International Journal of Solids and Structures 48 (2011) 2965–2976

Contents lists available at ScienceDirect

International Journal of Solids and Structures

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

Analytical and experimental study of a circular membrane in adhesive contact with a rigid substrate

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ARTICLE INFO

Article history:
Received 5 April 2011
Received in revised form 2 June 2011
Available online 28 June 2011

Keywords:
Adhesive contact mechanics
Membranes
Moiré deflectometry
Micro-electro-mechanical systems (MEMS)
Micro-opto-electro-mechanical systems (MOEMS)

ABSTRACT

The problem that is addressed here is that of a pressurized circular membrane in adhesive contact with a rigid substrate. A closed-form membrane analysis is developed for the JKR, DMT and Maugis regimes, which describes the relationships between adhesion energy, pressure, contact radius and contact force. The JKR–DMT transition is studied for this case of membrane contact by introducing an appropriate dimensionless parameter. Experiments are conducted with smooth and structured acrylate layers on a PET carrier film contacting a glass substrate using an apparatus based on moiré deflectometry to measure the contact radius and slope of these thin transparent films. They demonstrate that this analysis predicts the contact radius well. The adhesion energy extracted from the analysis of the measured pressure-contact radius response is constant during unloading but appears to increase during pressurization.

1. Introduction

The adhesion, contact and deformation of thin membranes have played important roles in many fields. For instance, in biological science, cell membrane and substratum adhesion is vital to normal cell functioning and locomotion (Fisher, 1993) and vesicle membrane fusion is of practical importance for targeted drug delivery (Bakowsky et al., 2008). In micro or micro-opto electro-mechanical systems (MEMS or MOEMS), electrostatically driven bridges or diaphragm membranes operate over trillions of cycles in their life span and the study of reliability and durability of such MEMS/MOEMS devices relies on a quantitative understanding and determination of change in adhesion and contact over time (Rebeiz, 2003). Furthermore, an accurate determination of contact size is necessary to evaluate contact resistance, heat dissipation and contact temperature in DC-contact-switch MEMS (Hyman and Mehregany, 1999; Rebeiz, 2003).

The contact mechanics of two elastic solids has been well established through the classical theories of Hertz (1881) , Johnson et al. (1971) (JKR), Derjaguin et al. (1975) and Maugis (1992) (DMT) and Maugis (1992). The valid regimes of these theories are summarized in the Johnson–Greenwood map (Johnson and Greenwood, 1997), which is based on the dimensionless parameter initiated by Tabor (1977). However, these theories for elastic solids are not applicable to thin membranes in contact. This is due to the fact that the elastic strain energy is determined by the membrane stresses which result from the large out-of-plane deflections of the thin membrane. Consequently, geometrical nonlinearity has to be considered and exact closed-form solutions are not possible.

The first configuration that was studied by membrane contact mechanics was a cellular membrane compressed between two parallel plates (Cole, 1932; Harvey, 1938; Hiramoto, 1963). This was used to characterize the mechanical properties of cellular membranes. The other extensively studied configuration is a spherical capsule adhered to a substrate (Shanahan, 1997; Wan and Liu, 2001). This configuration is widely used to explore cell/vesicle/liposome/microcapsule–substrate contact and adhesion which play critical roles in biological and biomedical science. The third class of problems includes one-dimensional strips or axisymmetric membranes contacting a rigid substrate or punch under adhesive surface forces (Nadler and Tang, 2008; Plaut et al., 2001, 1999; Wan, 2002; Wan and Duan, 2002; Wan and Julien, 2009; Wong et al., 2007; Yang, 2004). These configurations have been used to study the contact and adhesion between thin membranes and substrates and stiction and adhesion in biological/biomedical and MEMS structures.

In this paper, a pressurized circular membrane clamped peripherally and contacting a rigid substrate is studied. This can be regarded as a contact configuration in the third category mentioned above. This geometry is also reminiscent of the constrained blister test (Chang et al., 1989; Napolitano et al., 1988) but instead the edge of the blister is clamped and the contact and adhesion between the membrane and the constrained plate

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0020-7683/$ - see front matter
doi:10.1016/j.ijsolstr.2011.06.014