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Experiments and viscoelastic analysis of peel test with patterned strips for applications to transfer printing

Hang Chen [a,b], Xue Feng [a,b,*], Yin Huang [a,b], Yonggang Huang [c,d,**], John A. Rogers [e]

[a] AML, Department of Engineering Mechanics, Tsinghua University, Beijing 100084, China
[b] Center for Mechanics and Materials, Tsinghua University, Beijing 100084, China
[c] Department of Civil and Environmental Engineering, Northwestern University, Evanston, IL 60822, USA
[d] Department of Mechanical Engineering, Northwestern University, Evanston, IL 60822, USA
[e] Department of Materials Science and Engineering, University of Illinois, Urbana, IL 60208, USA

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ABSTRACT

Transfer printing is an exceptionally sophisticated approach to assembly and micro-/nanofabrication that relies on a soft, elastomeric ‘stamp’ to transfer solid, micro-/nanoscale materials or device components from one substrate to another, in a large-scale, parallel fashion. The most critical control parameter in transfer printing is the strength of adhesion between the stamp and materials/devices. Conventional peel tests provide effective and robust means for determining the interfacial adhesion strength, or equivalently the energy release rate, and its dependence on peel speed. The results presented here provide analytic solutions for tests of this type, performed using viscoelastic strips with and without patterns of relief on their surfaces, and validated by systematic experiments. For a flat strip, a simple method enables determination of the energy release rate as a function of the peel speed. Patterned strips can be designed to achieve desired interfacial properties, with either stronger or weaker adhesion than that for a flat strip. The pattern spacing influences the energy release rate, to give values that initially decrease to levels smaller than those for a corresponding flat strip, as the pattern spacing increases. Once the spacing reaches a critical value, the relief self-collapses onto the substrate, thereby significantly increasing the contact area and the strength of adhesion. Analytic solutions capture not only these behaviors, as confirmed by experiment, but also extend to strips with nearly any pattern geometry of cylindrical pillars.

1. Introduction

Transfer printing is an exceptionally sophisticated approach to assembly and micro-/nanofabrication that relies on a soft, elastomeric ‘stamp’ to retrieve solid, micro/nanoscale materials or device components from one substrate to print on a target substrate, in a large-scale, parallel fashion (Carlson et al., 2012a). This scheme creates a wide range of application opportunities through its ability to separate requirements associated with source and receiver substrates, and to enable heterogeneous integration of dissimilar materials into well-controlled two and three dimensional architectures. Enabled

* Corresponding author at: AML, Department of Engineering Mechanics, Tsinghua University, Beijing 100084, China.
** Corresponding author at: Department of Civil and Environmental Engineering, Northwestern University, Evanston, IL 60822, USA.
E-mail addresses: fengxue@tsinghua.edu.cn (X. Feng), y-huang@northwestern.edu (Y. Huang).

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devices range from cameras that use biologically inspired designs to achieve superior performance (Ko et al., 2008; Jung et al., 2010), to surgical and diagnostic tools that naturally integrate with the human body to provide advanced therapeutic capabilities (Someya et al., 2004; Kim et al., 2010a, 2010b, 2011a, 2011b; Viventi et al., 2010, 2011). The key challenge in efficient operation of transfer printing is to enable mechanisms for switching the strength of adhesion to the surface of the stamp, from strong to weak to facilitate the first and second steps of the process. Several strategies have been developed:

1) *kinetically-controlled transfer printing* (Meitl et al., 2006; Feng et al., 2007): here, the stamp is retracted rapidly during the first step, and slowly during the second, to make use of the strong and weak adhesion that occurs in these two regimes due to viscoelasticity of the materials used for the stamps;
2) *surface-relief-assisted transfer printing* (Kim et al., 2010c; Wu et al., 2011; Kim et al., 2012; Yang et al., 2012): here, strategically design structures of surface relief, such as sharp, pyramidal microtips at appropriate spacings, enable large and small contact areas during the first and second steps, respectively, as a means to control adhesion;
3) *shear-enhanced transfer printing* (Carlson et al., 2011; Cheng et al., 2012): here, degree of shear loading controls initiation of cracks at the edges of contact areas; low and high loadings yield strong and weak adhesion, respectively;
4) *laser-driven transfer printing* (Li et al., 2012a, 2012b; Saeidpourazar et al., 2012): here, a laser pulse creates local heating at the interface, to initiate separation by forces that arise from the large mismatch in coefficients of thermal expansion in the stamp and adhered materials/devices; and
5) *pneumatic-driven transfer printing* (Carlson et al., 2012b): here, the adhesion is modulated by pressurizing microchannels near the surface of the stamp, to affect release.

In all schemes, the mechanics and materials science associated with interfacial adhesion are critically important. Generally, the adhesion force is a constant (not "tunable") for an interface between two elastic materials, but may depend on the speed of interfacial delamination if one (or both) of the constituent(s) is (are) viscoelastic (Gent and Schultz, 1972; Maugis and Barquins, 1978; Tsai and Kim, 1993; Barquins and Ciccotti, 1997; Barthel and Roux, 2000). Surface textures that mimic gecko foot-hairs, can substantially increase the adhesion. Gao and Yao (2004) and Yao and Gao (2006) identified the basis mechanism of robust and releasable adhesion in biology. Geim et al. (2003) demonstrated that arrays of circular pillars can yield non-specific adhesion capable of supporting large weights. Substantial increase of adhesion has also been observed in the indentation experiments of arrays of circular pillars (Crosby et al., 2005), and in the peel tests of arrays of circular (Lamblet et al., 2007; Poulard et al., 2011), square and triangular pillars (Lamblet et al., 2007). Such approaches have been successfully applied in transfer printing (Kim et al., 2010c; Kim et al., 2012; Yang et al., 2012). Quantitative study of these and related effects by Arzt et al. (2003) in the context of gecko foot-hairs and by Persson and Gorb (2003) and Hui et al. (2005) in the context of patterned strips used the JKR model (Johnson et al., 1971). Such models, however, all assume linear elastic behavior in the materials. Such assumptions may not be valid for viscoelastic materials such as polydimethylsiloxane (PDMS) which is widely used in transfer printing; in fact, viscoelasticity is critically important for the kinetically-controlled and surface-relief-assisted schemes outlined above.

The peel test provides an effective and robust method to determine the adhesion strength of an interface between an elastic strip and an elastic substrate (Kendall, 1975; Brown, 1991; Gent, 1996). As illustrated in Fig. 1, a peel force (at a given peel angle) delaminates the strip from the underlying substrate. For steady-state peeling, the interfacial adhesion strength is obtained analytically from the measured peel force based on energy balance (Spies, 1953; Bikerman, 1957; Kaeble, 1959, 1960; Jouwersma, 1960; Yurenka, 1962; Gardon, 1963; Kendall, 1973; Nicholson, 1977). Such an approach has been extended to an elastic–plastic strip (e.g., Kim and Aravas, 1988; Kim et al., 1989), but is not readily applicable to peeling of a viscoelastic strip.

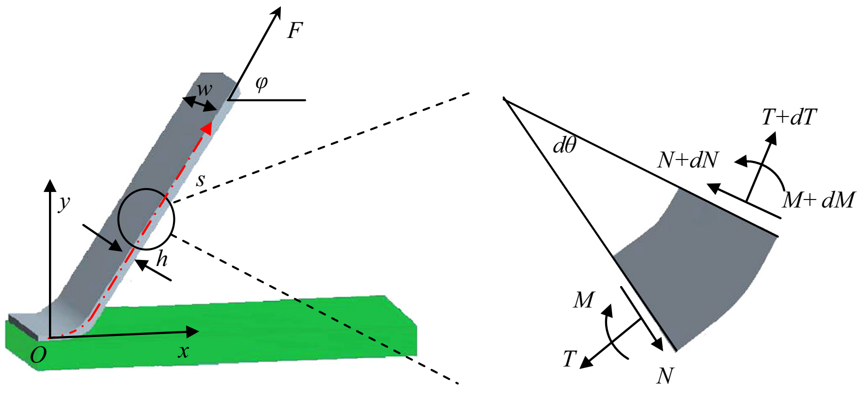

Fig. 1. Schematic illustration of an elastomeric strip in the peel test.