Design of a Manufacturing Process for the Fabrication and Testing of Electromechanical Transduction in Stretchable Electronics

Matthew Marcinko, Dr. Hector Medina

Abstract

In the engineering and scientific community today, there exists a great interest in the utilization of soft robots for applications in biomedical, construction, military, and environmental industries [1, 2]. Such mechatronic devices, characterized by their production from malleable materials, offer revolutionary advantages for application when compared with more traditional rigid robots. Soft electrets are among the types of devices that can have various applications as sensors, for example. A dilemma which exists in the soft robotic community today is the longevity and stretchability conflict, in which electret materials are unable to hold a charge for an extended duration unless they are contained in a rigid body [3].

In an effort to further explore this phenomenon, experiments must be conducted in which elastomer specimens are poled, charged, and analyzed. First, however, test specimens must be manufactured to accommodate such procedures. An iterative manufacturing process was designed to mass-fabricate thin test specimens. We manufactured, characterized, and tested stretchable electrets to validate their future use in experiments. Applications of this study include the development of stretchable/transparent touchpads, non-contacting electromechanical transducers, and a variety of industry-specific sensors.

Introduction

A soft robot is “an engineered mobile machine that is largely constructed from soft materials” [1]. That is, a device that is meant to elastically deform during typical use. The study of soft robots is a trending conversation that is happening in scientific, engineering, and academic environments. Motivation from soft robot development stems from the advancement of robots to become fluid and animal-like. A major challenge in the pursuit of this goal is the power requirements maintained by traditional robots. Sources like hydraulic and pneumatic systems can be implemented, but result in tether to a bulky, rigid, immobile pump or compressor. The goal in the scientific community is to achieve a soft robot capable of responding to electrical pulses in a similar manner to that of the nervous system of an animal. While the development of such a device is the long-term objective, preliminary steps must be taken to enable researchers to reach such a product. This investigation serves as a step toward reaching this goal.

A type of soft device is the dielectric elastomer. Characterized by its ability to respond to a deformation and output a voltage, dielectric elastomers consist of two electrodes on top of and below an elastomer. Effectively a flexible capacitor, dielectric elastomers are are able to store energy in the form of an electric field. For a successful soft sensor to be designed, electromechanical transduction is required. In other words, a mechanical movement, displacement, or deformation results in the generation of an output voltage. A conflict that exists in dielectric elastomers, however, is the relationship between longevity and stretchability. Electrets made from hard dielectrics are successfully able to retain charge but fail to exhibit stretchable behavior. Elastomer electrets do stretch but rapidly lose charge. The proposed solution to resolve the longevity-stretchability conflict is the introduction of carbon nanotubes to host nanoparticles in the bulk matrix of the polymer. This nanocomposite phenomenon is the motivation for our research.

For the successful development of dielectric elastomer sensors, an understanding of the properties, principles, and behavior of soft devices is required. While polymers have been studied and implemented for decades, a recent development has been the integration of nanoparticles into a matrix of polymer. The Translational Robotics And Controls Engineering Research (TRACER) Lab at Liberty University seeks to contribute to this study. This investigation aims to resolve just one component of the larger strategy of creating effective dielectric elastomer sensors: the design of the manufacturing process for the fabrication and testing of electromechanical transduction in stretchable electronics.

Methods

To contribute to the ultimate goal of manufacturing dielectric elastomer sensors capable of electromechanical transduction, we first need to create elastomer specimens capable of being mechanically, electrically, and optically tested. In doing so, we can compare the behavior of traditional polymers with that of nanocomposite-reinforced polymers. To facilitate this objective, we designed a manufacturing process by means of an iterative process. We first approached this investigation by using 201 mm x 201 mm x 55 mm Pyrex baking pans to cast SYLGARD 184 polydimethylsiloxane (PDMS) solutions (Figure 1, Figure 5). Mixed in a 10:1 ratio by mass, the SYLGARD was allowed to cure for 7 days in a room temperature environment. This approach ultimately failed to produce uniformly-thick specimens that could be tested. Because of the large size of the pan, the PDMS solution spread out unevenly, causing discontinuities in the thickness of the specimen according to the manner in which the solution was poured. Additionally, the PDMS solution heavily stuck to the bottom of the Pyrex container which tore the material, limiting the usability of the specimen (Figure 5).

To address the issue of sticking and uneven thicknesses, we proposed the use of 135 mm x 135 mm woven squares to act as a barrier between the Pyrex and the PDMS (Figure 6). With these materials, we developed an experiment to identify the best parameters through which uniform specimens could be created. Three samples were cured. The first sample, the control, consisted of the woven square being placed on the Pyrex surface and the PDMS solution being poured over the material. The solution was not forcibly distributed or leveled, although the surface on which the Pyrex sat was level. For the next sample, the woven square was taped to the bottom of the Pyrex container and the solution was not forcibly distributed or leveled. Again, the surface on which the Pyrex sat was level. Finally, the last case consisted of the square material being placed on the Pyrex glass and the PDMS solution being poured and distributed throughout the surface. For this case, we sought to evenly spread the solution throughout the container as we had done in previous experiments. The results for these trials demonstrated that the woven squares were not effective in establishing uniform specimen thickness but were effective in eliminating sticking effects. For each case, the PDMS solution seeped under the woven material, creating uncertainties in the specimen geometry. Although, in the case of the tests without tape, there was a useful portion of PDMS that was smooth and uniformly thick, controlling the dimensions of this specimen would be difficult as an unknown amount of solution could seep in between the Pyrex and the woven material. Using this information, alternative methods were considered. Mainly, we used soapy water to act as a surfactant on the surface of future molds. By using a surfactant, the PDMS solution avoided sticking to the mold and the cured specimens were easily removed.

A major issue encountered during the design of this manufacturing process was the presence of air bubbles in the test specimens (Figure 7). After mixing Parts A and B of SYLGARD 184 solutions, there was widespread bubbling throughout the specimen. To address this, we used an epoxy impregnator, the “Vacuprep” by Allied High Tech Products Inc. By using this device, air bubbles were removed and any issues corresponding to the presence of bubbles were eliminated (Figure 8).

Once the specimens were successfully manufactured, we performed a mechanical test using the MARK-10 Mechanical Testing Device in Figure 9. A tension test was conducted on 8 specimens of approximately equal length, width, and thickness (Figure 10). Due to irregularities from manufacturing and an error that corrupted one of the trials, we garnered 7 test results (Figure 11).

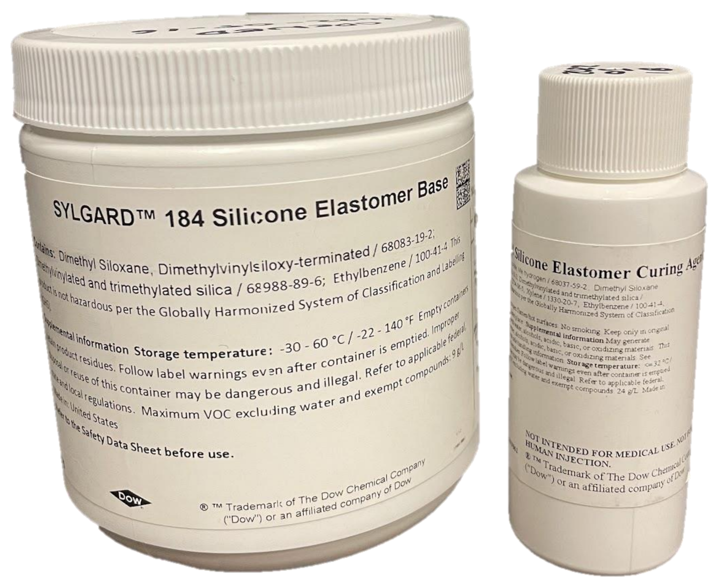

Figure 1. SYLGARD 184 Parts A & B. Photo by Matthew Marcinko. Containers of SYLGARD 184 Silicone Elastomer. Part A (left) was combined with Part B (right) in a 10:1 ratio and mixed to form a flexible elastomer once cured. Mixing was accomplished by hand and poured into mold. Curing time was 168 hours (1 week) in variable temperature conditions. These substances often resulted in a sticky contact surface and thus gloves were used when handling.

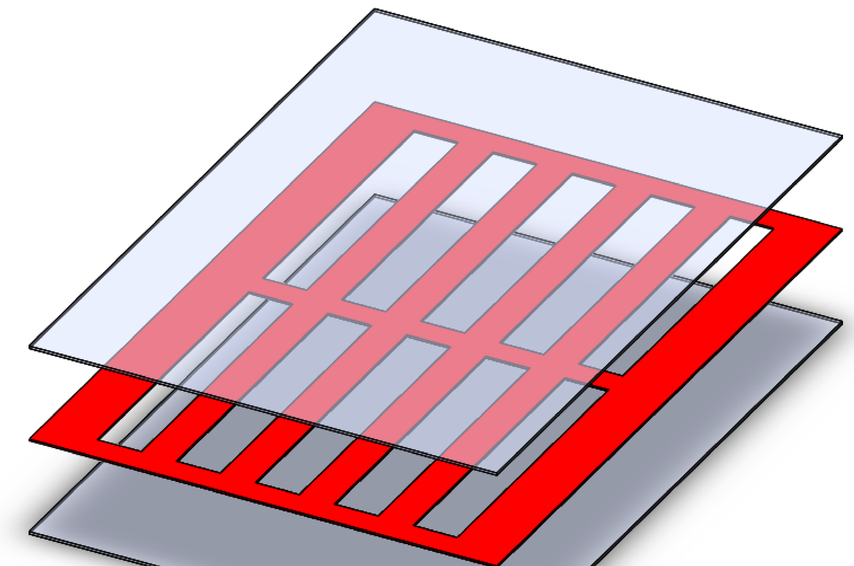

Figure 2. Three-Part Mold. Model generated by Matthew Marcinko. This model, generated in SolidWorks 2022, demonstrates the intended composition of the mold for casting PDMS specimens. Thin (0.5 mm) layers of smooth acrylic surrounded another layer of acrylic with dimensioned specimens removed by the Liberty University Waterjet. These specimens were 78 mm x 12 mm x 0.5 mm. The mold was held in place using binder clip mechanisms (see Figure 7) and ultimately shortened to accommodate space constraints (see Figure 8). This design concept replaced the use of the Pyrex dishes to allow for a smooth surface finish and a more efficient manufacturing process.

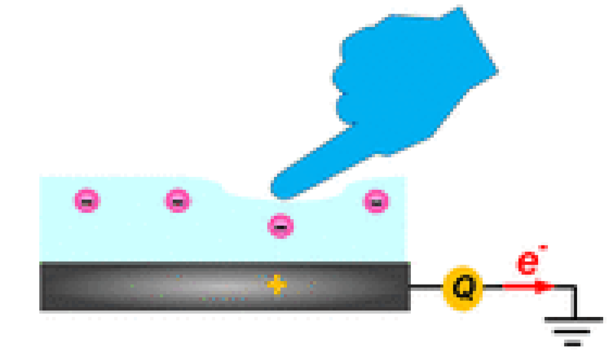

Figure 3. Schematic of the Sensing of the Compression in Electromechanical Transduction Due to a Finger. From “Stretchable electrets: Nanoparticle-elastomer composites” by Zhang et. al, retrieved from 10.1021/acs.nanolett.0c01434. Representation of potential application of specimens manufactured during this investigation.

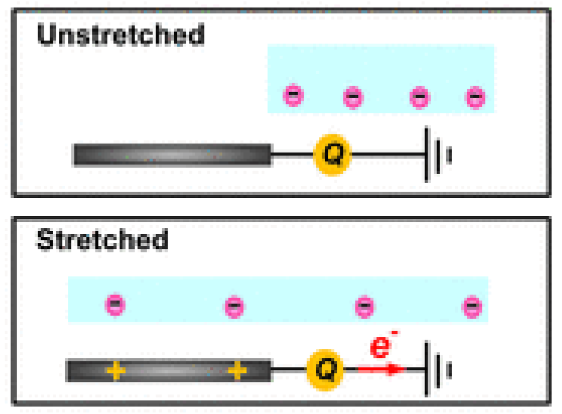

Figure 4. Schematic of Noncontact Stretch Sensing in Electromechanical Transduction
From “Stretchable electrets: Nanoparticle-elastomer composites” by Zhang et. al, retrieved from 10.1021/acs.nanolett.0c01434. Representation of potential application of specimens manufactured during this investigation.

Figure 5. Specimen from Pyrex Pan. Photos by Matthew Marcinko. The first approach we took to designing this manufacturing process was to use square Pyrex dishes to hold the 10:1 SYLGARD 184 as it cured. This presented many variables such as uneven thickness, extended curing times, and sticking. After several tests, we investigated alternative methods.

Figure 6. Specimen from Pyrex Pan with Woven Square. Photos by Mathew Marcinko. Note that the PDMS solution can be observed to be on both sides of the woven square. While one side of the cured polymer did meet the thickness requirement, the process was imprecise. This material did teach us that a boundary surface provided relief from sticking.

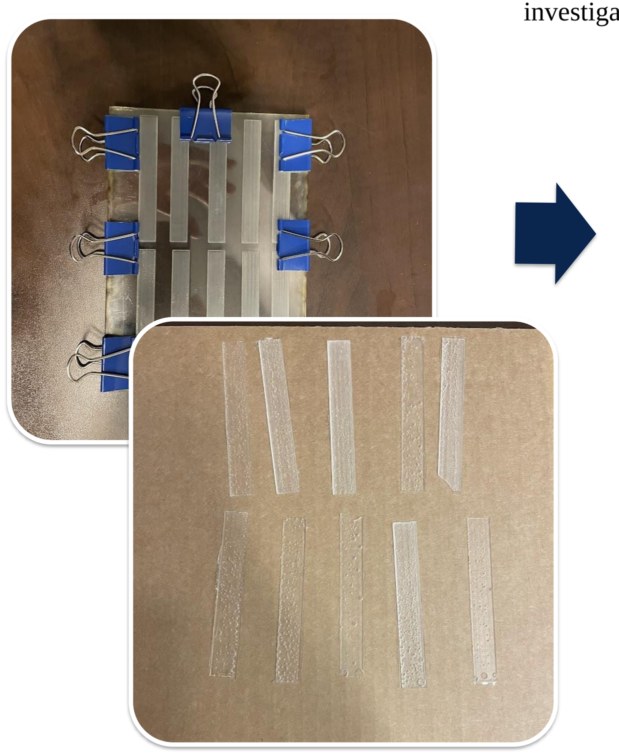

Figure 7. Specimens from Intermediate Manufactured Molding Process with Surfactant. Photos by Matthew Marcinko. While these specimens did not stick to the mold in the top image, the bottom image demonstrates the presence of air bubbles in the pieces which lead to inaccurate mechanical testing.

Figure 8. Specimens from Final Manufactured Molding Process with Surfactant, Impregnator, and Smooth Edges. Photos by Matthew Marcinko. These images represent the final development of the manufacturing process discussed herein. The mold in the top image produced five specimens that were geometrically identical, free of defects, and capable of being tested.

Figure 9. MARK-10 Mechanical Testing Device. Photo by Matthew Marcinko. This device was used to mechanically test ten specimens in tension as a proof-of-concept for future work. Students will be able to perform extensive mechanical, electrical, and optical tests on the specimens manufactured with the process designed herein.

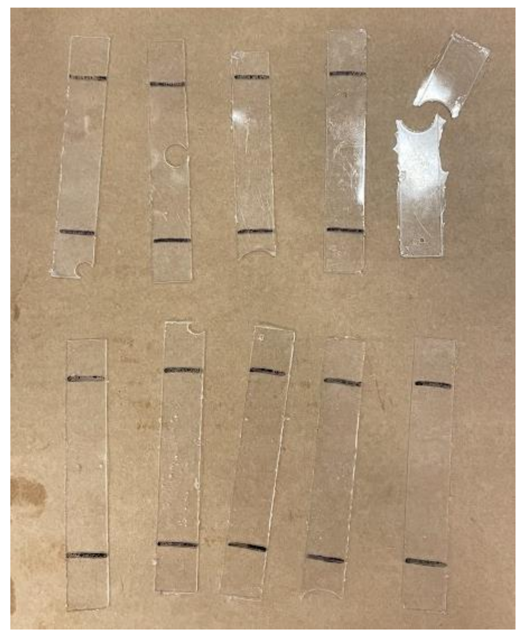

Figure 10. Test Specimens After Mechanical Tensile Test. Photo by Matthew Marcinko. Ten specimens were tested with only seven being successful. Two specimens had preexisting defects and one specimen garnered an error upon testing.

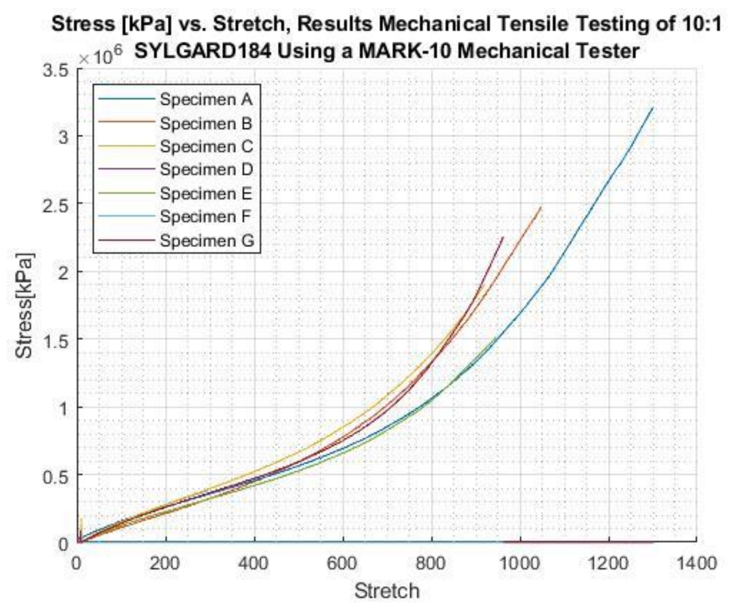

Figure 11. Results from Mechanical Tensile Test - Stress/Stretch Curve. Generated by Matthew Marcinko. Ten 10:1 SYLGARD 184 specimens were tested in tension using a MARK-10 Mechanical Tester. Stretch is the inverse of strain. Plot generated using MATLAB 2022.

Conclusion

A manufacturing process was successfully designed and implemented to facilitate the electromechanical transduction in a polymer specimen. A literature review of notable articles in the soft robotics community was conducted, initial manufacturing was performed, and subsequent process improvements were made. By the conclusion of the study, adequate test specimens were manufactured and mechanically tested.

Throughout this investigation, we determined the best procedures for the design of test specimens that are capable of testing electromechanical transduction. Further, the process developed herein will allow for moderate-scale production of test specimens to enable multiple sensors to be studied. While the mold developed for this experiment produced 10 specimens, there is no limit to the number of specimens that could be manufactured with a scaled PDMS A to B ratio. We determined the best practices for eliminating air bubbles in test specimens by using an epoxy impregnator. Using the vacuum, air was removed from the PDMS solution that arose from mixing. Additionally, we determined the best process for stopping sticking from occurring during curing by applying a surfactant to the mold surfaces. To conclude the investigation, we used the manufactured test specimens of equal dimensions to perform a mechanical tension test using the MARK-10 Mechanical Tester. The results from this study serve as a proof of concept for future mechanical, electrical, and optical tests. Further, these initial findings facilitate the comparison of results upon the addition of nanoparticles into the polymer.

Future students will be able to further this research and successfully produce and test dielectric elastomer sensors. Applications of Polymer Layered Silicate Nanocomposites and the use of these manufactured specimens include thermal stability, fire retardancy, barrier properties against gas and vapor transmissions, ionic conductivity, and self-passivation/self-healing capabilities. [4]. Soft robots are the future of robotic technology. By studying the nature of dielectric elastomers and furthering the manufacturing of soft devices, we draw the boundary of robust soft robot applications ever nearer.

Future Work

The manufacturing process discussed herein leaves a considerable amount of work to be continued in future investigations. With the primary motivation of this study being the development of soft sensors that are capable of electromechanical transduction, the specimens created during this study must be capable of integration with nanoparticles such as silica, for example. In doing so, the stretchability-longevity issue will be addressed [3] and improved mechanical, electrical, and optical properties are anticipated [4]. Future students will be able to progress from the end of this study and begin developing soft sensors capable of maintaining a charge for longer than 40 days while exhibiting stretchability. Further, experiments can be conducted to test the noncontact sensing capabilities of dielectric elastomers. Integrated with silica nanoparticles, the elastomers can be poled, charged, and studied in a circuit. Figure 3 demonstrates the procedure by which this could be accomplished. In Figure 4, a noncontact sensor is depicted. An electrode is connected to a resistor and then to ground. As the dielectric elastomer approaches the electrode, charges are induced on the electrode, generating a signal that can be quantified. Similarly, upon stretching of the dielectric elastomer, the induced charge on the electrode changes, causing a current to pass through the resistor. These demonstrations of noncontact sensing capabilities will be a noteworthy accomplishment in future work.

Improvement of this manufacturing process is also possible. For example, several variables can be eliminated to ensure specimens are uniformly and efficiently cured. Specifically, continuing the use of a bubble-eliminating method is a worthwhile strategy. As demonstrated in this investigation, the presence of bubbles in polymer specimens render the devices unsatisfactory. While an impregnator was used in this investigation, devices such as sonicators and desiccators could work just as well. Reducing curing time is also a notable objective for future work. Heating the samples are they cure should aid in increasing the rate at which these specimens are manufactured. Testing the SYLGARD 184 parts A and B at different ratios is another study of interest. Verifying that the mechanical properties of the polymer are influenced by this change will be a meaningful study. These exciting opportunities motivates the future investigation of PLSNs, and the utilization of the manufacturing process designed here.

References

[1] Trimmer, B. (2013). Soft robots. *Current Biology*, 23(15), 639-641. doi.org/10.1016/j.cub.2013.04.070.

[2] Sitti, M. (2018). Miniature soft robots - road to the clinic. *Nature Reviews - Materials*, 3(6), 74-75. doi.org/10.1038/s41578-018-0001-3.

[3] Zhang, S., Wang, Y., Yao, X., Le Floch, P., Yang, X., Liu, J., and Suo, Z. (2020). Stretchable electrets: Nanoparticle-elastomer composites, *Nano Letters*, 20(6), 4580-4587. DOI: 10.1021/acs.nanolett.0c01434.

[4] Vaia, R.A., Giannelis, E.P. (2001). Polymer nanocomposites: Status and opportunities. *MRS Bulletin 26*, 394–401. doi.org/10.1557/mrs2001.93

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