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The ultratough peeling of elastic tapes from viscoelastic substrates

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ABSTRACT

The peeling of an elastic thin tape from a flat smooth viscoelastic substrate is investigated. Based on a Green function approach and on the translational invariance, a closed form analytical solution is proposed, which takes into account the viscoelastic dissipation in the substrate material.

We find that peeling is prevented from taking place, only when the external force is smaller than the one predicted by Kendall's formula for elastic tapes on rigid substrates. However, we also find that, regardless of the value of the applied force, steady state detachment may occur when the elastic tape is sufficiently stiff. In this case, the constant peeling velocity can be modulated by properly defining the geometrical parameters and the material properties of tape and viscoelastic foundation. On the other hand, for relatively high peeling angles or compliant tapes a threshold value of the peeling force is found, above which the steady-state equilibrium is no longer possible and unstable detachment occurs.

The present study contributes to shed light on the behavior of pressure sensitive adhesives in contact with viscoelastic substrates like the human skin. At the same time, it can be considered a first step towards a better understanding of the effect of viscoelastic dissipation on the fracture behavior of solids.

1. Introduction

The adhesion of contacting surfaces is frequently encountered in nature and technological applications. The interest in this field has seen, in the last years, a growing attention of the scientific community due to the countless number of biomimetic applications inspired to the adhesive behavior of the attachment pads of many biological species, which show wondrous abilities in adhering and/or moving on many types of surfaces. For instance, many insects, spiders and lizards are able to strong adhere to the substrate and, at the same time, to quickly move when necessary. Controlling such abilities is usually delegated to geometrical and material characteristics of the contacting surfaces. For example, the mushroom-shaped microstructures of the attachment pads of the males of some beetle species (Gorb and Varenberg, 2007) (from the family Chrysomelidae) provide them with extraordinary adhesive capacities. In such case, the shape of the terminal plate is crucial for the achievement of high adhesive strength values (Carbone et al., 2011; Carbone and Pierro, 2012; Afferrante and Carbone, 2013). In the insect *Tettigonia viridissima* the adhesive capacities are due to the ultrastructural architecture of the attachment pads (Gorb et al., 2000; Jiao et al., 2000). Inspired by this biological setal system, new architectures, constituted

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by protruding fibrils (Jagota et al., 2007) or microwalls (Afferrante and Carbone, 2012; Afferrante et al., 2015) topped by a thin film, have been proposed with the aim of obtaining significantly improved adhesive properties. The outstanding adhesive capacities of the Tokay Geckos are a consequence of the hierarchical structure of their toe pads (Liang et al., 2000; Smith and Callow, 2006; Dittmore et al., 2006), whose fibers are made of a stiff biomaterial (β-keratin) with Young's modulus 4 GPa (Persson, 2003) and have diameters from 0.2 to 5 μm (Arzt et al., 2003). Such specific structure and material properties allow the fibers to individually bend and adapt to any type of surface roughness and also to return to their original shape after release from the surface.

Peeling models have been applied to the gecko spatula, with the aim of understanding the mechanism of detachment (Huber et al., 2005; Tian et al., 2007; Chen et al., 2009; Peng et al., 2010; Lepore et al., 2012; Sauer, 2011; Wu et al., 2012; Tian et al., 2006). The key factor that governs the gecko mechanism of attachment/detachment is the adhesion angle, θ, between the terminal structure attached to the surface and the surface itself. Several experimental and theoretical studies have been developed to calculate the peeling force from a rigid substrate, when the tape is inextensible (Rivlin, 1944; Deryagin and Krotova, 1948), elastic (Lindley, 1978; Kendall, 1971, 1975; Anderson et al., 1976; Maugis, 2000; Afferrante et al., 2013; Putignano et al., 2014; Pugno, 2011) and viscoelastic (Truman, 1963; Yamamoto et al., 1975; Loukis and Aravas, 1991; Chen and Chen, 2013; Peng et al., 2014; Peng and Chen, 2015). Much less is known about the peeling of tapes from a viscoelastic foundation. This problem is of utmost importance in many practical applications, where pressure sensitive adhesives have to adhere to many dissimilar surfaces (Steven-Fountain et al., 2002; Czech and Kowalczyk, 2011), showing viscoelastic properties. A clear example is the adhesion of medical Band-aids on human skin, the latter being a highly non-linear and extremely compliant viscoelastic material (Christensen et al., 1977; Agache et al., 1980; Escoffier et al., 1989; Pereira et al., 1991; Edwards and Marks, 1995; Silver et al., 2001; Boyer et al., 2007). In such applications, adhesives must stick firmly but also must be easily and cleanly removed (Chivers, 2001). Adhesion on soft viscoelastic substrates has important peculiarities, which make it differentiate from the classical peeling on rigid substrates as shown in Fig. 1, where the peeling of a tape from human skin is compared to the peeling from a rigid substrate.

In this respect, some works may be found in the literature dealing with the adherence of pressure sensitive adhesive in contact with viscoelastic substrate mimicking human skin (Chivers, 2001; Renvoise, 2006; Renvoise et al., 2007, 2009; Lir et al., 2007; Plaut, 2010).

From a strictly science point of view, thin film peeling has largely used as an inspiration for the study of the relation between fracture energy and crack speed occurring in more complex fracture problems. For example, an open challenge is to explain quantitatively the phenomenon of cracks healing and growth in viscoelastic media (Schapery, 1989; Barber et al., 1989). The mechanics of viscoelastic crack propagation is a fairly complicated problem. In fact, in an elastic medium the equilibrium simply requires the energy release rate G at the crack tip is equal to the work of adhesion w, so crack growth and adhesion can be characterized by w alone. In a viscoelastic material, the situation is much different because the energy dissipation in the bulk makes G not easily to be defined and the quantity w does not completely describe the crack growth process (Xu et al., 1992; Baney and Hui, 1999). In particular, the energy dissipation depends on the viscoelastic properties of the bulk polymer, the temperature and the crack growth velocity (Gent and Schultz, 1972; Barquins, 1978; Gent, 1996; Brener, 2005; Carbone and Persson, 2005). The viscoelastic dissipation vanishes at very small or very large speeds, thus the energy dissipation is maximal at an intermediate characteristic velocity as also experimentally shown in Gent and Petrich (1969).

Here, by following the formulation given in Carbone and Putignano (2013), which is based on the Green function methodology developed in Carbone et al. (2009), Putignano et al. (2012), Putignano et al. (2012), Afferrante et al. (2012), Putignano et al. (2013), and Menga et al. (2016), we propose a new approach, which takes into account the effect of dissipation in the viscoelastic material. From this point of view, the present work is useful to better understand the influence of viscoelastic dissipation on the fracture behavior of solids.

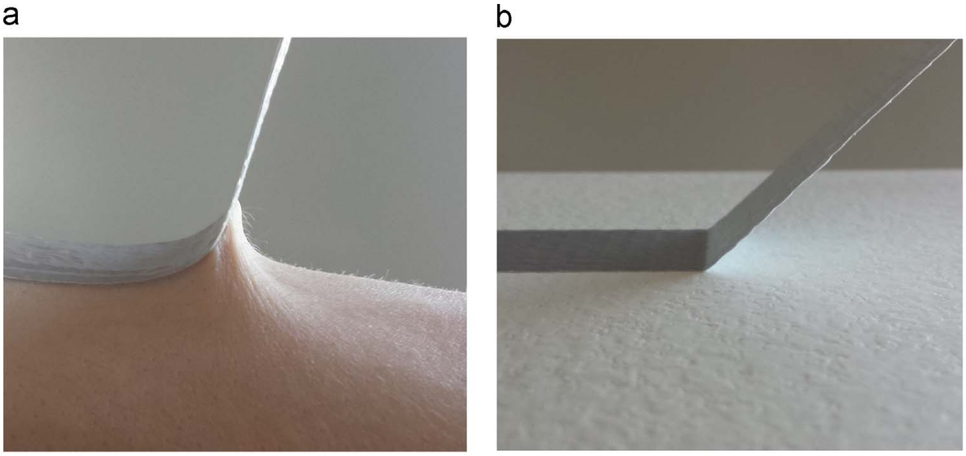

Fig. 1. Different peeling behavior of a tape on human skin (a), and rigid substrate (b).