	applied vertical load
R	stress ratio
Ue	elastic strain energy
Up	plastic strain energy
V	voltage
α	initial delamination length
Γ	fracture energy rate
δ	separation gap between sample and driving electromagnet
ε	strain
θ	peel angle
σ	stress

Relatively few studies have experimentally characterized interfacial FCP under constant stress amplitude loading, namely for metal-ceramic [1–7], ceramic-ceramic [8], polymer-metal [9–13], and polymer-glass [14] interfaces. Only a handful of these report delamination growth rates for systems involving thin films with thickness less than 10 μm [1,5,7,8,10]. This lack of available data is partly due to the reliance of these studies on sandwich-type test specimens, such as the double cantilever beam (DCB), double cleavage drilled compressive (DCBC), compact tension (CT), and four-point bend tests. The fabrication of these sandwich specimens, in which macroscale supporting substrates are bonded together by the thin films of interest, often involve unusual processes which result in non-representative films and interfaces. After bonding, specimens may then require precision cutting or drilling into the samples in order to initiate the crack, and/or have difficulty in controlling the crack propagation along the desired interface.

An alternative to the sandwich-style test is the peel test and its similar variations, which operate by stretching a partially detached film at an angle from the adhered substrate until the film delaminates. Although this test technique has been successfully used to characterize the critical interfacial fracture strength for many material systems, very few have reported testing films with thickness less than 10 μm due to complications with specimen handling and applying peel forces through mechanical fixtures [15]. These peel tests are generally performed using displacement controlled actuators, which pull on the film at a constant rate while measuring the reaction force. Consequently, any FCP study to date that has utilized a peel-type test has been conducted under constant displacement amplitude loading [16,17].

To address the limitations of other test techniques, the Magnetically Actuated Peel Test (MAPT) was developed to characterize thin film interfacial delamination under load-controlled conditions. This technique has many advantages, including: (1) fixtureless experimental setup, (2) non-contact actuation, (3) simple batch fabrication with representative films and interfaces, (4) scalable from micron to submicron thick films, (5) ability to conduct interfacial FCP studies under constant stress amplitude loading, and (6) potential ability to conduct peel experiments while enclosing the specimen within a small environmental chamber. The MAPT technique has already been used previously to determine the critical interfacial fracture toughness of thin Cu films on Si substrates under monotonic loading [18]. The focus of this work is therefore to perform an interfacial FCP study using the MAPT technique, which to the authors' knowledge is a first for a peel-type test under constant stress amplitude loading.

2. Magnetically actuated peel test design

In addition to the demonstrated ability to characterize a thin film interface under monotonic loading, the MAPT design is ideally suited to conduct interfacial FCP experiments under subcritical fatigue loading. As shown in Fig. 1, the test specimen