

## BISPHENOL-A BASED SHAPE MEMORY POLYMER FOR SOFT ROBOTIC GRIPPER APPLICATIONS

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**ABSTRACT:** Shape Memory Polymers (SMPs) are considered smart materials due to the continuous development of their applications in space, aerospace, construction, and biomedical fields. SMPs can be fabricated like other polymers, taking different complex shapes and having the ability to program them into another shape. This ability has made them ideal candidates, especially in soft robotics. This research develops a soft robotic gripper using an actuator made with epoxy-based SMP that can be fully activated using heat at 135.7°C. The SMP for the gripper mechanism was designed using Bisphenol-A based epoxy and m-Xylylenediamine. It was observed that the SMP gripping mechanism could apply a maximum force of 5 N to grip a spherical object adequately. These SMP actuators can be further enhanced to develop soft robotic devices that facilitate a wider range of engineering and biomedical applications such as invasive medical surgeries, nano-electromechanical systems (NEMS) and micro-electromechanical systems (MEMS) manufacturing.

*Keywords:* force sensitive resistor, shape memory polymer, soft robotic actuator, thermomechanical characteristics

### 1. INTRODUCTION

Shape memory polymers (SMPs) are a class of active, deformable material that can switch between a temporary shape, which can be freely designed, and the original shape (Mu et al., 2018). SMPs can be categorized as smart material due to their capability of deforming and holding a temporary shape and recovering to the original shape in response to external stimuli, such as temperature, light and magnetism (Jeevantha et al., 2022). This property can be applied to many potential and promising engineering applications in a wide range, including structural, biomedical, space and aerospace engineering. For example, light-activated SMP can be used in specific areas of the applications mentioned above since they can be activated remotely by sending light through optical fibres (Herath, et al., 2020).

The term Soft Robotics has come to light with the recent developments of smart materials. The word Soft Robotics is recently defined as “continuum robots made of soft materials that undergo continuous elastic deformation and produce motion through the generation of a smooth backbone curve” (Laschi et al., 2016). Most of the soft robotic designs are inspired by nature. The traditional actuators usually comprise large and complex structures to achieve their desired movements. This limits their use in smaller-scale applications (Shen et al., 2016). SMPs are a promising solution to break these limitations. Furthermore, imitating complex human body parts such as muscles and joints of hand movements needs to be developed by overcoming the boundaries remaining in conventional robotic technologies (Herath, et al., 2018).

The aim of this study is to manufacture a Bisphenol-A Epoxy based SMP to develop a soft actuator gripper. The actuator was designed to mimic the behaviour of a human finger. The human finger consists of three major joints: metacarpophalangeal (MCP) joint, proximal interphalangeal (PIP) joint and distal interphalangeal (DIP) joint (Yang et al., 2016) This research is focused on the behaviour of the DIP joint, which is simply the topmost joint of the index finger. Its significance is

the usage of lightweight material and a simpler design without moving parts. The proposed design consists of simpler and more improvable SMP material that can be further developed.

## 2. MATERIALS AND METHODS

### 2.1 Synthesis of SMP and Fabrication of the Finger

A precise mixture of materials was used to synthesise the epoxy-based SMP. The ratio of epoxy resin to hardener was 5:1. Bisphenol-A diglycidyl ether (BADGE) and m-Xylylenediamine (m-XDA) were used as the epoxy resin and the hardener, respectively. These materials were supplied by Sigma Aldrich Australia.

The dual curing method, which includes a post-curing cycle, proposed by (Dlugaj et al., 2024) was employed to speed up the curing process and minimise energy usage. The curing cycle consisted of four stages. The first stage was the degasification process to remove air bubbles in a vacuum oven at room temperature. Then, the mixture was poured into two types of moulds. One is to make flat sheets for the DMA test specimens. The SMP fingers were cast by using an Aluminium mould. The next three stages of the cycle were done in the curing oven. SMP was cured in the oven at 60°C for 2 hrs, 100°C for 3 hrs, 140°C for 1 hrs and finally at room temperature for 24 hours.

An Aluminium mould with a 10 mm thickness, 10 mm depth, and a 136° gripper angle was used to cast SMP fingers. To increase their durability, a Teflon coating was sprayed on the fingers. The SMP fingers were kept under pressure and heated until they achieved a 146° angle during the SMP programming stage.

### 2.2 Computer-aided Design of the Gripper

The CREO 6.0 commercial software package was used to design the base and actuator/ finger assembly of the gripper, as shown in Figure 1 (a). The base of the gripper assembly and the rigid fingers shown in figure 1(b) were fabricated using Polylactic Acid (PLA) via the 3D printing rapid prototyping method. Then, one of the moulded and programmed SMP fingers and two 3D-printed rigid fingers were assembled according to the 3D model of the gripper.

### 2.3 Measuring the Force Generated

Once the assembly was completed, a camera was set up to observe and video record the shape-recovering process. A plastic ball was placed in the middle of the gripper assembly. Haptic sensors (Force Sensitive Resistors, FSR) were attached to each finger before the gripping process was performed (Shaikh et al., 2015). An Arduino Uno microcontroller board was programmed for the haptic sensors to improve the force readings generated by finger movement.

### 2.4 Characterisation of SMP Material

The DMA and DSC techniques were used to observe the behaviour of the SMP material. A DMA test was performed to determine the primary glass transition temperature ( $T_g$ ) value and the influence of temperature on the storage modulus and loss modulus. The DMA test was conducted using TA Instruments, a dynamic mechanical analyser (DMA Q800). To measure the secondary  $T_g$  values of the SMP, a TA instruments DSC-25 was used. The shape recovering process was observed visually. These tests were primarily performed to gather data that can be used for the future development of the SMP finger. Furthermore, the morphology of the developed SMP was observed using Olympus DSX5000 microscope and JCM-600 Scanning Electron Microscope (SEM).

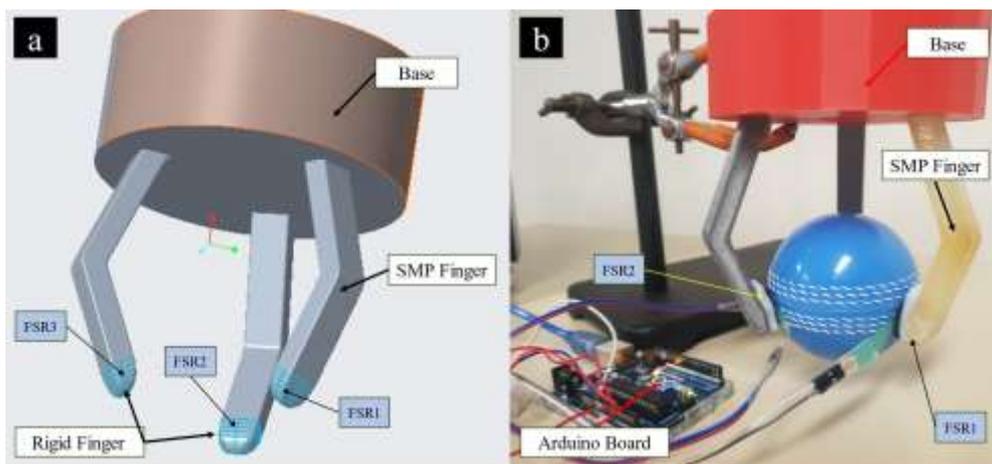


Fig. 1. (a) 3D gripper Assembly model and (b) Actual gripper assembly.

### 3. RESULTS AND DISCUSSION

#### 3.1 Properties and Morphology of SMP

At temperature exceeding the glass transition temperature ( $T_g$ ), an SMP material can be programmed into a desired shape by applying an external force. Then, the shape is then held until it is fixed, and the material is cooled down transforming it to a frozen polymer at a low temperature. Subsequently, when the temperature is raised above  $T_g$ , the shape recovers to its original shape (Jayalath et al., 2024). Therefore, measuring different  $T_g$  values using multiple methods is essential. The  $T_g$  helps determine the temperature where the SMP changes phase from glass to rubber. A DMA test was performed to observe the influence of temperature on the Viscoelastic behaviour of the SMP. The DMA graph showed storage onset temperature ( $T_s$ ) at  $120.57^\circ\text{C}$  and the peak temperature ( $T_\delta$ ) of  $\text{Tan}(\delta)$  at  $135.7^\circ\text{C}$  as shown in Fig. 2(a). The  $T_s$  temperature was considered the primary  $T_g$  value where the SMP starts recovering and losing its thermomechanical properties. The  $T_\delta$  temperature was considered the temperature for shape programming. Furthermore, secondary  $T_g$  values where the SMP change its phases were calculated using the midpoint half-height value of the DSC curve, as shown in Fig. 2(b).

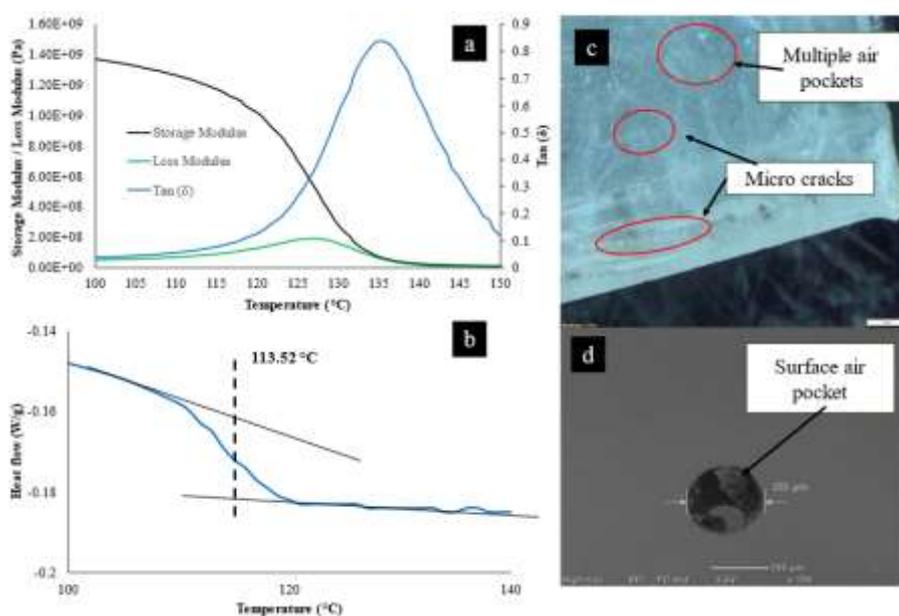


Fig. 2. Glass transition temperature evaluation using (a) DMA graph of the SMP and (b) DSC graph of the SMP. (c) Air pockets and micro-cracks in the SMP from the stereo microscope and (d) Scanning Electron Microscope (SEM).

A stereo microscopy and SEM were used to closely observe the surface structure of the SMP. It was observed that air pockets ( $\sim 255 \mu\text{m}$  wide) and micro-scale cracks in the specimen, as shown in Fig. 2(c). This can lead to poor shape memory behaviour and failure of the SMP finger during the programming stage. However, extending the vacuum degassing time can be used to avoid such morphological defects.

### 3.2 Performances of SMP Finger

The movement of the SMP fingers upon heating was observed, as shown in Fig. 3(a). After shape recovery, the Recovery factor ( $R_f$ ) was calculated by using the percentage value of the recovery angle divided by the deformed angle. As shown in Fig. 3(b), the SMP finger took 362 s to recover its original shape (from  $146^\circ$  to  $137^\circ$ ) with a  $R_f$  of 98.08%. It was observed that specimens with higher air pockets show a weak shape recovery process. The force generated on the plastic ball during the shape recovery process was recorded from the FSRs. And the data was collected to compare with future experiments. The purpose of measuring force was to control the pressure generated by the gripper on handling fragile objects. Force was measured in three different time intervals: 89 s, 142 s and 362 s. According to the force measurement from FSR1 on the SMP finger, the final stage of the recovery showed a maximum force of 5 N.

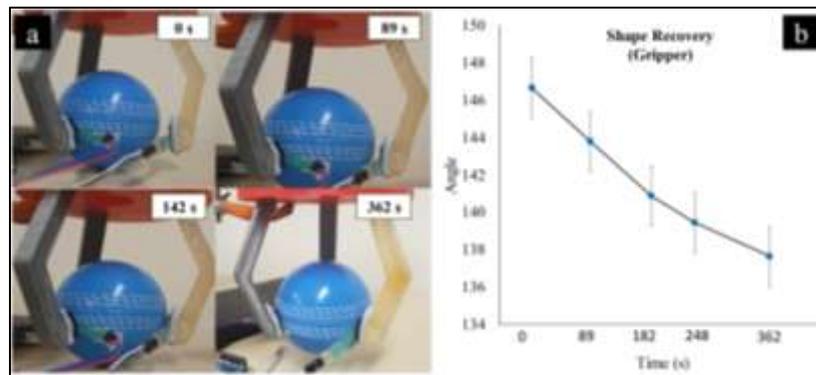


Fig. 3. (a) SMP finger recovery process in the gripper assemblies and (b) shape recovery of the SMP finger within 362 s

## 4. CONCLUSIONS

As the primary objective, designing, fabricating and operating the SMP actuator for the soft robotic gripper was accomplished. Heat simulation of the fabricated finger (actuator) was effective and has shown the potential for real-world applications. The force generated (5 N) on the objects by the finger is acceptable, and further studies are warranted to develop a force-controllable gripper. Air pockets caused microcavities and cracks in the SMP finger during the curing process. These air pockets can cause weak SMP shape memory and mechanical properties. Therefore, it is essential to minimize the air in the SMP uncured mixture by increasing vacuum degassing time.

The information gathered on the SMP soft robotic gripper can be used for further development. SMPs with faster recovery and lower activation temperatures can be an initial optimisation for the assembly. Finally, an intensive research study is needed to develop reversible or bidirectional SMPs with fast actuation time to gain a competitive advantage over electromechanical robotic grippers.

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