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Mechanics of magnet-controlled transfer printing

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A recently developed magnet-controlled dry adhesive, which offers rapidly tunable and highly reversible adhesion in both air and vacuum, is valuable to develop the magnet-controlled transfer printing for heterogeneous materials integration. An analytical mechanics model based on the energy method is developed to identify the underlying mechanism of the magnet-controlled transfer printing and to predict the interfacial delamination between the magnet-controlled stamp and the ink in the applied magnetic field. The analytical predictions agree well with experiments. The influences of the magnetic pressure, material properties, and geometric parameters of the stamp on the adhesion strength are fully investigated. The critical condition for non-contact printing, validated by experiments, is obtained to eliminate the constraints from the receiver substrate. These results may serve as the theoretical basis for stamp optimization, especially for determining optimal condition for the magnet-controlled transfer printing.

1. Introduction

Transfer printing, which utilizes a soft stamp to transfer inks (or solid objects) from a donor substrate to a receiver substrate, is an emerging technique for materials assembly and has attracted much attention [1–3] due to its valuable applications in the development of unconventional devices such as stretchable electronics [4–9], epidermal electronics [10–13], curvilinear electronics [14–16] and many others [17–20]. A typical transfer printing procedure involves two steps: the retrieval process to pick up the inks from the donor substrate and the printing process to deliver the inks onto the receiver substrate. Since the retrieval process requires a strong stamp/ink adhesion to ensure the pick-up of the inks from the donor substrate while the printing process requires a weak stamp/ink adhesion to ensure the release of the inks from the stamp, the successful transfer printing critically relies on the interfacial adhesion strength modulation. Several strategies have been explored to realize the interfacial adhesion strength modulation by controlling external physical stimuli (e.g., speed, laser and force) [21–26]. For example, kinetically controlled transfer printing takes advantage of the stamp viscoelasticity to pick up inks with a large peeling rate and print inks with a small peeling rate [21,27,28]. Laser-driven non-contact transfer printing induces a large interfacial thermal mismatch by introducing a laser pulse to separate the inks from the stamp [22,23,29,30]. Gecko-inspired transfer printing is based on the bio-inspired fibrillar surface micro-structures on the stamp with the manipulation of the retraction angle or lateral forces [24,25,31].

Recently, a simple yet robust design of magnet-controlled dry adhesive, where the magnetic particles are filled in the reservoirs in an elastomer body and encapsulated by a surface membrane, with rapid tunability and high reversibility was reported [32]. The localized bulge of the adhesive membrane hence the adhesion can be tuned by the magnetic field. The adhesion is rapidly tunable due to the fast response of the magnetic particles to the magnetic field and highly reversible such that it provides a universal tool to develop a high-yield magnet-controlled transfer printing for deterministic assembly.

Fig. 1 illustrates the typical process of the magnet-controlled transfer printing. During the retrieval process as shown in Fig. 1A, the magnetic field is off and the stamp membrane remains flat, which enables a conformal contact between the stamp and the ink. Rapid retraction of the stamp can maximize the adhesion and ensure the reliable pick-up of the ink. Upon printing as shown in Fig. 1B, the inked stamp is firstly brought into contact with the receiver substrate, and then retracted in the applied magnetic field. While exposed to the magnetic field, the magnetic particles are magnetized to induce a magnetic pressure on the stamp membrane. As the retraction reaches a certain limit, the membrane starts to peel at the outer perimeter and propagates to the center to form a bulge in a controlled manner, thereby decreasing the contact between the stamp and the ink, and reducing the interfacial adhesion.

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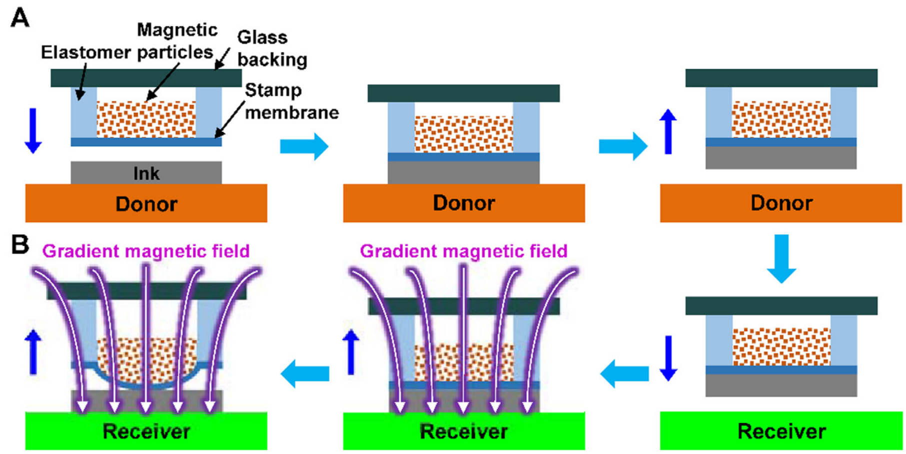

Fig. 1. Schematic illustration of the typical process of the magnet-controlled transfer printing. (**A**) During the retrieval process, the ink is picked up after the conformal contact between the stamp and the ink. (**B**) During the printing process, the stamp is retracted in the applied magnetic field.

An analytical mechanics model based on the energy method is developed to identify the underlying mechanism of the magnet-controlled transfer printing and to predict the interfacial delamination between the magnet-controlled stamp and the ink in the applied magnetic field. The influences of the magnetic pressure, material properties and geometric parameters of the stamp on the adhesion strength are fully investigated. The analytical model, validated by experiments, is very useful to provide design guidelines to optimize the stamp for the magnet-controlled transfer printing.

2. Mechanics model

2.1. Potential energy and stamp configuration evolution

Fig. 2 shows the cross-sectional illustration of the magnet-controlled stamp during the retraction process in the magnetic field (Fig. 2A) and the corresponding mechanics model (Fig. 2B). The stamp reservoir incorporates a cylindrical cavity (with the radius of L, the height of H) in a square elastomer block (with the side length of $2(L+A_R)$ and the height of H), and the reservoir width on the central cross-section is A_R. The stamp membrane is square with the in-plane size of $2(L+A_R)\times 2(L+A_R)$ and the thickness of h. The magnetic pressure on the stamp membrane due to the applied magnetic field is denoted by p_m, which is defined as the resultant magnetic force distributed over the surface area of the stamp membrane within the stamp cavity. The applied displacement on top of the stamp reservoir through the glass backing is denoted by v. A two-dimensional analytical mechanics model based on the energy method is developed to study the interfacial delamination between the stamp and the ink to simplify the analysis considering that the reservoir radius L is usually much larger than its width A_R. This mechanics model is similar to the previously reported one for an inflatable stamp [33], but quite different in geometry and loading conditions. For example, there is a bulk region between the stamp reservoir and the glass backing for the inflatable stamp [33] but for the magnet-controlled stamp, the stamp reservoir is directly bonded with the glass backing [32], thus the displacement applied on top of the stamp reservoir is equal to the displacement applied on the glass backing. For the inflatable stamp [33], the pressure is applied through an air pump thus the pressure is exerted in all directions, while for the magnet-controlled stamp, the magnetic pressure only exists in the vertical direction [33]. These differences require a new mechanics model for the magnet-controlled stamp to avoid the complex derivations. During the printing process with the increase of the displacement v, the stamp/ink system takes three deformed configurations: the stretch (no delamination) configuration, partial delamination configuration, and total delamination configuration as shown in Fig. 2B. Since the pull-off force (or the adhesion strength) can be determined by comparing the potential energies for the stretch and partial delamination configurations, we will focus on the derivation of the potential energies for these two configurations below.

For a small displacement v, the interfacial adhesion between the stamp membrane and the ink prevents the interfacial delamination and only the stamp reservoir is stretched. The system can be modeled as a column under uniaxial tension (Fig. 2B). The potential energy of the system is equal to the strain energy of the stamp reservoir and is obtained as

$$\Pi_1 = \frac{E_R A_R H}{2}\left(\frac{v}{H}\right)^2, \tag{1}$$

where H, A_R and E_R are the height, width and Young's modulus of the reservoir.

As the applied displacement increases, the stamp membrane begins to delaminate from the ink with l as the delamination length. The system can be treated as a double clamped beam subjected to the applied displacement v and the magnetic pressure p_m (Fig. 2B). This is a statically indetermined system and can be solved by the superposition of the solutions for the following two problems: (1) a horizontal cantilever beam subjected to a uniform pressure p_m on the top, a concentrated force P and a moment M at the right end; (2) a vertical cantilever beam clamped at one end and subjected to a lateral load Q, a concentrated force P and a moment $M - Q \times H$ at the other end. Neglecting the axial force in the horizontal beam and thus the elongation, deflection and rotation of the horizontal beam at the right end are given by

$$\begin{aligned} u_1 &= 0, \textit{right} \\ v_1 &= \frac{Pl^3}{3E_M I_M} - \frac{Ml^2}{2E_M I_M} - \frac{p_m l^4}{8E_M I_M}, \textit{up} \\ \theta_1 &= -\left(\frac{Pl^2}{2E_M I_M} - \frac{Ml}{E_M I_M} - \frac{p_m l^3}{6E_M I_M}\right), \textit{clockwise} \end{aligned} \tag{2}$$

where E_M and I_M are the Young's modulus and moment of inertia of the stamp membrane, and l is the delamination length (i.e., the length of the horizontal beam). The deflection, elongation and