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Acta Biomaterialia 2 (2006) 51–58
Acta BIOMATERIALIA
www.actamat-journals.com

Scaling effects of wet adhesion in biological attachment systems

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Received 30 May 2005; received in revised form 29 July 2005; accepted 10 August 2005

Abstract

Insects have evolved fibrillar attachment devices based on wet adhesion to attach themselves to a variety of surfaces. This paper investigates the scaling effects of wet adhesion mediated by a liquid bridge between a fiber and a solid surface. The influences of liquid volume and contact angles are discussed via a scaling law indicating that the adhesive strength can be enhanced by contact size reduction. Due to the maximum negative pressure in the liquid bridge, there exists a critical length scale at which the system achieves the theoretical tensile strength of the liquid. We conclude that size reduction down to a critical scale results in optimization of the adhesive strength.

Keywords: Wet adhesion; Adhesive strength; Adhesion energy; Scaling; Design

1. Introduction

The study of biological attachment mechanisms has a long history since it not only provides insights into biological systems but may also yield general principles employed in nature as inspiration and guidance for the development of biomimetic adhesive devices. Different hypotheses of bio-adhesion mechanisms, such as hooks, micro-suckers and electrostatic forces, have been proposed [1]. However, investigators have since rejected some of the mechanisms based on experiments or observations of a broad diversity of species. It has been concluded that van der Waals interactions (dry adhesion) and capillary interactions (wet adhesion) are the two main mechanisms attributable to biological attachments [2].

Dry adhesion is adopted by geckos, jumping spiders, etc. [3,4]. These animals have achieved superior attachment ability through elaborate adhesive structures on their feet. Experimental investigations have revealed that the bio-adhesive structures are often finely-split and hierarchical. Theoretical studies based on contact mechanics have pointed out that splitting of a contact patch into fine sub-divided elements can result in enhancement of adhesive strength [5]. Furthermore, it has been suggested that the concept of flaw tolerance may be a general principle in biological systems [6–10]. It is found that, in the presence of pre-existing flaws, the adhesive strength can be optimized by size reduction to the nanoscale [7–9], gradient material design [10] and hierarchical energy dissipation [10].

Animals like beetles, blowflies and ants have not evolved the same attachment terminals as geckos [11–19]. They resort to another strategy which is based more on wet adhesion. When they attach to surfaces, some secretory fluid is produced and delivered to the bottom of the attachment pads. The fluid footprints left behind by the animals are simply the replica pattern of their adhesive pads [11]. Recent experiments with flies have confirmed the special mechanisms for the release of secretion to individual pads [18]. The evidence that the secretion is crucial for successful attachment is provided by observations that animals appear to lose their ability to adhere on surfaces after treatments to remove secretion from their feet [19].

The present study aims to understand the underlying principles of fibrillar wet adhesion. The behavior of a liquid connecting bridge between a fiber and a substrate is analyzed as a model problem. The fiber is quasi-statically

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1742-7061/$ - see front matter
doi:10.1016/j.actbio.2005.08.005

pulled away from the substrate against the capillary forces of the liquid bridge. We investigate how the liquid volume and contact angles alter the stress–separation behavior of the liquid bridge. The influences of the system's characteristic length scale on the adhesive strength and adhesion energy are of special interest.

2. Model

The system to be investigated is described in Fig. 1. A solid fiber with a circular cross section and radius R is assumed to be in wet adhesion with a solid substrate through a liquid bridge. The contact angle of the liquid with the fiber surface is θ_1 and that with the substrate is θ_2. We make the following assumptions in the study: (i) the effect of gravity is assumed to be negligible at the size scale of individual fibers in a biological attachment system; (ii) the volume of the liquid is conserved; (iii) both the fiber and substrate are rigid solids, and the fiber has a flat-ended tip.

There have been a number of similar theoretical studies on capillary adhesion due to liquid bridges in the past. Orr et al. [20] considered a liquid bridge between a sphere and a plate and obtained analytical expressions for the bridge profile in terms of elliptic integrals. The results have been recently applied in a scheme to manipulate small objects via capillary forces [21]. In our model, the substrate is infinite and the fiber tip has a finite size; the liquid volume is conserved such that the liquid bridge may shrink or expand as the fiber is pulled or pressed. A critical solid separation, below which the liquid periphery becomes pinned at the edge of the fiber, defines a transition point between contact angle dominated adhesion and fiber radius dominated adhesion. A similar transition has been considered previously for liquid bridges between two identical plates [22].

The total adhesive force acting on the fiber, F, has two components. One is induced by the pressure difference across the liquid–gas interface. The other arises from the axial component of liquid surface tension acting along the liquid perimeter on the tip of the fiber. The sum of these forces can be written as [20]

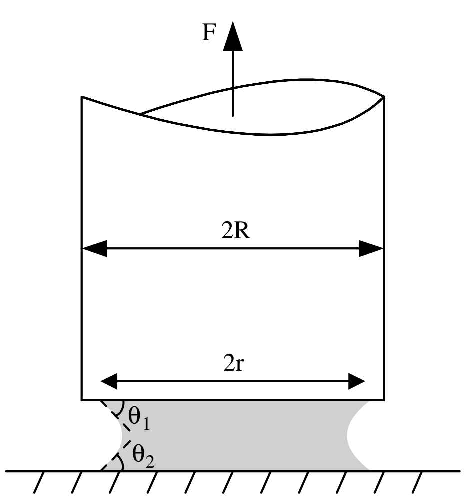

Fig. 1. The geometry of a flat-ended fiber adhering to a rigid substrate via a liquid bridge.

$$F = -\pi r^2 \cdot \Delta P + 2\pi r \cdot \gamma \sin\theta_1, \tag{1}$$

where r is the radius of the wet area on the fiber tip, γ is the liquid surface tension, and ΔP is the pressure difference inside and outside the meniscus, which is related to the local liquid profile by the Young–Laplace equation [23]

$$\Delta P = \gamma\left(\frac{1}{R_1} + \frac{1}{R_2}\right), \tag{2}$$

where R_1 and R_2 are the two local principal curvatures of the liquid profile. Since the effect of gravity is neglected in our study, ΔP is a constant within the meniscus and the liquid profile has the same mean curvature at any point.

3. Analysis

Calculation of adhesive force in Eq. (1) requires the solution to liquid profile for given liquid volume, contact angles and fiber–substrate separation. A variable transformation changes the original Young–Laplace equation into the following system of ordinary differential equations with the arc length as the independent variable:

$$\frac{dx}{ds} = \cos\varphi, \tag{3a}$$

$$\frac{dz}{ds} = \sin\varphi, \tag{3b}$$

$$\frac{d\varphi}{ds} = \frac{\Delta P}{\gamma} - \frac{\sin\varphi}{x}, \tag{3c}$$

where x and z are the co-ordinates of the axisymmetric liquid bridge, φ is the angle between the local tangent of liquid surface and the horizontal axis, and s is the arc length of the liquid profile, as indicated in Fig. 2. With the following normalization by fiber radius R : $\widehat{X} = x/R$, $\widehat{Z} = z/R$, $\widehat{S} = s/R$, the equation system can be rewritten as

$$\frac{d\widehat{X}}{d\widehat{S}} = \cos\varphi, \tag{4a}$$

$$\frac{d\widehat{Z}}{d\widehat{S}} = \sin\varphi, \tag{4b}$$

$$\frac{d\varphi}{d\widehat{S}} = \widehat{H} - \frac{\sin\varphi}{\widehat{X}}, \tag{4c}$$

where $\widehat{H} = (\Delta P \cdot R)/\gamma$ is a dimensionless parameter measuring the pressure difference. For given values of non-dimensional liquid volume $\widehat{V}$ (actual liquid volume normalized by R^3), contact angles θ_1 and θ_2, and non-dimensional fiber–substrate separation $\widehat{D}$ (actual separation normalized by R), a unique liquid surface profile can be obtained by simultaneous integration of above equation system. We treat Eqs. (4a)–(4c) as a typical initial value problem: A is assumed to be the point where the liquid profile meets the fiber tip, as indicated in Fig. 3(a). The initial values of point A are: $\widehat{X}(0) = \widehat{X}_0$, $\widehat{Z}(0) = 0$, $\varphi(0) = \pi - \theta_1$. Initial guesses of the values of $\widehat{X}_0$ and $\widehat{H}$ are made at the