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The multiple V-shaped double peeling of elastic thin films from elastic soft substrates

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ABSTRACT

In this paper, a periodic configuration of V-shaped double peeling process is investigated. Specifically, an elastic thin film is detached from a soft elastic material by applying multiple concentrated loads periodically distributed with spatial periodicity λ. The original Kendall's idea is extended to take into account the change in elastic energy occurring in the substrate when the detachment fronts propagate. The symmetric configuration typical of a V-peeling process causes the energy release rate to be sensitive to variations of the elastic energy stored in the soft substrate. This results in an enhancement of the adhesion strength because part of the external work required to trigger the peeling mechanism is converted in substrate elastic energy.

A key role is played by both spatial periodicity λ and elasticity ratio E/E_h, between tape and substrate elastic moduli, in determining the conditions of stable adhesion. Indeed, the presence of multiple peeling fronts determines a modification of the mechanism of interaction, because deformations close to each peeling front are also affected by the stresses related to the other fronts. Results show that the energy release rate depends on the detached length of the tape so that conditions can be established which lead to an increase of the supported load compared to the classical peeling on rigid substrates.

Finally, we also find that for any given value of the load per unit length, an optimum value of the wavelength λ exists that maximizes the tolerance of the system, before unstable propagation of the peeling front can occur.

1. Introduction

In the last decades, biological and biomechanical applications have boosted the interest in the adhesive contact of thin films, making it an important topic in contact mechanics (Afferrante and Carbone, 2013; Carbone et al., 2011; Dening et al., 2014; Ding et al., 2001; Jin, 2009; Menga et al., 2016a; Pesika et al., 2007; Pugno, 2011; Shanahan, 2000; Varenberg et al.,

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2010; Wan, 2001). In nature, several organisms show enhanced adhesion thanks to hierarchical structures of hairs or setae. For instance, hairy attachment systems of insects, arachnids and reptiles have been intensively studied during the past years, aiming at explaining and possibly mimic their extraordinary adhesive abilities in artificial bio-mimetic devices (Afferrante and Carbone, 2012; Afferrante et al., 2015; Carbone and Pierro, 2012a,b; Geim et al., 2003; Glassmaker et al., 2007; Gravish et al., 2008; Krahn et al., 2011; Murphy et al., 2011; Pugno, 2008).

To this regard, several studies have been devoted to soft elastic contacts in presence of adhesion (Carbone and Mangialardi, 2008; Hui et al., 2001; Menga et al., 2016a, 2018; Persson, 2003), and specifically to the detachment process (del Campo et al., 2007; Lee et al., 2008; Sekiguchi et al., 2015). Experimental observations of insects and spiders (Autumn et al., 2006b; Autumn and Peattie, 2002; Huber et al., 2005) and theoretical studies (O'Rorke et al., 2016; Ozer, 2016; Varenberg and Gorb, 2007) have made clear the crucial role played by highly flexible terminal spatula-shaped substructures attached to their legs, which finally allows them to easily climb on surfaces with different properties in terms of roughness and compliance.

The role of roughness is not yet completely understood. Several theoretical (Carbone and Mangialardi, 2004; Guduru, 2007; Persson, 2002), numerical (Carbone and Mangialardi, 2008; Carbone et al., 2016; Ciavarella et al., 2017; Wu, 2012) and experimental (Dies et al., 2015; Guduru and Bull, 2007; Martina et al., 2012a,b) studies have shown that high surface roughness reduces interfacial adhesion. However, some insects, like geckos, are able to achieve extremely high adhesive performance also on rough substrates. Some models have been proposed which attempt to explain this interesting behavior (Arzt et al., 2003; Huber et al., 2005; Persson, 2003; Pesika et al., 2007; Tian et al., 2006). For instance, in Ref. Tian et al. (2006), it is shown that high adhesion forces are obtained by rolling down and inward the toes to realize small peeling angle during the attachment. Detachment is instead obtained by rolling the toes upward and backward. Also, the gecko ability to remain stuck while inverted on the ceiling has been investigated in Refs. (Autumn et al., 2006a; Lepore et al., 2012). Those studies show that geckos use opposing feet and toes to prevent detachment of setae or peeling of toes.

Therefore, since the 50's, several studies have been devoted to understand the mechanism governing peeling (Barquins and Ciccotti, 1997; Kaelble, 1959, 1965; Kendall, 1975). Interest in practical applications, such as defining specific peeling tests standards to characterize the adhesive properties of joints involving thin films (ISO 8510-1, 1990; ISO 8510-2, 2006), has led researchers to focus on phenomena involved in peeling process. In this respect, a very comprehensive review is provided in Ref. (Creton and Ciccotti, 2016). About phenomena occurring at interface, several works have investigated the intrinsic bi-layered nature of typical commercial tapes (e.g. 3M Scotch), where the adhesive soft layer is backed to a thin stiffer one. In this case, during the peeling process a loss of confinement of the soft adhesive part gives rise to generation of a macroscopic debonding region characterized by fibrillar adhesive bridges and progressive bending deformation of the tape (Callies et al., 2016; Villey et al., 2017, 2015). It is also interesting to recall that when the adhering surfaces are rough, air pockets can remain trapped at the interface, depending on the material properties, the strength of adhesive interactions, and the topography of the surface (see, for example, Refs. (Creton and Leibler, 1996; Hui et al., 2000; Persson et al., 2004)). Moreover, in some cases, as the peeling process advances and the interface between the layers is interested by tensile stress, high speed camera images (see Ref. Lakrout et al., 1999) show nucleation and growth of cavities, near to the peak stress region, which make the layers deformation no longer homogeneous.

Such studies typically rely on the assumption of compliant films on rigid substrates. For a large class of practical applications, this hypothesis leads to physically realistic results. However, there exist several other applications, where a more proper formalism is required to take into account the effect of the substrate compliance on the detachment mechanism, as for instance studying the adhesive contact of medical Band-aids on human skin (Chivers, 2001; Kwak et al., 2011). In this case, indeed, the deformability of the substrate have to be taken into account, and although the skin is usually modeled as a very compliant viscoelastic material (Boyer et al., 2007; Edwards and Marks, 1995; Pereira et al., 1991; Silver et al., 2001), interesting results may be inferred neglecting viscous effects at low speeds, because in such case the behavior is essentially elastic (Menga et al., 2014, 2016b, 2017).

Moreover, dealing with deformable substrates, the specific geometrical configuration of the peeling system strongly affects the process evolution. As reported in Refs. (Bosia et al., 2014; Pugno, 2011; Wolff et al., 2015), specific patterns of multiple and opposite peeling fronts can be recognized in the detachment process of gecko's toes as well as in proximity of spider webs anchors (see Fig. 1). In these systems, the interaction between the elastic fields, generated by the multiple peeling fronts, plays a key role in determining the detachment behavior. Indeed, differently from the classical Kendall's peeling, where the mechanism of detachment is unaffected by the elastic properties of the substrate (Afferrante and Carbone, 2016; Kendall, 1975), in the V-shaped double peeling case translation invariance is lost. Consequently, as the peeling front advances, variation in the elastic energy stored in the substrate cannot be neglected. This entails a change in the external work required to trigger the detachment process, which in turn modifies the peeling mechanism.

We stress that for the first time it is made clear that the combined