# Fabrication and Testing of Polymer Nanocomposites for Use as Photothermal Soft Actuators

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By	
Duril q Dalana	

Daniel Dorfman

Mark Yandian

Approved by:

Pratap M. Rao

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## Abstract

Soft actuators offer many benefits over conventional servomotor-based actuators, including simplicity and scalability to the microscale. Moreover, photothermal energy delivery allows for non-contact actuation. The goal was to produce a soft actuator material with an improved photothermal response by the addition of metal nanoparticles. Aluminum nanoparticles were added to various polymers, followed by thermal and mechanical modeling and testing of the resulting composites. An aluminum/silicone rubber nanocomposite was found to convert light into heat energy and contract when heated under a pre-load. Based on a COMSOL multiphysics simulation, the thermal model accurately predicted the experimental temperature measurements, and a maximum temperature rise of 77° C was observed. The thermomechanical model was less accurate, with a theoretical result of 10% maximum length contraction versus an experimental result of 4.5%. Future research could be targeted towards miniaturizing the material and integrating it with a mechanical system for actuation.

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## **Table of Contents**

ABSTRACT	II
ACKNOWLEDGEMENTS	III
TABLE OF FIGURES	VI
1.0 INTRODUCTION	1
2.0 LITERATURE REVIEW	3
2.1 ALTERNATE FORMS OF SOFT ACTUATION	3
2.1.1 Stimuli Responsive Polymer Gels	3
2.2 THERMOMECHANICAL ACTUATION	4
2.3 Photothermal Mechanism	5
2.3.1 Energy Input by Photoexcitation	5
3.0 METHODOLOGY	7
3.1 Starting Objectives	7
3.2 Selecting Polymer candidate	7
3.2.1 THERMAL EXPANSION OF POLYSTYRENE (PS)	7
3.2.2 CONTRACTION BY THE GOUGH-JOULE EFFECT IN POLY-DIMETHYLSILOXANE (PDMS)	8
<b>3.3 FABRICATION</b>	9
3.3.1 CREATING MIXTURES FOR CASTING	9
3.3.2 SPIN-COATING SHEETS	10
3.3.3 DROP CASTING	13

3.3.4 OPTIMIZATION	13
<b>3.4 THERMAL MODEL</b>	16
3.4.1 Photoexcitation heat input	16
3.4.2 Effective conductivity	17
3.4.3 INCIDENT LIGHT DECAY	17
3.4.4 Computer Model	18
<b>3.5</b> Thermomechanical Model	21
<b>3.6 MECHANICAL TESTING</b>	23
4.0 RESULTS	25
4.1 Thermal Results	25
4.2 THERMOMECHANICAL RESULTS	27
5.0 CONCLUSION	30
6.0 APPENDICES	31
6.1 DATA TABLES FROM PHYSICAL TESTING	31
6.2 DATA TABLES FROM THERMAL TESTING	36
7.0 BIBLIOGRAPHY	37

## **Table of Figures**

Figure 1 - Force at constant length as a function of temperature (Anthony, Caston, and Guth
1942.)
Figure 2 - Variability of photoexcited NP Temp. in open air by size and packing density
Figure 3 - General outline of how objectives were accomplished
Figure 4 - Molecular structure of Polystyrene [17]
Figure 5 - Molecular structure of PDMS (Courtesy of Wikimedia Commons)
Figure 6- Initial Spin-coating of Al-PS 10
Figure 7 - Film Thickness of PS as a function of Spin Speed (Courtesy of people at the place).
Figure 8-Unevenly distributed PS sample
Figure 9 - Spin-coated Al-PDMS film
Figure 10- Drop-Casted Al-PDMS Film
Figure 11 - Comparison of the consistency of drop-casted samples
Figure 12 - COMSOL model diagram [24] 19
Figure 13 - Thermal contour of 7 wt% NP sample under 1 sun 20
Figure 14 - Thermal distribution of 7 wt% NP sample under 1 sun 20
Figure 15- Image Depicting the Setup for Mechanical Tests
Figure 16- Al-PDMS Nanocomposite under Xenon Light
Figure 17 - Thermal Results Chart
Figure 18- 0.5 Sun Thermomechanical Results Chart
Figure 19- 1 sun Thermomechanical Results Chart
Figure 20- 1.5 Sun Thermomechanical Results Chart
Figure 21- Thermomechanical Results for Specific Pre-Load

## **1.0 Introduction**

Traditional robots lend themselves well to industrial automation. In the static or mapped environments of a manufacturing facility, their actuators are designed to track known trajectories while imparting high mechanical impedance, meaning that the robotic limbs resist motion when a force is applied. However, this is less than ideal for applications that take place in an unmapped environment with dynamic forces. In applications like prosthetic limbs or medical robotics for instance, conventional actuators run into a host of problems, including fine position control, storing and releasing energy, and particularly applying force while yielding to external resistance [1]. Certain hard actuators can be designed to comply against external forces, but this usually requires feedback systems and complex algorithms [2]. Soft robots address these issues, and the benefits make soft actuation worth researching.

Early attempts at soft actuators produced the first pneumatic artificial muscles, or PAMs. They were able to mimic the compliant behavior of a natural muscle in a simple to manufacture, safe to operate package, but ran into problems with maximum strain and driving force [3]. Later research in the field of ionic polymers produced muscles that mimicked organic behavior even more, muscles that could be scaled with a high energy density required for independent robotics. However, these newer actuators are expensive to produce, and even more expensive to miniaturize [4]. Inexpensive, efficient, scalable soft actuators have yet to be produced.

For heat-based actuation, the conventional approach is to use resistive heating via electrodes to create a temperature rise, for instance in shape-memory alloys [5]. This approach is

wasteful, however, as the presence of conductive material causes an outlet for the heat generated [6]. Furthermore, any delivery of energy by resistive heating requires scaling of the wiring used, a factor that would affect the cost and processing required for bundled or microscale actuators. In contrast, photothermal actuation can be non-contact, and if reflection is limited, free of energy loss at the input. This method could provide efficient energy delivery to a soft actuator that only requires scaling at the point where the light enters. Ideally, light would be delivered at one end of an actuator, carried along its length, and be delivered as heat energy evenly throughout the material. Such an approach can be accomplished by the addition of nanoparticles, which have been found to heat up when exposed to light [7].

With the above in mind, the goals of the project were to improve the photothermal response of a plastic actuator material by adding nanoparticles. Such an approach would require developing a model to predict the behavior of the resulting composite, proving that both the energy delivery and actuation will be effective at a variety of degrees of "improvement" and operating conditions, and devising a method for reliably fabricating the composite.

## 2.0 Literature Review

#### **2.1 Alternate Forms of Soft Actuation**

#### Table 1 - Research Landscape [8] [9] [10] [11]

Туре	Mechanism	Advantages	Disadvantages
Pneumatic/H ydraulic	Compressed air/water fills soft cells.	<ul> <li>Ease/low cost of assembly</li> <li>Easy replacement</li> <li>Safe operation</li> </ul>	<ul> <li>Limited displacement</li> <li>Low actuation force</li> </ul>
Magnetic	Magnetism brings soft layers together, causing 2- dimensional expansion.	<ul><li>Large actuation force</li><li>Fast Response</li></ul>	<ul> <li>Complicated and expensive fabrication process</li> <li>High power consumption</li> </ul>
Thermal Gels	Cross linked gels that can actuate two and three dimensionally through expansion	<ul> <li>Shape memory upon removal of stress</li> <li>Two and Three dimensional actuation</li> </ul>	<ul> <li>Complicated fabrication process</li> <li>Limited Displacement</li> </ul>
Electrical	Piezo-electric effect Electrorestrictive Dielectric effect	<ul> <li>High response</li> <li>Large actuation force</li> <li>High mechanical energy density</li> <li>High efficiency</li> </ul>	<ul> <li>High voltage needed</li> <li>No effect of voltage polarity</li> </ul>
Chemical (Ionic)	Ion transfer causes a change in shape	<ul> <li>Low voltage needed</li> <li>High response</li> <li>Large displacement</li> <li>Wet and dry operating conditions</li> </ul>	<ul> <li>Low electromechanical efficiency</li> <li>Low actuating force</li> </ul>

#### 2.1.1 Stimuli Responsive Polymer Gels

Cross-linked polymer gels have been observed undergoing controlled shape change under different applied fields of stimulus including thermal, electrical, UV light, and magnetic [8]. Shape change in the material can come in the form of two or three-dimensional actuation. The polymer gels are fabricated through chemical or physical cross-linking. The chemical gels have a three dimensional network created by permanent covalent bonds while the physical gels form through the physically connected aggregates.

Since the mechanisms driving heat activated polymer gels is pure thermal expansion, the strains produced are of limited use in actuation. The fabrication process is also more complex than spin coating or drop casting polymer composites [8]. The field of thermally activated soft actuators needs a simple-to-fabricate actuator material that produces significant strain while also having an efficient method for depositing energy.

#### **2.2 Thermomechanical Actuation**

Elastomers are affected by temperature in an unusual way. When stretched, they behave as an ideal monatomic gas, storing work done on them as thermal energy, which is released immediately to the surroundings [12]. Conversely, a piece of rubber held in a stretched state contracts reversibly when heated, much like the heating of a gas causes a pressure increase under the Ideal Gas Law [13]. Naturalist John Gough observed the phenomena of rubber's thermoelasticity in 1804, and was the first to describe it as consisting of reversible reactions [14]. Physicist James Joule would confirm Gough's conclusions, and the phenomena were later called the Gough-Joule effect. The result of this effect is that rubbers have a modulus of elasticity that is proportional to absolute temperature, as shown in the following chart:



Figure 1 - Force at constant length as a function of temperature (Anthony, Caston, and Guth 1942.)

It is interesting to note that at some point between 6 percent and 13 percent strain, the increasing temperature switches from having a stress-reducing effect to a stress-increasing effect. This point is the strain at which the balance between thermal expansion and Gough-Joule contraction changes in favor of contraction, the so-called *thermoelastic inversion point* [15]. From the sources reviewed, it can be gathered that, for a rubber under load experiencing a temperature change, length change is a result of both thermal expansion and a change in the modulus of elasticity. This is important in modeling the thermoechanical response of a rubber.

#### **2.3 Photothermal Mechanism**

#### 2.3.1 Energy Input by Photoexcitation

Nanoparticles have been researched as an energy source for ignition reactions due to their ability to guide, localize, and trap light radiation in the particle as heat [16]. Such studies are useful because they are aimed at attaining much of the same goals as this one, namely that of tunable, efficient, rapid energy delivery to a material specimen. It has been shown that peak

temperature rise of multiple particles can vary from as low as less than 1K to 1500 K depending on packing density, which means the NPs can be adjusted so the polymer matrix responds but does not have its strength compromised [7]. Also, the mechanism is notable for only having energy loss through the material-surroundings boundary, as opposed to direct heating by electricity that would allow heat to escape through the heating element and its connecting wires [6].



Figure 2 - Variability of photoexcited NP Temp. in open air by size and packing density [7]

## **3.0 Methodology**

#### **3.1 Starting Objectives**

There are two mechanisms, photothermal and thermomechanical, being combined to produce actuation. A research plan that would allow for the best evaluation of predictions and reduction of error would involve separate models and laboratory testing for each. With this in mind, the following objectives were made, to be accomplished over the course of the project:



#### Figure 3 - General outline of how objectives were accomplished

#### 3.2 Selecting Polymer candidate

3.2.1 Thermal expansion of Polystyrene (PS)



Figure 4 - Molecular structure of Polystyrene [17]

On the recommendation of a project advisor, Polystyrene (PS) was first selected as an actuator material due to its ease of dry-spinning. PS is a polymer easily dissolved in chloroform after which it can be molded into a variety of shapes and then re-solidified by the evaporation of the solvent [18]. The mechanism of actuation was intended to be thermal expansion, the coefficient for which is  $7 \times 10^{-5}$  m/(m-K) [19]. PS found use in the project as a practice subject for the fabrication phase. After spin-coating samples of the plastic, though, it was found that PS was too brittle to serve as an actuator. Furthermore, initial measurement of thermal deformation could not observe any length change in a PS-NP composite with 5 wt% NPs, even after several minutes of light exposure. For these reasons, another actuator material was sought.

3.2.2 Contraction by the Gough-Joule effect in Poly-Dimethylsiloxane (PDMS)



#### Figure 5 - Molecular structure of PDMS (Courtesy of Wikimedia Commons)

In researching a plastic with a higher coefficient of thermal expansion, the silicone elastomer PDMS was selected as another actuator candidate due to its thermal expansion coefficient being an order of magnitude larger than that of PS [20]. The thermal-stiffening properties of elastomers were then found to hold promise as a mechanism to drive actuation behavior that could be predicted and observed visually [21]. The Dow-Corning Sylgard 184 kit was chosen as a silicone rubber product due to the fact that its properties were well-researched and its preparation process was simple, requiring no extra chemicals or tools beyond those needed to mix the components and cure the elastomer [20].

#### **3.3 Fabrication**

#### 3.3.1 Creating Mixtures for Casting

To shape Polystyrene, solid beads of PS were mixed with the solvent chloroform. The initial proportion of PS to chloroform was five percent by weight, but varied up to 30 percent. Changing the percentage of solid PS to chloroform allowed for variation in the viscosity of the liquid solution, which affected the thickness, shape, and distribution of the composite sample. Determining how much PS to solvent to use also depended on the amount of nanoparticles in the composite. The 70 nanometer particles varied from three to five weight percent, and were added to the PS/solvent mixture. The quantity of nanoparticles also affected the viscosity of the mixture and how evenly it would cover the substrate during the spin-coating process. Larger percentages of PS and nanoparticles were used to create viscous solutions and thick samples. The Al-PS mixture was then vigorously stirred by hand and with a magnetic stirrer.

To create an Al-PDMS mixture, an elastomer base for PDMS was heated for 5 minutes at 100 degrees Celsius to decrease its viscosity. Aluminum nanoparticles were then added to the elastomer base, followed by the addition of curing agent in a 10:1 base/cure weight ratio. The weight percentage of nanoparticle to PDMS varied throughout the experiment as different optimization techniques were implemented, however the 10:1 ratio for the PDMS solution remained constant for all mixtures to ensure the integrity of the polymer. PDMS differs from PS in the initial mixing process in the fact that it requires the addition of heat to properly cure. The mixture was then heated again for 20 minutes at 100 degrees Celsius to increase viscosity before being applied to the substrate.

#### 3.3.2 Spin-coating Sheets



Figure 6- Initial Spin-coating of Al-PS

Spin-coating as a casting method for fabrication was initially chosen because it could make thin, uniform samples that conform to the shape of a substrate. The spin-coating process was also time efficient, allowing for fast production of samples of varying thickness, size, and percentage of nanoparticles [22]. Around two thirds of the glass substrate had to be evenly covered with the mixture to get an evenly distributed thickness.

Research provided initial instructions on spin-coating chloroform-dissolved PS, giving baseline values for spin speed, acceleration, and spin time. The figure below shows film thickness as a function of spin speed for a PS chloroform solution [18].



Figure 7 - Film Thickness of PS as a function of Spin Speed (Courtesy of people at the place)

For the AI-PS mixture, spin speed varied from 600 rpm to 3000 rpm while the acceleration and spin time remained constant at 2 and 60 seconds respectively. Spin speed depended on the viscosity of the mixture. AI-PS mixtures of 30 weight percent Polystyrene required high rpm to evenly disperse across the substrate, while mixtures with less than 20 percent PS needed lower rpm. Overall AI-PS spin coated films were typically unevenly distributed, either too thin or too thick, and inconsistent on the shape size and thickness of the films.



Figure 8-Unevenly distributed PS sample

The spin coated Al-PDMS films were created after the Al-PS films, so the baseline values of spin speed, acceleration time, and spin time were taken from previous spin-coating trials. Al-PDMS mixtures were spun at a spin speed of 700 rpm, a 2 second acceleration, and a 60 second spin time. The parameters for the spin coater for Al-PDMS mixtures remained constant unlike the Al-PS mixtures. Overall, Al-PDMS spin-coated films formed easier than their Al-PS counterparts. Due to the properties of PDMS and the implementation of heat curing before the spin-coating process, the mixtures flowed more evenly over the glass substrate creating smooth, well distributed, uniform composite films



Figure 9 - Spin-coated Al-PDMS film

#### 3.3.3 Drop Casting

The second fabrication method utilized in this experiment was drop casting, performed on the Al-PDMS mixture. The drop casting method required placing a given amount of mixture on to a substrate and leaving it to cure. This method made the thickness of the film more difficult to control and required a long post curing treatment that lasted for at least twelve hours. However, drop casting Al-PDMS mixture was the preferred method of fabrication over spincoating, because it was a simpler process and produced a more homogeneous sample without wasting large amounts of Al-PDMS mixture in the spin coater. The resultant film samples possessed superior elastic properties, and the increased thickness allowed for more weight to be hung from the sample during the testing phase. Drop casting was the method selected for the fabrication of the final Al-PDMS test samples used for formulating the final data.



**Figure 10- Drop-Casted Al-PDMS Film** 

#### 3.3.4 Optimization

The optimization of the fabrication process was important in creating usable, uniform test samples and can be broken down into three categories of improvement: mixing, casting, and curing.

The challenges that arose during the mixing process typically stemmed from the addition of the aluminum nanoparticles. Before the particles were added to the mixture, they would generally clump together in their storage container. Early spin-coating trials revealed that if the nanoparticles were left clumped they would remain clumped in the resulting film sample making it unusable for testing. Different methods of de-clumping were implemented to create an even particle distribution within the film. A sifter was used to try and break up the bigger clumps, however the nanoparticles were too small for the sifter to be effective. Next, a mortar and pestle were used to try and break up the clumps, but just as before the nanoparticles were too small and were ground into the rough surface of the pestle and the mortar. The razorblade proved to be the most effective tool in eliminating clumps. Removing all the clumps from the nanoparticles was difficult to achieve but chopping the particles with the razorblade before adding them to the mixture was important in casting a uniform sheet. Other improvements in the mixing process included changing the amount of PS being dissolved in chloroform. The initial weight percentage of PS to chloroform was five percent, which was much too low to create a thick enough sample to hang weights from. The weight percentage was then moved up to 30 percent to get a much thicker solution, but was too thick for the spin coater to properly distribute it over the glass substrate. Eventually the weight percentage of PS was narrowed down to 20 percent of the mixture allowing for the most optimal thickness.

Optimization in casting included tuning the parameters of the spin coater to control the varying thicknesses of the films. Spin speed had the most effect on thickness of the film, followed by spin time and acceleration time. Initial parameter values for spin-coating Al-PDMS were 500 rpm for spin speed, 2 second acceleration, and 60 second spin time. This spin speed was much too low and did not effectively distribute the mixture across the substrate. After slowly

14

increasing spin speed in hope of seeing a better distribution of the mixture, the spin coater was set to its maximum spin speed of 3600 rpm, however this proved too fast and resulted in a majority of the mixture being wasted. After narrowing down the weight percentage of PS to 20 percent we were able to narrow down the spin speed to 2000 rpm, giving us the best usable test sample. For the AI-PDMS mixtures the spin speed, acceleration time, and spin time were set at 700 rpm, 2 seconds, and 60 seconds respectively. The parameters remained constant for the AI-PDMS mixtures because they were able to produce thick uniform sheets. Early fabrication of AI-PDMS composites revealed that the PDMS solution was not viscous enough for the mixture for 20 minutes at 150 degrees Celsius made the solution more viscous, which allowed for the distribution over the substrate to be more even. Drop casting did not require much optimization, besides measuring the amount of mixture being poured into the petri dish to record constant film thickness.

Optimization of the curing process was important in creating better quality test samples. Heat curing only took place for the Al-PDMS mixtures and films. The transition from spincoating to drop casting eliminated the need to pre-cure the mixture. Initially the Al-PDMS mixture was heat cured at 180 degrees Celsius for 20 minutes. However, the resulting films had air bubbles and were much more rigid then they were supposed to be. To fix these problems the mixture was heat cured for at least 12 hours on a low temperature of 40 degrees Celsius. Changing the curing process effectively eliminated the air bubbles inside of the composite and made the samples more elastic, which was important during the testing phase.

15



Figure 11 - Comparison of the consistency of drop-casted samples.

#### **3.4 Thermal Model**

#### 3.4.1 Photoexcitation heat input

For the heat input element, we consulted a previous project on photoexcited NPs. For a lamp with the exact same specifications as the one used in our experiments, Ohkura et al. [7] found the temperature rise was 0.18 K for a single 70 nm Al NP in open air under 1 sun of incident light. This result was attained using the following equation [7].

$$\Delta T_{Al,max} = \frac{P}{4\pi R^2} \left(\frac{1}{G} + \frac{R}{K}\right)$$

Where R is the radius of the particle, G is the surface conductance between the Al particle and air (MW/m^2 K), P is the total energy absorption rate per particle (W) and K is the thermal conductivity of air (W/mK). A finite G represents a temperature discontinuity between the interface of the particle and air. Working backwards from the temperature change towards the power input allowed for a simpler approach than manually computing it based on Planck's law.

#### 3.4.2 Effective conductivity

Many empirical and theoretical models have been proposed to predict effective thermal conductivity when dealing with two-phase mixtures. Maxwell [23] used potential theory to obtain a relationship for the conductivity of a combination of randomly distributed and non-interacting homogeneous spheres in a homogeneous medium. This model lends itself well to the volume fraction concentrations found in our experiments, and is given in the following equation [23]:

$$k_{eff} = \frac{k_p + 2k_m + 2\phi(k_p - k_m)}{k_p + 2k_m - \phi(k_p - k_m)} k_m$$

where  $k_{eff}$  is the effective thermal conductivity,  $k_m$  is the conductivity of the matrix,  $\phi$  is the particle volume fraction, and  $k_p$  is the thermal conductivity of the particle.

#### 3.4.3 Incident Light Decay

One factor that needed to be compensated for in the sheet model was the decay of incident light as it was absorbed by NPs while passing from the front to the back of the sample. We found that the incident light decay for a given volume was governed by the following equation:

$$P_n = \frac{I - \sum \Delta I_{n-1}}{I} P_{n-1}$$

Where  $P_n$  is the power input per volume of material for a given layer, I is the original incident light energy density in W/m<sup>2</sup>, and  $\sum \Delta I_{n-1}$  is the amount of incident light absorbed by all previous layers.

#### 3.4.4 Computer Model

For computer modeling, the COMSOL multiphysics software package was used for finite-element analysis. The model was a simplified, two-dimensional cross section viewed perpendicular to the incident light direction. Energy input by the photothermal effect was approximated as a wattage input that varied with depth. The layer where the light was being absorbed was divided into six sublayers of equal thickness, with specific wattages for each sublayer determined by the above power input equation. To determine the thickness of the active layer, the equation was further used to derive the point at which the material absorbed 99% of the light, leading to a functional P/vol of 0 W/m^3:

$$P_n = 1 - \frac{I - \sum \Delta I_{n-1}}{I} \approx 0.99$$

The rest of the sample was modeled as inactive, with no direct power input. The layers were free to conduct heat between them according to a thermal conductivity k calculated from the Maxwell model for each wt% of NPs, with no thermal boundary acting as an insulator anywhere in the model. Free convection from the sides, top, and bottom of the sample was modeled using inbuilt software functions, with the area/perimeter factor being calculated from the dimensions of each physical sample fabricated for testing.



Figure 12 - COMSOL model diagram [24]

To simulate testing conditions, the sample's initial thermal conditions were set to room temperature before undergoing the above-outlined process for a period of two minutes. This produced a thermal contour chart and a chart of the thermal distribution in the sample:







Time=2 min Surface: Temperature (K)

Figure 14 - Thermal distribution of 7 wt% NP sample under 1.5 sun

To generate a temperature prediction able to be checked by a spot-probe, COMSOL's "average" function was used to generate a line-average temperature from all vertical thermal boundaries in the model:

Light Intensity (Suns)	3 Wt% NPs	5 Wt% NPs	7 Wt% NPs
0.5	308.27 K	309 K	312.91 K
1	321.4 K	320.9 K	331 K
1.5	335.21 K	334.81 K	341.8 K
2	347.79 K	345.91 K	363.78 K

 Table 2 - Vertical average temperature predictions for various particle concentrations

#### **3.5 Thermomechanical Model**

In an elastomer, the stress present in a stretched sample is a function of the physical structure of the polymer chains, the temperature, and the change in length that produced the change from an unstressed to a stressed state [14]:

$$\frac{F}{A} = \frac{vkT}{V}\frac{\overline{r_1^2}}{\overline{r_0^2}}(\alpha - \frac{1}{\alpha^2})$$

Where F is the total force, A is the undistorted cross-sectional area corresponding to the volume V,  $r_i$  is the mean-square length of polymer chains in the undistorted state of the network at that volume,  $r_0$  the mean-square length of free chains at the temperature T, v the volume fraction of polymer chains, k the Boltzmann constant, and  $\alpha$  the extension ratio L/L<sub>0</sub>. From the

above equation, the conclusion can be derived that the stress, and therefore the Young's modulus, is proportional to the absolute temperature. This means that one measurement of the elasticity at a specific temperature can generate an elasticity curve across all temperature ranges. The temperature-dependent elasticity of an elastomer is therefore as follows:

$$E = E_0 \left(\frac{T}{T_0}\right)$$

Where  $E_0$  is the measured elasticity at a temperature  $T_0$ .

As mentioned in the literature review, length change in a stretched elastomer subjected to a temperature change is a balance between thermal expansion and a strain change from the Young's modulus transforming. Using the above equation, this balance is given in the following equation:

$$\frac{\Delta L}{L_{unstretched}} = \alpha (T - T_0) + \frac{\sigma}{E_0 \left(\frac{T}{T_0}\right)} - \frac{\sigma}{E_0}$$

Where  $\alpha$  is the coefficient of thermal expansion, T is the absolute final temperature, T<sub>0</sub> is room temperature (293° K),  $\sigma$  is the stress on the sample, and E<sub>0</sub> is the measured modulus of elasticity at room temperature. For the purposes of this project, E<sub>0</sub> was derived from a machine tensile test as 0.4 MPa.

#### **3.6 Mechanical Testing**



Figure 15- Image Depicting the Setup for Mechanical Tests

To achieve the objectives of the testing phase, which was to track the deformation of the composite while varying the intensity of the energy input, the amount of pre-loaded stress, and weight percentage of aluminum nanoparticles in the composite, we devised the following procedure.

To test the deformation of the composite, a pre-loaded sample of an Al-PDMS composite was suspended from a fixture in front of a xenon lamp as depicted in the figure above. The sample was marked with data points to visually track expansion and contraction of the material. A ruler that is accurate to the millimeter scale was then clamped to the side of the fixture close enough to the data points on the composite that any change in length from the sample could be quantified in millimeters. A separate fixture was then set up to hold a high resolution camera in a locked position to visually record the length of the composite before and after each test. For composite samples with 3, 5, and 7 weight % NPs the pre-loaded sample was then exposed to a specific light intensity for two minutes so that thermal equilibrium could be reached. The sample was then allowed to cool for one minute before the next test.



Figure 16- AI-PDMS Nanocomposite under Xenon Light

To vary the intensity of the energy input, the fixture holding the composite was placed at four different distances away from the lamp. Using an incident light detector, distances for each intensity level quantified in suns were produced. To ensure accuracy for each energy intensity, the table was marked at each distance.

The amount of stress each composite could sustain was calculated from the dimensions of each individual sample. To vary the pre-loaded stress, brass weights ranging from one pound to three pounds were hung from two rollers that were clamped around the bottom of the sample by rubber bands. Deformation in the composite was recorded at different stress levels.

## 4.0 Results

#### **4.1 Thermal Results**



#### **Temperature Rise Per Sun**

#### **Figure 17 - Thermal Results Chart**

The thermal results above were obtained from thermocouple readings of three separate Al-PDMS nanocomposites at different weight percentages and at varying incident light intensities. Over the range of 0.5 to 2 suns of incident light, trends showed that the 7 wt% sheet was consistently hotter, generally reaching temperatures 15 K higher than the next hottest sample and reaching a maximum change of 74 K up from room temperature. The 3 wt% and 5 wt% samples displayed the interesting behavior of having almost identical temperatures, though the 3 wt% tended to be slightly hotter. Both of the samples reached a peak change of roughly 55 K up from room temperature. Overall, the trend of final temperature as a function of light intensity was strongly linear in both the model and the recorded data. When considering these results, it is important to note that the samples with 3 and 5 wt% NPs had the same dimensions, while the 7 wt% sample was significantly thinner.

The thermal model was able to predict both the similarity of the 5 wt% and the 3 wt% and the intensity of the 7 wt%'s heat response. However, the COMSOL model did not explain the reason for why the 5 wt% and 3 wt% thermal trends were so similar and why the 7 wt% trend was visibly larger. These can be attributed to one or more of the following thermodynamic behaviors:

- The 3 wt% and 5 wt% nanocomposite samples did not reach equilibrium within the two minute testing timeframe, due to their greater thickness.
- The 5 wt% nanocomposite sample has the same dimensions as the 3 wt% sample but a larger thermal conductivity that would allow for greater heat conduction throughout the sample despite the heat-generating layer being smaller.
- 3. Since the following is true: Q = kΔT/L, where Q is heat transfer and L is the thickness of the conductive layer, then the 3 wt% sample would have an increased L due to more heat energy being deposited at greater depth, thus having to pass through a greater amount of insulating rubber. The 5 wt% sample, with its thinner active layer closer to the surface, would have less heat travelling from the lower depths.

### **4.2 Thermomechanical Results**



Figure 18-0.5 Sun Thermomechanical Results Chart



Figure 19-1 sun Thermomechanical Results Chart



Figure 20-1.5 Sun Thermomechanical Results Chart



Figure 21- Thermomechanical Results for Specific Pre-Load

Figures 16-18 show the change in length of 3 separate composites at different weight percentages and different light intensities as a function of stress. Figure 16 shows the change in length as a function of light intensity for a specific stress, and serves a summary for the thermomechanical results. As with the thermal results, there is a clear divergence between the 3

wt% and 5 wt% samples, which seem identical within the boundaries of error, and the 7 wt% sample. Figures 16-18 show that as the preloaded stress is increased, the size of the contractions in the samples also increases.

Using the reasoning from the thermal model, we can explain the relative position of the 3, 5, and 7 wt% data point trends on the thermomechanical charts. However, this does not explain the significant difference between the theoretical and experimental data. The separation between the theoretical and experimental data can likely be attributed to the inactive layer of the composite having a lower temperature than the active layer. According to the mathematical model, cooler temperatures will result in smaller contractions. The thermocouple readings that were used to generate the thermomechanical predictions were taken from the center of the sample and do not accurately reflect the temperature rise throughout the composite, and therefore the contraction of the entire composite. Until the variations in temperature are reduced, a more complex predictive model will be necessary for nanocomposite samples with "dead layers" present.

## **5.0 Conclusion**

Current methods for producing soft actuators are limited because of problems with ease of fabrication and scalability. Techniques involving the integration of photothermal nanoparticles with a heat-stiffening rubber have shown to be effective and adaptable to small device sizes. For the thermal aspect, testing displayed a high correlation to the models, which predicted temperature rises as high as 364 °K. In contrast, the thermomechanical results were less accurate when compared to predictions, but this error can be partially explained by the homogeneity of the composite and the uneven energy delivery. As shown in the computational models, a significant portion of the samples tested were inactive, serving to hamper the actuation. It is important to evenly heat the composite to its max temperature to acquire the best contractions. If this "dead layer" were eliminated, either by increasing light input or by reducing the volume fraction of nanoparticles so that light reaches all parts of the sample, then the nanocomposite developed in this project could be truly scalable to any size or shape, from micro-scale devices to prosthetic limbs. A good next step in this research would consist of spinning the actuator material into fibers that would serve to direct incident light to all parts of an actuator. Such methods would also be made easier by a model to give the most ideal particle concentration for a given light intensity and set of actuator dimensions.

## 6.0 Appendices

## 6.1 Data tables from physical testing

#### Table 3 - Mechanical Testing data (Length change in millimeters)

5 Percent	1/2 Sun	1 Sun	3/2 Sun	2 Sun
1.5 lbs	-0.1	-0.16	-0.35	-0.5
2 lbs	-0.08	-0.3	-0.4	-0.5
2.5 lbs	-0.4	-0.5	-0.5	-0.51
3 lbs	-0.5	-0.5	-0.6	-0.7
Dimensions: 1.5 cm wide, 2.5 mm thick, and 4 cm long.				
3 Percent				
1.5 lbs	-0.25	-0.3	-0.3	-0.5
2 lbs	-0.2	-0.6	-0.9	-1.05
2.5 lbs	-0.5	-0.6	-0.95	-1
3 lbs	-0.5	-0.8	-0.9	-1
Dimensions: 1.7 cm wide, 2.5 mm thick, 47.5 mm initial length				
7 Percent				
0.5 lbs	0	-0.2	-0.5	-0.45
1 lbs	-0.6	-1	-1	-1.4
1.2 lbs	-1	-1	-1.7	-1.7
1.5 lbs	-0.5	-2	-2.5	-1.4
Dimensions: for the 1.5 and 2 sun at 1.5 pounds and the 0.5 For everything else: 24 mm wide, 1.5 mm thick, and 4.85 cm long lb and 1.2 lbs, initial length of 3.7 cm				

Stress (KPa)	5%	3%	7%	5% Prediction	3% Prediction	7% Prediction
177.93	-					
	0.002380952					
237.2	-0.002					
296.5	-0.01					
356	-					
	0.011904762					
157		-				
200.2		0.005263158				
209.3		-				
261.66		0.004210320				
201.00		0.010526316				
313.99		-				
		0.010526316				
261			-0.012371134			
313.99			-0.027027027			
185.34			-0.010309278			
200				-0.012	-0.01	-0.025
300				-0.019	-0.0217	-0.04

Table 4 - 0.5 Sun Length change data compared to prediction of model

Stress (KPa)	5%	3%	7%	5% Prediction	3% Prediction	7% Prediction
177.93	-0.004					
237.2	-0.0075					
296.5	-0.0125					
356	-0.01190					
157		-0.006316				
209.3		-0.012632				
261.66		-0.012631579				
313.99		-0.016842105				
130.8			-0.005405405			
261			-0.020618557			
313.99			-0.027027027			
392.49			-0.041237113			
200				-0.021	-0.021	-0.047
300				-0.035	-0.038	-0.077

#### Table 5 - 1 Sun Length change data compared to prediction of model

Stress (KPa)	5%	3%	7%	5% Prediction	3% Prediction	7% Prediction
177.93	-0.00875					
237.2	-0.01					
296.5	-0.0125					
356	-0.014285714					
157		-0.006315789				
209.3		-0.018947368				
261.66		-0.02				
313.99		-0.018947368				
130.8			-0.013513514			
261			-0.020618557			
313.99			-0.045945946			
392.49			-0.067567568			
200				-0.038	-0.044	-0.058
300				-0.062	-0.072	-0.095

#### Table 6 - 1.5 Sun Length change data compared to prediction of model

Stress (KPa)	5%	3%	7%	5% Prediction	3% Prediction	7% Prediction
177.93	-0.0125					
237.2	-0.0125					
296.5	-0.01275					
356	-0.016666667					
157		-0.010526316				
209.3		-0.022105263				
261.66		-0.021052632				
313.99		-0.021052632				
130.8			-			
261			0.012162162			
201			0.028865979			
313.99			-			
302 10			0.045945946			
572.47			0.037837838			
200				-0.058	-0.058	-0.075
300				-0.095	-0.098	-0.124

#### Table 7 - 2 Sun length change data compared to prediction of model

## 6.2 Data tables from thermal testing

	Max (3%)	Min(3%)	Max(5%)	Min(5%)	Max(7%)	Min(7%)
0.5 Sun	309	304	310	304	314	308
1 Sun	323	312	323	311	332	321
1.5 Sun	338	322	339	319	350	332
2 Sun	352	330	350	326	365	343
Averages:						
	3	5	7			
0.5 Sun	308.27	309	312.91			
1 Sun	321.4	320.9	331			
1.5 Sun	335.21	334.81	341.8			
2 Sun	347.79	345.91	363.78			
Measurements:						
	3	5	7			
0.5 Sun	303	304	315			
1 Sun	314	312	336			
1.5 Sun	333	327	348			
2 Sun	350	348	369			

#### Table 8 - COMSOL model temperature predictions compared to measured data

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