Characterizing the Behavior of Nylon Actuators and Exploring Methods for Manufacturing Them to Get the Highest Amount of Output

by

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Abstract

Coiled nylon thermal actuators are polymer based artificial muscles introduced in 2014. Although there are many applications that can benefit from nylon actuators, there has not been much work on the methods of producing the actuators. To maximize the output of the actuators, various factors can be altered during the production phase. These factors are pre-anneal stretch, coiling tensile stress and annealing temperature. Results show that with a pre-anneal stretch of 70% and a coiling stress of 48 MPa, the highest amount of force generated can be reached without substantial failures. Also, it is found that the annealing temperature should be in the range of 170°C to 180°C. Annealing temperature needs to be in this range since the actuator should be above Brill transition temperature. Upon annealing in this temperature range, the actuator is fixed in its configuration, and it will not uncoil after it has been annealed.

Additionally, the creep of the actuators and its effect on the output, has been studied. A model for the creep is proposed. The model consists of a Kelvin and a Maxwell model. The proposed model for the creep includes two damper elements, which account for the short term and long-term creep. The model fits the observed response well for the short-term creep, but for the long-term creep the goodness of fit decreases. Additionally, a model for active deformation of the actuator behavior as the result of changes in tensile stress is proposed. In particular, shape memory effects are added to account for load history dependence of the response.

The active deformation model and the creep model are essential for developing a control system for using the actuators. The findings of this work can be used by researchers and device designers to bring the nylon actuators to real life applications.
Lay Summary

The main goal of this work is explaining the best method for making nylon actuators, so they can generate higher tensile stress and strain. The steps that need to be taken for making the actuators have been investigated thoroughly and the reasoning behind each step has been represented. Also, the actuator’s creep in cold state and actuator behavior in hot state and under isotonic condition have been modeled. The models are extremely important for designing a control system to run and use the actuators.
Preface

- Identification and design of the research program

This work is a follow up to the work on polymer based artificial muscles initiated by Dr. John D. Madden and our collaborators in UT Dallas, University of Wollongong and Hanyang University (reference paper number one). In the continuation of the published work I have considered the process of making the nylon actuators. To investigate the process of making the actuators and with Dr. Madden’s help, I have designed experiments to explore various factors such as annealing temperature, coiling tensile stress, annealing strain and tensile stress at the time of actuation. Additionally, with the help of Dr. Madden I have proposed a model for creep and active deformation of the actuators while they are undergoing isometric and isotonic actuation.

- Data analyses

The data in this thesis are analyzed by the author and Dr. John D. Madden. I have also benefitted from the comments made by Dr. Seyed Mohammad Mirvakili.
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1. Introduction

Artificial muscles can be used for variety of applications ranging from humanlike robots to wearable fabrics and clothing. However, there are some issues that limit the usage of the current artificial muscle such as cost problem and scalability [2]. Carbon nanotubes must be redrawn between each cycle. Electrochemically driven fibers have limited cyclability and electric field driven electrostrictive rubbers can be difficult to use since they require high electric field [1]. Shape-memory alloys have high response rate with large stroke output, but are expensive and hard to control [1,3]. In addition to cyclability, an ideal artificial muscle should be able to generate high range of stress and strain, it should have a long lifetime, and most importantly it should be controlled effortlessly.

The thermal nylon actuator is one of the recently explored materials in artificial muscle field, and shows some promising results in addressing the problems that most of the other materials are facing. It is can deliver reversible contraction of 5-50% with a short to medium response time up to half a second. It has lifting capabilities with a response rate of 15 to 20 seconds at room temperature and a life cycle of many hundreds of thousands of cycles. Also, it is cheaper and more readily available than most of the other materials used as artificial muscle [1-3].

Coiled nylon actuators are thermally driven actuators. Since nylon fiber has a negative thermal expansion coefficient, its length shrinks upon heating. The heat source for actuating can come from a variety of sources such as hot water, hot air and electrical current. Typically, nylon threads have the strain of 2-4% [1]. By coiling the nylon, the
strain can increase to as high as 40%. Specifically, uncoiled and untwisted nylon 6,6 fibers have thermal contraction of 4%. However, by inserting twist in the fibers to a great extent and coiling the polymer, the tensile contraction of the fibers can be increased 9 to 10-fold. This amplification in the tensile stress matches or exceeds is the maximum in vivo stroke of human skeletal muscles, which is around 20% [2].

Because of all the advantages that nylon offers, during the past few years, there has been significant research on the applications of nylon based artificial muscle [1-4]. However, there has been little work on how to prepare the nylon actuator itself. The work generated by nylon actuators is dependent on many independent variables and changing these variables or a combination of these variables will affect the actuator output to a great extent. Ideally, by improving the productivity of a single actuator we could use fewer actuators, which potentially can lead to less input energy. Additionally, fewer actuators mean a lower amount of material, which consequently leads to cheaper and more accessible products.

Although, different works have been published on the nominal output of nylon actuators there is still a lot of unknown. In one of the recent papers, Antonello Cherubini and Giacomo Moretti have shown that nylon actuators can reach high-level nominal stress of 40 MPa (see figure 1). They have tested the actuators with three different pre-actuation stretches [4]. They have shown that the nominal stress produced by the actuators is dependent on the pre-actuation stretches. Clearly, starting at a higher pre-stretch means that the starting stress is higher – so that, if actuation strain is the same, the resulting final stress will be higher. However, there may be a change in slope with pre-strain, but if so, this aspect has not been explored. In these tests, Cherubini and
Moretti have annealed the actuators at 150°C and they have not considered the effects of pre-anneal stretch on the actuator output.

![Graph showing stress vs. temperature for different datasets.](image)

*Figure 1: Stress vs. temperature measured for three isometric tests at 14.3% pre-actuation strain (dataset A), 21.4% (dataset B) and 28.6% (dataset C). Cherubini et al [4]. Reprinted with permission.*

This study examines the factors that can be altered during preparation and usage of the actuators, with the aim of generating higher strokes and stresses. During the initial research, four main factors were identified. These four factors are: (1) pre-anneal stretch, (2) pre-actuation tensile stress, (3) coiling tensile stress, and (4) annealing temperature. **Pre-anneal stretch** is the amount of the stretch that is applied to the actuators prior and during the annealing process. By stretching the nylon during the annealing process, the existing molecular bonds are broken and new bonds formed, providing the annealing temperature is right. The stretch can range from 0% of their original length all the way to 80%. **Pre-actuation stress** is the stress that would be applied on the actuators prior to heating. This factor plays an important role in determining the maximum stress that the actuators can generate. **Coiling tensile stress** is
the amount of the tensile stress applied to the fibers when they are coiling. This is a very important factor since it directly affects the actuator's spring index, which determines the force generating capability of the actuator. Spring index is the relationship between mean diameter of the actuator and the fiber diameter of the actuator. By reducing the index, the force generation by the actuator has been shown to increase [1]. It is important to choose the right amount of tensile stress since at very small stresses the fibers snarl and at a high weight the fiber tears. There is a significant range of tensile stress that can be applied, and here we seek to understand the trade-offs involved in the selection of this stress.

The **annealing temperature** is essential since at low temperature the fiber is not heat treated completely, and at too high a temperature it melts. Heat treatment of actuators is essential to lock the actuators in the working position. In order to improve the stress generated by the actuators and prevent them from uncoiling we need to heat treat them at a high temperature. At high temperature, some of the weak bonding of the nylon at molecular level breaks and reforms new bonds which results in the actuator being fixed in a new position. Fixation at the new position leads to reduction of tension stored in the actuator as the result of coiling under high tensile stress. Changes at the molecular levels happen at various levels depending on the temperature. The bonds that are being rearranged are in the amorphous region of the nylon and by rearranging them the amorphous structure converts to a crystalline structure. Total removal of elastic stress and amorphous region cannot happen since in order to rearrange all the amorphous region we need to heat treat the actuators at a temperature very close to the
melting temperature of nylon. These extremes set the limits on the temperature range that can be used.

Also, in this study I have looked into the actuator creep and actuator behavior in isotonic situations is a very important factor for controlling and predicting the behavior of the actuator.
2. **Background Knowledge**

In this section I will be explaining some of the background information that is needed to understand the behavior and response of the nylon actuator. Nylon structure, glass transition, Brill transition, and the effect of the glass and Brill transitions on nylon’s viscoelasticity model are discussed in this section.

2.1 **Nylon Structure**

Nylon is a polyamide with unique properties due to the hydrogen bonds between its amide groups. Amides consist of a Nitrogen atom bonded to a Carbonyl atom. Polyamides have crystalline and amorphous structures that make them semi crystalline. Polymer crystals are thin and have chains that are folded back and forth a so-called lamellar structure as shown in figure 2 [5].
Figure 2: Schematic of nylon unit cell. Adapted from Vinken [5].

The specific polyamide that we have studied in this paper is nylon 6,6. The synthesis of nylon 6,6 is described in figure 3 [5]. The structure of the polyamides has folded chain with hydrogen-bonded sheets, which are held together by van der Waals forces. The hydrogen bonds are between the oxygen of the carbonyl and the adjacent hydrogen of the amide group. The hydrogen bonds are formed within the sheets and the van der Waals forces are formed between the sheets. The hydrogen bonded sheets and the hydrogen bonds between adjacent chains are affected by the stereochemistry or three-dimensional arrangement of atoms and molecules. Therefore, the lamellar sheets stack up differently in different nyons [5].
Figure 3: Synthesis of nylon 6,6 (PA6, 6) from Adipic acid and Hexamethylenediamine.

Figure 4: Nylon 6,6 structure with its hydrogen bonds [6]. Copyright 2017 by American Chemical Society. Reprinted with permission.

The structure demonstrated in figure 2 is formed from the final molecules shown in figure 4 and the Van der Waals forces and hydrogen bonding between them. However, there are some inconsistencies in the structure of the nylon such as extra oxygen molecules and misalignments. The inconsistencies in the Van der Waals forces
and the hydrogen bonds lead to different regions with dissimilar properties in nylon. These regions are the amorphous regions of the nylon. The amorphous regions have lower melting point and they affect the thermal expansion coefficient of the nylon. Also, the amorphous regions affect the elasticity of the nylon.

2.2 Glass Transition Temperature

The main polymer’s chain gains mobility at or above the glass transition temperature. Polymers have semi crystalline structure with crystalline and amorphous regions, so there is more than one point that dynamic modulus of the nylon drops in response to increasing mobility temperature. Figure 5 shows, the drops happen at different temperatures. Drops at the lower temperature represent the mobility changes for the side chains, so their effects on overall modulus are small. Drops at higher temperatures affect the mobility at the main chain, so they affect the overall modulus extensively. In figure 5 the main change in the mobility occurs at 65 °C. The dynamic losses are measured by \( \tan \delta = \Delta f / f_0 \). \( f_0 \) is the resonant frequency and the \( \Delta f \) is bandwidth of the resonance curve [7].
Figure 5: Dynamic modulus and losses against temperature of nylon 6: 6. Willbourn [7]. TAN $\delta$ plot corresponds to left hand axis, upper modulus plot uses right hand vertical axis. Copyright 2017 by Royal Society of Chemistry. Reprinted with permission.

By looking at the above figure we can imagine the following mechanical model for the crystalline structure of nylon 6,6.

![Fractional order damping model](image)

Figure 6: Fractional order damping model with internal variables for nylon at all of the glass transition states.

The model shown in figure 6 is a combination of many Maxwell components. Every spring-dashpot component gives a particular response associated with the
viscoelastic response of nylon at a particular temperature. Each Maxwell component has two parts the damper, $C$, and the spring component with spring constant, $k$. It is important to know that, the changes in damper affect the Young’s modulus.

In this graph, the ‘g’ subscript is denoted for the major transition at high temperature and the other number subscripts are denoted to the minor transitions at low temperatures. Additionally, due to annealing, glass transition temperature shift toward higher temperature. This phenomenon is as the result of the changes in the crystalline structure of the nylon. Annealing makes the structure of the chains more packed, and shifts the glass transition to higher temperature [8]. The reason behind the shift in the glass transition is that at high temperatures the bonds in the amorphous regions of the nylon reorganize to form a new crystalline network that is more stable at high temperatures [9]. Accordingly, the volume of amorphous regions decreases after annealing. Subsequently this means that some of the minor transitions will disappear after annealing the nylon, so some of the minor drops shown in figure 5 will not be present anymore. The reason is that the minor transitions are the result of the amorphous regions, and after annealing these regions would transform to a crystalline structure and their effect on the modulus disappears.

In order to analyze this model all, the minor transition states are neglected and we have to look at the main glass transition state. In figure 7, $L_1$ and $L_2$ are the initial lengths in the unstrained state and they are constant and at equilibrium with $F=0$, $x_1 = x_2 = 0$
The embodiment shown in figure 7 is the representation for the glass transition state of nylon which correlates with the experimental response observed in figure 5.

### 2.3 The Brill Transition

The semi-crystalline structure of the nylon affects the physical and mechanical properties of the polymer such as its negative thermal expansion (NTE) property. Most polymers undergo a phase transition at high temperatures known as the Brill transition. At the Brill transition the interchain distance within a hydrogen bonded sheet and the distance between the sheets are equal [5-7,11]. In nylon, increasing temperature will disrupt the methylene ($\text{CH}_2$) sequences that are located between amide and the $\text{CH}_2\text{-C=O}$. Also, the $\text{CH}_2\text{-NH}$ bonds connecting the methylene and amide groups are twisted, (see figure 8).
The Brill temperature of Nylon 6,6 is around 160°C. The changes in the molecular structure of the nylon as the result of the temperature changes are visible in infrared spectra of nylon 6,6 (see figure 9).
In figure 9 the bands at 1200 and 935 cm\(^{-1}\) are associated with the crystalline phase and the bands at 1180 and 1144 cm\(^{-1}\) are associated with the amorphous phase. In figure 9 the sharp peaks associated with crystalline phase disappear as the temperature of the nylon increases and the broad peaks associated with amorphous state remain mainly unchanged. Additionally, some weaker peaks which are associated with the crystalline structure disappear between 160°C and 180°C and it has been reported
that these changes are reversible. These peaks are the Brill peaks and they can be seen at 1329, 1303, 1224, 1065, 1042, 1014 and 987 cm\(^{-1}\) [13]. Changes in the infrared spectra of the nylon at Brill temperature correspond to structural changes in the nylon, but the exact changes are not clear. It is only fair to say that the orientation of the hydrogen bonds within and between the sheets changes.

In order to explain the changes in Nylon’s molecular structure at Brill temperature, Kohji Tashiro and Yayoi Yoshikoa studied nylon 10/10 crystals. In their paper, they have shown that as the temperature rises above the Brill temperature the nylon chain length starts to shorten. In figure 10, \(a\) and \(b\) represent the plane axes and \(c\) is the chain axis. Also, \(a', b'\) are the projection of \(a\) and \(b\) along the chain axis and \(\gamma\) is the angle between \(a', b'\).

Figure 10: Temperature dependence of the lattice constants of nylon 10/10. Yoshioka et al [14].
The shortening of the nylon axial, \( c \), above Brill temperature is caused by disorientation of the structure from \textit{trans zigzag} form to the geometry consisting of shorter \textit{trans} segments and \textit{gauche} bonds \cite{9,14-15}. In \textit{gauche} bonds the methyl groups get close to each other which is extremely unfavorable, so the movement of atoms increases drastically. As the conformation changes take place in the nylon structure the fluctuation of N…O hydrogen bonds increases and the average distance between atoms exceeds the critical value of the hydrogen bond, so hydrogen bonds associated with the amide groups get broken for a short period of time \cite{16}. The barrier height between \textit{trans} and \textit{gauche} transformation in the amide group is 0.9 \textit{kcal.mol}^{-1}, but it is a lot higher for CH-C=O and CH-CH bonds which have 3.2 \textit{kcal.mol}^{-1} and 3.8 \textit{kcal.mol}^{-1} transition energy respectively. Therefore, at Brill temperature the structure does not get distorted completely (see figure 11). If this was not the case the crystalline structure of the nylon would be lost altogether. It is important to mention that since nylon 10/10 has more carbon atoms in its structure, it will be less distorted than nylon 6, 6 which is the structure discussed in this work.
Figure 11: Potential energy curves calculated for the torsional angles around the CH2–NH (CH3–CH2–NH–CO–CH3), CH2–CO (CH3–CH2–CO–NH–CH3) and CH2–CH2 (CH3–CH2–CH2–CH3) bonds. Tashiro [12].

Distortion of the methylene sequences (CH₂) and hydrogen bonds in nylon are the reason behind thermal expansion characteristic of nylon. In simpler words, as the temperature increases the Hydrogen bonds between different layers of the lamellar sheets break which in turn leads to contraction of the whole structure.

As explained in the previous section, by annealing the nylon above the glass transition temperature the crystalline size of the nylon increases, so if the actuator is annealed while it is stretched, the length of the actuator will increase permanently and will not shorten when it is cooled down. By annealing the actuator at or above the Brill temperature the crystalline structure and hydrogen bonding of the polymer are affected further and the length increase of the actuator will be even more. This suggests that in addition to the glass transition temperature the Brill temperature also influences the elasticity of nylon. Therefore, depending to the annealing temperature and whether or
not it is above or below the Brill temperature the nominal output of the actuators and NTE of the actuator would be altered.

Figure 12 is a simple representation of the nylon for the transition at brill temperature. Considering the following figure at equilibrium with $F=0$ and $x_b=0$.

\[ L_b^+ x_b^{(0)} \]

\[ k_b \quad C_b \rightarrow F \]

*Figure 12: Fractional order damping model with internal variables for nylon at the Brill transition state.*

Annealing the actuators above the Brill transition temperature is essential for increasing the volume the crystalline structure in the semi-crystalline structure of nylon. Additionally, annealing above Brill transition temperature fixes the actuators at their new position.

### 2.4 Proposed Nylon Viscoelasticity Model

As explained in the previous sections the mechanical properties, crystalline structure and the Young’s modulus of the nylon actuators are altered at the glass transition temperature and at Brill temperature. Therefore, the models shown in figures 7 and 12 are not complete on their own, so the best model is the one that combines brill transition and glass transition. The combined model is shown in figure 13. It is very important to consider the both the Glass transition and Brill transition states since, both of these affect the polymer in molecular level and alter its behavior.
The graph presented in figure 13 shows the nylon viscoelastic model for both glass transition state and Brill transition state. Once again, the elements shown are temperature dependent. The spring/dashpot combination models the fact that the molecular structure of nylon can be altered at two different transitions points. By annealing above Brill transition state, the actuators are above glass transition temperature as well since glass transition point for nylon is well below the Brill transition temperature.

In conclusion, the glass transition temperature for the nylon is around 80°C-100°C and the Brill transition temperature is around 160°C, so the nylon should be annealed at a temperature above 160°C. Annealing the nylon at high temperatures while stretched leads to changes in molecular structure of nylon. Also, the built-up stress in nylon which results from coiling the nylon will disappear after the annealing the actuators. As a result, the actuators will not unravel after they are cooled down.

Figure 13: Fractional order damping model with internal variables for nylon for all the glass transition state in addition to Brill transition state.
3. Experimental

In this section I will be discussing the materials, methods, procedure and the results obtained from the experiments.

3.1 Materials and Methods

In this thesis, electrically conductive nylon has been used. Using this kind of fiber electrical energy can be converted to heat energy, which in turn would be turned into mechanical energy. The particular conductive thread that we have used is Conductive Sewing Thread Size 92, sold under the brand name Shieldex™ and obtained from Jameco Electronics with mean diameter of 230 μm and it is a multi-filament fibre. The thread is made from nylon 6,6. This particular nylon was chosen since it was the only commercially available silver coated nylon. Using a commercially available product gives immediate, real life relevance to the findings of this report, so other developers who are using this nylon can benefit from the findings. The mechanical characteristics are tested using a Bose Biaxial system. It is important to note that due to Bose system limitation in displacement, we could only run our tests on a part of their length and not the entire actuators.

3.2 Experiments and Results

In this section I will explain the experiments, their results and how those results can be used to determine characteristics of the nylon actuators. The actuators are made by fixing one end of the nylon and rotating the other end until it is coiled completely. During this process, a mass should be hanging from the fixed end, so the fiber is under
nominal tensile stress. The amount of the mass is critical, since too heavy a mass results in fiber getting torn apart and a light mass results in yarn snarl. The coiling setup is shown in figure 14.

Figure 14: Coiling setup for nylon actuators.

After coiling the nylon, it is annealed at fixed length. Figure 15 shows the actuator after it has been annealed.
As a result of coiling, the torsional displacement will be converted to linear displacement [1]. By heating the stretched coil, the actuator untwists, which shortens the gap between coils and generates linear actuation [17].

3.2.1 Pre-Annealing Stretch, Pre-Actuation Stress and Coiling Tensile Stress

In this section, the effect of pre-annal stress, pre-actuation stress and coiling tensile stress on force generated of the actuators have been examined. Unless otherwise indicated, tensile stress and modulus are calculated as nominal values by normalizing the applied force with the diameter of the initial non-twisted fiber. Pre-annal strain is measured in respect to the initial length of the actuators just after they are coiled and prior to be annealed. Also, the temperature that actuators reach during the heating process is measured using a J-type thermocouple wrapped around the actuators.

3.2.1.1 Pre-Anneal Strain

The first variable that was looked into was the pre-annal strain, which is the amount of strain that is applied to the actuators prior to being annealed. After nylon is coiled, the actuator is stretched by a certain amount and it will be fixed at the stretched stage while it is being annealed. In order to examine the effect of this pre-annal
strain I made same length actuators from an initial length of 250 ± 5 mm silver coated nylon. The final length of actuators prior to being annealed was 65 ± 1 mm. It is important to mention that all of the actuators were coiled under a load of 200 g mass, equivalent to a tensile stress of 47.2 MPa. The annealing temperature for all samples was 200°C. The following table is a summary of actuators’ lengths after being annealed.

<table>
<thead>
<tr>
<th>Index</th>
<th>After anneal length (mm)</th>
<th>Length Increase (mm)</th>
<th>Annealing strain (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>91.65</td>
<td>26.9</td>
<td>41</td>
</tr>
<tr>
<td>2</td>
<td>98.54</td>
<td>33.54</td>
<td>51.6</td>
</tr>
<tr>
<td>3</td>
<td>101.68</td>
<td>36.68</td>
<td>56.32</td>
</tr>
<tr>
<td>4</td>
<td>102.61</td>
<td>37.61</td>
<td>57.86</td>
</tr>
<tr>
<td>5</td>
<td>106.2</td>
<td>41.2</td>
<td>63.41</td>
</tr>
<tr>
<td>6</td>
<td>111.9</td>
<td>46.9</td>
<td>72.21</td>
</tr>
<tr>
<td>7</td>
<td>120.54</td>
<td>55.54</td>
<td>85.45</td>
</tr>
</tbody>
</table>

*Table 1: Actuators length, length change and percent of length change after being annealed.*

After annealing the actuators at high temperature for about 2 hours, the actuators are cooled to room temperature, which is about 25°C, and they are tested using the Bose Biaxial testing bench. In order to keep all the variables constant, the actuators have been pulled by initial tensile stress of 21.67 MPa, 0.90 N, prior to the actuation. The input power into actuators was 1.2 W ± 3% which means the actuator was heated to about 80°C-85°C. Also, the length of the actuator that was under test was 17.5 ± 0.2 mm, with a power per length of 0.69 W/cm.

After pulling the actuators by 0.9 N, the actuators were activated using electrical current. Each actuator has been activated twice. Each cycle was 1 minute with 50% duty
cycle. It is important to mention that these tests are done under isometric conditions.

The following graph shows the response for the actuator with pre-anneal strain of 63.4%. As shown in figure 16, after turning on the power, the force generated by the actuator increases and reaches the maximum value. Figure 17 represents the maximum force that actuators reach.

![Graph showing force generation](image)

*Figure 16: Experimental procedure exploring the effect of pre-anneal strain. In the response shown, the pre-actuation stress is 0.9 N with pre-anneal strain of 63.41%.*
Figure 17: Max Force Vs. Pre-anneals stretch for actuators made with different pre-anneal stretch. The uncertainty for force is ± 0.03 N.

After turning the power off the force drops to a lower value than the initial value, and this is marked as the min force. Figure 18 represents the minimum force of the actuators. The drop in the minimum force is due to shape memory effect that exists in the actuators.

Figure 18: Minimum Force Vs. Pre-anneal stretch for actuators made with different pre-anneals strain. The uncertainty for force is ± 0.03 N.

The force generated by each is calculated using the following equation:
The force generated by the actuators is shown in figure 19.

![Figure 19: Amplitude generated Vs. Pre-anneals strain. The uncertainty for force is ± 0.03 N.](image)

The difference between smallest forces generated with largest force generated is only 0.2N, which is only 10% increase. The compelling difference is the max force that the actuators can reach. The largest max force reached is 20% bigger than the smallest max force. This peak force is important in characterizing and controlling the output of the actuators. Maximum force is important in applications where maximum force reached is more important than the force generated.

In order to explain the changes in the force generated, the changes in the actuators stiffness have been studied. Stress-strain tests have been performed. In these tests, the actuators had an original length of 250 mm with coiling length of 65 ± 1 mm and they were annealed at 180°C. At the room temperature, force was increased from zero to peak force for 10 cycles. The experiment was repeated for peak loads up to 4.5 N increased in 0.5N increments. As seen in figure 20, the coil is gradually stretched over time, indicating creep. Figure 20, represents the stress strain for actuators.
I. Stress-displacement, 1.2% pre-anneal stretch.

II. Stress-displacement, 13% pre-anneal stretch.
III. Stress-displacement, 26% pre-anneal stretch.

IV. Stress-displacement, 38% pre-anneal stretch.
Figure 20: Stress displacement test for actuators with different pre-anneal stretch at room temperature.

V. Stress-displacement, 50% pre-anneal stretch.

VI. Stress-displacement, 64% pre-anneal stretch.
Using Hooke’s law, equation 2, the effect of pre-anneal strain on the stiffness of the actuators is investigated.

\[ \Delta F = k \Delta L \]  

Eq. 2

In this equation, \( \Delta F \) is the force change, \( \Delta L \) is the displacement and \( k \) is the stiffness. The actuators stiffness for force change of 3.5 N is calculated by using equation two and measuring \( \Delta L \) in in figure 20 graphs. Figure 21 shows the stiffness of the actuators as the function of pre-anneals stretch.

![Figure 21: Changes in stiffness as the pre-anneal strain increases. The stiffness calculated is for force change of 3.5 N.](image)

The stiffness of the actuators increases as the pre-anneal stretch of the actuators increases. Therefore, considering equation 2 with equal displacement the force produced by the actuators increases. It is important to mention that according to figure 21, we expect that the generated force for the actuator with the highest pre-anneal strain to be double the generated force for the actuator with the smallest pre-anneal strain. However,
in reality the difference is a lot smaller. The difference can be explained by looking at figure 22. In figure 22 it shown that in isotonic condition as the pre-anneal stretch increases the active strain decreases and the strain for the actuator with highest pre-anneal stretch is half of the strain for the actuator for smallest pre-anneal stretch. Therefore, in equation 2 \( k \) doubles up while \( \Delta L \) is cut in half.

Another effect of pre-stretch is to reduce creep. This is evident in the stress-strain measurements of figure 29. As pre-stretch increases, the rightward shift in strain and displacement drops by a factor of 2 or more. The reduction in creep helps explain the increase in minimum force seen in figure 18. Creep will be discussed in chapter 4.

Additionally, an isotonic test was performed to measure the effect of the pre-anneal stretch on the active generated strain. In this test, the tensile stress is constant (isotonic) and the strain of the actuators is measured. The tensile stress that the actuators are subjected to in this test is 48 MPa. Table 2 shows the length change of the actuators under constant tensile stress. The actuation power was 0.35 ± 0.01 W, so the temperature of the actuator would reach 40°C to 45°C. The actuator length under test was 5 mm. Prior to the test the actuators, were gone through one cycle of heating under isotonically with tensile stress of 24 MPa. After the heating, the actuators’ tensile stress was reduced to zero and I waited for about 1 hour to measure their active generated strain.
<table>
<thead>
<tr>
<th>Pre anneal stretch (%)</th>
<th>Displacement (mm)</th>
<th>Strain (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.2</td>
<td>0.366</td>
<td>7.32</td>
</tr>
<tr>
<td>12.4</td>
<td>0.361</td>
<td>7.22</td>
</tr>
<tr>
<td>25.5</td>
<td>0.289</td>
<td>5.78</td>
</tr>
<tr>
<td>37.6</td>
<td>0.219</td>
<td>4.38</td>
</tr>
<tr>
<td>50</td>
<td>0.199</td>
<td>3.98</td>
</tr>
<tr>
<td>64</td>
<td>0.179</td>
<td>3.58</td>
</tr>
</tbody>
</table>

*Table 2: Summary for actuators’ strain annealed under pre-anneal stretches.*

Figure 22 shows actuation strain as functions of pre-anneal stretch.

![Graph showing actuation strains as the function of pre-anneal stretch.](image)

*Figure 22: Actuation strains as the function of pre-anneal stretch.*

As seen in figure 22 as the pre-anneal stretch increases the actuation strain decreases, so under equal and constant force the stiffness increases. Therefore, the result observed in figure 22 correlates with the result observed in figure 21.

In order to explain the effect of pre-anneal stretch on stiffness, I have looked into its effect on Young’s Modulus. An elastic solid can be viewed as a bundle of ideal springs, so its Young’s Modulus \( E \) is related to stress \( \sigma \) and strain \( \varepsilon \) by equation 3.
Equation 4 shows stress, calculated from applied force \( F \) and the section area \( A \). Also, equation 5 shows strain calculated from the length change \( \Delta L \) and the initial length of the actuator \( L_0 \) prior to the activation.

\[
E = \frac{\sigma}{\varepsilon}, \quad \text{Eq. 3}
\]

\[
\sigma = \frac{F}{A}, \quad \text{Eq. 4}
\]

\[
\varepsilon = \frac{\Delta L}{L_0}, \quad \text{Eq. 5}
\]

The spring constant \( k \) is function of the spring geometry and the spring material's shear modulus \( G \). Equation 7 is the spring constant equation:

\[
k = \frac{G d^4}{8 D^3 n_a}, \quad \text{Eq. 7-1}
\]

where \( G \) is found from the material's elastic modulus \( E \) and Poisson ratio \( \nu \),

\[
G = \frac{E}{2(1+\nu)}, \quad \text{Eq. 7-2}
\]

and \( D \) is the mean diameter of the spring (measured from the centers of the wire cross-sections),

\[
D = D_{\text{outer}} - d, \quad \text{Eq. 7-3}
\]

where \( d \) is non treated diameter of the silver coated nylon and \( n_a \) is number of coils.

By keeping force, length change and initial length constant we can investigate the effect of changes in cross section area on the spring constant. The cross-section area was measured using the outside diameter \( D_{\text{outer}} \) of the actuators, which is shown in figure 23.
The outside diameter of the actuators was measured using a Mitotoyo micrometer.

<table>
<thead>
<tr>
<th>Pre-anneal stretch (%)</th>
<th>Mean outer diameter (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>702</td>
</tr>
<tr>
<td>14</td>
<td>688</td>
</tr>
<tr>
<td>30</td>
<td>678</td>
</tr>
<tr>
<td>38</td>
<td>675</td>
</tr>
<tr>
<td>50</td>
<td>658</td>
</tr>
<tr>
<td>62</td>
<td>643</td>
</tr>
<tr>
<td>78</td>
<td>639</td>
</tr>
<tr>
<td>88</td>
<td>626</td>
</tr>
</tbody>
</table>

*Table 3: Summary of mean outer diameter of the actuators annealed under different pre-anneal stretches.*

As can be seen in table 3 as the pre-anneal stretch increases the actuator surface area decreases. In this experiment, it was assumed that Young’s modulus is constant. According to equation 7, spring constant is inversely related to the mean diameter, and the number of coils and as the pre-anneal stretch increases, the mean diameter and the number of coils decreases and the number of coils so the spring constant increases
which means the actuators get stiffer. The stiffer actuators undergoing isotonic experiments will generate smaller actuators strain. Also, stiffer actuators undergoing isometric experiments will generate higher tensile stress. Both of these results correlate with the experimental results.

Another reason behind the changes in the force generated by the actuators with different pre-anneal stretches comes from changes at the molecular structure of the actuators. As explained in section 2.3, at high temperature the molecular structure of nylon changes from gauche to trans structure. Therefore, by annealing the actuator under constant tensile stress the molecular structure of the actuators will be fixed at the new position. When the actuator is heated the molecular structure of the nylon will start to rotate to go back to the original structure. As the pre-anneal stretch increases the actuator molecular structure gets distorted further, so the actuator would have higher tendency to go back to original state and it produces higher force.

3.2.1.2 Pre-Actuation Stress (Offset Force)

The second variable that was looked into was pre-actuation stress. This is the load applied at the start of actuation. After the start of actuation, the actuator is held at constant length. It is an important factor that needs to be characterized since the output of the actuator is altered by the amount of pre-actuation stress. The actuators are made from an initial length nylon of 250 ± 5 mm, and the length of coiled actuator is 65 ± 1 mm. The annealing temperature is 180°C (above the Brill temperature) and actuators were stretched by 40% prior to and while being annealed. In order to investigate the effects of different offset forces, the actuators underwent various pre-actuation forces
and they have been actuated for three cycles. Each cycle was 1 minute with a duty cycle of 50%, and the test was done under zero change in strain condition (isometric). The following figure shows the actuator response while undergoing an offset stress of 47.8 MPa. In each test, the time for reaching the offset force is 20 s, so in figure 24 the force is ramped to 2N at a rate of 0.1 N/s. The actuation power is 1.1 W, and the actuation temperature reaches 70°C-75°C. The length under test was 17.5 ± 0.2 mm.

![Figure 24: Experimental procedure for exploring the effect of offset force. In this figure, the offset force is 2 N and the active portion of the experiment is performed under zero strain condition.](image)

In figure 24, the load is first ramped up to 2 N, and then the length is fixed. After a short time (a few seconds later), power is applied to heat the actuator. In the intervening period, a drop-in force is seen as the actuator undergoes stress relaxation. Then a sharp rise in force is evident as the actuator tries to contract. When the power goes off, the force relaxes back to a value that is lower than the starting force. This relaxation is, as before, due to a combination of stress relaxation, and perhaps also some shape memory effects. Subsequent cycles then alternate between the same hot and cold
states, with a constant amplitude. The effects of viscoelastic relaxation and shape memory will be explored further in chapter 5.

The following figure represents the maximum force that the actuators generate. This is obtained from the max force, as depicted in figure 24.

![Graph showing max force vs. pre-actuation force. The uncertainty for maximum force is ± 0.03 N.]

*Figure 25: Max Force Vs. Pre-actuation force. The uncertainty for maximum force is ± 0.03 N.*

As seen in figure 24 the generated force drops to the minimum level. The following figure shows the minimum forces that the actuators drop to.
The force amplitude as a function of load is shown in figure 27. The amplitude of the generated force increases as the offset stress increases. The increase in the
amplitude may be the result of increased actuator stiffness. As the offset stress increases, the actuators are stretched, which leads to decrease in the outer cross section area, increasing stiffness. As shown in equation 7 as the cross mean diameter decreases the stiffness increase. Under isometric conditions, maximum force and amplitude of force generated increase, providing that free strain remains the same. Also, by pulling the actuators more they have higher tendency to go back to their relaxed position. Actuators undergoing higher offset have more distortion in their structure, so they will have higher tendency to go back to their relaxed state.

3.2.1.3 Coiling Tensile Stress (Coiling Weight)

The next factor that was investigated was the effect of coiling weight on the generated force. In order to investigate the effect coiling tensile stress actuators are coiled while undergo various tensile stresses. After coiling all the actuators were pulled by about 50% as the pre-anneal stretch, so they all have equal length after being annealed. Also, the annealing temperature for all was 180°C. The initial length of the actuators was 250 mm and with a coiled length of 65 ± 1 mm. Only 10 mm of the actuators was under test. An offset force of 2 N pulled the actuators so they are under 48.2 MPa tensile stress while being actuated.
Figure 28: Amplitude generated as a function of coiling stress.

As the coiling weight increases, the force generated by the actuators increase. The increase in the generated force is likely as the result of changes in the spring index of the nylon actuators. As shown by Haines in figure 29, as the spring index, $C$, of the actuators decreases under equal nominal tensile stress, the tensile actuation of the actuators decreases. $C$ index of the actuators is defined as,

$$C = \frac{D}{d}$$  \hspace{1cm} \text{Eq. 8}

where $D$ is the coil diameter and $d$ is the fiber diameter prior to the coiling.
Figure 29: Tensile actuation as a function of Nominal tensile stress for actuators with different C indices. Haines et al [2].

Table 4 shows the C indices for the actuators coiled under different tensile stress. In the nylon employed in this study the mean initial diameter of the nylon was 230μm.

<table>
<thead>
<tr>
<th>Coiling mass (g)</th>
<th>Coiling stress (MPa)</th>
<th>Coil diameter (μm)</th>
<th>C index</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>23.59</td>
<td>735.6</td>
<td>1.4712</td>
</tr>
<tr>
<td>125</td>
<td>29.48</td>
<td>723.6</td>
<td>1.4472</td>
</tr>
<tr>
<td>150</td>
<td>35.38</td>
<td>715</td>
<td>1.43</td>
</tr>
<tr>
<td>175</td>
<td>41.28</td>
<td>704.4</td>
<td>1.4088</td>
</tr>
<tr>
<td>200</td>
<td>47.17</td>
<td>698.8</td>
<td>1.3976</td>
</tr>
<tr>
<td>225</td>
<td>53.07</td>
<td>692.4</td>
<td>1.3848</td>
</tr>
<tr>
<td>250</td>
<td>58.97</td>
<td>687.4</td>
<td>1.3748</td>
</tr>
</tbody>
</table>

Table 4: Summery of coil diameter and C-index of actuators coiled under different pre-anneal stresses.
The shear stress of the actuators can be calculated using equation 9.

\[
S_s = \frac{8FC}{\pi d^2} + \frac{BF}{2\pi d^2} \quad \text{Eq. 9}
\]

\[
\sigma = \frac{S}{2} + \sqrt{S_s^2 + \left(\frac{S}{2}\right)^2} \quad \text{Eq. 10}
\]

In these equations:

- \( C \): Spring index
- \( d \): Fiber diameter
- \( F \): Applied force
- \( S \): Shear stress
- \( \sigma \): Combined stress
- \( S \): Normal stress

According to equation 9, as the \( C \) index decreases, the shear stress decreases as well. Additionally, as seen in figure 24, as the actuator generated force reaches the maximum value, the force stays relatively constant, which means the combine stress, \( \sigma \), is constant. Therefore, according to equation 10, as the shear stress decreases the tensile stress should and will increase. Also, according to equation 6 as the outside area decreases, the Young’s modulus increases, and the actuators get stiffer.

### 3.2.2 Annealing Temperature

Considering the effect of the Brill temperature, I have annealed the nylon at a range of temperatures above and below this transition, and I have come to the conclusion that we need to anneal the nylon at a temperature above the Brill transition temperature. The reason is that, by annealing above the Brill temperature, the hydrogen bonding is released, so the nylon is able to relax into the new state. Some of the shape memory set into the structure by the hydrogen bonding is removed. After careful experiments and observing the actuators response and behavior such as the extent of
uncoiling, I have come to the conclusion that the best annealing temperature is 180°C. The reason for choosing this temperature is that at this temperature we are well above the Brill transition temperature, which allows the molecular changes necessary for actuators to reach the relaxed state. In section 2.3 it is explained that by annealing the actuators at a fixed position at temperatures at or above the Brill transition temperature (160°C), the hydrogen bonds in the nylon structure will be rearranged permanently in the more relaxed position. Also, at this temperature we are well below the melting temperature of the nylon. If we anneal the actuators at temperatures close to melting point of nylon we would disturb the molecular structure of the nylon to the extent that the actuators would lose their functionality. The reason is at temperatures close to melting point, the covalent bonds of the nylon will start to break which disturbs the molecular structure.

3.3 Discussion

In addition to the effect of changes in pre-anneal stress, pre actuation stress and coiling weight on the stiffness and generated force, the stiffness of the actuators can be altered as a result of heating during actuation. As explained in section 2.1, the mechanical model for the nylon has damping characteristics, which will be altered as the temperature changes. The expectation is that as the temperature increases, the stiffness decreases, which correlates with changes that happen to nylon’s young’s modulus, shown in figure 30 [18].
Figure 30: Variation of Elastic Modulus with temperature transforming from a more glassy state to a partially rubbery state. The dashed line indicates the trend [18].

Table 5 shows the effect of various factors on the stiffness of the actuators.

<table>
<thead>
<tr>
<th>Effecting factor</th>
<th>Effect on stiffness</th>
<th>Effect on generated stress</th>
</tr>
</thead>
<tbody>
<tr>
<td>Increase in Pre Anneal Stretch</td>
<td>Increase</td>
<td>Increase</td>
</tr>
<tr>
<td>Increase in offset force</td>
<td>Increase</td>
<td>Increase</td>
</tr>
<tr>
<td>Increase in input power/Temperature</td>
<td>Decrease</td>
<td>Increase</td>
</tr>
<tr>
<td>Coiling Weight</td>
<td>Increase</td>
<td>Increase</td>
</tr>
</tbody>
</table>

*Table 5: Summary of different factors effect on stiffness and generated force.*

Considering the findings in the previous sections, in order to generate the highest output, we should coil the nylon under a very high tensile stress, anneal them while they are stretched by a large amount, actuate them under a high amount of offset force and apply a high amount of input power. While this is correct, there are some other considerations that need to be made. Coiling the nylon under a high tensile stress will result in stiffer actuators, which prevents us from applying a high amount of pre-anneal stretch. Stiff actuators will break when are stretched extensively. In addition, the rate of actuator breaking while being coiled increases when the coiling tensile stress is above 50 MPa. Also, at pre-anneal strain above 65% the rate of actuator tearing
increases tremendously. Additionally, a high amount of input power will lead to a high temperature which leads to melt down of the actuators. As the result, it is extremely important to coil, prepare and activate the actuators under controlled and calculated conditions.
4. Creep

One of the issues that is observed in the actuator response is creep. When running the stress-strain tests on samples without creep, the start and end point for the graph on the strain axes are the same over a stress-strain cycle. However, as seen in the graphs of figure 20, the start and end point on the strain axis for the nylon actuators is different, which means there is creep in the actuators. Different materials have properties that vary with time due to creep. The time dependent behavior of polymers is due to their molecular structure.

One of the fundamental methods used to characterize the creep behavior of a polymer is the stress relaxation test. In a relaxation test the actuator is suddenly stretched to a new position and it will be fixed such that the stress remains constant for the duration of the test. Also, the assumption in a relaxation test is that the material has no previous stress or strain history and the sudden tensile stress will not induce any dynamic or inertia effects. When polymer is loaded in the described manner, the strain needed to maintain the constant stress will increase with time, but the rate of increase will decrease and, eventually, the length would not increase anymore. This is the creep elimination point.

In this section, first I propose a creep model for the actuators, and later of I will investigate the effect of different pre-anneal stretches and different coiling stresses on the creep.
4.1 Creep Modeling

In order to investigate the creep in the actuators several experiments have been performed. In the first set of experiments the effect of pre-anneal stretch was investigated. In this experiment, creep tests with static tensile stress of 48.2 MPa are performed. The length of the actuator under test was 10 mm. The following graph shows the response to the stress. The initial rise is as the result of elastic strain and creep is the visco-elastic response.

![Graph showing actuator response](image)

*Figure 31: Actuator response coiled with 200g weight, pre-anneal stretch is 14.2%.*

It is essential to note that the stress is applied to the actuators in the first half of a second of the experiment, which leads to a sudden rise in the displacement and the creep rise appears after the sudden rise.
Figure 32: Initial rise of actuator coiled with 200g weight, pre-anneal stretch is 14.2%.

After the initial rise the effect of creep starts to appear with an initial high slope which starts to decrease.

Figure 33: Actuator creep coiled with 200g weight, Pre-anneal stretch is 14.2%.
Figure 34 shows the model for actuators response.

\[ (1) \quad E_1 \quad \mu_1 \]
\[ (2) \quad E_2 \quad \mu_2 \]
\[ (3) \quad \alpha \Delta T \]

Figure 34: The predicted model for the creep in the actuators. \( \mu_1 \) and \( \mu_2 \) are the damper elements, \( E_1 \) and \( E_2 \) are the spring elements, \( \alpha \) is thermal expansion coefficient and \( \Delta T \) is temperature change.

The model has three major parts:

1. Kelvin solid model
2. Maxwell fluid model
3. Thermal expansion section with negative thermal expansion coefficient

Each of these parts effect is visible at certain times during the experiment. The sudden rise seen in figure 32 is as the result of the spring in Maxwell model with elastic constant of \( E_2 \). The creep seen in figure 33 is as the result of the dampers elements \( \mu_1 \) and \( \mu_2 \). Effect of \( \mu_1 \) can be observed in short term creep and effect of \( \mu_2 \) can be observed in long term creep. The effect of the third section comes to effect when the actuator is heated and activated. It is important to mention that the length of \( E_1 \) will not increase suddenly after increasing the stress as the damper, \( \mu_1 \), will not allow a sudden jump in the strain for \( E_1 \). Therefore, strain increases continuously over time under constant stress.
Using the predicted model in figure 34 the associated constants of the model for the actuator tested while undergo tensile stress of 48.2 MPa are calculated and presented in table 6.

| $\mu_e$ | 0.0224(TPa).s |
| $E_1$   | 131.19 (MPa)  |
| $\mu_2$ | 0.49 (TPa).s  |
| $E_2$   | 28 (MPa)      |

*Table 6: Creep elements for equation 11-1.*

After using the values in table 6 and the generic equations for the model, equation 11-1 and 11-2, equation 11-3 is realized for the same actuator which its response is shown in figure 33:

$$\varepsilon(t) = -\frac{\sigma_0}{E_1} e^{-\frac{t}{\tau_1}} + \sigma_0 \left(\frac{1}{E_2} + \frac{t}{\mu_2}\right) \quad \text{where,}$$

$$\tau = \frac{\mu}{E} \quad \text{Eq. 11-1}$$

$$\varepsilon(t) = -0.3674 e^{-5.843 \times 10^{-3} t} + 48.2 \left(\frac{1}{28} + \frac{t}{\frac{0.49}{0.49 \times 10^6}}\right) \quad \text{Eq. 11-3}$$

Graphing equation 11-3 gives us the response shown in figure 35.
Figure 35: Strain equation for proposed model $\varepsilon(t) = -0.3674e^{-5.843\times10^{-3}t} + 48.2\left(\frac{1}{20} + \frac{t}{0.49\times10^6}\right)$.

The response shown in figure 35 is very close to the real response seen in figure 33. The following figure represents both of equations in the same graph.

Figure 36: Actuator strain responses, $\varepsilon_1(t)$ is the observed response and $\varepsilon_2(t)$ is the predicted response.
4.2 Effect of Pre-Anneal Stretch on Creep

In this section, the effect of pre-anneal stretch on creep elements modeled is investigated.

In order to investigate the effect of pre-anneal stretch, actuators are made from an original fiber length of 250 mm, they are coiled under tensile stress of 47.2 MPa and they undergo tensile stress of 48.2 MPa while being tested. The tensile stress increases from zero to 48.2MPa in half a second and the length of actuator under test is 10 mm. The following table shows the different elements of model presented in figure 34 for actuators tested in this experiment. The values presented in table 7 have confidence level of 10% since they are average of 3 different tests.

<table>
<thead>
<tr>
<th>Pre-anneal stretch</th>
<th>μ₁ (TPa).s</th>
<th>E₁ (MPa)</th>
<th>μ₂ (TPa).s</th>
<th>E₂ (MPa)</th>
<th>Equation from proposed model: ε(t)</th>
</tr>
</thead>
<tbody>
<tr>
<td>14.2%</td>
<td>0.0224</td>
<td>131.19</td>
<td>0.49</td>
<td>28</td>
<td>$-0.3674e^{-0.005848t} + 48.2\left(\frac{1}{28} + \frac{t}{0.49\times10^6}\right)$</td>
</tr>
<tr>
<td>37.7%</td>
<td>0.0453</td>
<td>223.04</td>
<td>0.74</td>
<td>39.83</td>
<td>$-0.2161e^{-0.004926t} + 48.2\left(\frac{1}{39.83} + \frac{t}{0.74\times10^6}\right)$</td>
</tr>
<tr>
<td>50%</td>
<td>0.0685</td>
<td>345.03</td>
<td>0.99</td>
<td>51.74</td>
<td>$-0.1397e^{-0.004038t} + 48.2\left(\frac{1}{51.74} + \frac{t}{0.99\times10^6}\right)$</td>
</tr>
<tr>
<td>62%</td>
<td>0.0752</td>
<td>353.89</td>
<td>1.21</td>
<td>69.44</td>
<td>$-0.1362e^{-0.003707t} + 48.2\left(\frac{1}{69.44} + \frac{t}{1.21\times10^6}\right)$</td>
</tr>
<tr>
<td>78%</td>
<td>0.133</td>
<td>625.24</td>
<td>1.88</td>
<td>95.73</td>
<td>$-0.0771e^{-0.004685t} + 48.2\left(\frac{1}{95.73} + \frac{t}{1.88\times10^6}\right)$</td>
</tr>
</tbody>
</table>

Table 7: Different elements and strain equations for actuators annealed under different pre-anneal stretches.
The responses of the actuators discussed in table 7 are plotted in figure 37.

![Creep response of actuators annealed with different pre-anneal stretches in response to a step load of 48.2 MPa.](image)

By looking at table 7 it is obvious that as the pre-anneal stretch increases, all the elements identified in the previous section increase as well. It was explained in section 3.2.1.1 that as the pre-anneal stretch increases the actuators get stiffer, so it would be harder to pull them. In better words, it is harder to pull the actuators further when they already have been pulled by a great amount. Also, as seen, $\mu_2$ is 14 to 21 folds greater than $\mu_1$ depending to the pre-anneal stretch that means that the $\mu_2$ come into effect a lot later than the effect of $\mu_1$, so the short-term creep comes from $\mu_1$ and long-term creep as the result of $\mu_2$. Figure 38, shows the changes in actuators elasticity and damper element.
Figure 38: Different elements of creep as the pre-anneal stretch increases. (I) shows the changes in elasticity. (II) Shows the changes in damper elements.
It is obvious that as the pre-anneal stretch changes the creep and the rate of strain increasing change as well. The changes in the strain rate are calculated by getting the derivative of strain with respect to time. Table 8 represents the rate equations for actuators.

<table>
<thead>
<tr>
<th>Pre-anneal stretch</th>
<th>Strain rate equations</th>
</tr>
</thead>
<tbody>
<tr>
<td>14.2%</td>
<td>(0.00215e^{-5.843 \times 10^{-3} t} + \frac{48.2}{0.49 \times 10^6})</td>
</tr>
<tr>
<td>37.7%</td>
<td>(0.00106e^{-4.92 \times 10^{-3} t} + \frac{48.2}{0.74 \times 10^6})</td>
</tr>
<tr>
<td>50%</td>
<td>(0.000704e^{-5.038 \times 10^{-3} t} + \frac{48.2}{1.21 \times 10^6})</td>
</tr>
<tr>
<td>62%</td>
<td>(0.000361e^{-4.685 \times 10^{-3} t} + \frac{48.2}{1.88 \times 10^6})</td>
</tr>
<tr>
<td>78%</td>
<td>(0.000419e^{-5.55 \times 10^{-3} t} + \frac{48.2}{2.26 \times 10^6})</td>
</tr>
</tbody>
</table>

*Table 8: Strain rate equations for actuators annealed with various pre-anneal stretches.*

The equations of table 8 are plotted in Figure 39, which shows how the rate of strain is affected by the pre-anneal stretches. As can be seen, as the pre-anneal stretch increases, the actuators will stretch at a lower rate, so the length change for the same amount of time and under same tensile stress decreases as the pre-anneal stretch increases.
4.3 Effect of Coiling Stress on Creep

In this section the effect of coiling tensile stress on modulus, viscoelastic response and creep are investigated.

In order to investigate the effect of coiling tensile stress, actuators are made from an original fiber length of 250 mm and they are coiled while undergo various tensile stresses. They have been annealed with a similar pre-anneal stretch of 78%. Also, the length of the actuator under test is 10 mm. The following table shows the values of model elements presented in figure 34. It is essential to know that in this experiment the creep response of the actuator is recorded while the actuators were undergoing
tensile stress of 48 MPa. The values presented in table 9 have confidence level of 10% since they are average of 3 different tests.

<table>
<thead>
<tr>
<th>Coiling stress (MPa)</th>
<th>( \mu_1 ) (TPa)</th>
<th>( E_1 ) (MPa)</th>
<th>( \mu_2 ) (TPa)</th>
<th>( E_1 ) (MPa)</th>
<th>Equation from proposed model: ( \varepsilon(t) ) %</th>
</tr>
</thead>
<tbody>
<tr>
<td>23.59</td>
<td>0.044</td>
<td>250.65</td>
<td>0.89</td>
<td>56.31</td>
<td>(-0.192e^{-0.0057t} + 48.2\left(\frac{1}{56.31} + \frac{t}{0.89\times10^6}\right))</td>
</tr>
<tr>
<td>29.48</td>
<td>0.089</td>
<td>420.22</td>
<td>1.4</td>
<td>62.88</td>
<td>(-0.114e^{-0.0047t} + 48.2\left(\frac{1}{62.88} + \frac{t}{1.4\times10^6}\right))</td>
</tr>
<tr>
<td>35.38</td>
<td>0.088</td>
<td>435.01</td>
<td>1.34</td>
<td>65.17</td>
<td>(-0.111e^{-0.0049t} + 48.2\left(\frac{1}{65.17} + \frac{t}{1.34\times10^6}\right))</td>
</tr>
<tr>
<td>41.28</td>
<td>0.097</td>
<td>461.24</td>
<td>1.5</td>
<td>76.07</td>
<td>(-0.105e^{-0.0047t} + 48.2\left(\frac{1}{76.07} + \frac{t}{1.5\times10^6}\right))</td>
</tr>
<tr>
<td>47.2</td>
<td>0.133</td>
<td>625.24</td>
<td>1.88</td>
<td>95.73</td>
<td>(-0.077e^{-0.0046t} + 48.2\left(\frac{1}{95.73} + \frac{t}{1.88\times10^6}\right))</td>
</tr>
<tr>
<td>53.07</td>
<td>0.059</td>
<td>343.3</td>
<td>1.21</td>
<td>47.11</td>
<td>(-0.14e^{-0.0058t} + 48.2\left(\frac{1}{47.11} + \frac{t}{1.21\times10^6}\right))</td>
</tr>
<tr>
<td>58.97</td>
<td>0.091</td>
<td>496.6</td>
<td>1.56</td>
<td>68.21</td>
<td>(-0.097e^{-0.0055t} + 48.2\left(\frac{1}{68.21} + \frac{t}{1.56\times10^6}\right))</td>
</tr>
</tbody>
</table>

*Table 9: different elements and strain equations for actuators coiled under different tensile stresses.*

Figure 40 shows the creep response of actuators for which their mathematical model is shown in table 9.
Looking at figures 40 and 41, it is obvious that the viscoelasticity and damper both increase and creep reduces as the coiling tensile stress increases. However, the changes in viscoelasticity, damper and creep will not follow the predicted pattern when the actuator is coiled with a tensile stress greater than the experimental (relaxation test) tensile stress. A lower stress than the coiling stress would not pull the actuator to the extent needed to eliminate the creep, according to the predicted model. Therefore, when we are applying a lower force, the creep analysis would not be accurate and we would not be able to predict and calculate the creep elements. In order to relieve the tension and analyze the creep that exists in the actuators we need to pull them with a higher stress than the stress they have experienced during the preparation time.
Figure 41: Different elements of creep as the coiling tensile stress increases. (I) Shows the changes in elasticity. (II) Shows the changes in damper elements.
The rate equations for the actuators are shown in table 10.

<table>
<thead>
<tr>
<th>Coiling stress (MPa)</th>
<th>Strain rate equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>23.59</td>
<td>$0.00109e^{-5.843\times 10^{-3}t} + \frac{48.2}{0.89\times 10^6}$</td>
</tr>
<tr>
<td>29.48</td>
<td>$0.000536e^{-4.7\times 10^{-3}t} + \frac{48.2}{1.4\times 10^6}$</td>
</tr>
<tr>
<td>35.3</td>
<td>$0.000544e^{-4.9\times 10^{-3}t} + \frac{48.2}{1.34\times 10^6}$</td>
</tr>
<tr>
<td>41.28</td>
<td>$0.000493e^{-4.7\times 10^{-3}t} + \frac{48.2}{1.5\times 10^6}$</td>
</tr>
<tr>
<td>47.2</td>
<td>$0.000354e^{-4.6\times 10^{-3}t} + \frac{48.2}{1.88\times 10^6}$</td>
</tr>
<tr>
<td>53.07</td>
<td>$0.000812e^{-5.8\times 10^{-3}t} + \frac{48.2}{1.21\times 10^6}$</td>
</tr>
<tr>
<td>58.97</td>
<td>$0.000533e^{-5.5\times 10^{-3}t} + \frac{48.2}{1.56\times 10^6}$</td>
</tr>
</tbody>
</table>

*Table 10: Strain rate equations for actuators coiled with various coiling tensile stresses.*

Figure 42 shows how the rate of strain change is affected by the coiling stress.
Figure 42: Strain rate changes of actuators affected by coiling tensile stress.
5. Modeling of Actuator Behavior Under Isotonic and Isometric Conditions

In the previous sections I have discussed the production requirements for making the actuators and the model for creep of the actuators while they go under passive creep test. In this section I will be looking at the behavior of the actuators while they undergo active deformation. Predicting the actuators behavior while they are being activated is very important for making a control system to run the actuators.

In order to model the actuator behavior, the actuators need to be tested while they undergo isotonic and isometric experiments. Additionally, it is found that shape memory will affect actuator output. Heat shrink is a common example of a shape memory polymer, in which a tube, when heated, returns to its unloaded dimensions. Shape memory is also an innate characteristic of nylon actuators, which will be affected as both the tensile stress that actuators are undergoing and temperature change. Therefore, the isotonic and isometric modeling in this section have considered changes in the tensile stress occurring during temperature cycling.

As discussed in the previous section the behavior of the actuators follows the model shown in figure 43.

![Figure 43: Viscoelastic model for the actuation of nylon actuators.](image-url)
Table 9 provides the values for the elements of the model for actuators coiled under various tensile stresses, based on the measurements at the room temperature and fitting described in Chapter 4 at room temperature. In figure 43 the value for $\mu_2$ element is 15 to 20 times bigger than $\mu_1$ element. This difference between $\mu_1$ and $\mu_2$ affects the appearance time for the short-term and long-term creep. The short-term creep ($\frac{\mu_1}{E_1}$) is a lot smaller than long-term creep ($\frac{\mu_2}{E_2}$) since $\frac{\mu_1}{E_1} = 210 \, (s)$ and $\frac{\mu_2}{E_2} = 17400 \, (s)$, so the effect of the long-term creep will appear in the observed response a lot later after the effect of the short-term creep is observed. As the result, for actuation shorter than 17000 to 18000 (s) the equation 11-1 describing the passive strain (non-temperature driven room temperature) in response to a step-in load of magnitude, $\sigma$, can be reduced to equation 12:

$$\varepsilon(t) = -\frac{\sigma_0}{E_1} e^{\frac{-t}{\tau_1}} + \sigma_0 \left(\frac{1}{E_2}\right).$$

Eq.12

Also, the model can be simplified to graph shown in figure 44.

![Figure 44: Simplified Viscoelastic model for the actuation of nylon actuators.](image)

During heating the nylon actuators contract in length by an amount that is nearly independent of load [1]. However, on the first heating cycle after load is changed, the behavior is different. And the very first cycle of actuation, performed after annealing, also does not produce a constant amplitude contraction. Figure 45 shows the actuator
response after the initial heating. In this response, the load is first applied in the cold state. Clearly there is a step-in strain, followed by a viscoelastic response, which mostly slows down after about 200 s. This step and creep is similar to the response expected from the model in Figure 44. Then after about 920 s, the actuator is heated. In this first step, instead of contracting, the actuator extends. Upon cooling to room temperature, the actuator extends further still.

![Figure 45: Actuator response during first cycle of heating.](image)

The response shown in figure 45 is the result of changes in the tensile stress. During the annealing process the actuator experiences a high tensile stress in the range of 25-30 MPa initially, which drops to zero when annealing is complete. During the actuation time I have increased the tensile stress to 48 MPa. Therefore, during the
heating process and as the result of the increasing tensile stress the actuator length will increase instead of decreasing. This extension is the result of the softening of the actuation upon heating. Part of this extension will be counteracted by the active contraction, but in this case, the softening of the actuator dominates the response. When the actuator is cooled again (at the same load), the extension is frozen in, just as it is in heat shrink in the as purchased form. Upon cooling, there is a significant increase in length, this time due to the active thermal expansion (described by the $\alpha$ times change in temperature term in the model of Figure 44). We now add this shape memory effect to describe the response of the coiled actuator, which is shown in figure 46.

*Figure 46:* Simplified Viscoelastic model with $E_H$ and $S_H$ elements to account for shape memory effect.

In the model shown in figure 46, $E_H$ is the additional elasticity that is observed at high temperatures. $S_H$ acts like a switch that is closed at low temperatures, so the effect of $E_H$ will not be observed at low temperatures and it does not affect low temperature creep. At high temperatures $S_H$ opens, so $E_H$ can be freely stretched or compressed. It is important to mention that $S_H$ opens at high temperatures, and is otherwise closed.

In order to predict the behavior of the model shown in figure 46, the actuator is tested under isotonic and isometric conditions. The level of force or length is then
changed in each of these experiments, and a model is introduced that aims to predict the effect of this change.

5.1 Isotonic Modeling

For the isotonic test the tensile stress for the actuator is fixed. During the test, a similar amount of electric power is applied to the actuator each time it is heated, so with a close approximation the temperature at the hot states will be identical. Also, it is important to mention the actuator was heated for one cycle prior, so the creep would not affect the model. Figure 47 shows different stages of the isotonic experiment.

![Figure 47: Active actuation model under isotonic condition.](image)

The first step shows the actuator at resting state while it is under tensile stress of $F_0$. At the second step the tensile stress pulling the actuator increases from $F_0$ to $F_1$ and
the actuator length increases from the original state to the stretched state. The second step is preformed when the actuator is at ambient temperature. As the result of the increase in the applied tensile stress the actuator stretches by $X_s$, which can be calculated using Equation 13. The change in the actuator is assumed to be the sum of the immediate elastic response, plus any short time constant creep (as described by the parallel spring damper system $\frac{\mu_1}{E_1}$ in figure 43). The resulting strain, with $E_{eq}$ assumed to be the series equivalent of $E_2$, and $E_1$ in figure 46, is:

$$\frac{(F_1-F_0)}{E_{eq}}$$

Eq. 13-1

$$\frac{1}{E_{eq}} = \frac{1}{E_1} + \frac{1}{E_2} \Rightarrow E_{eq} = \frac{E_1E_2}{E_1+E_2}$$

Eq. 13-2

The third step shows the actuator being actuated under constant load, $F_1$. As the result of heating, the switch $S_H$ opens and, and $E_H$ will be expanded. This corresponds to the time constant associated with this shape memory element going from extremely long at ambient temperature, to extremely short at high temperature. In addition, the $\alpha \Delta T$ component will affect the actuator response, and the actuator will try to shrink. The superposition of these two effects results in actuator shrinking to the amount by $X_{H1}$ which is calculated in equation 14 to be:

$$X_{H1} = X_{E_H} - \alpha \Delta T$$

with,

$$X_{E_H} = \frac{(F_1-F_0)}{E_H}$$

Eq. 14-1

Eq. 14-2

Here it is assumed that the actuator was exposed to the high temperature when under load $F_0$, such that it is this load and stretch state that is ‘remembered’. In general, $F_0$ is the last load that the actuator experience when at high temperature.
In the 4th step the electric power is turned off, so the actuator cools down. As can be seen in this step, the length of actuator increases beyond its length in step 2. In this step, there thermal expansion upon cooling, given by $\alpha \Delta T$, determines the response. The actuator stretches further. As previously mentioned, $S_H$ closes as the temperature drops so $E_H$ will be locked in the stretched position. The actuator stiffness will be increased by dropping to low temperature.

In the 5th stage the actuator is heated again. In this stage $E_H$ does not affect the response anymore, since $E_H$ is already stretched to the maximum by $F_1$. Therefore, the only element that affects the actuator is $\alpha \Delta T$. At this stage, the actuator shrinks by $X_H$ and by removing the heat source it expands by $X_L$. Equation 15 show the equation for $X_H$ and $X_L$.

$$X_L = X_H = X_a = \alpha \Delta T,$$

Eq. 15

where the magnitudes are the same, but the signs are opposite since the temperature change is equal and opposite. In the case where the load is increased ($F_1 > F_0$), $X_H$ is larger than $X_{H1}$ since it is not being reduced by $X_{E_H}$. After step 5 the length of the actuator will keep changing at a constant amplitude from the cold to the hot state, as long the input power and the tensile stress stay constant. Equation 16 represents the amount of the length change:

$$X_{H2} = X_{H3} = X_{H4} = \cdots = X_{H_l} = X_a.$$

Eq. 16

$X_a$ is dependent on temperature and thermal expansion coefficient and it can be measured experimentally.

The key prediction of the model is that there is a change in overall length of the actuator every time it is exposed to the high temperature state and there has been a
change in load since the last time it reached the high temperature state. This change in length is given by:

\[ X_{E_H} = \frac{F_1 - F_0}{E_H}. \]

Eq. 17

This change is in addition to any reversible dimension change due to thermal expansion.

5.2 Experimental Confirmation of the Proposed Isotonic Model

In this experiment, the actuator was prepared while undergoing coiling tensile stress of 47.17 MPa and with pre-anneal stretch of 38%. The annealing temperature was 180°C. As shown in table 7, the actuator prepared with the above conditions has the properties at room temperature that are constants presented in table 11. These values are extracted from table 7 presented in chapter 4.

| \( \mu_1 \) | 0.0453 (TPa).s |
| \( E_1 \) | 223.04 (MPa) |
| \( \mu_2 \) | 0.74 (TPa).s |
| \( E_2 \) | 39.83 (MPa) |

Table 11: Damper and elasticity constant for actuator coiled under tensile stress of 47.17 MPa, with annealing stretch 37.7% and annealing temperature of 180°C.

In figure 48, the response of the actuator to changing load and temperature is shown. The pre-actuation tensile load increases from \( F_0 = 0 \) to \( F_1 = 48 \) MPa in half a second. Subsequently the actuator is heated and cooled through 3 cycles under a constant load, and the displacement is recorded. It is important to mention that previous to this experiment the actuator has gone through a heating cycle under tensile stress of 48 MPa, so the effects of \( \mu_1 \) and \( \mu_2 \) are eliminated. The response of the actuator would be affected by \( \mu_1 \) and \( \mu_2 \) if the tensile stress be different form the tensile stress in
the creep eliminating stage. The length changes predicted by the isotonic model of section 5.1 are indicated by dashed lines in figure 48.

![Figure 48: Monitoring changes in the displacement during an isotonic experiment. Horizontal dashed lines show predicted states based on the shape memory model of section 5.1.](image)

The experimental results show that the shape memory model is able to describe the response of the actuator to a change in load. Each time load is changed and the high temperature state is reached, a fixed change in length results that is frozen in until load is changed and the high temperature state is again reached. Further work is needed to add viscoelastic response to this model (there is some creep that is not accounted for in the model, as evident from gradual drift above the predicted ‘hot state’ in cycles 2 and 3). Also missing is the prediction of response under isometric conditions, and in fact
arbitrary conditions. Finally, and most difficult, is modeling for any temperature profile. The shape memory effect is expected to be a function of temperature and load history – with this modeling requiring significantly more sophistication. Nevertheless, this initial success with isotonic loading brings, for the first time, a method of understanding and modeling the material response that will be critical in predicted and controlling actuator response under changing loads.
6. Conclusion and Future Work

In this study, I studied the effects of annealing and pre-stretch on the performance of coiled actuators made from commercially available multifilament silver-coated nylon. The objective is to generate findings that benefit real world applications. In conclusion, I was able to achieve the highest generated force with minimum number actuators tearing when I coiled my actuators under a tension of 47 MPa (200 g weight) and applied a pre-anneal stretch of 60% on them.

In addition to exploring the factors involved in manufacturing and activating the actuators, creep of the actuators was investigated and a mathematical model is suggested. The model describes the passive response of the actuators to loading conditions applied at ambient temperature. The passive response is described by a spring, representing the elastic behavior, in series with a dashpot, describing creep, and a parallel spring/dashpot, describing the visco-elastic response. Experiments were performed at stresses of up to 48 MPa, normalized to the untwisted yarn cross-sectional area. The model shows that the creep is slow, and need not be considered except over timescales in excess of 20000 s. The viscoelastic response is significant, and has a time constant of 17000 s at room temperature. These results are useful since, in order to use the actuators in applications, we need to be able to predict the behavior and reaction of the actuators. Creep is an innate characteristic of the actuators and is a major effector on the behavior of the artificial muscle. Therefore, creep modeling is extremely important for designing a control system for using the actuators and the model that is presented in this work could be used for this purpose. In addition to creep, the behavior of actuators in isotonic and isometric conditions is important for designing control systems.
Coiled nylon actuators are known to generate active displacements that are nearly independent of load. This effect is modeled using a thermal expansion term. However, when load is changed, there is a one-time lengthening (on increasing load) or shortening (on reducing load) of the actuator following the first heating cycle. Here we describe this change with load by invoking a shape memory mechanism. A softening of the material is assumed to occur at high temperatures, with this softening represented by a spring. The spring length is locked in at low temperatures using a latch that sits in parallel. The length of this spring then depends on the load it experienced during the last high temperature cycle. This model is shown to describe the response of the actuator under a change in load. The model for isotonic and isometric conditions is discussed in section 5.

In order to construct a control system, factors in the behavior of the actuators such as creep recovery, relaxation time, rise time and the effect of temperature changes on the creep and on output response need to be further investigated. In future work, the proposed spring-viscoelastic-creep-shape memory-thermal expansion model will be applied to enable control. The changes in properties with temperature need to be followed as the actuator goes back and forth between hot and cold states at different actuation tensile stresses, and with varying temperature profiles. A primary system for managing the performance of the actuators and subsequently the application that use these actuators can be constructed, by using the findings of this work. Some of the applications that can benefit from active fabrics and applications that use the actuators for their lifting capabilities.
Bibliography


[15]. Yoshioka, Y., Tashiro, K., & Ramesh, C. (2003). Structural change in the brill transition of nylon m/ n (2) conformational disordering as viewed from the temperature-dependent infrared spectral measurements. Polymer, 44(20), 6407-6417. doi:10.1016/S0032-3861(03)00593-7

