FABRICATION OF SOFT ROBOTIC ACTUATORS BY USING INJECTION MOLDING TECHNOLOGY

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Wanying Li

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ABSTRACT

Compared with conventional rigid robots, soft robots composed of intrinsically soft materials are featured with compliance independent of their shapes, good adaptability under different environments, and safer interaction with human. High fabrication cost of actuators incurred by convention fabrication methods is one of the main challenges to commercialize soft robots. To reduce the fabrication cost of actuators, injection molding is adopted. Injection molded pneumatic bending actuators composed of elastomer bladder wrapped with patterned strain-limiting sleeve can achieve bending motion. The highest fingertip forces generated by nylon mesh sleeve actuators and hybrid fabric sleeve actuators are 6.9 N and 6.1 N respectively. A prosthetic hand composed of hybrid fabric actuators can hold and lift items. The hand is capable of handling delicate items without causing damages. A modified two-shot injection molding procedure can be a potential fabrication method of PneuNets actuators.

BIOGRAPHICAL SKETCH

Wanying Li was born in Zhengzhou, Henan, China and moved to Shanghai with her family when she was 14 years old. She left Shanghai in 2009 to pursue her Bachelor's degree at Purdue University in West Lafayette, Indiana. Wanying completed her Bachelor's degree in Materials Science and Engineering in May 2015 and a second Bachelor's degree in Accounting and Management in December 2015.

Wanying started to pursue her M.S. degree at Cornell University in August 2015. She focuses on using injection molding as an innovative method to fabricate commercializable soft robotic actuators in Dr. Robert Shepherd's ORL research group.

Under the guidance of Dr. Robert Shepherd and the support of ORL lab mates, Wanying gained valuable research experience and knowledge on soft robots and their fabrication materials.

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I would like to thank my amazing colleagues at ORL lab, Ben, Bryan, Chris, Gabe, Hedan, Huichan, Ilse, James, Justin, Juan, Kevin, Sanlin, Shuo, TJ, and Yaqi. Their generous help and support made this two-year time become an irreplaceably great experience to me.

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CHAPTER 1

INTRODUCTION

1.1 Conventional rigid robots and soft robots

Robots are defined as an automatically controlled and programmable machine [1]. The actuation, sensing, and control of robots are the most actively studied areas in robot field. As people are interacting with robots more frequently today, robots started playing a more and more important role in people's daily lives. For example, the SoftBank sensational robot named Pepper is able to read people's emotions and provide responses accordingly. [2] Surgical robots enable doctors to have more precision and control over complicated surgeries. The military robot BEAR is capable of locating victims in harsh environments and transfer them to safe places. [3] Although conventional robots can perform many tasks, their rigidity leads to poor compliance and the complexity of design and control. The rigidity also brings safety concerns when robots are interacting with humans.

Soft robotics field is a rapidly developing field because of its potential in filling the blank field left by conventional rigid robots. Unlike conventional robots, soft robots are primarily composed of soft materials with moduli of 10^4-10^9 Pa. Possible materials range from Alginate hydrogel to tendon. Soft robotics are featured with softness and body compliance that enable soft robotics to achieve closer interactions with users. [4] According to the Harlow's monkey study, primates have strong motivator for soft contact comfort. [5] This promotes the interaction between soft robots and human. Because soft robotics are usually made of elastomers with high elasticity, the designing of soft robotics requires less accurate control over movements than conventional rigid robotics do, which reduces the complexity of the controlling system. Soft robots design and fabrication have gained substantial progresses in the past decade, various design and fabrication methods of actuators have been developed and improved.

The Harvard Whitesides group has developed the multi-gait soft robot. This robot can crawl and undulate, which enables it to navigate a difficult obstacle. [6] The wearable rehabilitation devices developed by Polygerinos, P. *et al* can provide high degree of freedom active assistance to patients by using pneumatic artificial muscle actuators. [7] Mac Murray, B. C. *et al.* from the ORL group at Cornell University has developed a foam-based heart model that is able to pump liquid directly, which paved the way for possible applications of soft actuator technology in the medical field. [8]

According to the Business Insider report, the expected global market of robots and related products will reach $135.4 billion in 2019. [9] However, the current market is still dominated by conventional rigid robots. To overcome the barrier between soft robotic products and consumers, the high fabrication cost of soft robotic actuators must be reduced.

1.2 Literature review

<u>Silicone Casting Based Fabrication Methods</u>

Pneumatic PneuNets Bending Actuators

PnueNets actuators are composed of a series of parallel channels and chambers and achieve movements through asymmetric elongation of opposite channel walls when being pressurized. The channels do not only create the stiffness differential, they also prevent the actuator from radial expansion when being pressurized. An inextensible layer like fabric or paper can be inserted or attached to the bottom part to achieve an enhanced bending motion. PneuNets actuators are generally powered via pressurized fluid. PnueNets actuators are conventionally fabricated by static casting silicone elastomers. The casting materials can be PDMS, Ecoflex, or other elastomers. [10] The main body of actuators with PnueNets features are silicone casted first. Once the main body part is cured, uncured silicone is manually applied on the open-channel main body to act as glue for the base part and the actuator is finally closed. The connecting edges between the main part and the bottom part result in “seam” area that usually creates weak spots on actuators and causes delamination failure. [10] Delamination failures can significantly increase scrap rate and related manufacturing cost under mass production situations. Moreover, static silicone casting methods require long curing time in the unit of hours. The fabrication time of PneuNets actuators by static casting is approximately 3 hours. [10] The static casting procedure is human labor intensive and the product quality is unpredictable, which makes the mass production difficult.

Fiber-Reinforced Actuators

Fiber-reinforced actuators is featured with the capability of wide range of motions like bending, twisting, extending and the combination of these motions. Fiber-reinforced actuators consist of an elastomer bladder wrapped with inextensible reinforcements that prevent the actuator from radial expansion. Kevlar thread is usually hand-wrapped around the bladder as reinforcements. The fabrication process of fiber-reinforced actuators starts with silicone casting the elastomer bladder, Dragon Skin 10 (Smooth-on, Inc) and ELASTOSIL M4601 (Wacker Chemical) have been used as the fabrication material for the elastomer bladder. [11][12] The cross-section of fiber-reinforced actuators is in a half-circle shape. Once the bladder is cured, the inextensible layer is attached to the flat side of the actuator and fiber reinforcements are hand wound around the actuator. Afterwards, another layer of silicone is applied around the actuator and the ends of the actuator is closed with caps. This fabrication process is so complex that large amount of human-labor involvement is demanded and the fabricating time is significantly increased. Fast and slow curing processes are available. Under slow curing, the silicone elastomer is left in room temperature to cure and it takes 12 hours until the elastomer cures completely. Under fast curing process, the curing process is accelerated by placing the elastomer into an oven. However, fast process can lead to weak bonding and potential delamination problems. Moreover, the heating process can also cause the layers of actuators to contract and shrink, this produces pre-bent actuators.

Alternative Fabrication Methods

Rotational Casted PneuNets Actuators

Rotational casting fabricates PneuNets actuators by slowly rotating silicone in a hollow mold. During the procedure, silicone is dispersed and stick to the walls of the mold. Rotational casting is featured with low human labor requirement. The process can be a scalable production method with high throughput if there are large numbers of rotational molds. By using rotational casting, seamless actuators can be achieved, which leads to high fingertip force. When ELASTOSIL M4601(Wacker Chemical) is used as the fabrication material, a rotational casted actuator can achieve a fingertip force of 25 N, which is significantly higher than the force being achieved by similar actuators fabricated by conventional methods. The fabrication time of making one actuator is approximately 4 hours -- 3 hours of rotating mold and 1 hour curing in oven at 60 °C. [13] However, due to the complexity of fluid viscosity, the possible mold design is extremely complex and the geometries can be rotational casted are very limited.

3D Printing Antagonistic System

3D printing antagonistic system is an innovative fabricating method developed by *Peele B. et al* from the ORL Group at Cornell University. The fabricating method can create actuators with high degree of freedom. 3D printing fabrication method is featured with the reduction of fabrication complexity by the elimination of mold design and the involvement of human labor works. The fabrication time is approximately 35 minutes, which is significantly lower than other fabrication methods, but still too long for industrial mass production. The actuators adopted a modified PneuNets design, where air channels are used to preventing radial expansion and creating stiffness differentials causing the actuator to bend toward one direction. Multiple single-channel actuators can be incorporated together to achieve more complex motions. [14] An automated, layer-by-layer stereolithography system was used to fabricate actuators. The actuator was fabricated by building up photopolymerizable resin from a resin reservoir in a “bottom up” way. Since qualifying materials should not only be photopolymerizable but also have properties of softness and resilience, commercially available materials option is very limited. Elastomeric Precursor (EP; Spot-E resin, Spot-A Materials, Inc.) is one of the commercially available materials having the required properties, but its strain to failure is approximately 50%, while most silicone elastomers have a strain to failure of approximately 700%.

1.3 Challenges to reduce the fabrication cost

Multiple factors contributing to the high fabrication cost of soft robotic actuators.

1. Materials availability: In order to reduce the fabrication cost to an acceptable level for mass production, there should be sufficient commercially available material options so that the cost of fabrication is predictable and do not fluctuate with certain raw material.
2. Fabrication time: As industrial fabrication time of one unit of product is usually in the unit of seconds, the fabrication time of soft robotic actuators should be reduced from the unit of hours and minutes to the unit of seconds. Otherwise, the long fabrication times makes it difficult to achieve economies of scale.
3. Seams (weak regions): Fabrication methods like multi-step silicone casting usually involves the integration of multiple parts together. The connecting regions created from integrating multiple parts together always become the weak regions and tend to delaminate. [10] Delamination problem leads to high scrap rate and limits the fingertip force can be achieved. Therefore, by eliminating or minimizing the occurrence of connecting seams can increase the quality of the product and avoid the unnecessary expenses of scrap.
4. Complexity of design: The design of the fabrication procedure should be as simple as possible. It is also important to have a simple design that can be used in a broad and general scope. For example, the mold design of rotational casting is very time-consuming and complicated due to the complexity of fluid viscosity. Moreover, since different materials have different rheological profiles, using a different material for rotational casting requires complete re-design of the mold. The processing parameters also need to be recalculated and tuned for every new mold.

5. Human labor dependence: Heavy dependence on human labor when fabricating actuators lead to high cost because skilled labors are expensive. On the other hand, it is difficult to control the output quality of different workers, which makes the quality of actuators unstable and hard to predict.

The factors contributing to the high fabrication cost of conventional methods are summarized in Table 1.1:

	Silicone Casting	**Rotational Casting**	**3D Printing**
Materials	✔	✔	✘
Time	✘	✘	✘
Seams	✘	✔	✔
Complexity	✔	✘	✔
Labor	✘	✔	✔

Table 1.1 The summary of cost contributing factors of conventional fabrication method

1.4 Dissertation scope and organization

Hand injuries consist more than 30% of total work injuries [15], negatively influence people's life roles [16], and the related annual treatment cost in the US was over $18 billion [17]. There's an increasing need for affordable hand prosthetic and orthotic devices. On the other hand, the compliance and adaptability of soft robots make them candidates for handling delicate target objects that cannot be handled by conventional robots. Therefore, in my dissertation, I focus on fabricating soft robotic actuators by a method featured with the potential of mass production. The application of this method is not limited to this specific field. The method could be modified and used in other fields and applications.

In Chapter 2, I chose injection molding technology as an innovative method for soft robotic actuators. The criteria of selecting material is described. The selected material's properties are also described. I present an injection molded actuator inspired by McKibben muscles that can generate a fingertip force of >5 N. The actuators are used to make a prosthetic hand that is capable of conforming to different shapes, handling delicate objects and lifting items.

In Chapter 3, I used the injection molding technology to replicate PneuNets actuators. This two-shot process replaced indirect bonding of gluing two parts together with direct bonding of thermal fusion, which could be solution to the delamination problem caused by multiple-step silicone casting.

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CHAPTER 2

THE FABRICATION OF PNEUMATIC BENDING ACTUATORS BY USING INJECTION MOLDING TECHNOLOGY

2.1 Introduction

As people are interacting more frequently with robots in their daily lives, robots and the related products are composing a new business market growing into multi-billion dollars. [1] At the same time, safety concerns regarding the interaction between human and robots are emerging. Compared to conventional rigid robots, soft robots are featured with characteristics of softness, compliance, and flexibility. These characteristics promote safer interactions between human and robots. The complexity of design and behavior control is reduced by these characteristics. [2] However, the business market is still dominated by conventional robots composed of rigid parts and joints. One reason that soft robots are so far away from commercial market is the high fabrication cost of actuators.

The high actuator fabrication cost of conventional methods can be summarized as the following: 1) the complexity of fabrication procedure and system. Too many fabricating steps involving hard-to-control handworks by people make the quality and performance of actuators inconsistent and hard-to-predict. 2) Long fabrication time that ranges from hours to days. Therefore, an effective fabricating method that reduces the fabrication time and complexity while ensuring good mechanical performance is needed. Therefore, we introduce an innovative method for fabricating soft robotic actuators featured with high-throughput and the potential of mass production in this chapter.

2.2 Experimental design

2.2.1 Injection molding technology

We chose injection molding as the processing method because this technology is a high speed, automated process that is capable of making parts with very complex geometries and various sizes in high volume. Moreover, as a well-developed manufacturing process, there are large amounts of materials that are injection moldable. [3] Finally, since there already exists global manufacturing infrastructure, there's no need to build new factories and plants for future mass production.

Injection molding machine

The components of an industrial injection molding machine are shown in Figure 2.1.

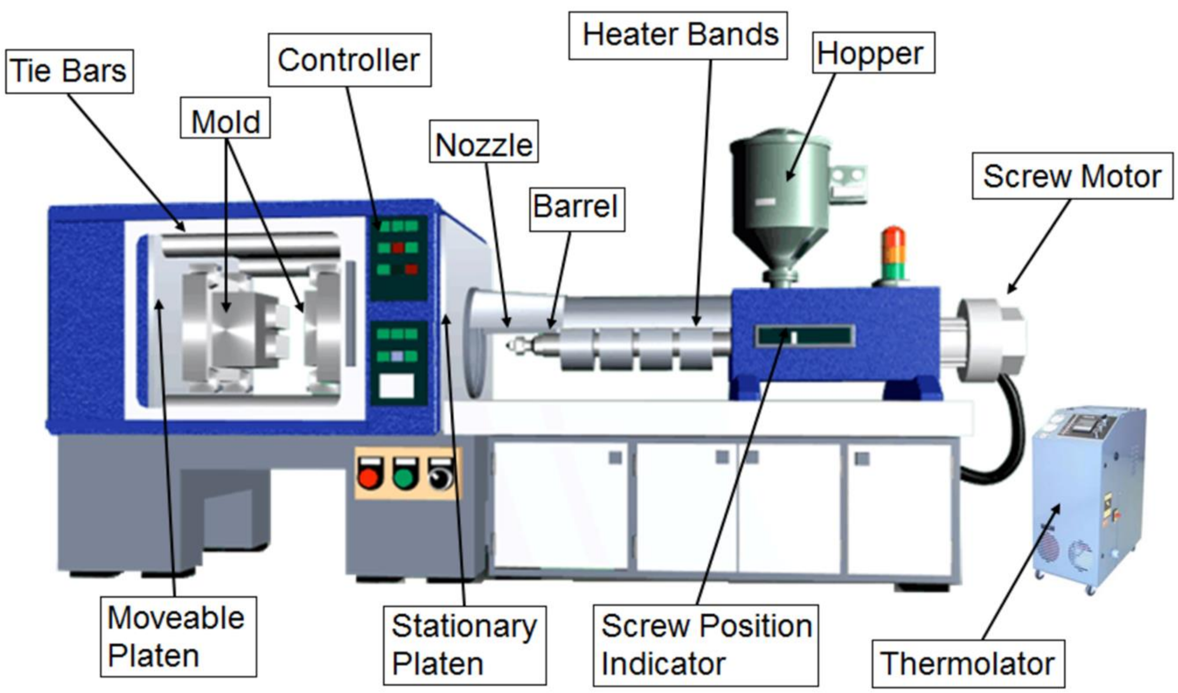

Figure 2.1 The structure and components of injection molding machine. [4]

Tie bars: functions as the support of the platens and ensure that the platens are well-aligned. The length of tie bars determines the size of mold can be placed in the injection molding machine.

Mold: the cavity of mold determines the shape and size of the injection molded product

Controller: the processing parameters like clamping force, nozzle pressure, etc. are controlled by controller.

Nozzle: through which the molten polymer flow is delivered from the injection molding barrel into the mold.

Barrel: where the polymer pallets are heated. A screw is usually located inside.

Heater bands: provide heat to the barrel and keep the temperature of polymer flow at constant.

Hopper: where polymer pellets are kept, and fed into the injection molding machine.

Screw motor: rotate the screw inside the barrel.

Movable platen: moves up to the stationary platen to clamp the mold before injection molding starts.

Screw position indicator: indicates the size of the shot.

Thermolator: controls the coolant.

Injection molding process

The pre-injection molding preparation includes the following steps: [3]

1. Polymer pallets heating: the polymer pellets are heated in barrel. The heating time varies from material to material, which is usually determined by the polymer structure and suggested by the manufacturer.

2. Clamping: the movable platen needs to be raised to close with the stationary platen to hold the mold. Clamping force must be large enough to keep the mold together during the injection molding process. The required clamp force is calculated by:

$$F = P^*A \qquad \text{(Equation 2.1)}$$

with packing pressure, P^*, total cavity area, A.

The injection molding process is a series of sequential steps, which is summarized as the following:

Mold filling: In this phase, once the mold is clamped and closed, the molten polymer flow is compressed from the injection molding machine unit into the mold.

Packing: The molten polymer flow is compressed into the mold and fills the cavity.

Holding: The mold filled with polymer flow need to be held under the packing pressure until the gate solidifies to compensate the shrinkage as finished part cools.

Cooling: The part continues to cool down.

Part ejection: The mold is opened and the finished part is moved from the mold cavity.

Mold structure

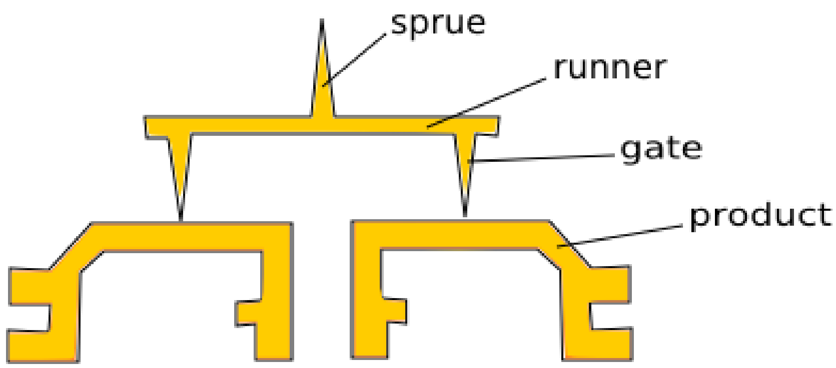

Figure 2.2 The typical cold runner, two-plate multi-cavity mold configuration. [5]

Sprue: Through which polymer flow is introduced into the mold.

Runner: Small channels leading polymer flow from sprue to the product.

Gate: Through which polymer flow enters the mold cavity.

Experimental injection molding machine

The injection molding machine used in this research is MORGAN-PRESS ® G-100 T. The injection molding machine is designed for prototype and low-volume production. The vertical injection molding machine is a simplified version of industrial injection molding machines. The maximum clamping force can be achieved in our experimental condition is 117,680 N (12 ton), which is limited by the pressure from the wall. The maximum single shot is 98 mL (4 oz.).

Figure 2.3 MORGAN-PRESS ® G-100 T injection molding machine. [6]

2.2.2 Design of pneumatic bending actuator

We decided to choose a pneumatic actuation system because it is a high specific power system. The system is featured with high force vs. weight ratio and relatively fast actuation.[7] The design of the actuator is based on the inspiration of pneumatic artificial muscles (McKibben artificial muscles) that were first designed in the 1950's and 1960's in artificial limb research. McKibben muscles inspired us because they are featured with simple structure and similar length-load curve to human muscles. McKibben artificial muscles are composed of an inflatable elastomer bladder inside an outer expansion-limiting sleeve. [8] This sleeve functions to create linear contraction instead of radial expansion. [9] [10] McKibben artificial muscles, however, is limited to only one actuation mode – contraction and extension.

Based on the structure of McKibben artificial muscles, we designed soft robotic actuators composed of an elastomer bladder that expands when being pressurized and embedded strain limiting sleeve that functions to prevent radial expansion of the actuator (Figure 2.4). In order to create bending motion, it's essential to create strain differential on opposite side of walls of the actuator. Slits are cut on one side of the strain-limiting sleeve and the regions with slits have a lower stiffness because of the disconnection of sleeve fibrils. The bending motion can be tuned by the pattern of the strain-limiting sleeve.

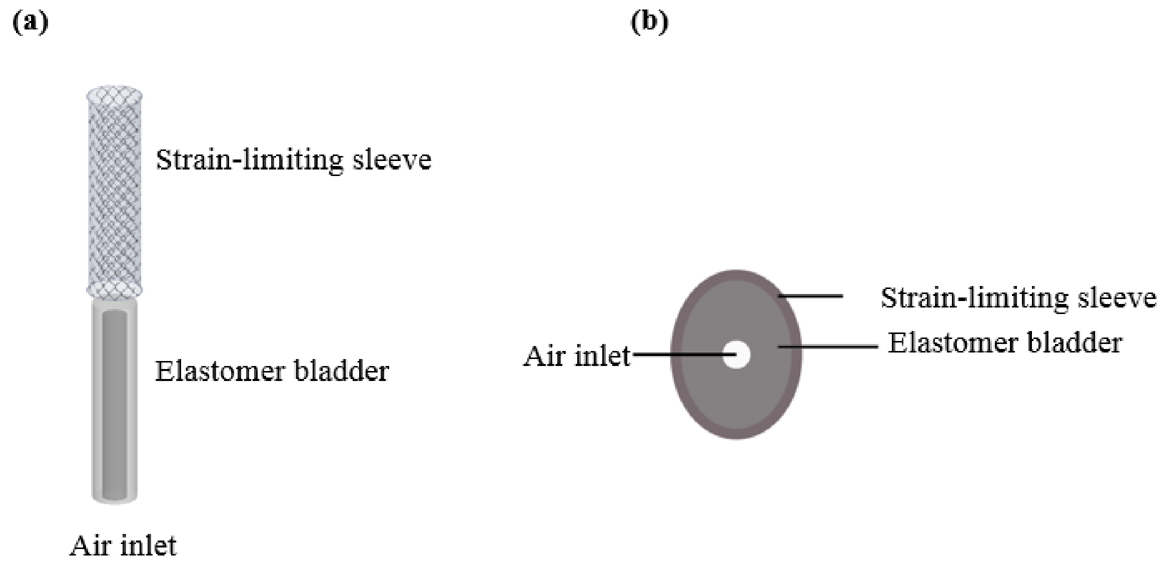

Figure 2.4 The design of pneumatic bending actuator. (a)The actuator is composed of an elastomer bladder with air inlet and wrapped with strain-limiting sleeve embedded in the actuator. (b) The cross section of the design of pneumatic bending actuator.

2.2.3 Materials selection

Considering injection molding is the most widely used manufacturing method in polymer processing, main classifications of polymers and their properties were researched. Qualified fabrication material should be in liquid form when heat is applied, which enable them to be molded into desired shape by injection molding. Moreover, the material should be resilient and have elongation to failure comparable to that of silicone, which is approximately 300%. Besides processability, the specified requirements on mechanical properties of fabrication materials are summarized in Table 2.1.

Ultimate tensile strength	1-5 MPa
Strain to failure	≥ 300%
Resilience	recover >90% energy flow work of extension

Table 2.1 The summary of required mechanical properties on qualified fabrication materials.

Thermoplastics, elastomers, thermosets, and thermoplastic elastomers are researched to find the qualified fabrication materials. Thermoplastics composed of linear or branched polymers chains can be processed by injection molding because thermoplastic polymer chains are held together by intermolecular attraction and heating breaks this attraction. [11] Although thermoplastics can be injection molded, most thermoplastics are neither resilient nor stretchable. Elastomers polymer chains are chemically cross-linked and form rubbery networks. Due to the chemical cross-linking, elastomers can be stretched to high elongation and they can recover their original dimensions once the applied force is removed. [11] However, because elastomer polymer chains are cross-linked by covalent bonds, when being heated, elastomers degrade instead of becoming fluid. To injection mold elastomers, special injection molding technology, such as reaction injection molding, and associated devices are required. [12] Therefore, it’s difficult to injection mold elastomers in this research due to the experimental equipment limitation. Thermosets polymer chains form networks with high degree of crosslinking. Like elastomers, when being heated, thermosets degrade instead of becoming fluid. It is possible to process thermosets by using reaction injection molding, in which a curing reaction happens in the mold. [13] Similar to elastomers, thermosets cannot be processed by injection molding due to limited available experimental equipment. Thermoplastic elastomers (TPE) are featured with the elastomeric properties while having the processability like thermoplastics. TPE’s special feature is due to its physical cross-linking. In a styrenic block copolymer (SBC) TPE, the copolymer chain has an ABA tri-block structure with styrenic part and rubbery part and different kinds of chemical blocks tend to be incompatible with the other on molecular level. Therefore, the copolymer have a structure with rigid domains that are rich in the styrenic block dispersed in the rubbery matrix. [11]

We chose a commercially available resilient thermoplastic elastomer, RTP 2700 S-30A MD Natural (RTP Co.), which is referred as S-30 A in the following content, because of its easy accessibility and economical cost. S-30 A has a Shore A hardness of 30, which is close to the gel shoe insole.

2.2.4 Material characterizations

2.2.4.1 Tensile Test

We conducted tensile test (Zwick/Roell Z010) on injection molded S-30A dumbbell specimens according to the ASTM D421 by using Die D at testing speed 500 mm/min. Dumbbell specimens were injection molded under barrel melting temperature from 350 °F (177 °C) to 400 °F (204 °C) by an increment of 25 °F and nozzle pressure ranging from 30 psi (207 kPa) to 60 psi (414 kPa) by an increment of 10 psi (69 kPa). The injection molded dumbbell specimen and ASTM D421 Die D mold are shown in Figure 2.5.

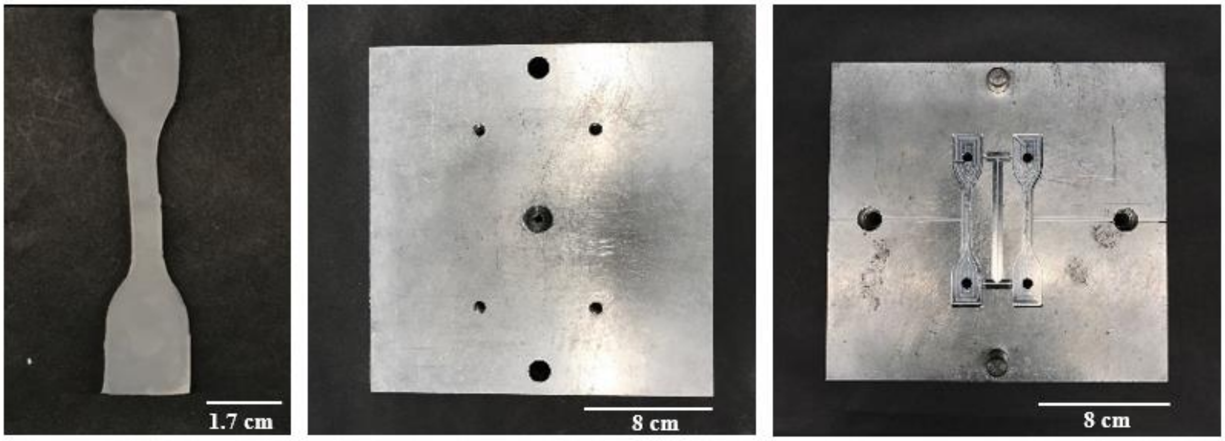

Figure 2.5 The ASTM 421 Die D being used in this experiment to make dumbbell tensile test specimens. Left: the dumbbell specimen under barrel temperature of 191 °C (375 °F) and nozzle pressure of 207 kPa (30 psi). Middle: the top part of the injection molding mold. Right: the bottom part of the injection molding mold with cavity.

The average ultimate tensile strength results of S-30A were summarized in table 2.2. Each result is based on 7 test samples under the same processing condition and the stress was calculated by equation 2.2 with applied force, F, cross-sectional area of dumbbell sample before deformation has taken place, A_0.

$$Stress\ (\sigma) = \frac{F}{A_0} \qquad \text{(Equation 2.2)}$$

UTS (MPa)	177 °C (350 °F)	STD	191 °C (375 °F)	STD	204 °C (400 °F)	STD
207 kPa (30 psi)	1.81	0.24	2.12	0.20	2.21	0.19
276 kPa (40 psi)	1.23	0.04	2.17	0.21	2.69	0.38
345 kPa (50 psi)	1.38	0.19	2.29	0.20	2.37	0.15
414 kPa (60 psi)	1.36	0.09	2.53	0.18	2.21	0.41

Table 2.2 The average ultimate tensile strength and standard deviations of S-30A under different temperatures and nozzle pressure.

The average strain to failure results of S-30A were summarized in table 2.3. Each result is based on 7 test samples under the same processing condition.

The strain is calculated by the following equation with successive values of the length as it changes, l, the original gage length l_0. [14]

$$Strain\ (\varepsilon) = \frac{l - l_0}{l_0} \qquad \text{(Equation 2.3)}$$

Strain to failure	177 °C (350 °F)	STD	191 °C (375 °F)	STD	204 °C (400 °F)	STD
207 kPa (30 psi)	4.51	0.66	5.41	0.52	5.52	0.53
276 kPa (40 psi)	2.16	0.17	5.55	0.48	7.11	0.91
345 kPa (50 psi)	2.89	1.03	5.78	0.42	6.26	0.16
414 kPa (60 psi)	2.18	0.23	6.08	0.52	5.61	0.97

Table 2.3 The average strain to failure and standard deviations of S-30A under different temperatures and nozzle pressure.

The average ultimate tensile strength with standard deviation and strain to failure of S-30A under different barrel temperatures and nozzle pressures are shown in Figure 2.6. Both the highest average ultimate tensile strength and strain to failure were achieved when barrel temperature is 204 °C (400 °F) and nozzle pressure is 276 kPa (40 psi). The highest average ultimate tensile strength and strain to failure are 2.69 MPa and 7.11, respectively.

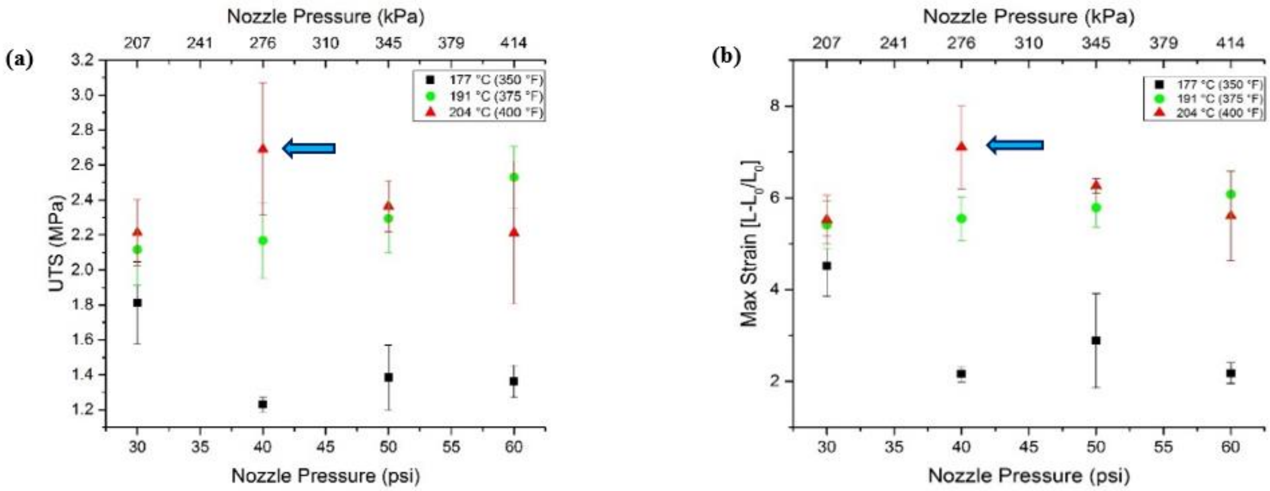

Figure 2.6 Tensile test results for injection molded dumbbell specimens. (a) Ultimate tensile strength of S-30A under different barrel temperatures and nozzle pressures and (b) strain to failure of S-30A under different barrel temperatures and nozzle pressures

We decided to use barrel temperature of is 204 °C (400 °F) and nozzle pressure of 276 kPa (40 psi) as the processing temperature based on the tensile test results. The stress-strain curve of the S-30A dumbbell specimen injection molded under 204 °C (400 °F) barrel temperature and 276 kPa (40 psi) nozzle pressure is shown in Figure 2.7, there exist a linear relationship between the strain and stress and the sample shows an elastomer-like behavior with high strain to failure but low ultimate tensile strength.

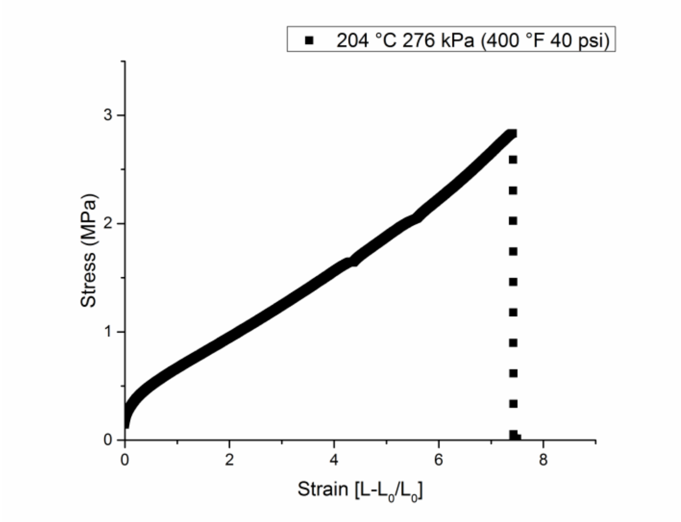

Figure 2.7 The stress-strain curve of S-30A dumbbell specimen injection molded under is 204 °C (400 °F) barrel temperature and 276 kPa (40 psi) pressure.

2.2.4.2 Rheology test

RTP 2700 S-30A MD NATURAL is designed and marketed for commercial products that need soft and resilient features. During the injection molding process, the polymer pellets are heated, molten, and pressed into the mold cavity. Therefore, the rheological properties of the materials are critical and can be useful to future simulation analysis. To understand the rheological properties, a controlled stress rheometer (DHR3, TA instruments; 25 mm parallel plate geometry) was used to determine viscosity according to shear rate. During the measurement, the top plate rotates and the applied torque is measured by the rheometer and then calculated to obtain the apparent viscosity. The viscosity is measured at a constant temperature of 204 °C (400 °F) by using a heating chamber. The polymer flow in the injection molding process experiences high strain rate when being compressed from nozzle into the mold cavity. Since the material was extruded from the gap between the measuring fixtures before the injection molding strain rate was reached, the complex viscosity according to changing frequency of the material was measured based on Cox-Merz rule. [15] Cox-Merz rule is an empirical rule stating that the apparent viscosity, η, measured by changing shear rate, $\dot{\gamma}$, is very similar to the complex viscosity, η^*, measured by changing frequency, ω (Equation 2.4).

$$\eta\ (\dot{\gamma} = \omega) = \eta^*(\omega) \qquad \text{(Equation 2.4)}$$

With a constant frequency of 10 1/s, linear viscoelastic regime (Figure 2.8 (a)) was determined as 0.001% to 1.58% by varying strain amplitude from 0.001% to 100%. With constant strain set to 0.02%, temperature set to 204 °C (400 °F), and varying frequency from 0.1 to 300 rad/s, the viscosity vs. shear rate behavior of the fabrication material S-30A is plotted in Figure 2.8 (b). The viscosity of Newtonian fluids are usually independent of shear rate. [16] Under the test regime, the viscosity of S-30A decreases as shear rate increases, which is a non-Newtonian shear-thinning behavior. Materials showing this behavior usually consist of long polymeric chains that tangle and coil together when shear is low. As shear rate increases, these chains uncoil and align with the direction of applied force, which reduces the viscosity. The behavior is consistent with the structure S-30A, which is a thermoplastic elastomer consists of block copolymer chains coil and crosslink physically. Ostwald–de Waele power law approximately describes the viscosity of non-Newtonian fluids in terms of flow consistency index (*k*), shear rate ($\dot{\gamma}$), and flow behavior index (n). [17]

$$\eta = k(\dot{\gamma})^{n-1} \qquad \text{(Equation 2.5)}$$

By fitting the viscosity data to Equation 2.5, we obtain the value of *k* = 60315 and n = 0.16. A flow behavior index less than 1 means that the fluid has a shear-thinning behavior.

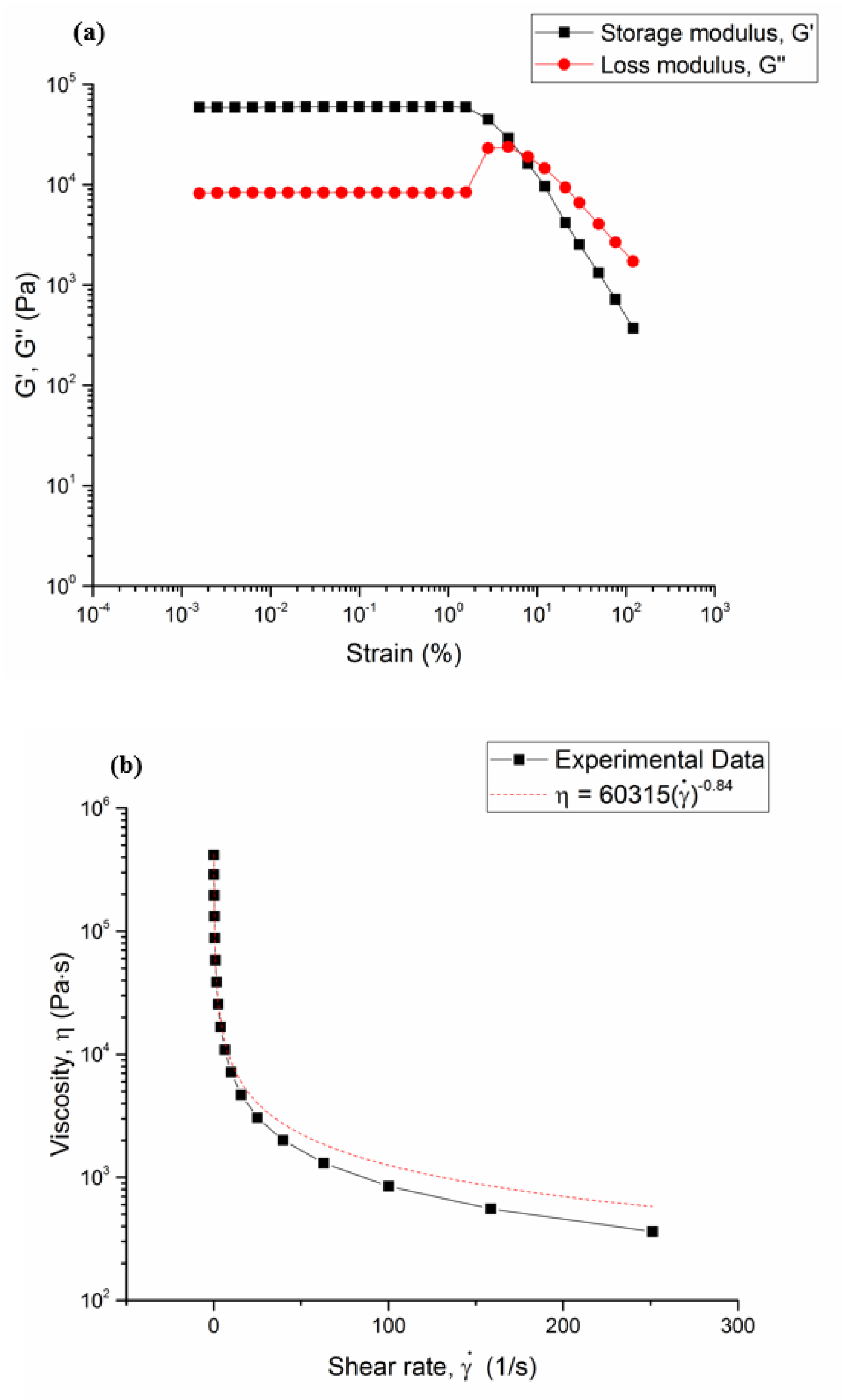

Figure 2.8 (a) The rheological results of S-30A with varying strain from 0.001% to 100% with constant frequency 10 1/s. When shear amplitude is 0.001% to 1.58%, the polymer flow is in linear viscoelastic regime. (b) The rheological results of S-30A based on Cox-Merz rule.

During the injection molding process, at barrel temperature of 204 °C (400 °F) and nozzle pressure of 276 kPa (40 psi), it takes 6 seconds for the polymer flow to fill a 14.9 cm^3 cavity, which gives a flow rate of 2.5 cm^3/s and a shear rate of 234.2 1/s. The apparent shear rate, $\dot{\gamma}_A$, is estimated by Equation 2.5, with flow rate, Q, and pipe radius, R.

$$\dot{\gamma}_A = \frac{4Q}{\pi R^3} \qquad \text{(Equation 2.6)}$$

At this shear rate, the fluid is still in the shear-thinning region and the viscosity is approximately 616.6 Pa·s based on Ostwald–de Waele power law with *k* = 60315 and n = 0.16.

2.2.5 Design of mold

Designing a mold for injection molding requires careful planning and considerations. The injection molding process include high temperature, high pressure, and the combination of two materials under the temperature and pressure situation. We used 3-D printer (Scholar 30, Objet, Inc.) to make our molds because 3-D printing is fast and does not require high tooling expenses and time as metal molds do. The following requirements on the mold design should be met:

1. Simple mold and demold process.
2. Strain-limiting layer must be easily incorporated.
3. The process is compatible with the 3-D printing material VeroBlue™ .
4. The limit of VeroBlue™.

Simple mold and demold process reduces the level of human labor involvement and fabrication time. Being able to incorporate the strain-limiting layer into the injection molding process can eliminate the involvement of human labor. During the injection molding process, there should be no reaction between the 3-D printing materials and the S-30A. The glass transition temperature of VeroBlue™ is T_g = 48 °C – 50 °C while the barrel melting temperature of the process is 204 °C, which much higher than the limit of VeroBlue™. Failing to consider the limit of VeroBlue™ will produce incomplete part (Figure 2.9) because the warped core is pushed by the injection polymer flow to touch the inside wall of the mold cavity.

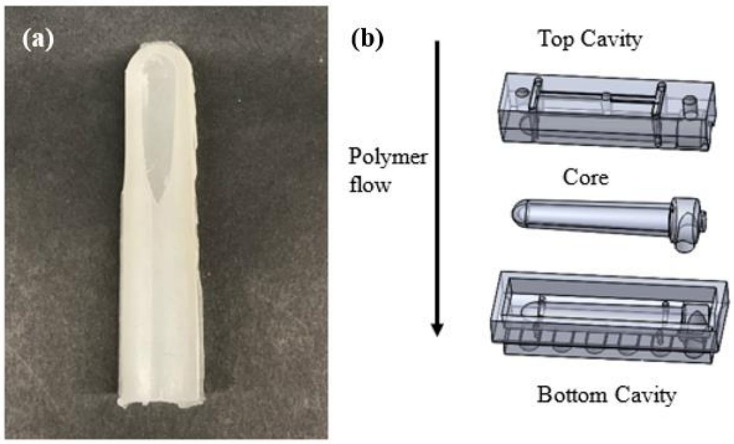

Figure 2.9(a) The incomplete injection molded soft robotic actuator caused by the warping of ineffective mold core. (b) The exploded view of the all 3-D printed three-part mold.

With the requirements for the mold, we used a hybrid mold composed of 3-D printed cavity and machine aluminum core incorporated into 3-D printed mold bottom. (Figure 2.10) We used a vertical mold design with top sprue location instead of a side sprue location to minimize the impact of polymer flow.

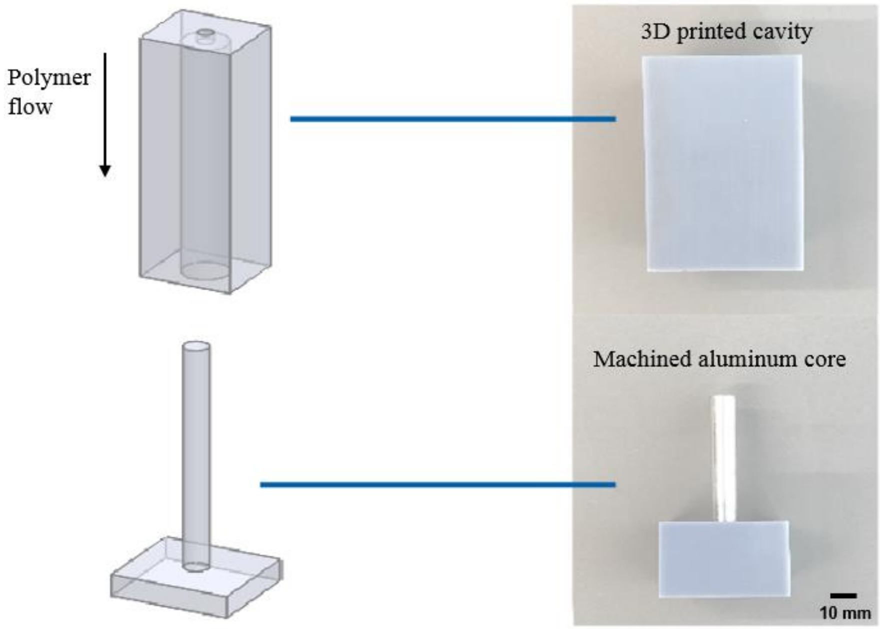

Figure 2.10 Vertical hybrid mold for injection molding soft robotic actuator. The cavity part and the bottom were 3-D printed while the mold core was made by machined aluminum.

2.2.6 Nylon mesh strain-limiting sleeve actuators

The fabrication process started with laser cut (Zing 24, Epilog Laser) rectangular 17x17 nylon plastic mesh. The dimension of the nylon mesh is 6 cm (W) x 7 cm (L). The S-30A pellets are heated in the barrel for 30 minutes before injection molding. The rectangular nylon mesh sheet is wrapped into a cylindrical shape and inserted into the mold cavity. The closed mold is clamped and the injection molding process is conducted with nozzle pressure of 276 kPa (40 psi). The injection molding time to form a pneumatic bending actuator is 6 seconds. Once the injection molding process ends, the clamp is held together for 3 minutes to let the finished part cool down. And then, the formed actuator (Figure 2.11) is demolded and slits are cut on the formed actuators by using laser cutter. The pattern is composed of six parallel 1-cm slits with 0.8 cm gap. The flow of the process is summarized in Figure 2.12.

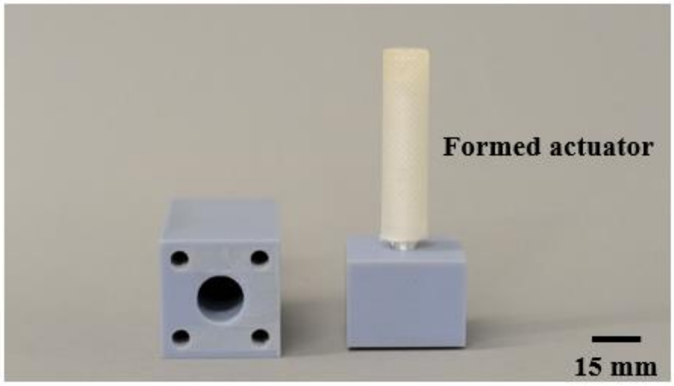

Figure 2.11 The actuator formed by using injection molding before demolding.

Figure 2.12 The flow chart of pneumatic bending actuators' fabrication procedures.

The behaviors of nylon mesh strain-limiting actuators under different actuation pressures are shown in Figure 2.13. As actuation pressure increases, the bending curvature increases accordingly. The behavior of actuators becomes unstable and shows tendency of overexpansion at the interface of strain-limiting sleeve and bladder, when actuation pressure reaches 345 kPa (50 psi). Continuing increasing the actuation pressure will lead to final failure caused by over-expansion and rupture of bladder at the cut slits of the strain-limiting sleeve and the connection region where the two edges of the nylon mesh meet. Joint connecting the air inlet tube and the actuator starts leaking when the actuation pressure reaches 275.8 kPa (40 psi), which influences the performance of actuators and can lead to the disassembling problem if actuators were incorporated into robots and devices. To measure the fingertip force, the end of the actuator is fixed (Figure 2.14 (a)) and the fingertip of the actuator slowly bends downward as actuation pressure increases. The fingertip force reads zero until the actuator reached the curvature enabling it to touch the scale. The measured fingertip force is converted from the unit of gram to Newton by using the relationship 1g = 0.0098N. The fingertip force vs. actuation pressure shows an approximately linear relationship and the highest achieved force is 6.9 N (Figure 2.14 (b)).

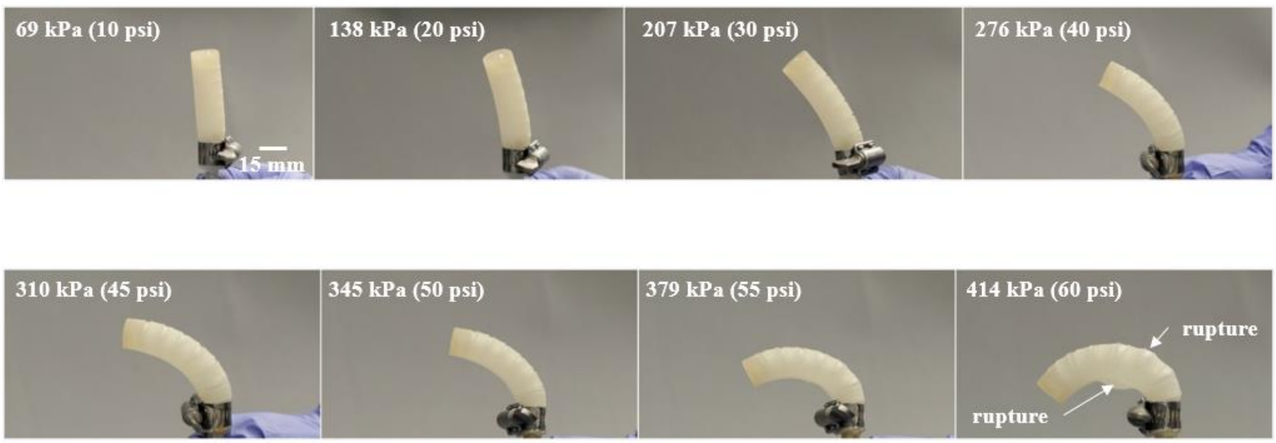

Figure 2.13 Actuation behavior of nylon mesh strain-limiting actuators under different actuation pressures. The achieved bending curvature increases as actuation pressure increases. Weak regions usually lead to rupture and the failure of actuators.

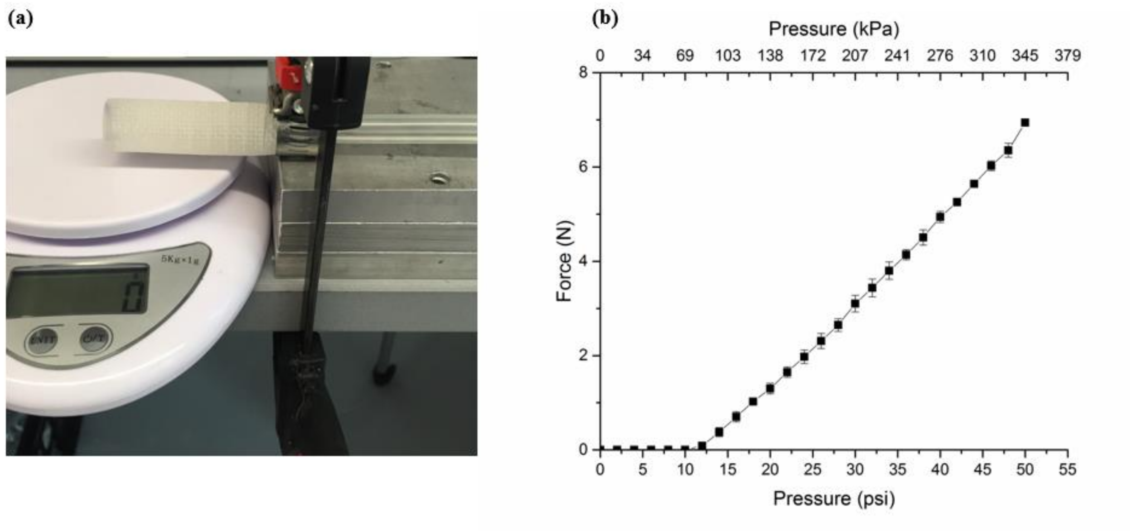

Figure 2.14 Fingertip force test for injection molded nylon mesh actuators. (a) Blocking force test set up (b) fingertip force vs. actuation pressure based on three specimens.

2.2.7 Hybrid fabric strain-limiting sleeve actuators

Another fabrication method aiming to improve the performance of actuators by replacing nylon mesh strain-limiting sleeve with the hybrid strain-limiting sleeve is also tested and studied. This fabrication method improves the performance of actuators through preventing the separation of the connecting edges of sleeve, enhancing bending curvature, and solving the joint leaking problems associated with nylon mesh actuators. The stretchable fabric is composed of 70% polyester and 30% rubber (Strechrite® Heavy Stretch Elastic). The hybrid sleeve is made by jointing one piece of stretchable fabric to a piece of inextensible fabric (cloth) together to form a cylindrical sleeve by using sewing machine and Kevlar thread. The stretchable fabric occupies 2/3 of the hybrid sleeve and the inextensible fabric occupies 1/3 of the hybrid sleeve. The following fabrication procedure is the same as nylon mesh strain-limiting sleeve.

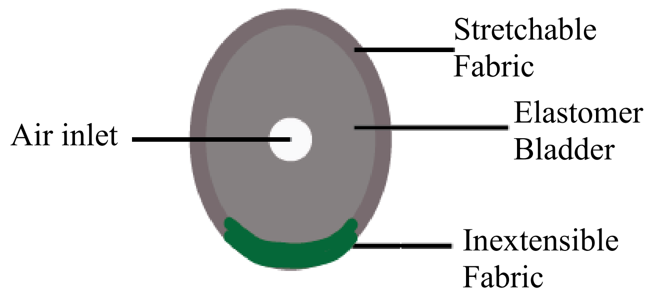

Figure 2.15 The cross-section of the hybrid strain-limiting sleeve.

Besides the change of strain-limiting sleeve, other improvements are added to pursue better performance of the actuator. The slits are reinforced by applying instant adhesive (Loctite® 495) to prevent slits failure at elastomer-sleeve interface. Fingertip part is reinforced by gluing (Loctite® 495) stretchable fabric to the fingertip. To prevent leaking at joints when actuation pressure is high, Sil-Poxy® silicone adhesive is used to glue the actuator and the air-path plastic tube and seal the joint from leaking.

The behaviors of fabric strain-limiting actuators according to different actuation pressures are shown in Figure 2.16. Fabric strain-limiting actuators can achieve higher curvature under the same actuation pressure than nylon mesh actuators do. The fabric actuators have more stable actuation performance. Fabric strain-limiting actuators shows overexpansion at the interface of sleeve and bladder when actuation pressure reaches 414 kPa (60 psi), while nylon mesh actuators usually fail at 345 kPa (50 psi). Since the fabric strain-limiting sleeve is made by sewing fabrics together, the failure caused by the separation from connection edges is eliminated.

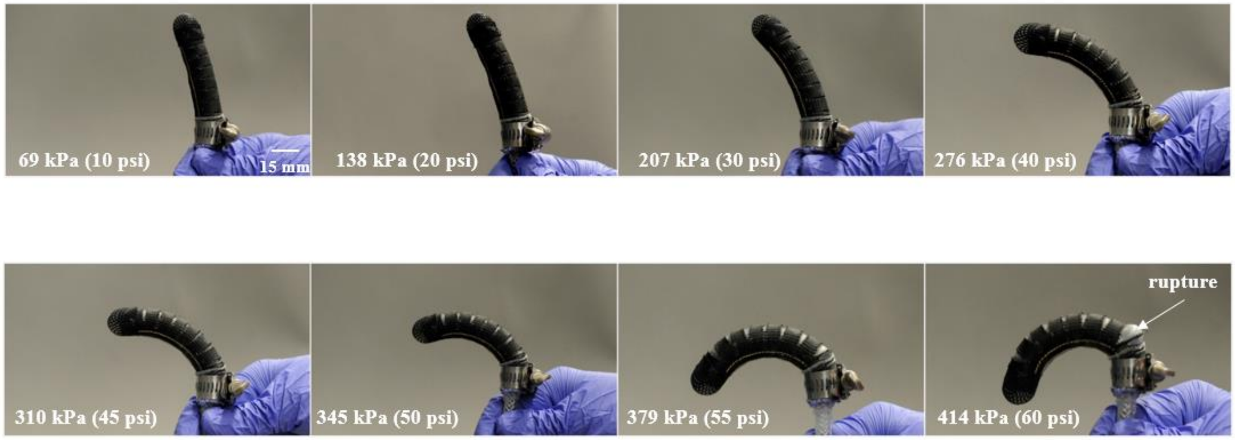

Figure 2.16 Actuation behavior of hybrid fabric strain-limiting actuators under different actuation pressures.

The maximum pressure and maximum force we tested for injection molded fabric strain-limiting actuators are 372 kPa (54 psi) and 6.1 N (Figure 2.17). Compared with the nylon mesh strain-limiting sleeve actuators, the fabric strain-limiting sleeve actuators achieved lower force under the same actuation pressure.

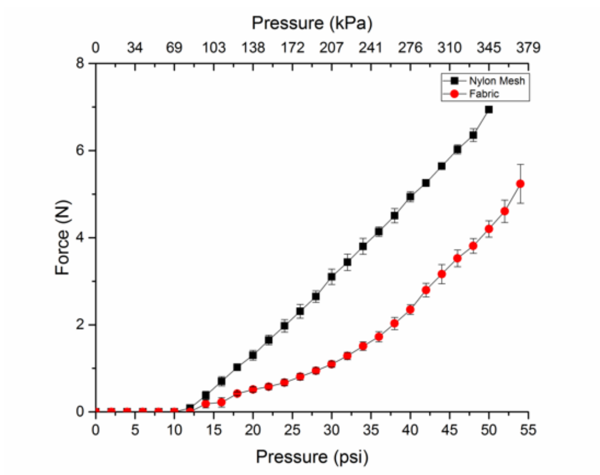

Figure 2.17 Fingertip force test results comparison of injection molded nylon mesh actuators and fabric actuators. At the same actuation pressure, fabric actuators achieve lower fingertip force than nylon actuators do.

To explain the difference of fingertip forces achieved by nylon mesh and hybrid fabric actuators, we analogize the pressurized actuator to an elastic solid bar subject to axial force, F. The incremental strain energy,dU, of the solid bar can be expressed by Equation 2.6, with incremental volume element, dV, cross-sectional area, A, displacement along the bar, $u(x)$, and elastic modulus, E. With Equation 2.6, the total strain energy in an elastic bar subject to axial force can be expressed by Equation 2.7 with *l* as the initial length of the bar.

$$dU = \frac{1}{2}\sigma\varepsilon\, dV = \frac{1}{2}\left(\frac{F}{A}\right)\left(u'(x)\right)dV = \frac{1}{2}\frac{F^2}{EA^2}dV \qquad \text{(Equation 2.6)}$$

$$U = \frac{1}{2}\int_l \frac{F^2}{EA}dx \qquad \text{(Equation 2.7)}$$

Tensile test was conducted on injection molded composite rectangular S-30A specimens and specimens with nylon mesh (Figure 2.18 (a) left) and stretchable fabric (Figure 2.18 (a) right). The stress-strain curves (Figure 2.18 (b)) show that the incorporation of nylon mesh and stretchable fabric leads to higher stiffness and different mechanical behaviors. The nylon mesh specimens achieved a mean elastic modulus of 19.88 ± 1.88 (SD) MPa and an ultimate tensile strength of 3.18 ± 0.33 (SD) MPa. The stretchable fabric specimens achieved a mean elastic modulus of 2.23 ± 0.21 (SD) MPa that is approximately 8 times lower than the elastic modulus of nylon mesh specimens and an ultimate tensile strength of 1.63 ± 0.23 (SD) MPa. According to Equation 2.7, higher elastic modulus of hybrid fabric actuators leads to higher stored elastic strain energy, U, which means more work need to be done in actuating the system, or the actuator. On the other hand, more work is required to deflect the actuated hybrid fabric actuators. Therefore, when subject to external force, hybrid fabric actuators are doing better in maintaining the actuated shape than nylon mesh actuators do. This feature enables hybrid fabric actuators to perform better than nylon mesh actuators do when lifting items.

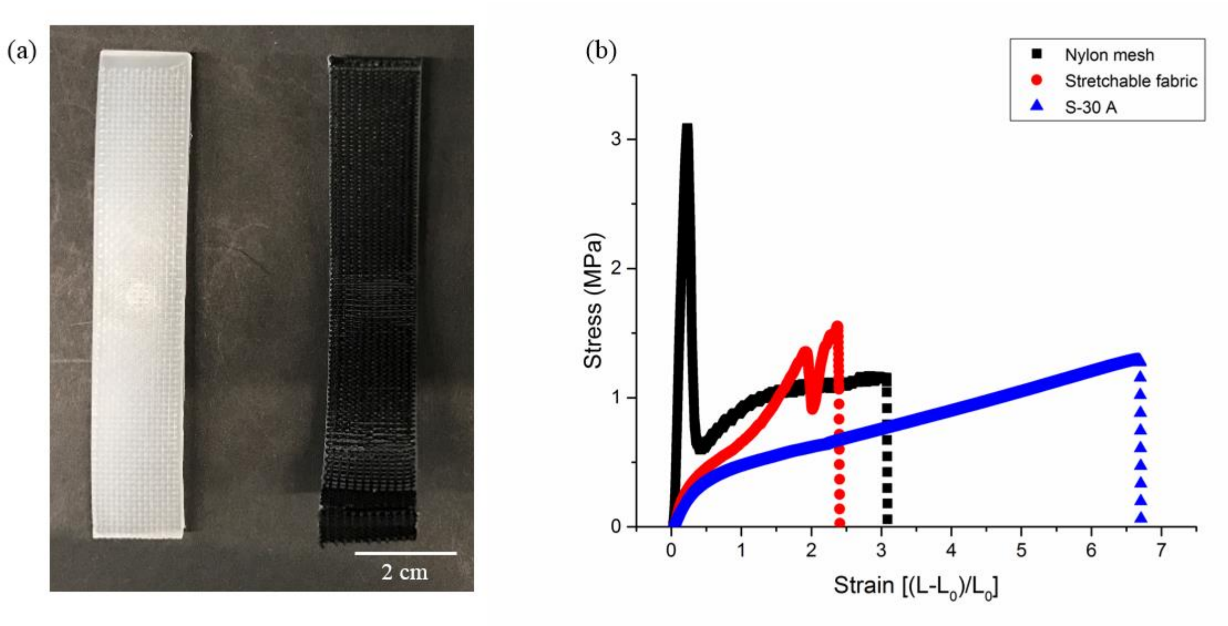

Figure 2.18 (a) Nylon mesh rectangular specimen (left) and stretchable fabric rectangular specimen (right). (b) Stress-strain curves of nylon mesh specimen, stretchable fabric specimen, and S-30 A specimen without any reinforcements.

2.3 The application of injection molded actuators to prosthetic hand

Injection molded hybrid-fabric actuators are incorporated into a silicone casted palm to make a prosthetic hand, which can provide assistance to patients suffering from the loss of limbs. The capabilities of the actuators and the prosthetic hand were tested on different target objects (Figure 2.19). The prosthetic hand is capable of holding objects of different surfaces and shapes (cup of water, full Redbull can, and acetone spray bottle). The soft robotic hand is also capable of handling delicate objects without damaging the target objects (empty Redbull can, uncooked egg, and grape).

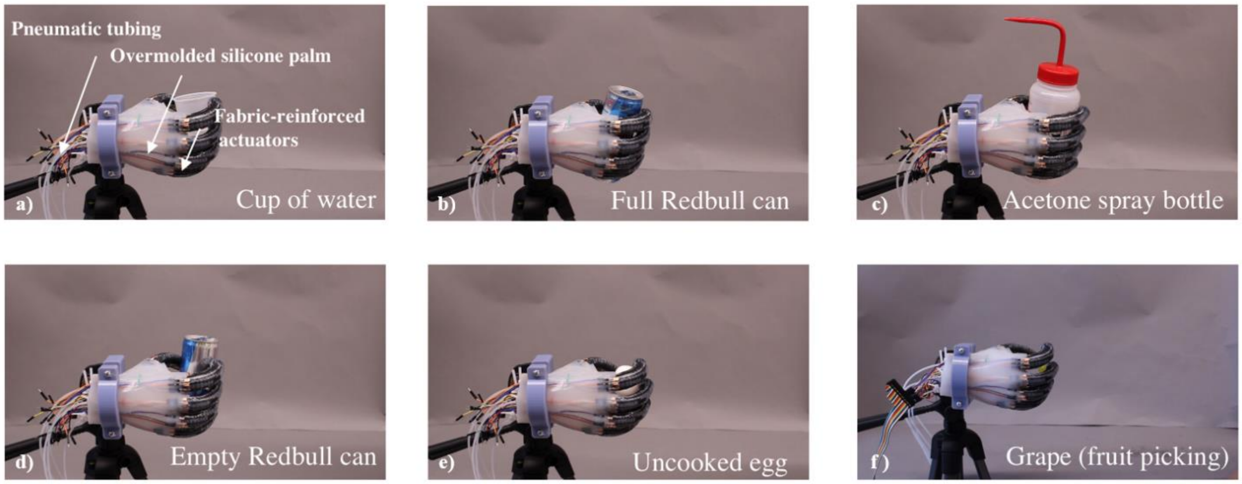

Figure 2.19 The prosthetic hand composed of silicone casted palm and injection molded fabric strain-limiting actuators. The prosthetic hand can hold (a) cup of water, (b) full Redbull can, and (c) acetone spray bottle. The prosthetic hand is capable of handling delicate objects (d) empty Redbull can, (e) uncooked egg, and (f) grape without causing damages.

The high stiffness created by the hybrid fabric strain-limiting sleeve and reinforcements lead to high stored elastic strain energy and high force is required to deflect the actuators, which enables the prosthetic hand to lift items (Figure 2.20).

Figure 2.20 The prosthetic hand composed of silicone casted palm and injection molded hybrid fabric strain-limiting actuators can lift an approximately 20 N toolbox.

2.4 Conclusions

I have developed an innovative soft robotic actuator fabrication method by using injection molding technology. Since injection molding is an automated and high-speed processing method, the fabrication cycle time is shortened to less than 5 minutes and the human labor involvement is significantly reduced than current available fabrication method. Compared with conventional fabrication method, the cost of soft robotic actuators is also reduced. The hybrid fabric stain-limiting sleeve actuators with multiple reinforcements equip the actuators with higher stiffness, which leads to higher stored elastic strain energy. This feature makes the actuators hard to deflect and able to lift objects.

The actuators fabricated by injection molding can be incorporated to prosthetic hand. The prosthetic hand conforms to different surfaces and shapes and has the capability of holding and handling delicate objects without causing damages. This provides a possibility of using the actuators in fields where the ability to handle delicate objects is necessary. To summarize, injection molding could be a viable candidate to fabricate soft robotic actuators capable of holding and lifting items. This fabrication method has the potential to be high throughput and low cost, which could lead affordable soft robotic products to customers.

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CHAPTER 3

THE FABRICATION OF PNEUNETS ACTUATORS BY USING INJECTION MOLDING TECHNOLOGY

3.1 Introduction

Injection molding pneumatic bending actuators based on the inspiration of McKibben artificial muscles provides a potential fabrication method that could assist the commercialization of soft robots. Inspired by this idea, injection molding technology could be extended into the fabrication of soft robotic actuators of different actuation mechanisms. PneuNets actuators consist of embedded parallel chambers in elastomer bladders. By tuning the distribution, configuration, and size of the PneuNet chambers, it's possible to achieve different motions and movements. [1] Conventional fabrication method of PneuNets actuators involves the gluing process to integrate the main part with patterns to the bottom part together to create the closed-channel structure. The bottom part is usually made of materials like PDMS with limited range of deformation, and the main part with patterns is usually made of materials like Ecoflex that are more flexible. The gluing of these two part by using uncured bottom part is creating an indirection bonding. [2], which creates weak regions and leads to delamination problems limiting the actuation pressure. [3] On the other hand, for injection molded actuators discussed in Chapter 2, the interfaces between elastomer and strain-limiting sleeve tend to result in the final failure of actuators and limit the maximum fingertip force to less than 7 N. The rotational casted monolithic PneuNets actuators, however, can achieve a maximum fingertip force of 25 N, which implies that the elimination of indirect bonding can increase the performance of actuators. [3] Therefore, a fabrication method that can achieve high fingertip force by eliminating weak regions while having the commercializable features of short fabrication time and low human labor involvement is in need. In this chapter, I introduce a soft robotic actuator fabrication method that may be able to achieve the commercializability of injection molded pneumatic bending actuators and the high fingertip force of rotational casted PneuNets actuators.

3.2 Structure of PneuNets actuators

PneuNets actuators composed of parallel air chambers actuate by the stiffness difference created by the chamber structure. (Figure 3.1) When being pressurized, the channels expand at the portion with thinnest wall or lowest stiffness expand first and work to prevent radial expansion of the actuator. As pressure increases, the chambers expand more due to the asymmetry of stiffness and thus lead to the bending of the actuator. Making actuators with composite structure by inserting one layer of material with higher stiffness than the elastomer material can enhance the bending motion. [1]

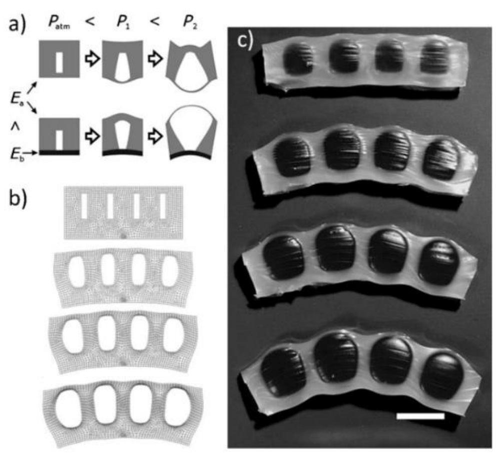

Figure 3.1 The structure of PneuNets actuator. (a) Top: the actuator composed of homogeneous elastomer. Bottom: the actuator composed of elastomer and a layer of material with higher stiffness enhancing the bending motion. (b)Finite element analysis of PneuNets actuator under different pressure. (c)Cross-sectional structure of PneuNets actuator under pressure with injected dyed Ecoflex.

3.3 The fabrication procedure and mold design

To create a closed channel structure, the fabrication procedure is a two-shot injection molding process. S-30A is used as the fabrication material. The main part of the actuator with features is made from the first shot. The 3-D printed (printer: Scholar 30, Objet, Inc.) first-shot mold is a three-part mold composed of top cavity part, spine with PneuNets features, and the bottom cavity part. (Figure 3.2) Four runners are located on the top cavity.

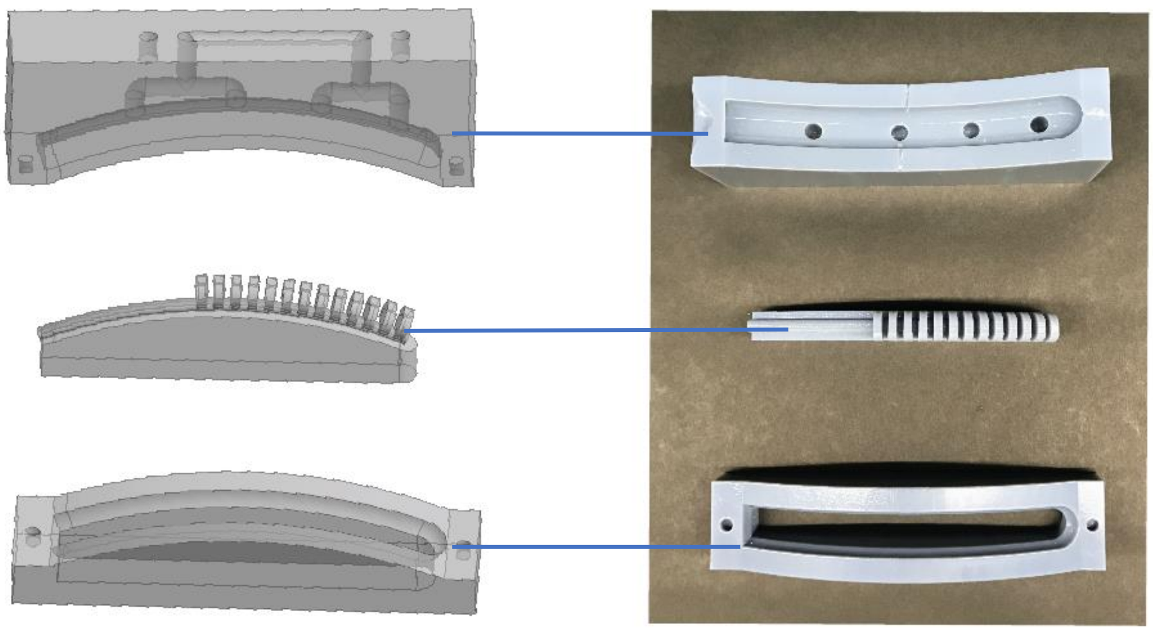

Figure 3.2 The 3-D printed first-shot mold for PneuNets actuators. From top to bottom: top cavity part, spine with PneuNets features, and bottom cavity part.

The second-shot injection molding process creates the finished actuator with closed channel structure. The second-shot mold consists of three parts. The top cavity part, the core, and the bottom cavity part. (Figure 3.3) The runner is located at the fingertip position of the top mold. The bottom cavity part is the top cavity part from the first-shot mold. In this procedure, a 3-D printed core is inserted into the open-channel actuator with features from the first-shot to keep the air path of the actuator and placed into the bottom cavity (Figure 3.3). The runners are blocked by the body of the open-channel actuator so that the mold cavity is sealed when the top cavity part is clamped in the injection molding process (Figure 3.4).

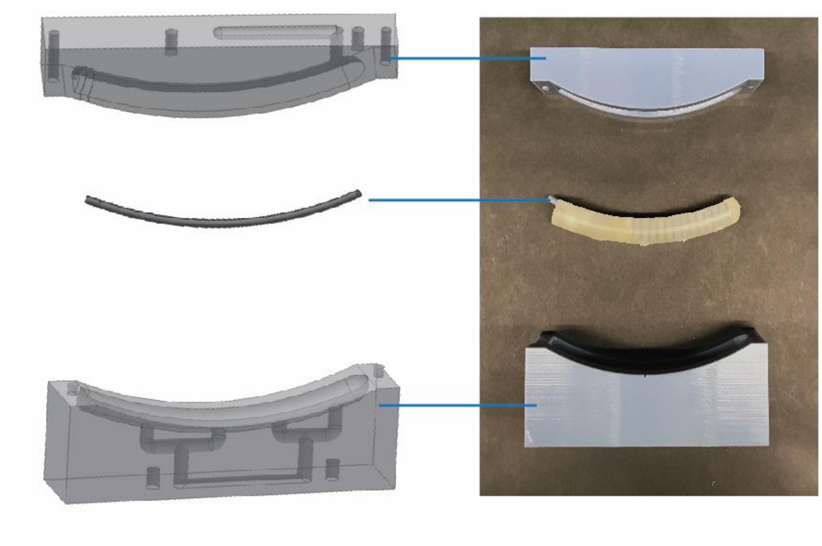

Figure 3.3 The mold design of the second-shot injection molding procedure. From top to bottom: the top cavity part, the core, and the bottom cavity part.

Figure 3.4 The open-channel actuator with core inserted and placed in the bottom cavity part for second-injection molding.

3.4 Current progress and future plan

We have successfully fabricated open-channel actuators with complete PneuNets features. However, the bonding between the main part from the first shot and the bottom part from the second shot is not satisfying. The reason for the weak bonding issue is still actively researched. On the other hand, the bending motion achieved by the injection molded PneuNets actuator is not satisfying and a larger curvature is needed. Nylon mesh sheet has been inserted into the actuator trying to enhance the bending curvature, but the result was not very satisfying and no obvious improvements have been observed. In order to solve the current bonding problem and achieve higher bending curvature. We tested blending S-30 A and 10 wt% of polyethylene pellets and heated the blended pellets in the barrel for 30 minutes to create a bottom part with higher stiffness. However, the injection molded S-30A-10 wt% polyethylene specimen fractured when being bent. For next step, we plan to use localized welding by introducing ultrasonic energy [4][5] to heat and soften the connecting region to enhance the bonding after the second-shot of injection molding. We plan to use the styrenic block copolymer thermoplastic elastomer with higher stiffness to increase the bending motion.

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CHAPTER 4

CONCLUSIONS

This thesis reports two fabrication methods of soft robotic actuators based on injection molding technology. These fabrication methods have the potential to assist the commercialization of soft robotic actuators by reducing the fabrication cost through the shortening of fabrication time and minimizing of human labor involvement.

The pneumatic bending actuators inspired by McKibben artificial muscle is reported in Chapter 2. The fabrication method can produce actuators featured with sufficient fabrication materials availability, short fabrication time, no connecting seam created by integrating multiple parts, fabrication system with low complexity, and minimum involvement of human labor. Nylon mesh strain-limiting sleeve and the reinforced fabric strain-limiting sleeve actuators are developed based on the pneumatic bending actuator idea. Hybrid fabric strain-limiting actuators are featured with higher stored elastic strain energy and it’s difficult to deflect these actuators once they are pressurized. The application of hybrid fabric strain-limiting actuators to a prosthetic hand shows these actuators can perform holding and lifting tasks. The pneumatic bending actuators can conform to different surfaces and shapes while do not damage delicate items like uncooked eggs and grapes.

The replication of PnueNets bending actuators by using a two-shot injection molding procedure is also studied. The procedure is featured with replacing conventional indirect bonding with direct thermal fusion bonding, which could possibly eliminate the delamination problems being caused due to the integration of two different materials. The fabrication method is still actively researched. Open-channel actuator with PneuNets features can be successfully achieved. There currently exists difficulties in stably bonding the first-shot part to the second-shot bottom and a larger bending curvature is need to make the actuators have the capability of performing movements like holding, gripping and lifting. For future studies, we plan to test localized ultrasonic welding to enhance the bonding between the first and the second injection molded parts. To enhance the bending curvature of the injection molded PneuNets bending actuator, we plan to use a styrenic block copolymer thermoplastic with higher stiffness.

To summarize, injection molding could be viable candidate to fabricate soft robotic actuators capable of holding and lifting objects and items. The fabrication method has the potential to be high throughput and low cost to lead to affordable soft robotic products to customers.