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Manufacturing of a Helical, Self-Coiling Dielectric Polymer Actuator †

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† Presented at the First International Electronic Conference on Actuator Technology: Materials, Devices and Applications, 23–27 November 2020; Available online: https://iecat2020.sciforum.net/.

Published: 22 November 2020

Abstract: For the next generation of soft robotics, novel materials are needed that overcome the limitations of established active materials, such as shape memory alloys or dielectric elastomer actuators. These new actuator types should offer fast actuation and good electromechanical coupling. In this publication, the manufacturing process and the resulting prototype of a helical dielectric polymer actuator are presented. The actuator material consists of several layers of thermoplastic elastomer and thermoplastic polymer layers with conductive fillers that are then thermally bonded and stretched, which leads to self-coiling into a helical configuration. In the targeted setup, the thermoplastic dielectric layer, which is compressed by Maxwell pressure, is significantly thinner but much easier to handle than silicone films frequently used in dielectric elastomer actuators. Several manufacturing strategies are discussed and experimentally evaluated. This includes the use of different materials, their preliminary treatment, the implementation of electrically conducting layers functioning as electrodes, and the contact of the conducting layers. By identifying feasible settings and properties for these parameters, potential defects occurring during manufacturing or high-voltage activation can be minimized. By pre-stretching and then releasing a thin strip of the laminate structure, a helix is formed. The resulting prototype actuator setup is characterized under voltages of 2 to 5 kV and shows high-speed actuation at deformation speeds of >5%/s. Due to the helical configuration, the observed contraction is orders of magnitude higher than the theoretical value for the corresponding flat configuration, showing the potential of the newly developed actuator material.

Keywords: actuator material; soft actuator; dielectric polymer actuator; artificial muscle

1. Introduction

Currently investigated active materials for soft robotics include shape memory alloys (SMA) or polymers (SMP), dielectric elastomer actuators (DEA), fluidic actuators, or combinations thereof [1–5]. However, to date, none of these has achieved broad success in soft robotics for real-world applications. That is due to different disadvantages the actuator material classes have, which require a trade-off between those and their inherent promising advantages. For example, the tremendous work density and high forces of SMA actuators come together with low strain and a limited number of actuating cycles. Similarly, any thermally activated material, even those that are novel, such as promising actuator materials like twisted coiled polymeric actuators, are severely limited in strain

rate if not cooled actively [6]. This factor is even more important in the case in which actuators are be bundled similarly to natural muscle fibers.

In contrast, DEAs offer high-speed actuation and large maximum strains. However, the forces exerted by DEAs are limited and the thin silicone membranes used in their production process are exceedingly difficult to handle and prone to tearing [7]. Some of these disadvantages are circumvented by HASEL actuators that amplify their force output by moving a dielectric fluid in a sealed bag of thermoplastic films [8]. Their uncovered electrodes can still lead to malfunctions and potential leakage of the dielectric fluid poses a major challenge.

In this work, a novel actuator material is introduced that consists of a minimum of four layers in fiber shape: two electrode layers, one thermoplastic layer, and one thermoplastic elastomer layer. The two electrodes lead to Maxwell pressure being applied to the thermoplastic layer when high voltage is applied. Usually, because of the high elastic modulus of the thermoplastic material the resulting deformation in thickness and subsequent in-plane deformation are minimal. However, by pre-stretching the fiber, plastically deforming the thermoplastic layer and thereafter releasing the stretch, the thermoplastic elastomer layer resets and the fiber forms a helix, as illustrated in Figure 1.

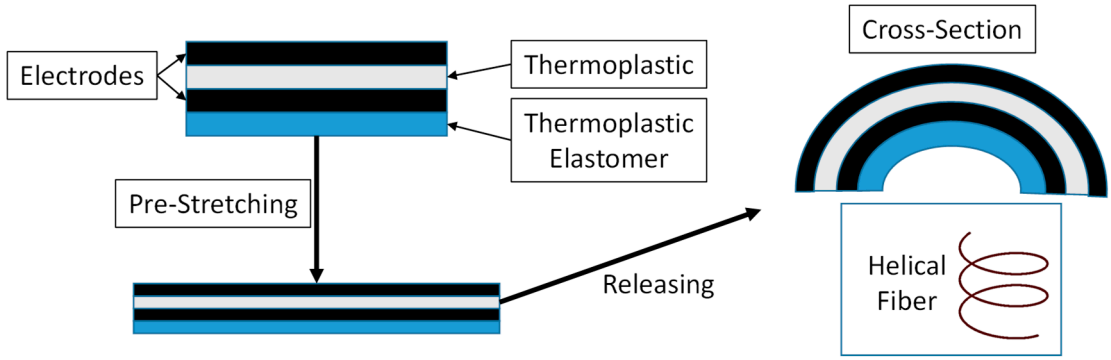

Figure 1. Schematic of the basic set up of the dielectric polymer actuator with its four layers and the procedure to a self-coiled helix.

As recently shown by Kanik et al., a helix can drastically increase the strain potential of actuator materials [9]. They showed that even a very small temperature induced strain of 0.14% leads to a global contraction of nearly 50%. This principle is translated in this work to a dielectric polymer actuator. The advantages are that very thin but still robust thermoplastic films can be used and drastically higher actuation frequencies can be achieved. However, some major challenges arise in the manufacturing process, and these are discussed and experimentally evaluated in the following sections.

2. Experiments

In the following section, the manufacturing process and its parameters, in addition to contacting strategies, are discussed. In general, the manufacturing process consists of five steps: stacking, pressing, contacting, cutting, and pre-stretching (see Figure 2).

As conductive particles, theoretically any conductive filler materials can be used in compliant electrodes, and in this work carbon black (CB) and carbon nano tubes (CNT) are investigated. The conductive fillers are mixed with isopropyl alcohol and applied to the polymer films by squeegee, brush, or pouring. As polymer films, standard plastic wraps (polyethylene (PE)) of 12 and 23 µm are used for the thermoplastic layer and a 100 µm thermoplastic polyurethane (TPU) film as the thermoplastic elastomer (bonobo repair, Germany). The layers are pressed and joined together in a laboratory hot press (P300 PV, Dr. Collin GmbH, Ebersberg, Germany). This layer stack can be joined in one pressing step or in multiple steps at different temperatures and pressures, and with or without applied vacuum. Another challenge in the manufacturing process is the contact of the electrodes, especially the inner electrode, to be able to connect the high-voltage supply. Several materials, such as copper wires, aluminum foils, silver-plated yarn, or conducting epoxy, are evaluated for their

suitability. The contact locations can either be both on the same side of the fiber or one on each side. The latter maybe disadvantageous in some application scenarios, because a power line would need to be inserted in the structure parallel to the actuator.

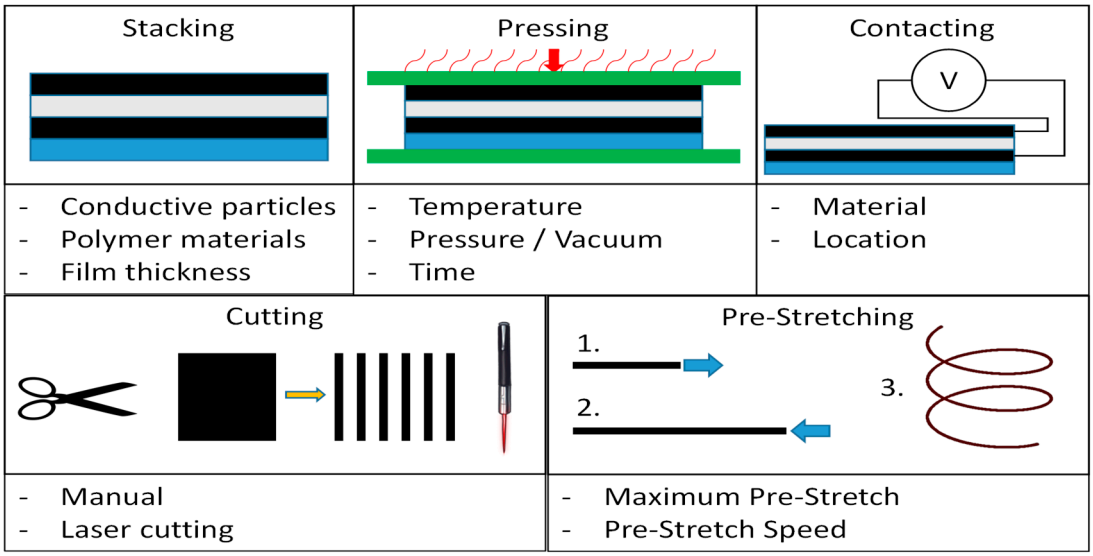

Figure 2. Manufacturing process of the dielectric polymer actuator with stacking, pressing, contacting, cutting, and pre-stretching with the relevant parameters during the processes.

The final contact will be realized after the cutting step. To cut the joined film stack into thin strips, two basic procedures are used: manual cutting with scissors, or scalpel or laser cutting. Then, the thin strips are pre-stretched by 20 to 50% and, after releasing the stretch, the strip coils up into a helix. Lastly, the helical dielectric polymer actuator is activated by applying a voltage to the electrodes.

3. Results

In the following subsections, the impact of different manufacturing strategies and parameters is shown. The order in which the results are presented generally follows the manufacturing process.

3.1. Stacking

The stacking process includes, on one hand, the selection of the films' material and thickness, and on the other hand, the implementation of the electrodes. In our experience, there is no difference regarding the adhesion when using the thicker or thinner PE films. However, pressing several of these and the TPU film together in one step often results in poor adhesion between the layers, as is visible in Figure 3b. The best results are achieved when the electrode layer and a PE film is first pressed together and these are then joined to the TPU film in a second step.

Moreover, the most consistent results and homogeneous electrodes are achieved when using a pasteous carbon black solution because CNTs or too much solvent lead to agglomerations of the conductive particles (Figure 3a). Applying too much conductive ink leads to the formation of a flaky, discontinuous surface. Regarding the electrodes, the best results are achieved when applying 0.15 g of carbon black mixed with 8.5 g of isopropyl alcohol with a squeegee.

With regard to the layer sequence, a multi-step process has been found as most favorable. Because of the increase in Maxwell pressure when using a thinner dielectric layer, the 12 µm PE film is better suited. However, it is also more prone to single larger particles of carbon black protruding through the film during the pressing process. Hence, a 23 µm film is better suited to produce electrically insulated electrodes, however, a single layer of PE film is also likely to tear during the pre-stretching step (see Figure 3c). Therefore, the most stable samples are produced by first pressing together one CB electrode with one 12 µm PE film. After repeating this step, the two PE–CB

compounds are separated by another thin PE film and joined with the TPU film. The resulting thickness of the dielectric layer is 36 µm, which is not as effective as single layers of PE film in maximizing Maxwell pressure; however, this layer sequence minimizes the risk of breakage or local tearing of the dielectric layer.

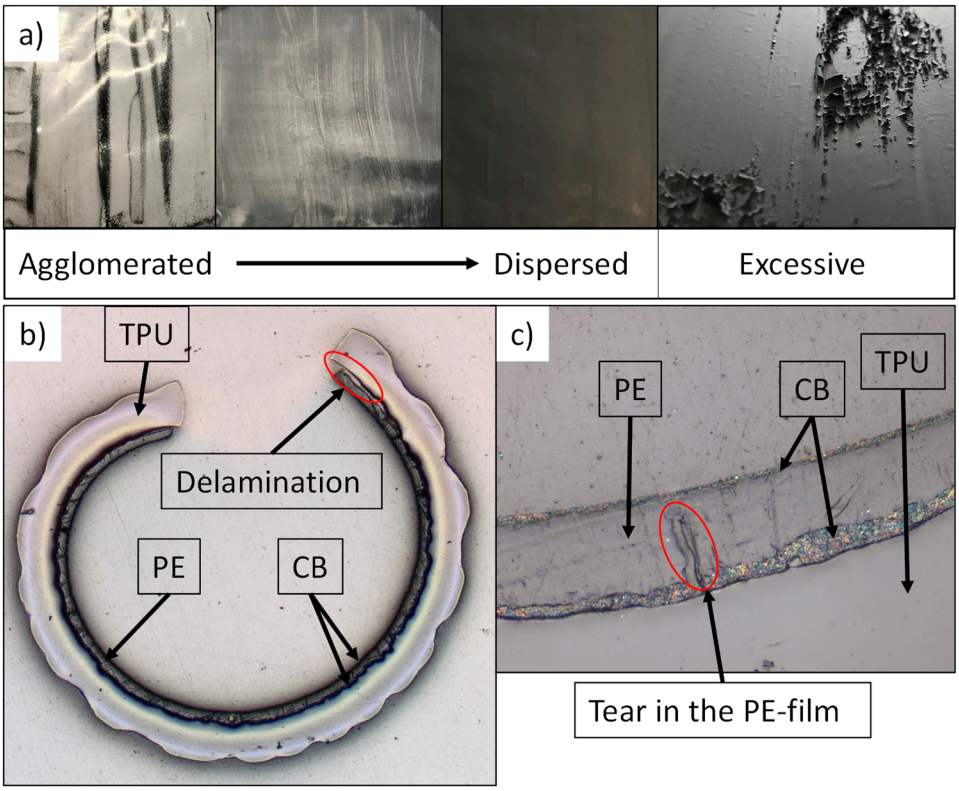

Figure 3. Different manufacturing defects occurring in the production of the helical dielectric polymer actuators: (**a**) unsuitable distribution of the conducting particles; (**b**) delamination after cutting and stretching; (**c**) tear in the PE film after overstretching.

3.2. Pressing

To securely join the carbon black particles with the PE film, in addition to the PE film with the TPU film, the right temperature and pressure need to be applied during the pressing processes. Because the melting temperature of PE is lower than the temperature at which TPU starts to soften, the PE film is the layer that melts and adheres to the other materials. The relevant temperatures were found by conducting differential scanning calorimetry. The best connection without the carbon black protruding through the PE layer is achieved at 130 °C at a pressure of 10 bar under vacuum. To join the PE carbon black compound to the TPU layer, 135 °C and 10 bar under vacuum is used. The air evacuation in the press helps to avoid air inclusions in the stack. After the intended temperature is reached, the pressure is applied for two minutes.

3.3. Contacting

The contact of the electrodes poses a major challenge because one electrode is embedded in the stack. As a result, trying to contact it after pressing often leads to damaging of the layers or an undesirable short-circuit between both electrodes. The first attempts to insert thin aluminum foils during the pressing process led to insufficient adhesion between the layers with large, unjoined areas. Similar but less-pronounced problems are visible when using silver-coated polyamide yarns. Consequently, the use of any additional material needs to be eliminated. Finally, the approach that leads to the production of functioning samples is the use of open electrodes with the inner electrode extending further than the top electrode. These areas are then contacted with conducting silver-filled epoxy, which is used to glue wires of strips of copper foil to the them.

3.4. Cutting

To cut the pressed stacks into thin strips, two solutions were evaluated: manual cutting with a scalpel and laser cutting. In a first attempt, the samples were cut manually, which is feasible and led to the production of a functioning specimen. However, many of the specimen were damaged during the process and prone to tearing during pre-stretching, or experienced short-circuits between both electrodes. Better reproducibility and lower risk of errors is achieved via cutting by laser. Therefore, the pressed stack was taped to a sheet of paper to prevent the stack from bulging during cutting, which leads to uneven strip widths. The stack was cut with the TPU film facing upwards with a Lasermaxx Plott 60 (Lotus Laser Systems, Basildon, UK) working at 70% of the maximum power with a cutting speed of 350 mm/s.

3.5. Stretching

The resulting strips are then pre-stretched in a 3D printed stretching device. Kanik et al. showed that stretching speed also has an influence on coil formation. To eliminate this influence, the pre-stretch is applied quasi-statically. Too much pre-stretch results in tearing of the PE film, whereas too little, i.e., under 10%, is not sufficient to initiate the formation of coils. The optimal pre-stretch amount was determined experimentally by trial-and-error to be 35%.

3.6. Prototype Actuator

The unstretched strips and one specimen of the self-coiled prototype actuator is depicted in Figure 4. A piece of paper six times the weight of the actuator is attached and high voltage applied to the electrodes to test the actuation potential of the manufactured self-coiled actuator. The motion was tracked using a Lumix Camera while applying the voltage at a frequency of 2 Hz.

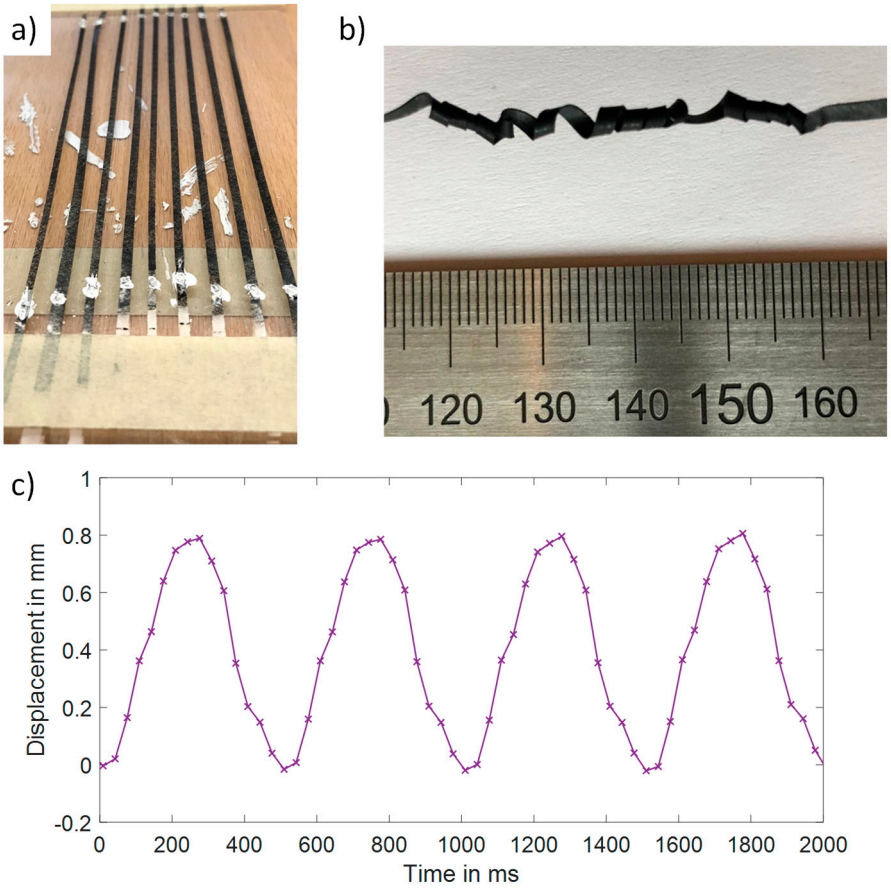

Figure 4. (**a**) Thin strips of the pressed stack after cutting and contacting, (**b**) self-coiled actuator after pre-stretching and releasing, (**c**) contraction of the dielectric polymer actuator at an excitation voltage of 5 kV and 2 Hz.

The actuator contracts 0.8 mm at 5 kV, which corresponds to 2% for a starting length of 40 mm. With regard to the deformation rate, the actuator offers high-speed actuation with 8%/s because the strain rate is mostly limited by the inertia of the mechanical structure and not the buildup of the electric potential.

4. Discussion

The manufactured actuators offer high-speed actuation similar to that of other dielectric actuator types. However, the maximum contraction is limited to 2%, which is closer to that of thermally activated materials, such as shape memory alloys. In contrast to thermally activated materials, however, the process is fast without the need for active cooling. Nonetheless, the deformation is orders of magnitude higher than if the PE film is used as a dielectric actuator itself. Additionally, it offers a powerless halting state and is more robust than the fragile silicone or acrylic membranes used in DEAs. Furthermore, the used materials are relatively cheap.

The developed manufacturing approach still requires optimization in many areas because it consists of several steps that make production costly and also drastically increase the risk of errors. Moreover, it does not allow the production of endless fiber, which is required for further processing of fibers in textiles or to use them on a larger scale. Therefore, technologies that allow one-step continuous production of the novel actuator material are needed. Potential solutions include thermal drawing or continuous laminating of the materials. These processes could also allow further reduction of the cross-section and, in particular, the height of the dielectric layer, to improve the maximum contraction.

5. Conclusions

In this work, a successful manufacturing process for a novel type of actuator material is presented. The self-coiled dielectric polymer actuator consists of four layers and is activated by applying a high voltage. Because this actuator material is robust, fast, and fiber-shaped, and can potentially offer maximum contractions similar to those of natural muscle, it is worthy of further exploration. A proof-of-concept is achieved with the actuator material contracting under an activation voltage as expected. However, both the manufacturing process and geometry, polymer, and conducting particle material can be further optimized. Potentially, the developed actuator material can serve as an artificial muscle in soft robotic applications.

Author Contributions: For research articles with several authors, a short paragraph specifying their individual contributions must be provided. J.M developed the actuator concept, designed the experiments, analysed the data and wrote the paper. M.K. performed and evaluated the experiments. A.N., C.C. and G.G. provided scientific guidance, proof-reading and laboratory equipment.

Funding: This research was funded by the German Research Foundation grant number 380321452/GRK2430. And the APC was funded by SLUB Dresden.

Acknowledgments: The DFG research project 380321452/GRK2430 is supported by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation). The financial support is gratefully acknowledged.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

CB	carbon black
CNT	carbon nano tubes
DEA	dielectric elastomer actuator
PE	polyethylene
SMA	shape memory alloy
SMP	shape memory polymer
TPU	thermoplastic polyurethane elastomer

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