

Self-Folding Origami: Shape Memory Composites Activated by Uniform Heating

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Abstract. Self-folding is an approach used frequently in nature for the efficient fabrication of structures that is seldom used in engineered systems. Here, self-folding origami is presented, which consist of shape memory composites that are activated with uniform heating in an oven or a heated bath. These composites are rapidly fabricated using inexpensive materials and tools. The folding mechanism—based on the in-plane contraction of a sheet of shape memory polymer—is modeled, and parameters for the design of composites that self-fold into target shapes are characterized. Four self-folding shapes are demonstrated: a cube, an icosahedron, a prolate spheroid (egg) shape, and a Miura pattern; each of which is activated in an oven in <3 minutes. Self-sealing is also investigated using hot melt adhesive, and the resulting structures are found to be up to twice the load of unsealed structures.

1. Introduction

Manufactured systems typically require complex, expensive, and time-consuming 3-D fabrication process, and require complicated infrastructures for assembly and/or deployment. Nature, on the other hand, is often able to rapidly fabricate lightweight structures using self-folding strings or sheets. Self-folding structures can be found in biology at length scales from nanometers to meters, such as organic molecules [1], winged insects [2], brains [3], and tree leaves [4, 5]. Self-folding automates the construction of arbitrarily complex geometries at arbitrarily large or small scales. Folding also has many advantages over traditional manufacturing methods, including reduced material consumption and creation of structures with improved strength-to-weight ratios.

Folded designs have found useful engineering applications in areas such as space exploration [6] and logistics [7]. Complimentary theoretical work has proven that folding is in fact capable of achieving a large set of target geometries [8, 9, 10]. Recently, origami inspired folding has also enabled great strides in the fabrication of mm to cm scale robotics [11, 12, 13]. However, fold actuation remains a challenge as these robots often require many hours and/or microsurgeon dexterity to assemble manually. Reliable self-folding techniques would be a boon to automated fabrication of folded devices, as well as to self-deployable systems.

Research in small-scale fabrication has developed a variety of self-folding mechanisms. One approach folded lithographically patterned thin films spontaneously via residual stress [14], while another folded hydrogel composites with differential swelling when exposed to water [15]. Layered composites have been shown to self-fold when exposed to a change in pH, temperature, or the addition of a solvent [16]. Self-folding mesoscale structures have been activated by lasers and magnetic fields [17, 18], and complex machines have been assembled via Pop-Up MEMS [19, 20, 21]. In focusing on how to fold structures too small to be directly manipulated in an accurate way, these previous approaches have employed expensive tools and materials, and in many cases used complex infrastructure for deployment (such as lasers and magnetic fields).

At the centimeter scale, we have previously used shape memory alloys to actuate a self-folding sheet of programmable matter [22]. In designing a universal sheet capable of folding into any shape, this approach relied on the use of complex materials and fabrication approaches, and would not be efficient in the assembly of specific target structures.

Recent work has employed selective light absorption to cause inexpensive, single-use shape memory polymers (SMPs) to self-fold into target structures [23]. While this is a simple and inexpensive approach to self-folding, it faces a number of practical challenges. First, light-induced activation of self-folding is inherently directional, which leads to occlusions during folding (a problem which can be partially alleviated by using a transparent SMP). Achieving uniform light intensity over large areas is an additional challenge. Furthermore, it is difficult to achieve well defined fold lines (i.e. sharp edges) using SMP alone. Finally, the use of the fold actuation material as the structural

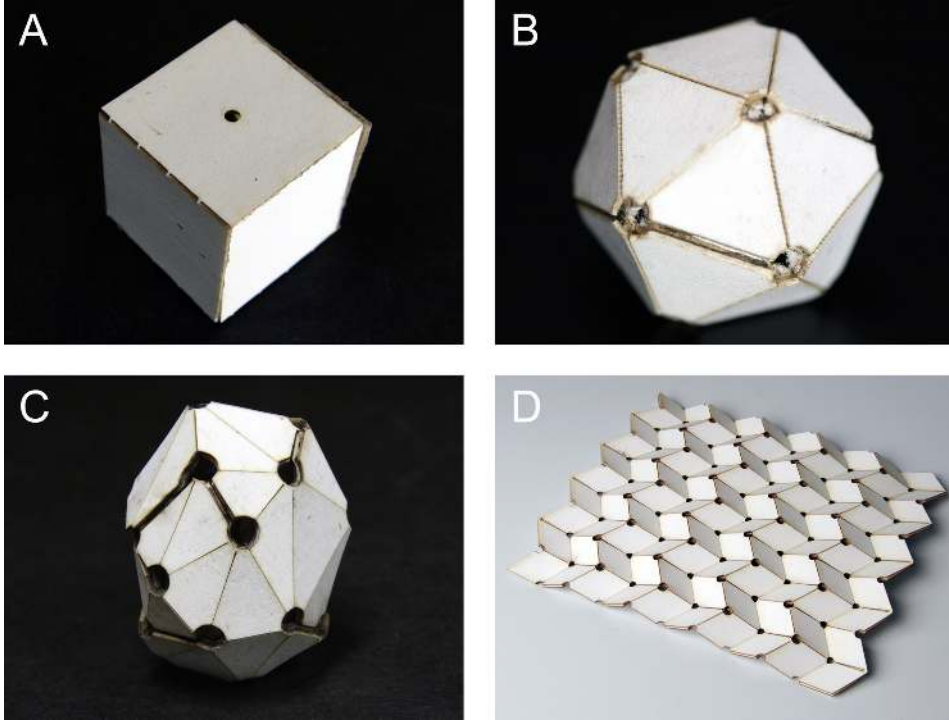


Figure 1. Self-folded geometries. Each of these three-dimensional geometries, namely a cube (A), icosahedron (B), egg (C), and Miura pattern (D), was folded from a flat shape memory composite upon activation with uniform heating in an oven.

material limits the strength and potential applications of the structures formed.

We have recently demonstrated the use of similar SMPs, selectively actuated by resistive heaters, to realize self-folding robots and structures [24, 25, 26]. While this selective activation of SMPs for self-folding is powerful, it requires the inclusion of an electrical layer for the controlled electrical heating required for folding. For many applications, this additional complexity may be unnecessary and undesired.

Here we present an approach to the rapid, inexpensive fabrication of self-folding shape memory composites, or *self-folding origami*, which are activated with uniform heating (i.e. in an oven or a heated bath). We designed a process for the fabrication of shape memory composites consisting of three layers: A layer of our SMP material sandwiched between two structural layers (with two additional adhesive layers holding the laminate together). When placed into an oven or heated bath, these composites fold into target structures. We present models for predicting the geometry (i.e. angle) of a fold after actuation, and the overall torque applied by the SMP at a fold edge. We present experimental results demonstrating the folding of a variety of target structures (Fig. 1), both in an oven and in a heated bath. We also present an approach to the "locking" of self-folded structures.

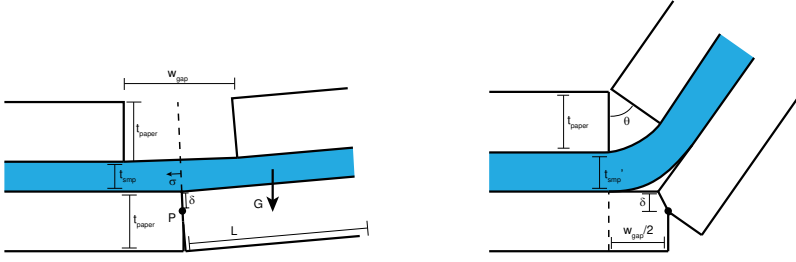


Figure 2. Schematic cross-section of a shape memory composite self-folding hinge. The shape memory composite consists of a layer of shape memory polymer (SMP, colored here in blue), with two patterned layers of paper (colored here in white). Left: when the laminate is activated with uniform heating, the SMP layer contracts, causing the laminate to bend towards the side with a gap about point P . Right: The laminate continues bending until the two sides of the upper layer come into contact, resulting in a final bend angle θ .

2. Modeling

2.1. Fold angle model

Our self-folding laminates have built in mechanical fold stops. The removal of a strip of the structural layer along the inside of fold lines frees the underlying SMP material to contract when heated (Fig. 2). In addition, the edges of this gap form mechanical stops which limit the fold angle. Consequently, it is possible to encode the fold angle in the design itself by adjusting the width of the gap at the hinges (w_{gap}). From the geometry of the folded state (Fig. 2, right), we can find the following relation between the final fold angle, θ , the thickness of the paper, t_{paper} , the thickness of the SMP after actuation, t'_{smp} , and the distance δ between the bottom of the SMP and the point of rotation P . (Note that the laminates do not bend about the corner of the bottom layer due to compression in the paper, hence the distance δ .)

$$\tan\left(\frac{\theta}{2}\right) = \frac{w_{gap}}{2(t_{paper} + t'_{smp} + \delta)} \quad (1)$$

2.2. Folding torque

The torque exerted by a self-folding hinge is dependent on the young's modulus E and thickness t_{smp} of the SMP, as well as the distance δ between the SMP and the point of rotation P and the width W of the hinge (Fig. 2).

$$T = \sigma_x W t_{smp} (t_{smp}/2 + \delta) \quad (2)$$

The stress σ_x of the SMP is first calculated by assuming that the SMP is constrained in the x- and y-directions, while undergoing no stress in the z-direction, and the Poisson ratio ν is 0.5. Therefore, the x- and y-strains ϵ_x and ϵ_y are both 1.

$$\epsilon_x = (1/E) (\sigma_x - \sigma_y \nu - \sigma_z \nu) \quad (3)$$

$$\epsilon_y = (1/E) (\sigma_y - \sigma_x \nu - \sigma_z \nu) \quad (4)$$

$$\sigma_x = 2E \quad (5)$$

Combining eqs. X and Y results in our expression for torque

$$T = 2EWt_{smp} (t_{smp}/2 + \delta) \quad (6)$$

The moment due to gravity, however, is due to the length L of the folding face and the mass m of the composite

$$m_{sub} = 2WLt_{sub}\rho_{sub} \quad (7)$$

$$m_{smp} = WLt_{smp}\rho_{sub} \quad (8)$$

$$M = \frac{9.8 (m_{sub} + m_{smp}) L}{2} \quad (9)$$

Because of this, for any given composite, there is a maximum effective face length that can successfully self-fold. However, the width of the hinge is linearly related to both the torque and the moment, so a self-folding face can be arbitrarily wide.

3. Results and Discussions

3.1. Materials and Fabrication

Our approach to the fabrication of self-folding shape memory composites is inspired by the "PC-MEMS" or "Pop-up book MEMS" techniques developed recently for the fabrication of microscale robotic systems [20, 19, 21]. However, there are a number of key differences in our approach. First, we limited ourselves to the use of inexpensive, readily available materials and tools. Second, inspired by origami, we chose to use a single mechanical layer (sheet) to achieve complex three dimensional shapes with multiple folds following different degrees of freedom (as opposed to "pop-up" devices which are complex linkages connected to a single degree of freedom). Third, the use of a heat-activated shape memory polymer layer precludes the use of solid sheet adhesives used to achieve the "mechanical vias" in previous complex pop-up designs [19]. This is because the SMP layer would be prematurely activated while setting the adhesive. Otherwise, a solid adhesive with an activation temperature lower than that of the SMP would likely lose adhesive strength during activation of the SMP. Thus, we are limited to liquid adhesives or two-sided tapes.

Taking the constraints mentioned above into account, we designed a process for the fabrication of shape memory composites consisting of three layers: A layer of our SMP material sandwiched between two structural layers, with two additional adhesive layers holding the laminate together (Fig. 3).

For our SMP material we used pre-strained polystyrene shrink film sheets (commercially available as the children's toy, Shrinky Dinks), which have previously been used in the fabrication of microfluidic molds [27], and folded structures activated

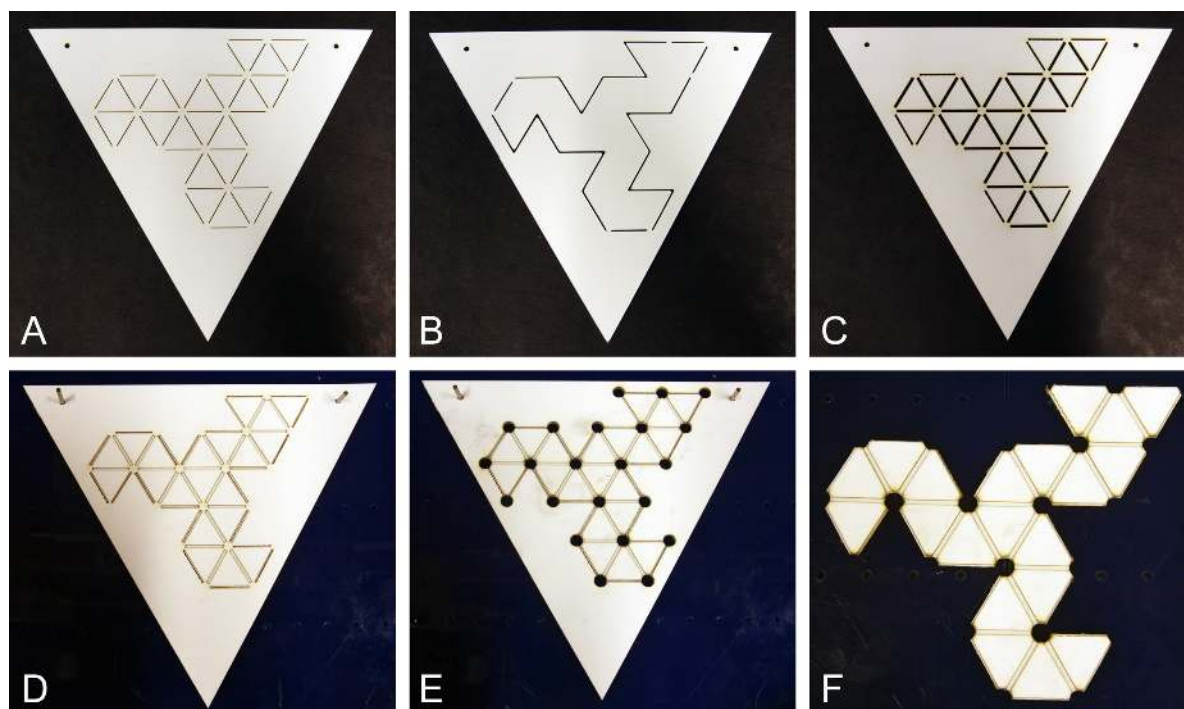


Figure 3. Self-folding laminate fabrication. Three layers patterned with a CO₂ laser machining system make up a self-folding laminate: A) A lower structural paperboard layer, B) a shape memory polymer layer, and C) an upper structural paperboard layer. D) These layers are aligned on pins and adhered together with double-sided silicone tape. E) A final release cut removes the support structure, leaving only F) the shape memory laminate.

with light [23]. These sheets contract isotropically to $\sim 50\%$ of their initial size when heated above their activation temperature of $\sim 107^\circ\text{C}$. These sheets are inexpensive, and easily patterned on a CO₂ laser machining system.

For the structural layers we tested two materials: $510\ \mu\text{m}$ (20 mil) thick paper, and $255\ \mu\text{m}$ (10 mil) thick transparent PET film. The paper was used for composites activated in an oven (see Section 3.4), while the PET film was used for composites activated in a liquid bath (see Section 3.6).

We bonded the three layers together with double-sided, 50 mm thick silicone tape (ARclad 7876, Adhesives Research). We tested many double-sided tapes (mostly acrylic-based) and only silicone tape maintained adhesion at the elevated temperatures required to activate the SMP. Silicone tape also performed well when immersed in water.

To fabricate the self-folding composites, we predefined the fold patterns on the paper and SMP layers using a CO₂ laser machining system (VLS 2.3, Universal Laser Systems; Fig. 3a-c). Connections at the end of each fold edge held the faces of the composite in place after laser machining. We stacked the three layers, using alignment pins, and dispensed a layer of the silicone tape in between each for adhesion (Fig. 3d). A final cut consisting of a circle at the end of each fold line (Fig. 3e) then released the self-folding composite from the surrounding supporting structure (Fig. 3f).

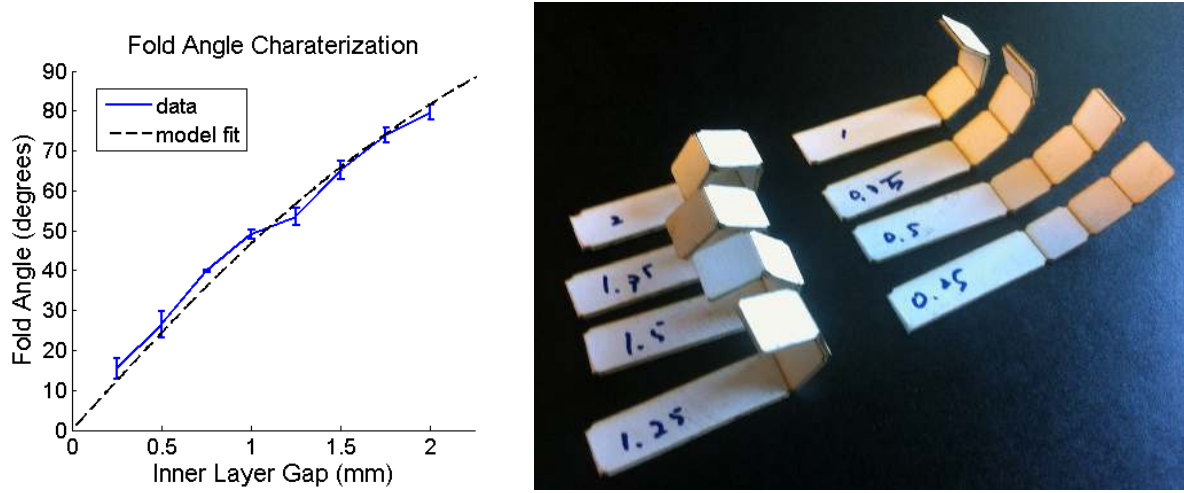


Figure 4. Experimental characterization of the final fold angle of a self-folding shape memory composite fold as a function of the patterned inner gap layer. Our experimental results showed close correlation with the geometric model presented in Section 2.1.

3.2. Fold angle characterization

To characterize the fold angle as a function of the actuator geometry, we built eight self-folding strips with gaps on the inner layer in the range of 0.25 mm to 2 mm, in 0.25 mm increments (4, right). We activated these strips in an oven at 170°C. Each strip had three folds with identical gap dimensions. After baking, we measured the fold angle of each self-folded actuator.

Fig. 4 (left) shows the average and standard error of each angle measurement, as well as the geometric model presented in Section 2.1. We found close agreement between the model and experimental results. This allowed us to use the model in the subsequent design of self-folding shape memory composites.

3.3. Folding torque characterization

We created test hinges that were 30 mm wide and had arbitrary lengths in order to characterize the folding torque of the self-folding composite. One side of these hinges was held flat in the oven, while the other was allowed to move freely during folding. The lengths of the moving faces on these test hinges varied from 60 to 220 mm. The final angle that these hinges folded to is shown in Figure 5. This data is compared to the calculated moment exerted on these self-folding hinges due to gravity, as well as the calculated torque exerted by the hinges. We expected that the hinges which had a folding torque greater than the resisting moment would fold completely to a final angle of approximately 45°, while those with insufficient torque to overcome gravity would remain at 0°. Instead, as the face length approached the crossover point, the final angle slowly decreased, until it fell rapidly at the crossover point. We believe this discrepancy is due to the viscoelastic properties of the SMP in its rubber state, allowing for plastic

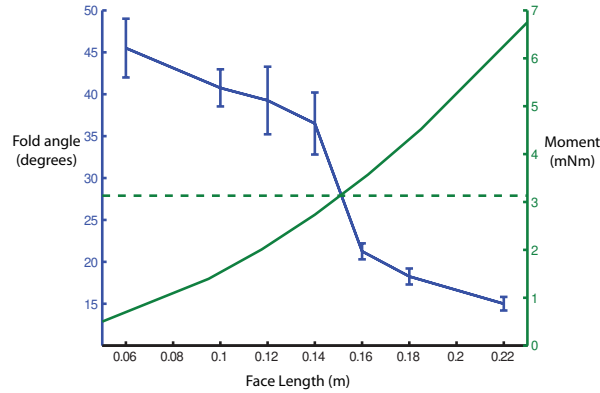


Figure 5. A plot of measured final fold angle (blue) of test hinges with varying face lengths, compared to a graph of the modeled moment (green) due to gravity on the face that is resisting the folding torque. The dashed line indicates the torque exerted by each test hinge, and the length at which the dashed and solid green lines cross indicates the expected maximum face length that can still be folded.

deformation due to the resisting moment. For hinges with faces longer than 150 mm, we see another slow decrease in fold angle, which may be due to viscoelasticity, but all of our samples showed minor angular deflections of at least 15° . We believe that this is due to residual stress in the SMP; during the activation, these samples remained flat, but once cooled and removed from the oven, they stiffened and exhibited minor deflections.

We determined the Young's modulus of the PSPS by measuring and averaging the contractile force of five dogbone samples of the material in a mechanical test machine (make, Instron). The strips were 10 mm wide at their thinnest points, and force was measured as the samples were heated with a heat gun (make, model) to their melting point. We measured the Young's modulus of the activated PSPS to be 696 kPa. We assume that at some point during the measurement the PSPS has uniformly transitioned to its rubber state, but has not yet plastically deformed. In this state, the strain is considered to be 1, and the stress ($\sigma = F/A$) is equal to the Young's modulus. This experiment has the benefit of measuring the stress of the SMP in the same state as it is in the composite, so even if the strain is not equal to one and/or the stress/strain relationship is not linear, the measured stress is equivalent to the stress exerted by the PSPS during the folding process.

3.4. Self-Folding in Air

Using the results of our fold angle characterization (see Section 3.3), we designed and four self-folding origami shapes: a cube, an icosahedron, an egg, and a Miura pattern (Fig. 1). We then tested each of these self-folding composites by activating them in an oven an oven preheated to $\sim 130^\circ\text{C}$. The laminates were placed on preheated ceramic stones to limit the rate of heat conduction into the bottom of the laminates and heat them as evenly as possible. Fig. 6 shows frames from each of these experiments with

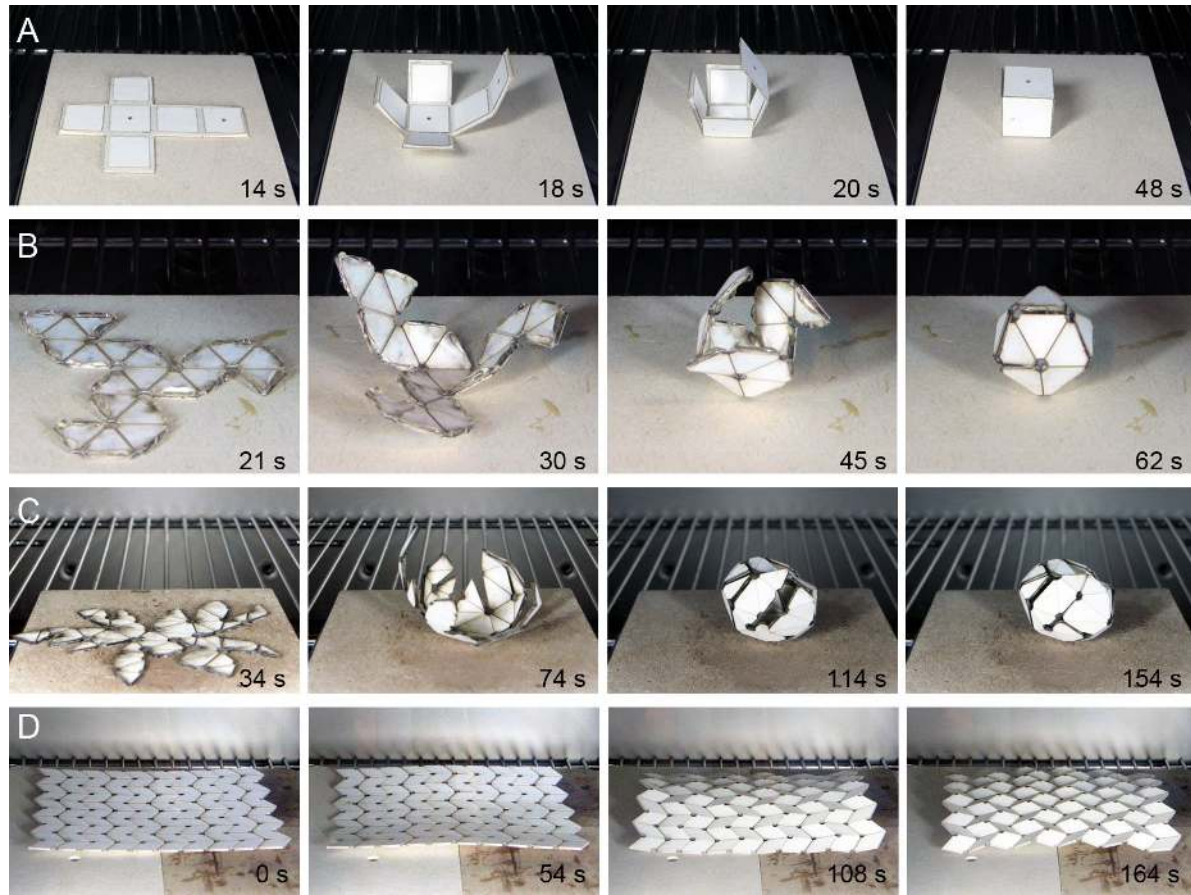


Figure 6. Self-folding experiments. These image sequences are from self-folding experiments for the cube (A), icosahedron (B), egg (C) and Miura pattern (D) shapes (see also Movie S1). In each case, the self-folding shape memory composite was inserted into an oven preheated to 130°C. The time elapsed since the start of the experiment is indicated in the lower-right corner of each frame.

the time elapsed since being inserted into the oven indicated on each frame. After an initial heating period of 14 to 34 s, the laminates began folding, completing the target structure in less than 1 to 3 minutes (more complex structures took more time to complete folding). At this point, the structures were removed from the oven manually. While the SMP was still soft at the activation temperature, it quickly solidified when removed from the oven, resulting in a rigid structure. The number of faces, actuated folds, and overall dimensions of each test geometry are summarized in Table 1.

The four self-folding origami geometries folded successfully when activated in the oven. However, as the complexity of the geometries increased, so did the variability in the final shape. In particular, we observed increased variability in shapes with many serially connected fold edges such as the egg shape (Fig. 7), which is expected since we observed variability in the final fold angle of single edges due to manufacturing variability (Fig. 4). Additionally, larger structures were more affected by gravity, as predicted observed in our folding torque model and characterization (respectively).

However, we observed little variability in the most complex shape (the Miura



Figure 7. Repeatability of folding. Several challenges limited the repeatable self-folding of complex structures, including the number of serial folds, and the differential effect of gravity on the faces of the object depending on their size and position in the structure.

Table 1. Experimental self-folded geometries.

Geometry	Faces	Actuated Edges	Length (folded)
Cube	6	5	15 mm
Icosahedron	20	19	25 mm
Egg	50	48	50 mm
Miura Pattern	100	180	140 mm

pattern). This origami pattern nominally has only a single degree of freedom, and in theory it could be folded with a single (sufficiently strong) actuator. However, since we actuated every edge, and actuated edges worked in parallel to determine fold angles, the errors tended to cancel one another out (instead of add up as in the serial case).

3.5. Sealing with hot melt adhesive

We investigated the possibility of achieving both self-folding and self-sealing structures with the use of hot melt adhesive (HMA). HMAs, commonly used in "glue guns", melt at temperatures in the range of 120°C to 193°C. Thus, lower melting point HMAs can be activated at the same temperature as our self-folding composites (130°C) in order to seal the edges of structure during self-folding.

We manually deposited HMA onto the edges of our self-folding cube and icosahedron composites (Fig. 8a). These shapes folded as before, except the glue added some resistance to folding that led to incomplete folds (Fig. 8b). This increased resistance was overcome by increasing the gap widths of the laminate cut pattern, increasing the "desired" fold angle.

We compared the strength of sealed and unsealed self-folded structures on a universal testing machine (5544A, Instron) by subjecting them to compressive testing. The loads borne by the sealed and unsealed cube and icosahedron are plotted versus compression in Fig. 8c and d, respectively. While the failure mode of these folded structures in compression is complex, it is apparent that sealing did increase the strength

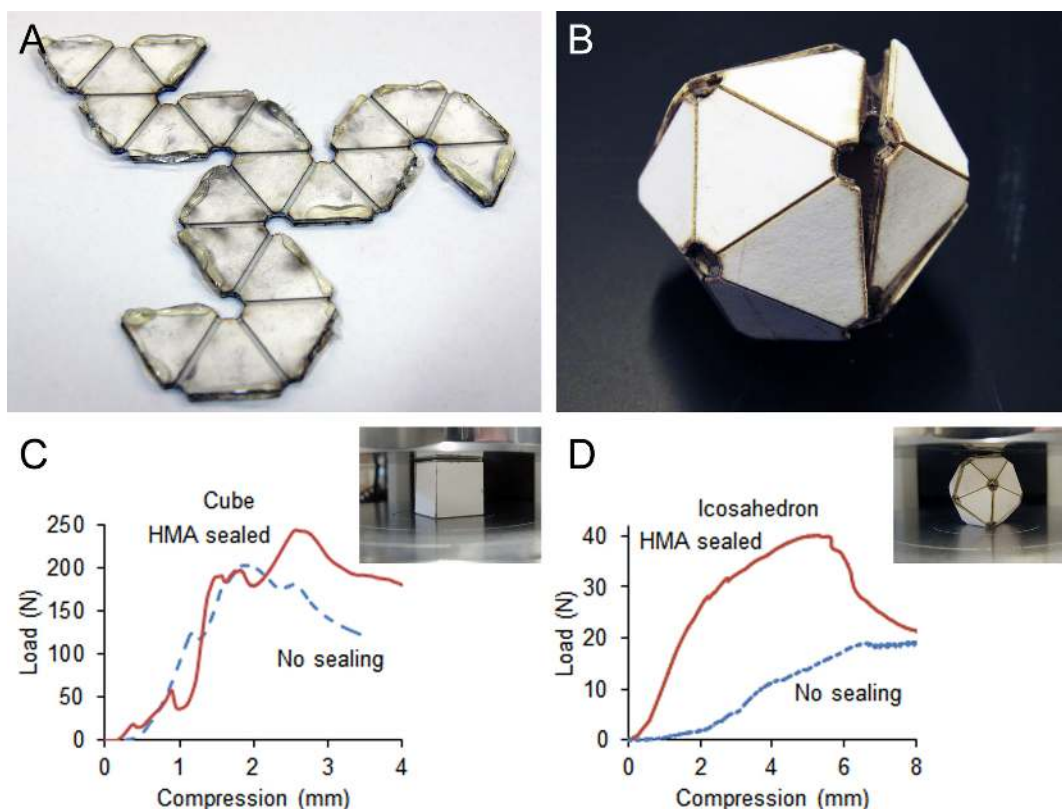


Figure 8. Sealing with hot melt adhesive. A) Hot melt adhesive is patterned around the edges of the self-folding laminate prior to activation in an oven. B) A glue bridge formed between two edges is visible because of misalignment. C) Strength testing shows the increased load carrying capacity of sealed cube and D) icosahedron shapes.

of each structure.

3.6. Liquid activation of self-folding

We encountered many challenges in activating our self-folding origami in an oven. In addition to the differential effect of gravity discussed in the previous section, achieving even heating was a challenge (e.g. ovens tend to be hotter in the rear). The elevated temperatures required for rapid activation had the potential to melt the SMP if set too high (we observed melting with the oven set to 170°C). Also, complex structures occasionally became jammed during folding due to friction. In order to address these challenges, we investigated activating the self-folding origami in water.

Due to the increased heat transfer coefficient of water, the composites could be activated in water at a temperature much closer to their transition temperature of $\sim 107^{\circ}\text{C}$. However, boiling prevents the temperature of water from increasing beyond $\sim 100^{\circ}\text{C}$ at atmospheric pressure. Since we found oil to be incompatible with our adhesives, we circumvented the problem of boiling by adding salt (NaCl) to the water.

Fig. 9 shows frames from an experiment in which we introduced a self-folding icosahedron composite into water nearly saturated with salt boiling at $\sim 108^{\circ}\text{C}$ at

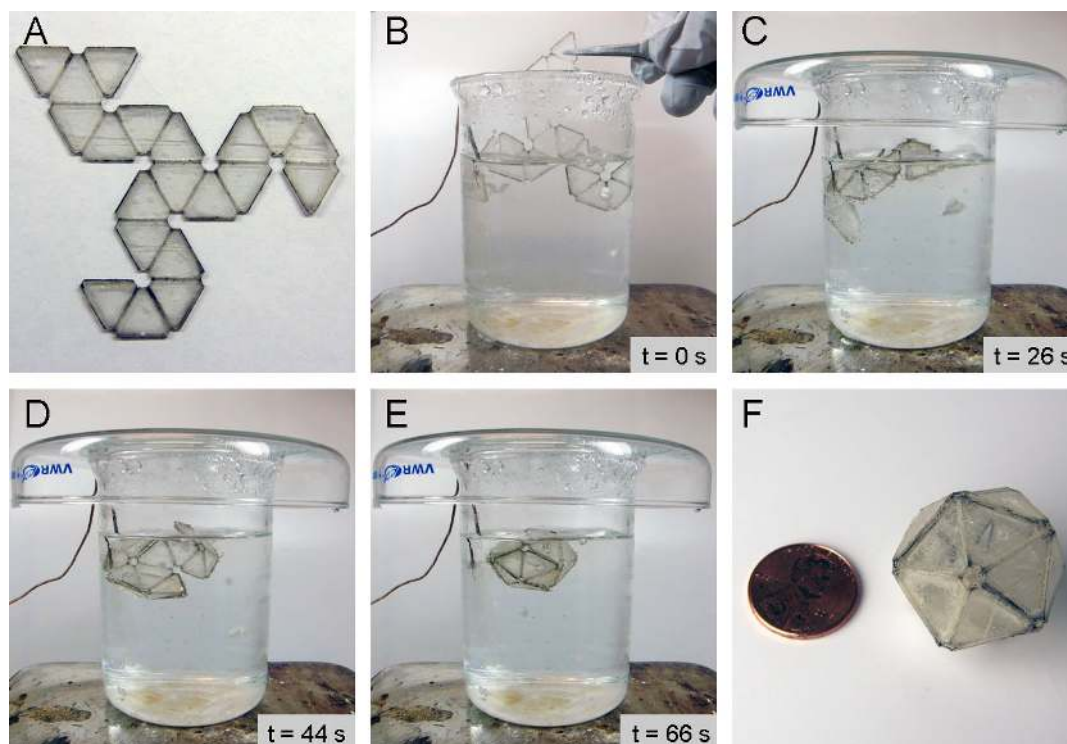


Figure 9. Liquid activation of self-folding. A) A self-folding icosahedron composite with transparent PET film for the structural layers is B) inserted into water nearly saturated with salt boiling at $\sim 108^{\circ}\text{C}$. C-E) In just over a minute (experimental times indicated in the lower right of each frame), the composite folds into F) the target shape, shown with a penny for scale.

atmospheric pressure. Instead of paper, we used transparent PET film as our structural layer for resistance to water. After 66 s this laminate folded into the target shape which was removed from the water with tweezers (Fig. 9f, Movie S2).

4. Conclusions

We have presented self-folding origami composed of shape memory composites which are activated with uniform heating in an oven or a heated bath. These composites can be rapidly fabricated using inexpensive materials and tools. We have modeled the folding mechanism and characterized parameters for the design of composites that self-fold into target shapes. We demonstrated this process with four shapes, and discovered that shapes with folds that act in parallel (such as the Miura pattern) exhibit less variability in self-folding than shapes with sets of serial folds (such as the egg shape). We additionally presented an approach to the self-sealing of these laminates using hot melt adhesive, and an approach to activating folding in a liquid bath which overcomes some of the challenges of folding in air.

Future work could investigate the automatic generation of 2-D composite designs to achieve a desired 3-D shape, a reduction in the variability in folded structures through

improvements in composite design or fabrication, or increasing the functionality of the folded structures by adding additional layers for post-folding actuation, sensing, communication, etc.

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