

Automated Fabrication of Elastomeric Prepregs for Soft Robotics Applications

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Fluidic elastomer soft robots typically consist of a top and a strain-limiting bottom part. Both parts are usually cast and then glued together. Elastomeric prepregs, which can be stored at low temperatures for several months without significant cross-linking, simplify this manufacturing process. A cured top part of an arbitrary shape is placed on the wet prepreg, which later forms the strain-limiting layer, and the actuator is finally cured in an oven. Herein, a machine is designed and developed that automatically produces prepregs. Three different concepts are realized in a modular prototype: direct roller application, reverse roller application, and application with slot dies. Experiments show that the direct and the reverse roller application concepts are both suitable for the automated production of prepregs, where the latter one may be preferred due to the smaller number of contact surfaces. Three different textiles (polyester/cotton-blended fabric, nylon fabric, and fleece) are impregnated with the reverse roller application concept using Sylgard 184 and stored at -25°C for 12 days. Using these prepregs, soft bending actuators are manufactured and tested for their functionality. Long-term fatigue tests show that only actuators produced with fleece prepregs are durable, without any signs of delamination.

Soft robotics is an emerging field of research that can complement conventional hard robotics. Soft robots consist almost entirely of soft materials, whereby their Young's moduli typically lie in the range of biological structures (10^4 – 10^9 Pa).^[1] They often mimic the movements of animals without endo- or exoskeletons,^[2] are usually cheaper than rigid robots, can move better in difficult terrain,^[2,3] and grasp fragile objects (e.g., an egg).^[4] Pneumatically operated soft robots are resistant to many external influences, such as tensile and compressive stresses, hammer strikes,^[5] and high temperatures,^[3] but are vulnerable to cuts and punctures.^[6] Many soft robots consist of room temperature-vulcanizing two-component (RTV-2) elastomers and use

pneumatic networks (PneuNets) for actuation.^[2–5,7] The upper part contains several chambers that expand when filled with compressed air and the lower part forms a strain-limiting layer. This layer usually consists of a composite material (inlaid paper^[7] or textile^[3,4]), a material with a higher Young's modulus,^[2,4] or has a larger thickness.^[4] The casting of the lower part, the insertion of paper or fabric, and the bonding with the upper part is considerable amount of work and a potential source of leakage at the seam.


Therefore, in a previous work,^[8] elastomeric prepregs, which form the strain-limiting layer of soft robots, were developed by the authors. Their goal is not lightweight design but the simplification of production. Similar to conventional prepregs,^[9] these textile semi-finished products are preimpregnated with elastomer and can be stored for a long period of time (up to several months) at a low temperature (-25°C) without significant cross-linking. By using

prepregs, the casting or impregnation process is (spatially and temporally) separated from further processing, such as shaping and bonding. In this way, prepregs can be viewed as a first step toward the industrial production of soft robots.

The subject of this Communication is the design and development of a machine that automatically impregnates textiles with liquid RTV-2 elastomer. Automated production is expected to improve the product quality due to a more uniform impregnation than by hand. Three different impregnation concepts are realized in a modular prototype, in which the liquid elastomer is mixed immediately before impregnation. The parameters of the machine are determined and the concepts compared with each other in terms of achievable prepreg quality. By applying the reverse roller application concept, different textiles are impregnated and stored at a temperature of -25°C for 12 days. Using these prepregs, fast PneuNet soft bending actuators are manufactured and tested in long-term experiments for fatigue resistance.

In the previous work,^[8] three RTV-2 silicone rubbers frequently used in soft robotics were investigated to determine how long their pot life (processing time) can be extended by cooling (-25°C). For this purpose, viscosities were measured at weekly intervals over 12 weeks. For Elastosil M 4601 (Wacker Chemie) and Sylgard 184 (Dow Corning), the cross-linking reaction was slowed down so much that they can be stored for several weeks before further processing and are therefore suitable for

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elastomeric prepregs. With Ecoflex 00-30 (Smooth-On), the pot life was almost reached after only 2 weeks. Since Sylgard 184 with 3500 mPas has a much lower viscosity than Elastosil M 4601 (10 000 mPas) and with >12 weeks a much longer pot life extension when cooling (≈ 9 weeks for Elastosil M 4601), it is used in this study.

Sylgard 184 is transparent in the liquid state and partially white milky in the vulcanized state. Due to the hardness of 48 Shore A and low elongation at break of 150%, applications with large strains are not possible. However, this is not problematic with strain-limiting layers. The mechanical properties of Sylgard 184, such as elongation and tensile strength at break, can be influenced by the mixing ratio (recommended is 10:1).^[10] Thus, Sylgard 184 could be used to produce soft actuators with gradual stiffness. Furthermore, the curing or heating temperature also has an influence on the material properties.^[11]

Various textiles were examined in the previous work,^[8] including polyester/cotton-blended fabric (extremtextil), nylon fabric (extremtextil), and fleece (R&G Faserverbundwerkstoffe). Because flax fabric (Suter Kunststoffe AG) frays at the edges and is relatively stiff, it is not considered here, and only the former three textiles are analyzed for their suitability.

Polytetrafluoroethylene (PTFE) virgin foil 0.05–200 from Hightechflon is used to separate the prepregs from each other. This foil is thin enough to be wound, can be easily removed from the elastomer without causing reaction problems, and can be purchased in small quantities.

In the following paragraphs, three different concepts are presented that differ in the type of impregnation, as shown in **Figure 1**. Due to the relatively short pot life of Sylgard 184 compared with thermosetting resins, impregnation mechanisms that require a basin are not considered. The individual concepts are based on principles known from coating technology.^[12]

In the direct roller application concept (Figure 1a), the elastomer is applied via two slot dies on two opposite application rollers between which the dry textile web runs. One of the two driven rollers is pressed against the other via a spring. The rotational speed of the rollers corresponds to the web speed. However, slip can be adjusted by varying the rollers' rotational speed. A wiper above the rollers smoothens the remaining elastomer film or wipes it off if set accordingly. The constructive realization of this concept is shown in Figure 1b.

The reverse roller application concept (Figure 1c) largely corresponds to the direct roller application concept. However, the dry textile web is guided in the opposite direction through the application rollers, so an additional deflection pulley is necessary. This results in higher overall friction. The reverse roller application concept can be combined with the direct roller application concept in one machine if corresponding deflection pulleys are provided. The constructive realization of the reverse roller application concept is shown in Figure 1d.

In the concept "application with slot dies" (Figure 1e), two slot dies apply the elastomer directly to each side of the dry textile web. The application rollers deflect the web and simultaneously incorporate the elastomer into the textile. The constructive realization of this concept is shown in Figure 1f.

In all these concepts, the dry textile web is unwound from a mechanically braked core holder. It runs through a dancer system, which measures the web tension. The elastomer

components are located in syringes in the dosing unit and are conveyed through hoses (not shown in Figure 1) to the dies containing the mixers. The mixing unit of the slot dies is adapted from a previous study.^[13] After impregnation, the prepreg—when guided over the last deflection pulley—is stripped off using a commabar to achieve a constant film thickness. It is then wound onto a driven core holder between two release films (not shown in Figure 1a,c,e) that are unwound from mechanically braked core holders. All modules are mounted in an aluminum frame. The designs of the individual modules are described in detail in the Supporting Information.

For the test runs, the textiles and foils were cut to a width of 60 mm. Usually, the web is attached to a cardboard core with an adhesive tape strip and then rolled up. For an easier handling, the cardboard cores were slit and the end of the web was inserted into the slit.

The different concepts, "direct roller application" (Figure 1b), "reverse roller application" (Figure 1d), and "application with slot dies" (Figure 1f), were compared in a series of experiments. The following optimum parameters were used for this purpose: web speed 3.33 mm s^{-1} , volume flow per die 0.3 mL s^{-1} , distance between the application rollers 2 mm, and web tension 1 N (the determination of these parameters is described in the Supporting Information).

Fleece was used for the direct comparison of the impregnation concepts as it is best suited for elastomeric prepregs due to its good absorbency.^[8] With the direct roller application concept, the achievable thicknesses are 2.5–3.1 mm. A reverse threading of the textile results in the reverse roller application concept. The resulting prepregs have about the same thicknesses (2.5–3.0 mm) as when impregnated with the direct roller application concept. The advantage of the reverse roller application concept compared with the direct roller application concept is that the prepreg does not wrap around the right application roller, which removes the elastomer again, but is pulled out of the elastomer bead (**Figure 2a**) and thus has a top elastomer layer. Further deflection pulleys then touch the prepreg only on the underside so that the elastomer layer on the upper side remains.

When impregnating with slot dies, the web tension must be increased to 3 N; otherwise, the fleece will hang obliquely under the slot die. After the material has been coated by the first die, it is not yet completely soaked, and during impregnation, a relatively large amount of material is wasted by passing through the distance between the two dies ($\approx 0.5 \text{ m}$). Although the fleece is soaked through the second slot die, the surface appears relatively dry and individual fibers are visible.

In further experiments, the three different textiles (polyester/cotton-blended fabric, nylon fabric, and fleece) were impregnated with the preferable concept "reverse roller application" (Figure 2b). For this purpose, $\approx 22 \text{ cm}$ -long strips of polyester/cotton-blended fabric, nylon fabric, and fleece were sewn into a fleece roll, and the resulting web was threaded into the impregnation machine (Figure 2c). The edges of the nylon fabric were fused with a hot-air dryer to prevent the fibers from fraying. At the end of the machine, the prepregs were covered by release films and wound onto the core (Figure 2d).

In the following paragraphs, the quality of the cured prepregs produced with the reverse roller application concept shall be assessed.

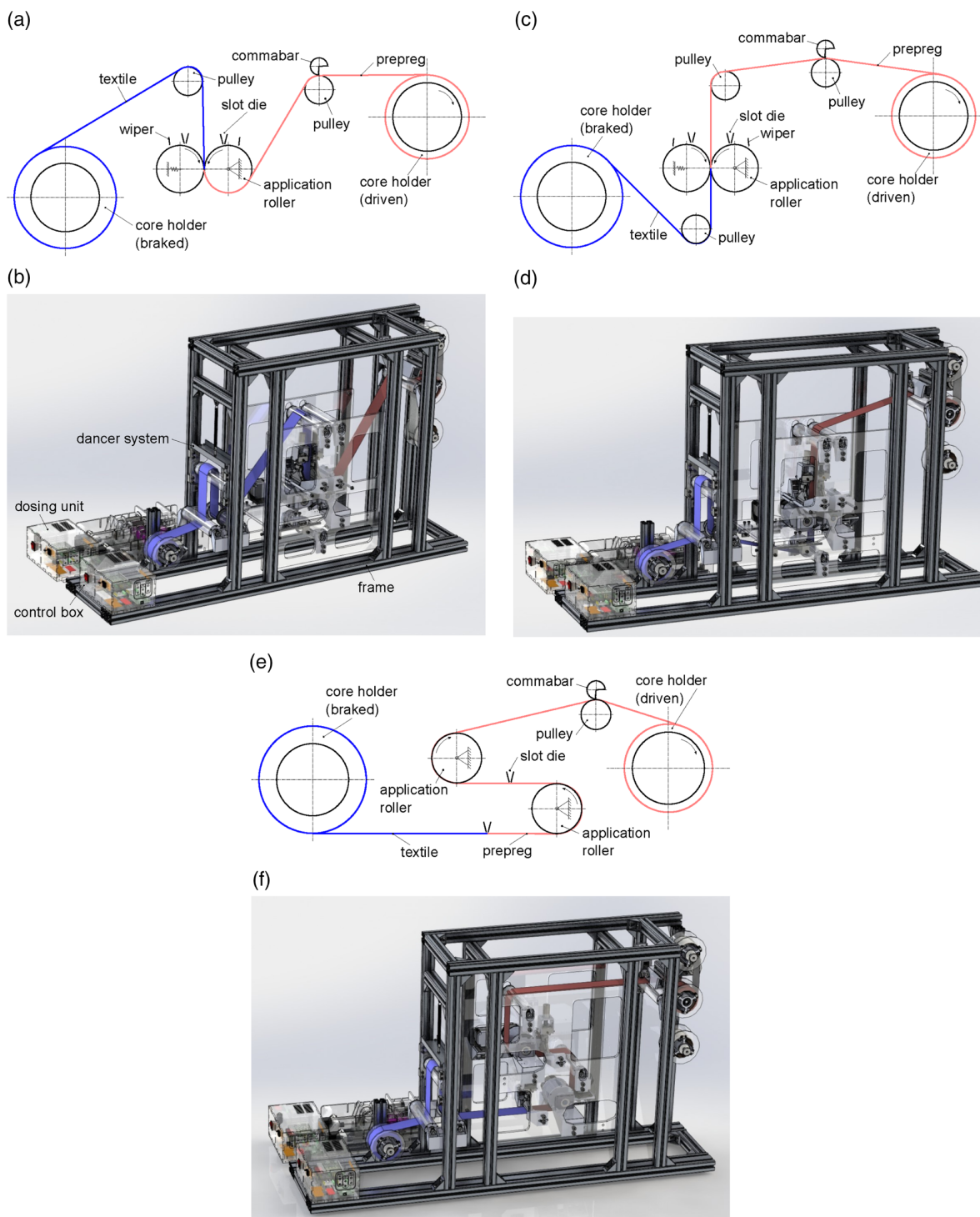


Figure 1. Different impregnation concepts (a,c,e) and their constructive realizations (b,d,f): a,b) direct roller application, c,d) reverse roller application, and e,f) application with slot dies (blue: dry textile, red: impregnated textile). The frame dimensions are $1500 \times 880 \times 360 \text{ mm}^3$.

Two layers of impregnated polyester/cotton blended fabric were each joined together to produce prepreg composites. The upper sides of the cured composites are covered with a thin elastomer layer (Figure S18a, Supporting Information). The top surfaces of the composites are rough, the reverse sides

are smooth and have some imperfections where the elastomer layer is interrupted (Figure S18b, Supporting Information). The composites are on average 0.5–0.7 mm thick.

The structure of the cross-linked prepreps made of nylon fabric is retained on the front (Figure S18c, Supporting

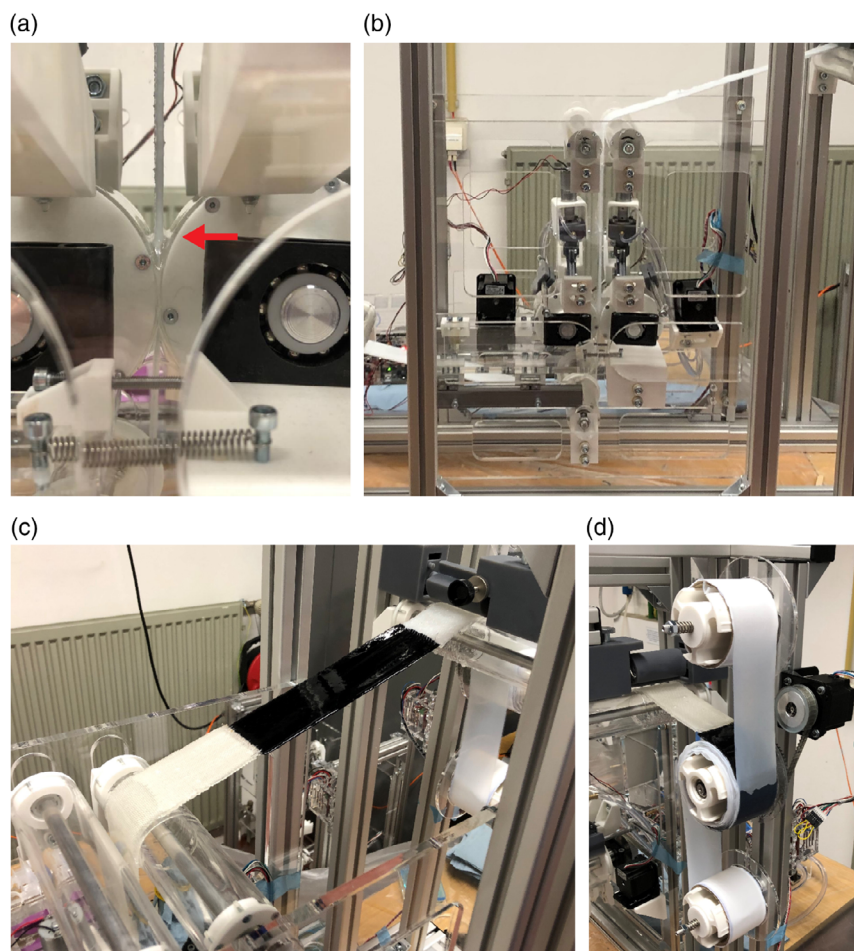


Figure 2. Preferable impregnation concept for fabricating elastomeric preregs: reverse roller application. a) Fleece between the application rollers; the accumulated elastomer bead can be seen (red arrow). b) Impregnation module. c) Various sewn textiles are impregnated, from left to right: nylon fabric, polyester/cotton-blended fabric, fleece. d) Application of the release films and winding up.

Information). The reverse sides (Figure S18d, Supporting Information) are smooth but have larger imperfections. The thicknesses of the preregs are about 0.7 mm.

The cured fleece preregs are rough on the upper sides (Figure S18e, Supporting Information). More individual fibers are visible than in the test runs. Some elastomers are removed by removing the release film. The reverse sides (Figure S18f, Supporting Information) are smooth and have small imperfections. The preregs are ≈ 2.3 – 2.7 mm thick.

In general, the automatically produced preregs are much more consistent and have fewer imperfections compared with handcrafted preregs.^[8]

For the last experiments, preregs were produced with the reverse roller application concept and stored for 12 days at -25°C in a refrigeration chamber. These preregs were used to build fast PneuNet soft bending actuators,^[7] where the upper parts of the actuators were made of Elastosil M 4601. To increase the stiffness, the actuators were equipped with 1 mm-thick side walls.

Three actuators were manufactured for each prepreg type and fatigue tests were conducted in a self-constructed fixation device

(Figure 3a). A total of nine actuators were tested. In each load cycle, the actuators were first subjected to an internal pressure of 0.6 bar for 10 s and then relaxed for 5 s. The bending angle was measured using inertial measuring units (IMUs) according to the sensor concept from a previous study^[13] (Figure 3b).

The results of the long-term tests show that only preregs made of fleece result in fatigue-resistant actuators. The corresponding actuators failed at 14.817 cycles (initial bending angle $\approx 80^\circ$), 17.386 cycles (initial bending angle $\approx 70^\circ$), and 47.763 cycles (initial bending angle $\approx 45^\circ$). These actuators all burst in the walls between the air chambers. The connections between the upper parts and the preregs showed no signs of delamination. Actuators made of other preregs failed after only a few load cycles (≈ 10) and are therefore not fatigue resistant. The reason for this is assumed to be the undulation of fibers in textiles, which prevent a flat contact with the upper part. This is not present in undirected fleece.

To demonstrate that the large variance in the number of load cycles is not due to the preregs but to the actuators' top parts, the initial bending angle is plotted against the number of load

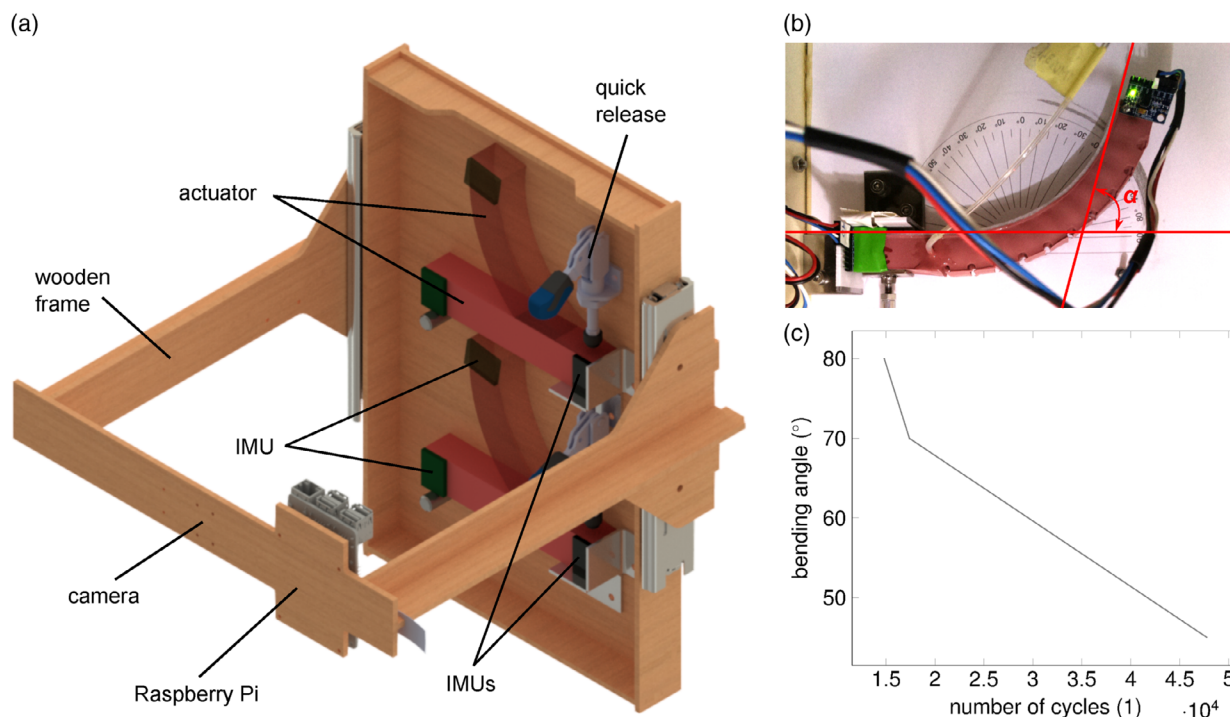


Figure 3. a) Experimental setup for the fatigue experiments: Two fast PneuNet soft bending actuators are fixed by quick releases in a horizontal position so that they bend against gravity. b) The bending angle α is measured by two IMUs that are mounted at the fixed and free end of the actuator (the actuator is 15 cm long). c) The results for fleece prepregs show an exponentially decreasing bending angle over the number of load cycles.

cycles survived (Figure 3c). The graph shows an exponentially decreasing curve, which suggests a typical Wöhler curve (though statistically not significant).

In this work, a machine was designed and developed that automatically produces elastomeric prepregs which can form the strain-limiting layer of PneuNets. Three different concepts were realized in which the elastomer is automatically mixed in a mixer immediately before impregnation: direct roller application, reverse roller application, and application with slot dies. The machine was then put into operation, optimal working parameters were determined, and preliminary tests were conducted. The most preferable concept proved to be the reverse roller application. Three different textiles, polyester/cotton blended fabric, nylon fabric, and fleece, were impregnated with the reverse roller application concept, and the quality of the cured prepregs was assessed. Produced prepregs were then stored for 12 days at -25°C and soft bending actuators were manufactured using the three textiles. These actuators were tested for durability. It was shown that only fleece prepregs resulted in fatigue-resistant bending actuators and that it is therefore to be preferred in the automated production of prepregs.

This work offers the potential to manufacture pneumatically actuated soft bending actuators or robots in an industrial setting by placing an upper part with arbitrary geometry on a previously produced prepreg and curing it. Prepregs could also be used in 3D printing, such as direct ink writing.^[14,15] For example, a robot can be printed directly onto a prepreg located on the printing bed.

Compared with handmade prepregs, automatically fabricated prepregs are more uniform and have a better quality (less air

bubbles). This quality is expected to be even more improved by the transition from laboratory to industrial production.

In future work, the machine for reverse roller application should be optimized, and further experiments with more quantitative determinations and larger sample sizes shall be conducted. The actuators produced should also prove their reliability in extended fatigue tests.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest

The authors declare no conflict of interest.

Keywords

automated fabrication, elastomeric prepregs, fluid-driven robots, impregnation mechanisms, soft robotics

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