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Combined dry and wet adhesion between a particle and an elastic substrate

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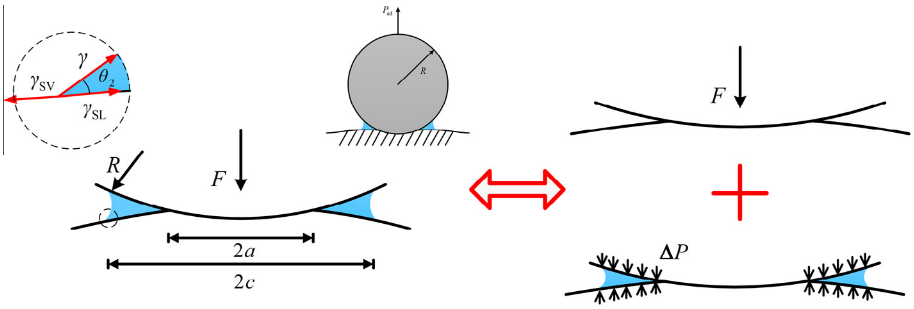
GRAPHICAL ABSTRACT



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ABSTRACT

We theoretically model the combined dry and wet adhesion between a rigid sphere and an elastic substrate, where the dry contact area is surrounded by a liquid meniscus. The influence of the liquid on the interfacial adhesion is twofold: inducing the Laplace pressure around the dry contact area and altering the adhesion energy between solid surfaces. The behavior of such combined dry and wet adhesion shows a smooth transition between the JKR and DMT models for hydrophilic solids, governed by the prescribed liquid volume or environmental humidity. The JKR-DMT transition vanishes when the solids become hydrophobic. An inverse scaling law of adhesive strength indicates that size reduction helps to enhance the adhesive strength until a theoretical limit is reached. This study also demonstrates the jumping-on and jumping-off hysteresis between the combined dry-wet adhesion and pure liquid bridge in a complete separation and approach cycle.

1. Introduction

It is widely known that capillary bridges may form at the interface between two solid surfaces when they are in contact or proximity, as a consequence of either intentionally added liquid or condensation of water from a humid atmosphere. Such liquid-mediated capillary interaction may contribute attraction between solid surfaces in addition to the van der Waals interactions, and influence the resultant interfacial energy in various physical or technological systems, particularly at small scales [1,2]. For example, the capillary force formed between micro- or nano-machined structures can be vital to cause the structures to collapse [3]. The effects of water condensation on probe-substrate interaction in atomic force microscope (AFM) or nano-indentation technique

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are always an outstanding issue that requires cautious interpretation of the measurements [4,5]. Wet adhesive interaction may also be responsible for the aggregation of granular materials exposed to humid environments [6], in which the presence of liquid smoothens the irregularities and thus increases the effective contact area between solids surfaces [7].

The crucial importance of capillary interaction is also exemplified by many biological attachment systems. Capillary-based wet adhesion has been shown to play a dominant role in contributing to the attachment systems of beetles [8], blowflies [9], ants [10,11] and tree frogs [12], in contrast to other animals that use elaborate hierarchical hairs in their feet to achieve superior dry adhesion without the presence of liquid, purely relying on van der Waals forces [13,14]. The presence of secretory fluids on foot pads has been reported for various insects [8–11], and special mechanism for the release of secretion to individual pads has been confirmed by recent experiments with flies [15]. This liquid secretion has been shown to play a critically important role for successful attachment: animals catastrophically lost their ability to adhere on surfaces after the treatment of removing secretion from their feet [16]. The quantitative modeling of how the presence of liquid would affect the overall adhesion between deformable solid surfaces should provide inspiration and guidance for the development of biomimetic adhesive devices [17–20].

Wet adhesion is based on the capillary forces through a liquid bridge, with or without dry contact area between solid surfaces. For the case of liquid meniscus surrounding a dry contact area (Fig. 1a), wet adhesion may introduce additional Laplace pressure in the annulus, causing deformation in the compliant solids and modifying the adhesion energy between the solids. For the other case of pure wet bridge without dry contact area (Fig. 4), the region of Laplace pressure induced by wet adhesion becomes a circle acting on the solid surfaces. In both cases, additional capillary force is induced by the relative pressure change within the liquid, which may have a significant influence on the resultant adhesion between the solids. A simple equation has been widely used to calculate the capillary-based adhesive force between a sphere and a flat substrate: $P_{ad} = 2\pi R\gamma(\cos\theta_1 + \cos\theta_2)$ [21], where R is the radius of the sphere, γ is the surface tension of the liquid, and θ_1, θ_2 are the contact angles of liquid on individual surfaces. This formula simplifies the problem in a number of aspects: neither material deformation nor solid–solid interaction is considered, and it implies that the resultant adhesive force is independent of liquid volume and humidity.

More rigorous analysis and modeling of the combined dry and wet adhesion are crucial for advancing conceptual insights and the development of capillary-based adhesive devices. Early theories by Fogden and White [22], as well as Maugis and Gauthier-Manuel [23] studied the elastic contact between a sphere and a deformable substrate in the presence of liquid meniscus, showing that an effective Dugdale-type cohesive zone [24] owing to the uniform capillary attraction within the liquid meniscus leads to a transition between Johnson-Kendall-Robert (JKR) model [25] and Derjaguin-Muller-Toporov (DMT) model [26]. However in their studies, the capillary attraction of meniscus was approximated by a phenomenological cohesive law, and the role of liquid volume in affecting the cohesive zone was not explicitly considered. Fan and Gao [27] studied the adhesion problem that couples sphere-plane contact and liquid-bridging forces, where Hertzian distribution of interfacial pressure was assumed in the area of dry contact. Chen and Yu [28] considered the contact problem between a spherical punch and a piezoelectric base in the presence of capillary annulus. These analyses ignored the adhesion energy of solid-solid interface immersed in liquid. Moreover, wet adhesion mediated by pure liquid bridges between rigid surfaces has been studied with emphasis on the size effect [29] and shape effect [30–32], without considering the possibility of forming dry contact area. Wexler et al. [33] also studied the liquid bridge that is trapped in the thin gap between two soft planar surfaces, without considering solid-solid contact. As evident from the numerous studies above, the issues of combined dry-wet contact, effects of solid deformation, solid-solid interaction surrounded by liquid medium, and how liquid volume at various thermodynamic conditions may influence the combined adhesion were often treated separately, and a coherent theoretical modeling is still lacking.

Built upon previous progress, the present work aims to address the aforementioned issues by considering a classical JKR set-up where a sphere is in combined dry and wet adhesion with an elastic substrate. The scaling law of adhesive strength, effects of liquid volume on force-displacement relation, jumping transitions between the combined dry-wet adhesion and pure liquid bridge, and other adhesive performance of the problem will be discussed in a coherent framework. Besides the wet adhesive attachment from natural or artificial devices where the liquid is intentionally added, the problem under investigation should be relevant to asperity-surface interactions (e.g., those in AFM and nano-indentation measurements) as well, where liquid bridges inevitably emerge from vapor condensation at the solid gaps in humid environments.

2. Model

We consider a classical JKR-type problem where a rigid sphere of radius R is in adhesive and frictionless contact with the planar surface of a semi-infinite elastic body under a tensile force P_{ad} (Fig. 1a). The half-space material has Young's modulus E and

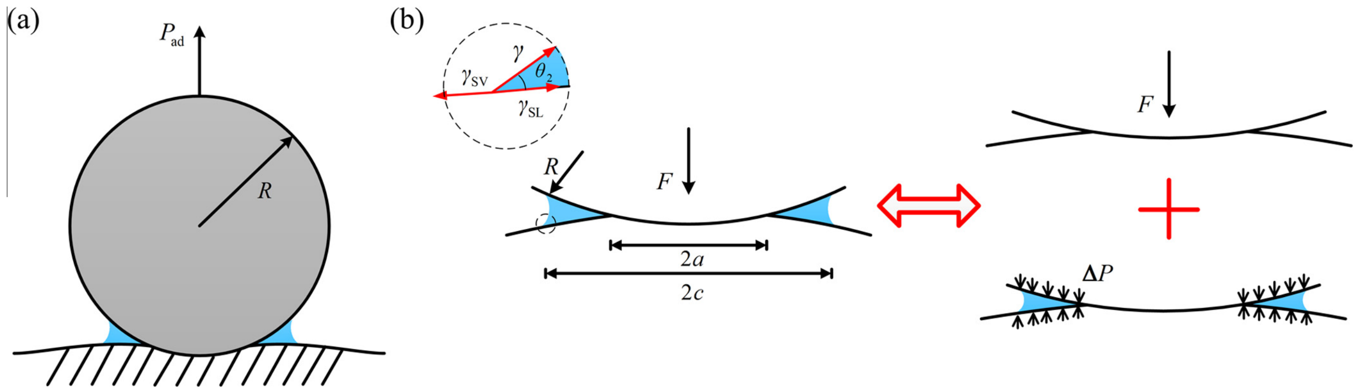

Fig. 1. (a) Schematic of the adhesion problem with combined dry contact area and liquid meniscus between a rigid particle and an elastic substrate. (b) The analytical model of combined dry and wet adhesion, as a superposition of external Mode I crack subjected to load F and uniform Laplace pressure ΔP, respectively.