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Theoretical study of adhesion energy measurement for film/substrate interface using pressurized blister test: Energy release rate

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ABSTRACT

In this paper, a new loading method able to subtly control the crack driving force for pressurized blister test was proposed. A theoretical study of the adhesion energy measurement for film/substrate interface using this loading method was presented. Problems considered include solving the exact volume under a circular blister and the elastic strain energy stored in a thin blistering film, determining the work done by the poured colored liquid as external force to the system and the elastic strain energy stored in the compressed air. A new formula of energy release rate was finally presented. A comparison between the work presented here and the existing work was made.

1. Introduction

Thin films have found increasing applications in many advancing technologies [1,2]. Reliability, lifespan, and structural stability of layered structures demand a better understanding of the mechanical performance of thin film–substrate systems. Blister tests are often used for measuring the mechanical properties of thin films or film/substrate interfaces [3–10]. The relevant mechanical quantities include hardness, Young's modulus of elasticity, Poisson's ratio, residual stress, fracture toughness of thin films and interfacial fracture toughness (or adhesion energy) [11–15].

The blister test technique was first suggested by Dannenberg [3] and was developed into many variant forms by subsequent investigators [4–9]. In all such tests, a hole is bored (or chemically etched) through the rigid substrate of a specimen until it reaches the dissimilar interface with the adhered film. There are two major variants of the blister test classified by the crack driving force: (i) fluid pressure and (ii) shaft loading, as shown in Fig. 1. The overhanging membrane is pressurized progressively, in Fig. 1a by either a liquid or working gas, while in Fig. 1b by a loading-shaft, until an axisymmetrical blister crack runs into the interface of a film–substrate system. The interfacial energy of adhesion is then determined by measuring the debonding radius a, the blister height w_m, and the corresponding driving force q or F (where q denotes uniformly-distributed loads and F denotes concentrated force). Compared with peeling test technique, the blister test technique has advantages of axisymmetrical blister geometry and small angle at the crack front.

However, there are still some disadvantages associated with the existing blister test technique. In conventional pressurized blister test, besides that catastrophic debonding occurs once a critical pressure is reached during loading [5], the complications due to the compressibility of the fluid medium, the presence of dissolved air/moisture, and the requirement for the sophisticated apparatus to

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Nomenclature

E	Young's modulus of elasticity	W	dimensionless form of w
v	Poisson's ratio	w_m	maximum deflection at the central portion ($r = 0$)
l	thickness of films	W_m	dimensionless form of w_m
a	radius of a circular membrane or a blister	θ	slope angle (see Fig. 4)
d	radius of the hole through the substrate of a specimen	σ_r	radial stress
b_1	inner radius of the smaller plexiglass circular container	S_r	dimensionless form of σ_r
b_2	inner radius of the bigger plexiglass circular container	σ_t	circumferential stress
h_1	height of the colored liquid in the container of radius b_1	S_t	dimensionless form of σ_t
h_2	height of the colored liquid in the container of radius b_2	e_r	radial strain
ρ	density of the colored liquid	e_t	circumferential strain
g	acceleration of gravity	Z	substituting variable of S_r
q	uniformly-distributed loads	$f(x)$, $\varphi(x)$, $\omega(x)$	functions
Q	dimensionless form of q	c, A	undetermined integral constants
r	radial coordinate	B_0	undetermined parameter
x	dimensionless form of r	C_1	numerical coefficient
w	transversal displacement	V	volume under a blister
u	radial displacement	U_{ef}	elastic strain energy stored in blistering film
		U_{ea}	elastic strain energy stored in compressed air
		U_F	work done by the poured colored liquid as external force to system
		G	energy release rate

simultaneously measure both blister height and pressure, all still continue. While at the same time, in shaft-loaded blister test, the radius of the loading-shaft was generally taken to be as small as possible in order that the relation of the blister height w_m and load F will follow the exact analytical solution of axisymmetrical deformation problem of circular membrane fixed at its perimeter under the action of a point load, but this will easily lead to plastic yielding and piercing of thin film. It is unreasonable to regard the applied load F as an infinitesimal central point load, since the shaft/film contact is, in fact, not a point contact. Notwithstanding the subsequent shaft-loading technique applying the external load F via a stainless-steel ball of finite radius overcame the plastic yielding and piercing of thin film [9], it is difficult to obtain an exact analytical solution of such a membrane problem. Thereby, some assumptions, such as (i) assuming a membrane profile of conic geometry [7,9] and (ii) assuming a uniform and isotropic in-plane stress [9,16–19], had to be introduced in solving process. In circular membrane problems, however, it is well known that the radial and tangential stresses are generally neither equal in magnitude nor spatially uniform. So, adopting those assumptions will inevitably lead to much loss of accuracy.

This paper proposed a new loading method able to subtly control the crack driving force for pressurized blister test and was devoted to the theoretical derivation of the exact formula for calculating the energy release rate of film/substrate interface. The new loading method, which was presented in Section 2, can overcome all disadvantages in conventional pressurized blister test. The theoretical derivation was presented in Section 3, and a comparison between our work and existing work was presented in Section 4.

2. Method

The experimental setup is illustrated as shown in Fig. 2. Two circular Plexiglas containers of wall thickness 10 mm and with scale in millimeter are prepared, in which the height and inner radius (denoted by b_1) of the smaller circular Plexiglas container are 100 mm and 10 mm, and the height and inner radius (denoted by b_2) of the bigger one are about 1500–2000 mm and

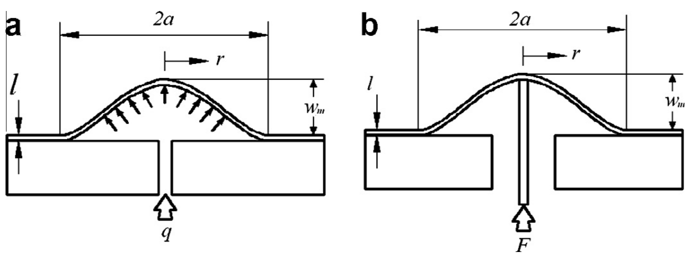

Fig. 1. Schematics of the loading configuration. (a) A pressurized circular blister configuration and (b) a shaft-loaded circular blister configuration.