Incorporation of Shape Memory Polymers in Interactive Design

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Abstract

This paper seeks to explore the question of how to incorporate smart materials into a design to demonstrate science and engineering concepts in an interactive way. This work introduces the development of artwork using a shape memory polymer (SMP) material that changes shape based on an external thermal stimulus. In this paper we explore how interdisciplinary work between engineering and science is needed to create an artwork that mimics the world around us. This paper discusses fabrication and electronic implementation challenges associated with utilizing the shape memory properties of the material. Specifically, the paper explores some ways to obtain different geometric shapes of the SMP and to create utilize different sources of thermal stimulus to create a shape memory effect (SME).

Keywords

smart materials, shape memory polymer, interactive artwork, interdisciplinary collaboration

Introduction

Creating artistic models that allow children to experience science, technology, engineering, and mathematics (STEM) fields, may increase their propensity towards choosing these fields to career paths. Smart materials provide a unique medium to present scientific information, because they are materials that exhibit a change based on an applied stimulus. Some examples of smart materials are shape memory alloys (SMAs), shape memory polymers, thermo-chromatic powders and photo-chromatic powders. Solar Color Dust is a brand of thermo-chromatic and photo-chromatic powders that change from a given color to a white color with heat, body temperature, or light stimulus [1].

SMAs and SMPs exhibit the what is known as the shape memory effect, the ability to hold a temporary structure and geometric configuration until a stimulus reverses it structure back to its original configuration. This behavior is known as the shape memory effect. For SMAs, this effect is due to the phase change in the metal from the martensitic phase to the austenitic phase. In a SMA a shape is trained by holding a shape at a temperature higher than the austenitic finish temperature, A_f, and then cooling it to a temperature lower than the martensitic finish temperature, M_f [2]. Once, the SME is trained, the SME occurs by applying shear stress to the metal in the martensitic phase (low temperature phase). This stress causes the cubic crystal structure to shift and deforms the object on a macroscopic level. Then the applied stress is removed and the material is heated to above A_f. At this temperature the metal returns to the austenitic cubic structure which causes it to return to its trained shape [3]. Once, the SMA is cooled again, it can be deformed again to another shape.

The stimulus for SMPs maybe physical (*i.e.* temperature, magnetic field, electrical field) or chemical (*i.e.* pH) and cause a variety of changes in the material [4]. SMPs that have a shape change from a thermal stimulus are of interest to this paper. The SME within these types of SMPs is based on a network of ”netpoints”, the bonds which form a permanent network, and ”switching segments” which form the temporary network. The ”netpoints” are chemical covalent bonds or physical intermolecular interactions and the switching segments are parts which are flexible above the glass transition temperature, T_g, and inflexible below the T_g [5] [6]. This flexibility allows for the shape to be deformed at $T > T_g$ and then frozen at $T < T_g$ then heated to return to its original undeformed shape.

Other artists have explored the area of using smart materials as a medium. Elaine Ng Yan Ling is a textile artist creating designs she describes a ”naturology” the combination of nature and technology. Her work incorporates shape memory polymer and alloys and wood [7]. Among her pieces she has created a Living Furnishing Fabric with uses shape-memory polymer to allow the textile to respond to humidity. Also, a shape memory polymer and wood veneer piece for seasonal depression disorder. This is designed to allow light during the winter months a projects interact shadows indoors in response to heat [8]. Other artist include Jie Qi whose main focus is on creating activation and movement of origami using SMAs. Among some of her projects she has tested how making origami cranes with incorporated SMA can be used as an educational tool with children ages 9-15 [9]. The Texas Institute for Intelligent Materials and Structures (TiiMS) at Texas A&M University have installed a ’Pop-Op’ which is a shape memory alloy wall installation composed of resin and C-glass fiber. The installation contains several components like flowers and flaps that are actuated by SMA and controlled by an Arduino [10].

Fabrication of Shape Memory Polymer

The polymer used in this study is based on the work of Xie and Rosseau [11]. This polymer consists of three components, diglycidyl ether bisphenol A epoxy (Epon 826), poly(propylene glycol) bis(2-aminopropyl) ether (Jeffamine D-230), and neopentyl glycol diglycol ether (NGDE). The SME is created due to the chemical structural differences and reactivity of NGDE and Epon 826. Jeffamine D-230 is the cross-linking agent in this structure, meaning its amine groups, $-NH_2$, react with the epoxide groups of Epon 826 and NGDE to create the structure given in Figure 1. Note in the structure of NGDE is a flexible aliphatic diepoxide, meaning it contains carbon atoms forming open chains, while the structure of Epon 826 is a rigid aromatic epoxide, meaning it contains carbon rings on its backbone. The shape memory in this polymer occurs because when the polymer is heated, above the T_g, the NGDE segments become flexible and bendable [11]. These segments are able to be rotated around their cross-links to form a new shape. Once, the shape deformed and cooled to below the T_g, the new shape is set. If the material is heated again, the shape will return to its pre-deformed shape.

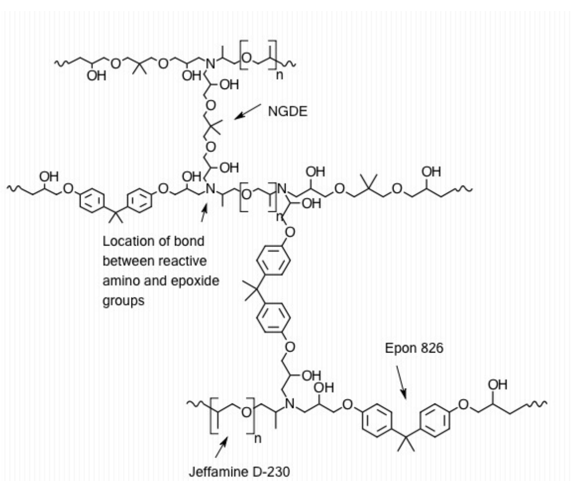

Figure 1: Fully Bonded SMP Structure [12]

The polymers used in this study were fabricated according to the Xie and Rosseau formulations given in Table 1. To mix the samples initially, some of the Epon 826 was placed in a glass vile and heated on a hot plate until the viscosity was reduced and there was no appearance of bubbles in the mixture. The Solar Color Dust was weighed based on the appropriate amount for the recommended mix ratio of 10 g powder to 1 pint of solution. This dust was placed in a glass jar. The amount of Jeffamine D230 for the desired T_g was measured with a graduated cylinder and placed into the same glass jar. This mixture was then sonicated. The NGDE was then measured and added to the Jeffamine and the mixture was again sonicated. After the Epon 826 was sufficiently heated, it was measured and then added to the mixture, stirred, and sonicated. The mixture was vacuumed with a for approximately 20 minutes and then placed in a silicone rubber mold. Then the mixture was cured for 1.5 hours at 100°C and post-cured for 1 hour at 130°C [11].

Table 1: Shape Memory Polymer Volumetric Mix Ratios [11]

Samples	Epon 826 (ml)	D230 (ml)	NGDE (ml)	T_g (°C)
1	4.7	2.43	1	60-80
2	3.14	2.43	2.08	40-60
3	1.57	2.43	3.12	20-40
4	0	2.43	4.15	0-10

Working with Shape Memory Polymer

Creating an interactive artistic work using shape memory polymers provides some challenging components. Since, additional thermal energy is needed to cure the polymer, the temperature of the oven make it difficult to incorporate electronic components or sensors into the polymer itself. Also, the shape memory polymer must be heated and deformed at a high temperature and then cooled quickly. Therefore, the environment for an installation should be considered when determining which T_g is appropriate. Molding of a SMP can also require time to obtain the correct mold for the artistic structure desired. To make the mold, first a plastic female mold is made with a 3D printer, then a silicone rubber male mold is cast from the 3D printed mold. This silicone mold is used to cast the SMP. Therefore, it can be time consuming to create new shapes with the SMP. Also, incorporation internal heating means, such as wires, can create a stress concentration, which causes the material to break at the interface when deformed.

Auxesis

This work was made to help describe the mechanism in which chameleons change color. Chameleons change color to send visual signals to other animals regarding their mood, aggression, territorial instincts, or for mating purposes. The change of color in a chameleon occurs at the microscopic level based on cells called chromatophores. These chromatophores behave as a flexible bags of color that is either stretched out to cover a large flat area or retracted back to a small, retracted point [13]. Each chromatophore is attached to radial muscle fibers at various points along its edge controlled by a nerve fiber. When a nerve impulse is sent, it causes these muscles to contract and expand the chromatophore. When the muscles relax, the chromatophore returns to a small, compact shape, thus reducing its area and making the pigmented area shrink [13].

This art piece explored the use of SMP materials to mimic the cells of the chameleon. In order to accomplish this task, the SMP was molded into a rectangular mold and then laser cutter was used to explore different shapes. Through trial and error a chiral shape with is a type of auxetic shape, meaning the shape has a negative Poisson's ratio (the lateral width increases when stretched from either end), was chosen. The idea of SMP based that utilizes the geometry of the auxetic

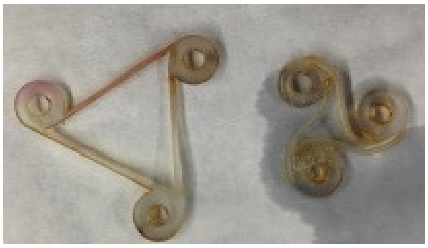

Figure 2: Contraction of Chiral Structure: Expanded and Compressed States

shape was based no the work of Rossiter *et. al.* [14]. A picture of the chiral shape in the curled and uncurled states are given in Figure 2.

In laser-cutting the chiral shape, several iterations are done in order to maintain the correct thickness for the struts of the chiral to avoid breaking the chiral. Also, the heat from the CO_2 laser resulted in a gummy polymer, if the T_g of the polymer was lower. The polymer performed better during laser cutting if it was taped and place in a freezer prior to laser-cutting.

In order to mimic the color expansion and retraction of chromatophores, Solar Color Dust and Castin' Craft dye was incorporated into the SMP matrix and fabric was added to the inside of the SMP chirals. Photos of these color and fabric chirals are given in Figure 3 and Figure 4.

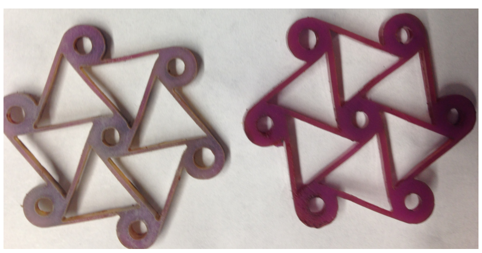

Figure 3: Chiral changes from purple to blue based on heat stimulus

Figure 4: Colored Shape Memory Chirals with Fabric Incorporated

These shapes were mounted on a canvas and attached to servo motors. A Lilypad thermal sensor was placed in close proximity to the shape. Once the thermal sensor detected a sufficient temperature change, above the T_g, due to the hair dryer stimulus a command was sent from the Arduino to rotate the servo motor. The motor curled in the SMP chirals until the thermal sensor detected that the temperature was reduced to below T_g. Then the motors were told to release their hold on the SMP chirals. The chirals remained in the deformed until the temperature raised to return them back to their original shape. The artwork is named ”Auxesis” which is from the greek meaning growth, which describes the mechanism of the chromatophore and the structure that the chromatophore uses. A depiction of the artwork is given in Figure 5.

Figure 5: Front of ”Auxesis” contains the color changing components

The Secret Garden

This artwork seeks create a piece where the observer can reveal the beauty in nature. The artwork contains three components that can be revealed based on thermal stimulus the components utilize SMP and Solar Color Dust. The first of which is the blossoming of a flower. The hidden flower concept is inspired by the Chinese flowering tea, which is created by needle tea leaves being wrapped and compressed around a flower into a small ball. When the tea is heat the ball is opened to reveal a beautiful flower. To mimic the revealing of the flower, a shape memory polymer was laser-cut from a 2D sheet into the shape of a flower. The behavior of the flowering shape in hot water is given in Figure 6 and Figure 7. In an installation setting, the observer will place the flowers in clear bowl of water on a hot plate to open the flower.

Figure 6: SMP Flower Before Exposed to Hot Water

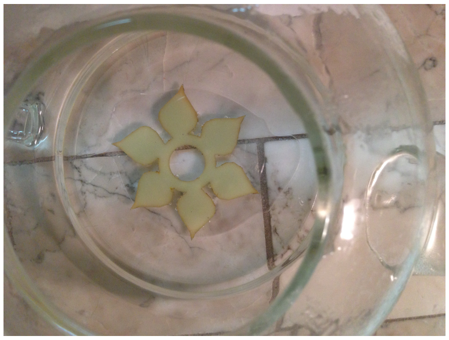

Figure 7: SMP Flower After Exposed to Hot Water

The other two aspects of the artwork are the revealing of hidden properties, beneath the surface. Specifically, moss is cast with clear resin and Solar Color Dust. When the material is cool only some parts of visible to the observer, however as it is heated the viewer can see the intricate structure of the moss. From experimentation with different thicknesses of the resin with the moss, it was found that a thin layer of resin provided the most ideal aesthetic, allowing the user to view more of the intricate details of the structure and requiring less thermal energy to heat to reveal the moss. The third aspect of the artwork focuses on the changing of the leaves with the seasons. This aspect utilizes Solar Color Dust, clear resin, and heat pad. The leaves are coated with a black thermochromatic powder in a medium are cast into a clear epoxy resin. When the heat source is applied, the beautiful colors of fall appear. Initially, conductive thread was used as the heat source, however the thread only heats a small area around the thread, so for more through heating, a larger source is needed.

Conclusion and Future Work

SMP materials provide a unique challenge for interactive artwork due to the nature how the SME must be activated. Some of the issues in working with this specific SMP include, difficulty in testing new shapes. Eventhough the laser-cutter provides a much faster method to test out new geometries, the heat from the CO_2 laser does induce some thermal residual stress by breaking cross-links in the polymer and weakening the material. In the laser-cut chiral structure, often the struts of the structure broke down due to thermal stress concentrations. Future work will explore the direct casting of the chiral shape. Also, some current work has been done on machining the SMP using a drill press. When measuring the hole created by drilling the size of the hole and the size of the tool are approximately the same size. This result, could mean that there is some mild thermal residual stress due to covalent cross-links in the SMP breaking by the drilling action and causing open chains of NGDE to reconfigure at the high temperature. From the qualitative preliminary testing, it appears that machining provides a lower stress on the SMP than laser-cutting, resulting in a better end-product. Exploring the pros and cons of machining, casting, and laser-cutting will provide valuable information on effective ways to create new shapes. Also, for the "Auxesis" work, a restructuring of the visual aesthetics to greater visualize the action of the SMP would create a work that is a better representation of the chromatophores movement.

For "The Secret Garden" piece, experimentation with a more complex layered 3D flowering shape is required. Also, the method of casting the hidden moss into thin sheets needs to be modified to create a consistent thin size of the cast. Further testing with a heating pad is needed on the changing leave aspect of this work.

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