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Technical paper

Multi-physics modeling for laser micro-transfer printing delamination

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ABSTRACT

Micro-transfer printing technology is rapidly emerging as an effective pathway for large-scale heterogeneous materials integration. In its basic embodiment, micro-transfer printing is used to deterministically transfer and micro-assemble prefabricated structures/devices, referred to as "ink," from a donor substrate to a receiving substrate using a viscoelastic elastomer stamp, usually made out of polydimethylsiloxane (PDMS). Laser Micro Transfer Printing (LMTP) is a laser-driven non-contact variant of the process that makes it independent of the receiving substrate's properties, geometry, and preparation. In this paper, an opto-thermo-mechanical model is developed to understand how the laser beam energy is converted to thermally-induced strains around the ink-stamp interface to initiate the ink delamination process. The opto-thermo-mechanical model is developed based on decoupling the optical absorption physics from the thermo-mechanical model physics. An optical absorption model for the laser beam energy absorbed by the ink is first developed and verified experimentally to estimate the heating rates of the ink-stamp system, which in turn are used as an input for a couple thermo-mechanical Finite Element Analysis (FEA) model. Further, high speed camera recordings for LMTP delamination are used to calibrate the thermo-mechanical model and verify its predictions. Besides providing a fundamental understanding of the delamination mechanism and the LMTP process capabilities, the developed opto-thermo-mechanical model is useful in selecting process parameters (laser pulse duration, stand-off distance), estimating the ink-stamp temperature rise during the LMTP process, and quantifying and decomposing the stresses at the ink-stamp interface to its main sources (Coefficient of Thermal Expansion (CTE) mismatch and thermal gradient strains).

1. Introduction

Micro-transfer printing, due to its simplicity, accuracy, repeatability, and large-area substrate printing capabilities, is rapidly emerging as an effective method to enable large-scale heterogeneous materials integration (examples shown in Fig. 1 [1–6]). In its basic embodiment, micro-transfer printing is used to deterministically transfer and micro-assemble prefabricated structures/devices, referred to as "ink," from a donor substrate to a receiving substrate. The mechanism of ink pick-up and release is based on modulating the adhesion energy kinetically between the ink and a viscoelastic elastomer stamp [7], usually made out of polydimethylsiloxane (PDMS). To enhance and extend the transfer printing technology capabilities and performance, several contact mode variants of the process have been introduced by modifying the stamp's geometry (patterned stamps [8], pedestal-shaped stamps [9], and microtipped stamps [1]) or enhancing the transfer mechanism (shear-enhanced [10] and fluidic-chamber actuated [11]). Recently, Laser Micro Transfer Printing (LMTP) has been introduced [12,13] to enable non-contact printing, allowing the transfer printing performance to become independent of the receiving substrate's properties, preparation, and geometry (examples shown in Fig. 2). The LMTP printing cycle starts by selectively picking-up ink from a donor substrate with a patterned PDMS stamp (Fig. 3a and b), then positioning the ink above a desired location on the receiver substrate at a stand-off height (Fig. 3c), and then pulsing a laser to drive the release of the ink from the stamp (Fig. 3d). Since the ink pick-up and transfer steps are similar to micro-transfer printing, the LMTP process is different in terms of the release mechanism that is based on generating laser-induced thermo-mechanical stress at the ink-stamp interface. A NIR laser beam (805 nm wavelength with ~700 μm spot size) is transmitted through the glass stamp holder and the PDMS stamp and absorbed by the ink, usually Si or GaAs. The laser beam power absorbed by the ink heats the ink which, in turn, transfers heat to the PDMS stamp, raising the ink-stamp interface temperature. Due to the low thermal conductivity of the PDMS, a localized

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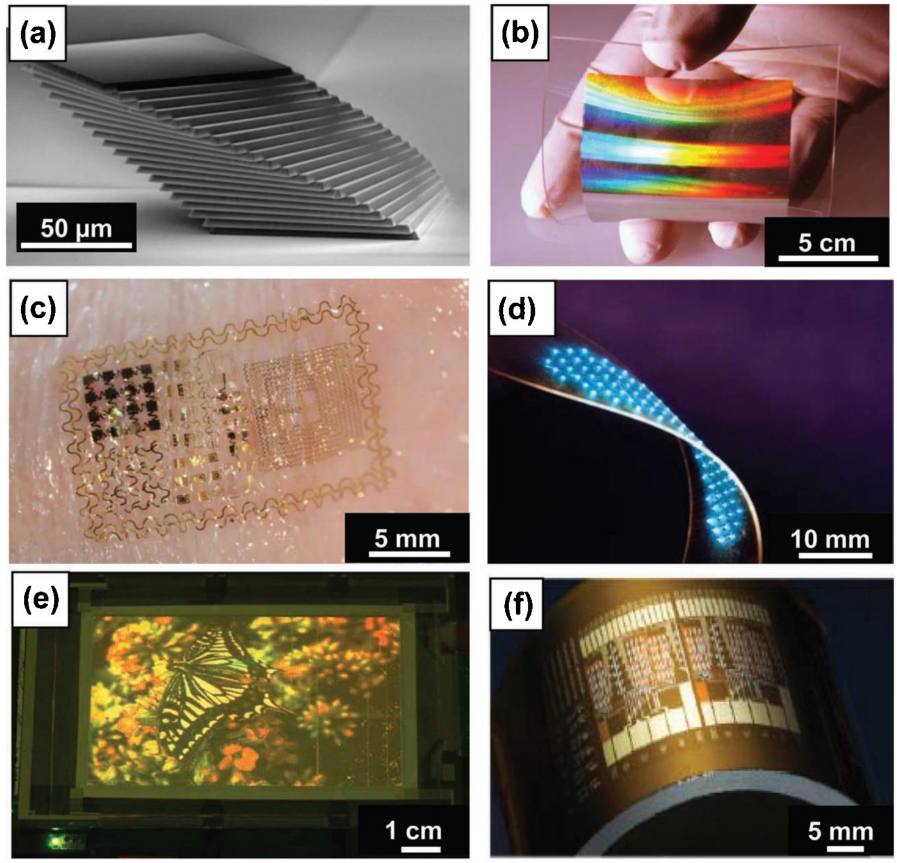

Fig. 1. Examples of uncommon constructs, devices and integrated systems realized by micro transfer printing. (a) SEM image of a printed multilayer stack of silicon platelets [1]. (b) Photograph of a large area (10 cm × 10 cm) negative index metamaterial (NIM) comprised of alternating layers of Ag and MgF_2 in a nano-scale fishnet pattern printed onto a flexible substrate [2]. (c) Photograph of an 'epidermal' electronic device, conformally laminated onto the surface of the skin. (d) Image of a mechanically flexed array of ultrathin, micro-scale, blue LEDs printed from a source wafer onto a thin strip of plastic [3]. (e) Picture of a 4-inch, full-color quantum dot (QD) LED display [4]. (f) Photograph of a flexible integrated circuit that uses printed networks of single walled carbon nanotubes for the semiconductor [5].
Composite figure taken from [6].

hot zone is developed in the PDMS in the vicinity of the ink-stamp interfaces. The PDMS in this zone expands because of its large CTE (310 ppm/°C). Constrained by the silicon ink (CTE 2.6 ppm/°C) and the surrounding unheated PDMS, this expansion is accommodated by the development of a curvature or bulge at the contact interface. The curvature gives a rise to a bending moment that stresses the ink-stamp interface normal to the interface direction (opening mode) and along the interface (shear mode). Further, the sharp

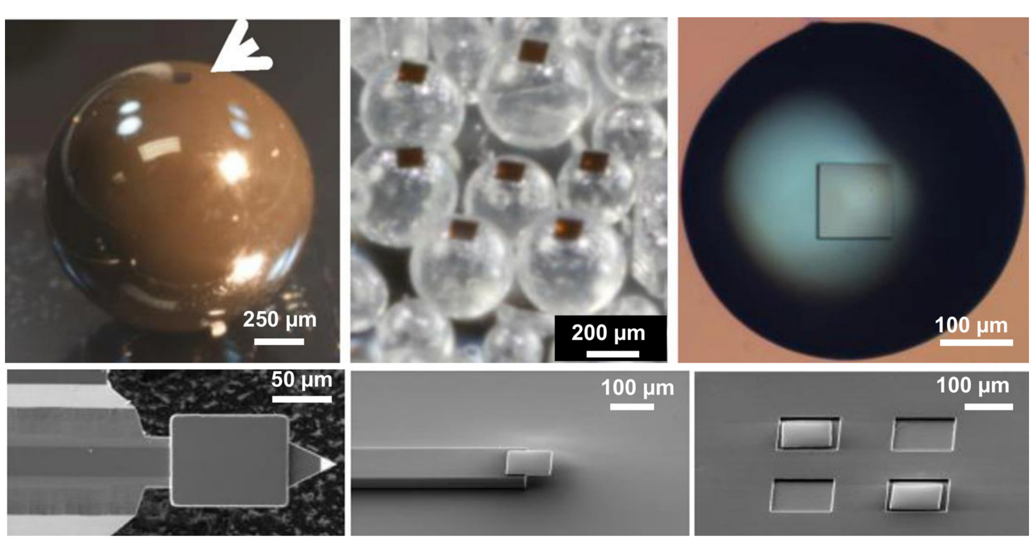

Fig. 2. Examples of printing on different surfaces, (left-top) printing on a single 1 mm ceramic sphere, (middle-top) printing on a non-uniform array of 500 μm silica beads, (right-top) printing on to a liquid NOA droplet, (left-bottom) a silicon square printed on to a AFM cantilever, demonstrating assembly on an active structure, (middle-bottom) printing on a ledge, and (right-bottom) printing into recessed spaces. (Scale: in all the micrographs, the printed squares have sides of 100 μm) [8].