Self-folding of polymer sheets using local light absorption†

Ying Liu, Julie K. Boyles, Jan Genzer and Michael D. Dickey*

Received 16th August 2011, Accepted 13th October 2011
DOI: 10.1039/c1sm06564e

This paper demonstrates experimentally and models computationally a novel and simple approach for self-folding of thin sheets of polymer using unfocused light. The sheets are made of optically transparent, pre-strained polystyrene (also known as Shrinky-Dinks) that shrink in-plane if heated uniformly. Black ink patterned on either side of the polymer sheet provides localized absorption of light, which heats the underlying polymer to temperatures above its glass transition. At these temperatures, the predefined inked regions (i.e., hinges) relax and shrink, and thereby cause the planar sheet to fold into a three-dimensional object. Self-folding is therefore achieved in a simple manner without the use of multiple fabrication steps and converts a uniform external stimulus (i.e., unfocused light) on an otherwise compositionally homogenous substrate into a hinging response. Modeling captures effectively the experimental folding trends as a function of the hinge width and support temperature and suggests that the hinged region must exceed the glass transition temperature of the sheet for folding to occur.

Introduction

This paper describes a simple approach for converting two-dimensional (2D) patterns on polymer sheets into 3D objects. Conventional high-throughput patterning techniques (i.e., photolithography, screen printing, and inkjet printing) are inherently 2D. However, the ability to convert 2D patterns into 3D structures is attractive for a number of applications, including assembly, packaging, and mechanical actuation. Self-folding is a deterministic assembly process that causes a predefined 2D template to fold into a desired 3D structure with high fidelity. Self-folding has been used for robotic actuators and sensors, containers for drug delivery and biological devices, and reconfigurable devices.

The general strategy for self-folding involves defining hinges on planar surfaces that fold in response to an external stimulus. Previous efforts for self-folding have been accomplished by harnessing various forces including surface tension, intrinsic residual stress of thin films, and stress generated by external stimuli (e.g., magnets, pneumatics, swelling, heat, and light). Thermal actuation, the approach used here, represents a particularly attractive strategy because of its simplicity and the availability of thermal triggers (i.e., light, Joule heating, and thermal radiation).

Most examples of self-folding employ hinges that actuate when the substrate is exposed evenly to an external stimulus. Hinges can be defined in shape memory polymers (SMPs) that return to a pre-programmed shape when a certain critical temperature is exceeded (cf. Fig. 1a). SMPs have been designed and synthesized to respond to various stimuli, including light and heat. The use of SMPs typically requires processing at elevated temperatures and necessitates pre-programming the desired shape (in contrast, our approach induces a SMP to fold into shapes that are not pre-programmed in the SMP). An alternative approach is to define hinges composed of a material (or stack of materials) that differs from the bulk substrate such that only the hinges respond to a uniform stimulus (cf. Fig. 1b). Examples include polyimide hinges that shrink at temperatures >500 °C and shape memory metal alloys that actuate with resistive heating. These methods require multiple fabrication steps to define the hinges since they must differ in chemical composition from the folding ‘panels’. Multilayer film stacks (cf. Fig. 1c) with different thermal expansion coefficients or swelling ratios can also be employed as hinges.

Our approach to self-folding (cf. Fig. 1d) employs localized absorption of light from an inexpensive infrared (IR) light bulb on an otherwise compositionally homogenous sheet of shape memory polymer to convert a uniform external triggering stimulus (i.e., unfocused light) into a hinging response. This approach uses mass-produced materials without the use of multiple fabrication steps. Black ink defines the hinges, which can be patterned, in principle, by nearly any conventional printing process; we chose to use a desktop printer out of simplicity. The polymer directly underneath the ink heats rapidly to exceed the glass transition temperature (T_g) of the polymer. As a result, the hinged regions relax and bend the sheet. Bidirectional folding (i.e., folding both toward the light source and away from the...
source) can be realized by patterning black ink on opposite sides of the polymer film as schematized in Fig. 1d.

We use sheets of inkjet printable Shrinky-Dinks, commercially available toys composed of pre-stressed polystyrene shrink sheets (the printable versions of Shrinky-Dinks include a proprietary surface coating to improve adhesion of ink or toner).

Pre-stressed polymer sheets are essentially shape memory materials that are fabricated by heating the polymer above $T_g$, stretching, and subsequently cooling below $T_g$ to preserve the deformed shape.

As a consequence of such processing, the stress stored temporarily in the sheets releases rapidly when heated above the $T_g$ (e.g., sheets of Shrinky Dinks contract in-plane by 50–60% in both the x and y dimensions; cf. Figure S1 in the supporting information†). Shrinky-Dinks have been used previously as substrates for the fabrication of microfluidic chips, the densification of metal microdot arrays, and the topographical patterning of surfaces. All of these applications make use of uniform heating of Shrinky-Dinks to cause the entire film to shrink. In contrast, our self-folding process requires rapid local heating of the hinges to induce self-folding. We achieve hinging without doing any shape pre-programming by selectively heating ink patternsed regions of the sheets. In this paper, we demonstrate and characterize this simple self-folding process experimentally and present a simple theoretical model that provides insight into the folding mechanism.

**Results and discussion**

We patterned black toner on Shrinky-Dinks using a desktop printer and induced folding by placing the sheets under an IR light bulb at a set distance (5 cm from the lamp). The samples folded typically within seconds upon exposure to the light (cf. Video S1 in the supporting information†). The onset of folding and the time required to complete folding depends on the intensity of the IR light (fixed in our experiment at 988 mW cm$^{-2}$), the hinge width ($w$), and the temperature ($T_s$) of the base support (e.g., a hot plate on which the 2D patterned sheet rested during the IR light exposure). The folding angle ($\alpha_f$, the angle between two adjacent facets on the inked side of the hinge) can be controlled by varying the exposure time to light and the shape, size, and pattern of the inked region that defines the hinge. For clarity, we note that $\alpha_f$ is related complementarily to the angular displacement of the fold, $\alpha_B$, by $\alpha_f = 180^\circ - \alpha_B$. For instance, to achieve a folding angle of 60°, the originally flat sheet has to bend by 120°.

Fig. 2a–c depict three examples of 3D folds generated via our approach. The left column depicts the 2D patterns before irradiation with IR light and the right column displays the corresponding 3D structures after self-folding. Fig. 2b–c demonstrate bidirectional folding of patterned Shrinky-Dinks; black ink patterned on the backside of the sheet absorbs the IR light that passes through the sheet (The sheets are slightly hazy due to light scattering, but transmit light effectively as shown in Figure S1). Measurements using an integrating sphere attachment on a UV-Vis spectrometer show ~90% transmission.). White Shrinky-Dinks featuring patterns of black lines also undergo unidirectional self-folding, but bidirectional folding requires transparent substrates.

Self-folding can form 3D structures, including rectangular and polyhedral boxes, as shown in Fig. 2d–f. The folding angle generated by a single hinge is typically 90°, which is convenient for forming boxes. The folding angle can, however, range from 60° to 90° depending on the duration of exposure to light and the width of the hinge (cf. Table S1 in the supporting information†). We created tetrahedrons by defining hinges with folding angles of 60° (cf. Fig. 2e). Single line hinges with line widths narrower than 2 mm result in folding angles larger than 60° and thus incomplete closing of the tetrahedron. This limitation can be overcome by increasing the width of the printed line (cf. Fig. 2e). Alternatively, adjacent parallel lines (cf. Fig. 2f) also produce hinges that possess small folding angles (cf. Table S2 in the supporting information†). These empirical results suggest that various 3D structures can be realized by controlling the line width and pattern of the hinge.

We measured the surface temperature of the polymer sheet as a function of time during exposure to light using an IR camera (FLIR A325). The measurements reveal that folding begins when
the surface of the hinge exceeds 120 °C (cf. Figure S2 in the supporting information†), which is above Tg of the polymer sheet (≈102.7 °C, as measured by differential scanning calorimetry). At temperatures above Tg, the polymer starts relaxing to obtain sufficient shrinkage for folding. Notably, the temperature of the non-patterned regions of the polymer does not change significantly in most cases (e.g., a sheet pre-heated to 80 °C stays within the range of 80–90 °C during folding).

We performed systematic experimental measurements to study the impact of the line width and the temperature of the support on the onset of folding. For these studies, we define the ‘onset of folding’ as the exposure time of the Shrinky-Dink to the IR source required to initiate folding as observed by the naked eye. Since heat is required for folding, it is intuitive that the onset of folding occurs faster at higher TS values (which require less light absorption to generate the heat required to exceed Tg) and larger w values (which provide more heat absorption), as shown in Fig. 3a. With TS set to 90 °C, folding commences within one second regardless of the width of the patterned line (2.0 mm down to 0.5 mm, w < 0.5 mm gives imperfect folding). Lines having w ranging from 1.5 mm to 2.0 mm at TS values of 50 °C and 70 °C also initiate folding at a similar rate. At the other extreme, TS at 20 °C and line widths <0.7 mm, folding occurs after prolonged exposure times, which results in imperfect folding and deformation of non-hinged regions of the substrate (Figure S3 in the supporting information† shows deformed panels resulting from over exposure to the IR light). During long exposure times, heat dissipates and is no longer localized at the hinge; this observation underscores the importance of differential heating of the hinge relative to the facets.

We modeled the temperature profile inside the polymer films using COMSOL Multiphysics 4.0a software and compared the simulation results to the experimental measurements to gain more insight into the folding mechanism. The model assumes that (1) the black patterned lines act as heat sources with a heat flux equivalent to the local intensity of the lamp, (2) the only source of heat originates from the absorption of light by the printed lines, (3) the bare surface of the Shrinky-Dinks does not absorb light, (4) the initial temperatures for the polymer sheets are the same as the temperatures of the support, and (5) the thermal conductivity and heat capacity of the polymer sheet are those of polystyrene.9 Based on our thermal imaging measurements we define the theoretical onset of folding as the instant at which any point on the top surface reaches ≈120 °C (cf. Figure S2 in supporting information†).

Fig. 2 Photographs of 3D structures created by self-folding of Shrinky-Dinks patterned with a desktop printer. a) Single line (w = 1 mm, L’ = 10 mm) patterned on the top side of the Shrinky-Dink; b) two lines (w = 1 mm, 12 mm spacing, L’ = 10 mm) patterned on either side of the Shrinky-Dink; c) three lines patterned on alternating sides of the Shrinky-Dink (w = 1 mm, 12 mm spacing, L’ = 10 mm); d) rectangular box (20 mm × 10 mm × 10 mm, w = 1.5 mm); e) tetrahedral box (w = 2.0 mm); and f) tetrahedral box with adjacent double hinges (w = 1.0 mm, inter-hinge spacing 0.3 mm). Both tetrahedrons have a square bottom facet (10 mm × 10 mm) and equilateral triangles on the other facets.

Fig. 3 a) Experimental onset of folding (t_{folding, exp}) as a function of different patterned line widths and support temperatures and b) Time difference between the experimental and simulated onset of folding (t_{folding, exp} - t_{folding, simul}) as a function of different patterned line widths and support temperatures. Shrinky-Dinks (25 mm × 10 mm) feature a single line of ink patterned across the center of the sample. The initial support temperatures (TS) range from 20 to 90 °C and the widths of the lines vary from 0.5 mm to 2.0 mm.
In Fig. 3b we plot the difference between the experimental and theoretical times for the onset of folding as a function of the width of the line hinge. It is apparent from the data that the model captures effectively the folding trends measured experimentally at elevated support temperatures (50–90 °C). This agreement supports the assumptions in the model including the heat fluxes and the threshold surface temperature of the hinge (120 °C) needed for folding to commence. This agreement supports the assumptions in the model including the heat fluxes and the threshold surface temperature of the hinge (120 °C) needed for folding to commence. The model is less accurate in describing the onset of folding in the samples that possess narrow line widths (<1.5 mm) and low TS values (20 °C). At long onset of folding times, heat can transfer to and from the substrate in ways that are neglected by the model. In addition, heat is transferred radially from the surface of the line to the bulk and the temperature of the polymer near the lines increase as a function of time (cf. Figure S4 in supporting information†). The polymer sheet is able to dissipate the heat created by light absorption by the narrow lines. It therefore takes more time for the hinges to get warm enough to relax and cause folding at these conditions. During this time, the non-patterned regions of the polymer also heat up due to heat transfer from the lines and the supporting substrate. It is also possible that due to rather slow folding under these conditions we may not observe the initial onset of folding with the naked eye; consequently the observed times for the onset of folding appear longer than predicted theoretically by the model. Regardless of the reasons for the aforementioned small discrepancies, the model and experimental data are in satisfactory agreement to justify thermal flux as the stimulus for folding.

Fig. 4 compares the simulated temperature profiles of both the top and bottom sides of the polymer sheets with different line widths patterned on the top surfaces of the sheet. The thermal profiles represent snapshots captured when folding begins (i.e., when the maximum temperature reaches 120 °C). The data are plotted as a function of the two most extreme support temperatures explored in this study (the two top-most plots are at $T_S = 20 ^\circ$C and the two bottom-most plots are at $T_S = 90 ^\circ$C) and the two most extreme line widths (the two left-most plots have $w = 0.5$ mm and the two right-most plots have $w = 2.0$ mm). Importantly, the temperature at the bottom sides does not exceed $T_g$ as noted by the horizontal dotted line, which is consistent with the observation that only the top faces bearing the ink pattern shrink. If the hinge shrank uniformly throughout the depth of the film, then the film would likely shrink in-plane or distort, rather than fold.

For a given $T_S$, the temperature profiles of samples with different line widths show the same temperature peak height but different peak widths. Wider hinges ($w = 2.0$ mm) have more area between the temperature profile and $T_g$ than that for narrower hinges ($w = 0.5$ mm). This result is consistent with intuition; the amount of energy absorbed increases while increasing the width of the printed line hinge. The result is also consistent with observation; the time required for the onset of folding decreases as the width of the printed hinge increases.

The model predicts longer times for the onset of folding in samples with low support temperature ($T_S = 20 ^\circ$C) relative to those with high support temperature ($T_S = 90 ^\circ$C), consistent with experimental observations. Moreover, high support temperatures produce profiles with a more significant portion of the sheet above the $T_g$ than those at low support temperatures. At high support temperatures, the difference in onset of folding times between different line widths is smaller than the difference at low support temperatures.

In addition, for a given line width, the temperature profiles spread further outside the line width at lower support temperatures.
temperatures than at higher support temperatures. This results likely in more imperfect folding (i.e., bare regions of the Shrinky-Dinks contract) due to the heating of non-patterned region, as observed experimentally.

Besides w and Tg, other parameters may also affect the folding behavior. The folding of the hinged region is similar to a bending beam. The thermal gradient throughout the thickness of the sheet below the inked hinge induces a gradient in strain relaxation. The top of the film, which is hottest, relaxes the fastest and therefore relieves the most strain to induce folding. This asymmetric relaxation is critical for folding. Although our experiments focus on a small set of materials and geometries, based on the proposed mechanism we believe that the general folding behavior will depend on factors such as the magnitude of the heat flux, the support temperature, the geometry of the sample (e.g., sheet thickness and area of the hinge), the mechanical properties of the polymer (e.g., the amount of stored stress, the time scales of relaxation, and the bending modulus as a function of temperature), the optical properties of the hinge and sheet, and the thermal transport properties. In the current state, the hinging response is irreversible. The folded shapes, however, can revert back to a flat, shrunken version of the initial 2D sheet by uniformly heating the shapes above Tg as shown in Fig. 5.

Folding of the polymer film can be also realized by employing a light source with other wavelengths (i.e., 320–500 nm). Although we focused on simple line hinges in this study, other hinge geometries, i.e. circular hinges, can form curvilinear saddle points (cf. Figure S5 in the supporting information†). Moreover, lines created by markers (e.g., Sharpie markers and China markers) can also absorb light and induce folding, but toner patterned with a desktop printer offers better control of the geometry of the hinge. The folding also depends on the loads imposed on the facets. We measured crudely the force exerted by the folding process by clamping weights (i.e., small binder clips) on the end of a sample like the one depicted in Fig. 2a and measured the weight at which it would no longer fold (≈2.8 g placed a distance of 1 cm from a hinge with w = 1 mm).

**Conclusion**

We demonstrate self-folding of pre-stressed, planar polymer films (Shrink-Dinks) by using local light absorption that heats pre-defined hinges patterned by black toner from a desktop printer. The appeal of our simple approach is the ability to convert 2D patterns into 3D structures using inexpensive materials without the use of complex fabrication steps. We achieve folded structures by choosing an appropriate geometry of the inked pattern, line width and the support temperature. A model based on heat transfer captures effectively the timescale of the onset of folding measured experimentally. Wide hinges initiate folding faster than narrow hinges, which may be useful for creating chronologically synchronized folding. Although we kept light intensity and the light source constant in the experiments, increased light intensity and more focused light should result in faster and more uniform folding; this may be required to achieve the necessary differential heating between the hinge and substrate to miniaturize the process. It may also be possible to induce folding with patterned light rather than patterned hinges. Moreover, inks absorbing heat corresponding to different wavelengths can be applied for self-folding. The process should extend to other types of shrink films with different properties (e.g., optical, mechanical, geometrical).

**Experimental**

A desktop laser printer (HP-P3005dn) produced 2D patterns (designed in CorelDRAW®) onto clear inkjet printable Shrinky-Dinks (Grafix Shrink Film). We cut the patterned polymer sheets into smaller samples (e.g., L = 25 mm, L’ = 10 mm). An unfocused IR heat lamp ($S4998, $a toe) placed a constant distance of 5 cm from the polymer films to provide consistent light intensity for each experiment. We centered the polymer films under the lamp to improve the uniformity of irradiation. A thermopile (818P-001-12, Newport) measured the flux to be 988 mW cm⁻² at this distance. In some cases, we carried out the folding experiments on a hot plate (EchoTherm™ HS30, Torrey Pines Scientific) to raise the support temperature of the polymer sheet closer to $T_g$ prior to irradiation. We separated the samples from the hotplate using a 0.5 mm thick polydimethylsiloxane (PDMS) network sheet to minimize heat flux at the bottom of the Shrinky-Dink during exposure to light (the surface of the PDMS was typically ~2 °C within the hot plate temperature).

**Acknowledgements**

The authors would like to acknowledge Dr Orlin Velev’s lab for assistance with the modeling, Kevin A. Ross for measuring the thermal photographs with the IR camera and Dr Henderson’s lab for using the DSC. This work was supported by DOE Grant 08NT0001925 (Supporting Information is available online†).

**References**

This journal is © The Royal Society of Chemistry 2011