International Journal of Solids and Structures 69–70 (2015) 189–194

Contents lists available at ScienceDirect

International Journal of Solids and Structures

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

Adhesion of a gas-filled membrane on a stretched substrate

Lei Chen, Shaohua Chen *

LNM, Institute of Mechanics, Chinese Academy of Sciences, Beijing 100190, China

ARTICLE INFO

Article history:
Received 25 January 2015
Received in revised form 19 April 2015
Available online 10 June 2015

Keywords:
Adhesive contact
Gas-filled membrane
Stretched substrate
Free energy
Cell adhesion

ABSTRACT

A two-dimensionally adhesive contact model is established, in which a gas-filled elastic membrane adheres on a stretched substrate. The free energy of the system is achieved, minimization of which leads to the relationship between the contact width and the global substrate strain. The contact solution exhibits three distinct regimes characterized by two threshold strains: (i) the contact size is hardly affected by the external loading acted on the substrate when the global substrate strain is below the first threshold value; (ii) the size of the contact is reduced quickly as the force is between the two threshold levels; (iii) the contact size tends to vanish when the global substrate strain exceeds the second threshold level. All the results share a number of common features with the experimental observation of cell orientation on a stretched substrate. Effects of the internal pressure, the tensile stiffness of the membrane and the interface work of adhesion on the two threshold levels are further discussed. The finding in the present paper should be helpful for deep understanding of adhesion mediated deformation sensing mechanism by which cells can detect mechanical signals in extracellular matrices and the design of adhesion mediated deformation sensors.

1. Introduction

Adhesion among different types of cells and between cells and substrates is of great interest in many fields of biology, including embryonic development, cancer metastasis, cellular transport, endo- and exocytosis, tissue and cellular engineering (Alberts et al., 1994; Bao and Suresh, 2003; Gao et al., 2005). Mechanical signals are believed to play an important role in cell adhesion. For example, cells are known to respond to mechanical forces exerted by the surrounding fluid, adhering beads or substrates (Choquet et al., 1997; Girard and Nerem, 1995; Ingber, 1993; Wang et al., 1993), they could detach, slip or roll on a substrate in response to these forces (Bischofs and Schwarz, 2003; Galbraith and Sheetz, 1998; Geiger and Bershadsky, 2002; Haston et al., 1983; Huang and Ingber, 1999; Lorz et al., 2000; Wong et al., 2003). Furthermore, cells could sense the stiffness gradient of substrates and migrate towards the stiffer segment (Lo et al., 2000). Even for oosperm transport from ovary to uterus, the behavior of smooth muscle contraction is much essential, which could induce a moving strain gradient field as a driving force for oosperms' rolling. A recently biomimetic experiment further suggests that an elastic strain gradient in substrates can be utilized to transport spherical particles on a stretchable substrate by rolling (Chen et al., 2014).

Another set of experiments have shown that cells cultured on a cyclically stretched substrate tend to reorient themselves away from the stretch direction (Buck, 1980; Dartsch and Hammerle, 1986; Jungbauer et al., 2008; Moretti et al., 2004; Neidlingerwilke et al., 1994; Wang et al., 1995). Dartsch and Hammerle (1986) further noted that cells did not respond to small stretch amplitudes (less than 2%), suggesting that there exists a threshold stretch amplitude to initiate cell reorientation. Above this threshold, an increasing number of cells begin to respond to substrate deformation by reorienting themselves away from the stretch direction. The larger the stretch amplitude, the more cells reorient. Almost all cells join the reorientation process once the stretch amplitude exceeds a second threshold level about 5–6% (Neidlingerwilke et al., 1994).

How could cells sense the substrate deformation? An adhesive contact model (Chen and Gao, 2006b) was established in order to explain cells reorientation from the mechanics point of view, in which an elastic solid cylinder was used and the contact interface was treated as a well-bonded region without slippage to simulate tremendously focal adhesion between cells and substrates. Theoretical predictions agree well with experimental observations, especially the two threshold strains controlling the process of cell reorientation. Non-slipping adhesive contact model between two dissimilar solid spheres subjected to a pair of pulling forces and a mismatch strain suggests an adhesion mediated deformation sensing mechanism by which cells and molecules can detect mechanical signals in the environment via adhesive interactions (Chen and Gao,

* Corresponding author. Tel.: +86 10 82543960; fax: +86 10 82543977.
E-mail address: chenshaohua72@hotmail.com (S. Chen).

http://dx.doi.org/10.1016/j.ijsolstr.2015.04.037
0020-7683/

2006a). In microscopic views, cell–cell and cell-substrate adhesion was studied with statistical physics method, such as the well-known Bell's model (Bell, 1978). In order to interpret cell reorientation in experiments, Kong et al. (2008) established a stochastic model to investigate the stability of focal adhesion under a dynamic load by applying an externally cyclical strain on substrates, and found that a threshold of the external strain amplitude exists beyond which the adhesion cluster disrupts quickly. Combining the statistical physics and the elastic contact theory, series of theoretical models were proposed in order to characterize cell-substrate adhesion (Gao et al., 2011; Qian and Gao, 2010; Zhang et al., 2013, 2012), in which the effect of matrix stiffness (Qian and Gao, 2010), anisotropy of matrix material (Zhang et al., 2013), graded modulus of substrates (Zhang et al., 2012) and the pulling angle of external forces (Gao et al., 2011) were considered. Most of the researches treated cells as spherical membranes or capsules rather than elastic solids, which should be much closer to the real morphology of cells apparently (Hiramoto, 1963; Liu et al., 1996; Sen et al., 2005). Is there any difference between the model of an elastic solid and that of an elastic membrane in order to disclose the adhesion mediated deformation sensing mechanism of cells? Could a membrane model predict the two threshold levels for cell reorientation? What factors would influence the two values?

As for a spherical membrane in adhesion with a rigid substrate, several models have already been proposed and studied by Shanahan (1997, 2003), which was also adopted to investigate interactions between soft particles and substrates (Liu, 2006; Lulevich et al., 2004; Xu and Liechti, 2011). With the similar idea, a contact model of a gas-filled membrane adhering on a stretched substrate is first studied in the present paper. A liquid-filled membrane case will be considered in our future work though it looks more like a cell.

2. Theoretical model and analysis

A two-dimensionally adhesive contact model is shown in Fig. 1, which consists of three continuous stages: (i) the first one is called as a self-inflated stage, in which an elastic membrane of an intrinsic radius ρ and a tensile stiffness $E_m^* t_m$ is inflated by an internal pressure P_i, comparing to an environmental pressure P_0, in which $E_m^* = E_m$ is for a plane stress case and $E_m^* = E_m/(1-\upsilon_m^2)$ for a plane strain one, E_m and υ_m denote the Young's modulus and Poisson's ratio of the membrane, respectively. t_m is the membrane thickness with an assumption $t_m \ll \rho$. As a result, the additive gas pressure is $\Delta P_i = P_i - P_0$, which induces an inflated radius R_i and a tensile strain ε_i in the membrane. (ii) The second stage is addressed as a self-adhesion stage, in which the inflated membrane adhesively contacts an elastic substrate of length $2L$ and tensile stiffness $E_s^* t_s$, leading to a self-adhesion area of half-width a_a with a small contact central angle θ_a as shown in Fig. 1. Due to the self-adhesion, the internal pressure inside the membrane and the membrane radius change to be P_a and R_a, respectively. The tensile strain of the membrane changes from ε_i to ε_a, while the strain in the adhesion area remains to be ε_i due to an assumption of $E_s^* t_s \gg E_m^* t_m$ and a neglected deformation of the substrate in this stage. (iii) The last stage is called as a stretch stage, in which the elastic substrate is tensioned by an external force F, leading to a global substrate strain $\varepsilon_g = F/(E_s^* t_s)$. As a result, an updated adhesion width is $2a_F$ with a small contact central angle θ_F. The elastic membrane is further deformed, leading to an internal pressure P_F, radius R_F and membrane strain ε_F. Due to the assumption of a perfect adhesive interface between the membrane and the substrate, the adhesion part of the membrane will deform further along with the substrate.

Without loss of generality, we assume that the tensile stiffness of the membrane keeps unchanged in all three stages and the contact width is much smaller than the membrane radius, i.e. $a_a \ll R_a$ and $a_F \ll R_F$.

The quantity of internal gas is conservative, which abides by the ideal gas law, i.e.,

$$P_i V_i = P_a V_a = P_F V_F = n\tilde{R}\tilde{T} = K \text{ (constant)}, \tag{1}$$

where V_i, V_a and V_F denote volumes of the membrane in the first, second and last stages, respectively. n is the mole number of the gas contained, $\tilde{R}$ is the ideal gas constant and $\tilde{T}$ the absolute temperature with a constant $K = n\tilde{R}\tilde{T}$.

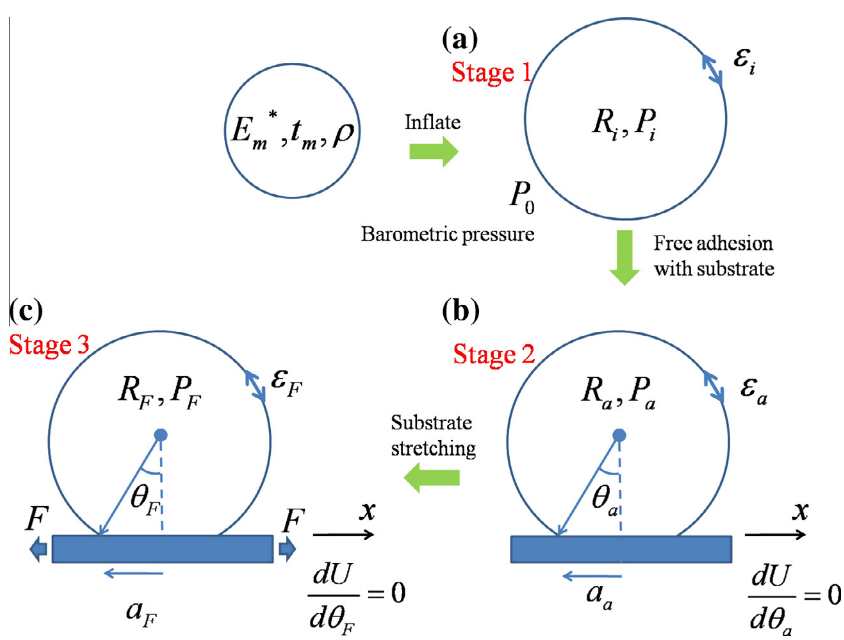

Fig. 1. The two-dimensionally adhesive contact model of an elastically gas-filled circular membrane on an elastic substrate and schematics of the included three stages, i.e., the self-inflated stage, the self-adhesion stage and the one subjected to an external loading on the substrate.