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A theoretical model of reversible adhesion in shape memory surface relief structures and its application in transfer printing

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ABSTRACT

Transfer printing is an important and versatile tool for deterministic assembly and integration of micro/nanomaterials on unusual substrates, with promising applications in fabrication of stretchable and flexible electronics. The shape memory polymers (SMP) with triangular surface relief structures are introduced to achieve large, reversible adhesion, thereby with potential applications in temperature-controlled transfer printing. An analytic model is established, and it identifies two mechanisms to increase the adhesion: (1) transition of contact mode from the triangular to trapezoidal configurations, and (2) explicit enhancement in the contact area. The surface relief structures are optimized to achieve reversible adhesion and transfer printing. The theoretical model and results presented can be exploited as design guidelines for future applications of SMP in reversible adhesion and stretchable electronics.

1. Introduction

Transfer printing, as an emerging technique for assembly and integration of two and three dimensional structures of heterogeneous materials at micro/nanoscale, has many important applications in the classes of stretchable/flexible electronic and optoelectronic systems that combine rigid inorganic and deformable organic materials (Meitl et al., 2006; Yoon et al., 2008; Fan et al., 2009; Jeong et al., 2009; Murphy et al., 2009; Park et al., 2009; Carbone et al., 2011; Fakhr et al., 2011; Fang et al., 2011; Guillon et al., 2012; Huang et al., 2012; Xu et al., 2013b; Zhang et al., 2013; Fan et al., 2014; Zhang et al., 2014). Examples of stretchable/flexible systems with functionalities not addressable using previously established technologies include "epidermal" health/wellness monitors (Yu et al., 2012; Kaltenbrunner et al., 2013; Schwartz et al., 2013; Xu et al., 2014), eyeball-like digital cameras (Ko et al., 2008; Song et al., 2013), and sensitive robotic skins (Someya et al., 2004;

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Wagner et al., 2004; Mannsfeld et al., 2010; Lu et al., 2012). Transfer printing typically involves the use of a soft elastomeric stamp to transfer solid micro/nanostructured materials (i.e., "inks") from the (donor) substrate where they are generated or grown onto a different (receiver) substrate for device integration (Meitl et al., 2006; Feng et al., 2007; Kim et al., 2010; Carlson et al., 2012a). Several types of transfer printing technologies have been proposed: (1) kinetically controlled transfer printing (Meitl et al., 2006; Feng et al., 2007; Park et al., 2009; Packard et al., 2010; Qi et al., 2011): the viscoelastic stamp is adopted to pick up the micro-devices rapidly and then to print them slowly onto the receiver substrate, enabled by the high and low adhesion strengths at the large and small peeling rates, respectively; (2) surface-relief-assisted transfer printing (Kim et al., 2010; Wu et al., 2011b): surface relief structures (e.g., microtips) are fabricated at the stamp surface to render large surface contact with the inks (and therefore large adhesion force) during pick-up, and small contact area during printing; (3) load-enhanced transfer printing (Kim et al., 2009; Carlson et al., 2011, 2012b): the mechanical loading protocols, such as the directional shearing at the interface and the pressure actuation of a thin elastomeric membrane through microfluidic channels, are employed to enable large and small adhesion forces during pick-up and printing, respectively; (4) laser-driven transfer printing (Li et al., 2012; Saeidpourazar et al., 2012): a laser pulse is adopted during printing to induce large thermal mismatch between the stamp and micro-devices, and therefore initiate separation at the adhesive surface. The key enabling technology of transfer printing is the active control over the interfacial adhesion between the stamp and micro-devices.

Shape memory polymer (SMP) is a type of smart material that can memorize temporary shapes and revert to its permanent shape upon exposure to an external stimulus such as heat (Liu et al., 2007; Yu et al., 2014), light (Koerner et al., 2004; Lendlein et al., 2005), or moisture (Huang et al., 2005a). Several representative mechanics models (Nguyen et al., 2008, 2010; Qi et al., 2008; Long et al., 2009; Ge et al., 2012; Yu et al., 2012; Long et al., 2013) have been established to analyze the underlying mechanisms and stress–strain curves associated with the shape memory effect. When combined with surface relief structures of various patterns (e.g., microprism array, microlens, transmission gratings, which can be fabricated using the technique of compression molding) (Xu et al., 2013a), the shape memory effect can be employed to manipulate the micro-optical performances via temperature change. However, the use of SMP in tuning the interfacial adhesion has been rarely explored. Recently, Eisenhaure et al. (2013) demonstrated experimentally that reversible dry adhesion can be achieved by exploiting the shape memory effect and surface microstructuring, but no theoretical analysis has been reported and the underlying physics is still far from clear. In this paper, a theoretical model is developed for the interfacial adhesion between the microstructured stamp in a general trapezoidal shape and a flat micro-device. The analytic solution of design optimization is obtained for the surface relief structure to maximize the difference of adhesion before and after temperature actuation. Furthermore, the application of this concept in temperature controlled transfer printing is illustrated, which could facilitate automatic operation and selective printing.

2. Design of shape memory surface relief microstructures for reversible adhesion and transfer printing

Fig. 1 illustrates the surface relief structures made of a temperature stimulated SMP that is capable of memorizing one temporary shape, corresponding to dual-shape memory effect (Liu et al., 2007; Xie, 2010). Generally, the shape memory effect can be realized through the glass transition, melting transition, strain induced crystallization transition, etc. In this study, we will focus on the category of SMP realized through melting transition, since melting transition usually gives a sharper recovery event than glass transition (Liu et al., 2007; Ratna and Karger-Kocsis, 2008). For this type of material, there exists a transition temperature T_m (i.e., the melting point) above which the SMP restores its permanent shape. At high temperature ($>T_m$) the permanent configuration of SMP can be deformed into a prescribed configuration by external loads. After cooling down to room temperature ($<T_m$) this deformed configuration can be maintained even when the loads are

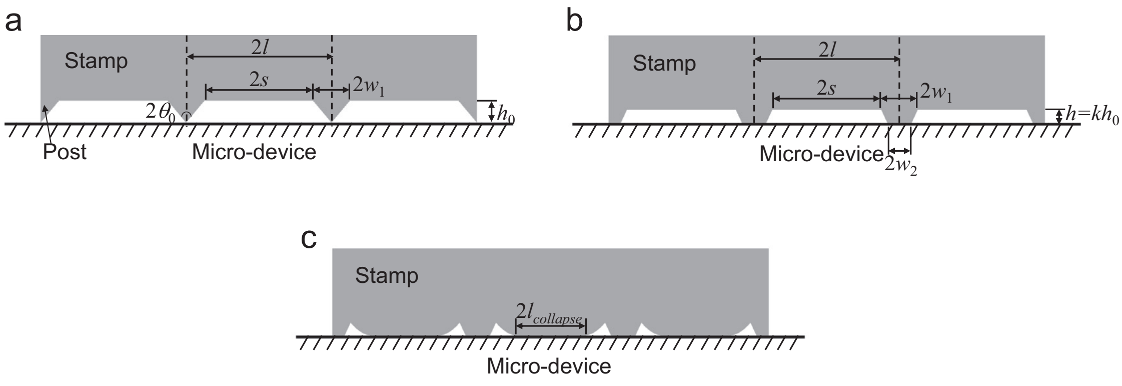

Fig. 1. Schematics of the microstructured stamp in contact with the flat surface of the micro-device. (a) The permanent configuration of the stamp with triangular posts in the absence of roof collapse; (b) the temporary configuration of the stamp with trapezoidal posts in the absence of roof collapse; and (c) the temporary configuration of the stamp with trapezoidal posts in the mode of roof collapse.