A Variable Stiffness Soft Robotic Gripper with Low-Melting-Point Alloy

HAO Yufei[1], WANG Tianmiao[1], FANG Xi[1], YANG Kang[2], MAO Ling[2], GUAN Juan[2], WEN Li[1]*

1. School of Mechanical Engineering and Automation, Beihang University, Beijing, 100191
E-mail: liwen@buaa.edu.cn

2. School of Materials Science and Engineering, Beihang University, Beijing, 100191

Abstract: In this paper, we present the design, fabrication and the function of a soft actuator embedded with Low-Melting-Point Alloy (LMPA). By melting the metal via joule heating, the phase of the metal transformed from the solid state to the liquid state, by which the stiffness of the actuator changed over nearly one order of magnitude. Through a reheating- recrystallizing circle, the actuator can self-healing and recovered from the crack state. The melting speed under different electrical currents was measured. Besides, two experiments were conducted to investigate the self-healing property and stiffness enhancement of the actuator. The LMPA could be melted within 40 seconds. By using three actuators embedding with LMPA, we implemented a soft gripper with variable mechanical stiffness. Experimental results show that the actuator not only has the self-healing property but also enhance the mechanical stiffness compared to the no-LMPA actuator (control). While the LMPA was under solid (recrystallized) state, the bending stiffness of the actuator increased up to 3.5 times over that of the control; while the pull-off force of the gripper increased 6.5 times. The LMPA provide the soft robots with capacities of variable mechanical stiffness and the self-healing.

Key Words: Variable Stiffness, Low-Melting-Point Alloy, Soft Robotics

1 Introduction

Soft robotics, which has promising features such as lightweight, low-cost, easy fabrication and high compliance [1, 2], is a multi-disciplinary research area involving chemistry [3], material science [4], biology [5] and mechanics [6], etc. Soft robotic technologies have been widely used in actuation [7], sensing [8], and the nonlinear dynamics control [9]. Moreover, soft robots have been widely studied in the applications like manipulation [10], locomotion [11], the wearable device [12] and invasive surgery [13]. However, the materials, which are mostly silicon rubbers and contribute to the high compliance and dexterity of soft robots, also limit the capability of the robots in some situations that require them to have a high stiffness to exert or sustain considerable forces. For example, inherent compliance allows the soft gripper to grasp soft, fragile and irregular objects [10], but cannot afford the heavy ones. Similarly, the soft surgery manipulators can reduce patient trauma, shorten hospitalization and improve patient recovery by actively interacting with or bypassing the biological structures thanks to the multiple degrees of freedoms [14]. However, they are not rigid enough to exert adequate force on the target or withstand the weight of organs under some extreme circumstances. How to improve the load capacity of the soft robots while maintaining their adaptability is becoming an urgent problem.

Recent work on variable stiffness shows promise in overcoming the tradeoff between maintaining sufficient compliance and maximizing load capacity. Many materials with controllable stiffness have been integrated into the structures of soft robots. Under external stimuli, these materials can actively change the solid-liquid phase, density or viscosity, thus change the stiffness and enhance the load-bearing of soft robots. For example, magnetorheological (MR) or electrorheological (ER) fluids can change the viscosity of the macro-particle under the stimulus of the electric or magnetic field [15, 16]. However, their low stiffness extension and the demand for external electromagnets or high voltage capacitors limited the further development. Shape memory polymers (SMP) can change their elasticity by heating them above the glass transition temperature and were widely used in selective stiffness change and DOFs locking [17, 18], but their response speed are two slow for their poor thermal conductivity [19]. The jamming mechanism, which contains particles such as the ground coffee packed within a membrane, can achieve higher stiffness when a vacuum pressure was exerted and the particles were jammed firmly. This mechanism is also explored in soft robots for its simple mechanism and quick response [20, 21]. However, it requires tube, vacuum pump as well as valves, etc., to work. Therefore, the whole actuation system would be fairly heavy. In addition, the jamming structure cannot recover from its damaged state. Namely, it does not have self-healing property [20].

Low-Melting-Point Alloys (LMPA), which can switch to the liquid state at a relative low temperatures (42℃-70℃), are promising for soft robots compared with others. They are solid state with large mechanical stiffness at high temperatures, and are liquid state at room or lower temperature [22]. The LMPA can be melted to liquid state by the joule heating, which only require a very simple heat system. Besides, they have self-healing property accordingly to a reheating-recrystallizing process [23, 24]. Very recently, researchers started to apply the LMPA to the soft

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manipulators [25, 26], the metal-elastomer foams [23] and the fibers [27].

In this paper, we demonstrated a soft actuator embedded with LMPA for stiffness enhancement. The melting speed under different currents was tested. Then we conducted two experiments to investigate the self-healing property and stiffness enhancement of the actuator. By assembling three actuators to a base, we made a soft gripper and tested the pull-off force of the gripper when grasping a cylinder shape object.

2 Materials and Methods

2.1 The structure and fabrication of the variable stiffness soft actuator

The structure of the variable stiffness actuator contains mainly two parts: the upper extensible layer and the bottom inextensible layer which is embedded with LMPA in the inner channel (shown in Fig. 1a). The materials of both the two layers are silicon rubber (dragon skin 30, smooth-on Inc., America). Two electrodes are inserted into the LMPA to melt the material directly. The LMPA is a kind of alloy with the following composition by weight: 45% bismuth, 23% lead, 19% indium, 8% tin, and 5% cadmium. We choose this material for its low melting point which is about 47℃. When the LMPA is molten, the actuator will bend into either incurve or outcurve state by inflating or deflating the chamber in the extensible layer. For the elongation/contraction motion of the extensible layer is constrained by the inextensible layer, resulting in the bending motion. When the LMPA is solid, the stiffness of the inextensible layer will be strongly enhanced, and the load capacity of the actuator will be improved. The fabrication of the actuator was a multi-step layered molding and casting process, similar to the fabrication process in our previous paper [10]. Firstly, the extensible layer was fabricated through the molding process, and the inextensible layer with inner channel was fabricated by casting and bonding. Then the LMPA was injected into the channel using the method demonstrated in [28]. To inject the LMPA into the channel, we heated the alloy and the inextensible layer at 80 ℃ for 30 min in the heating oven, to ensure that the material was molten and silicon rubber had a high temperature to keep the alloy in the molten state during the injection process. Then two syringes were inserted into the two ends of the channel separately; one was to inject the molten metal while the other was to exhaust the air in the channel. At the final step, the extensible layer and the inextensible layer were bonded together, and the electrodes were inserted into the LMPA.

2.2 Thermal behavior test

By heating the LMPA to a temperature above 47 ℃, the phase of the material will transform from solid state to liquid state. Thus the stiffness of the actuator will change dramatically. To test the melting speed of the LMPA, we designed an experiment. For the experiment, a fixed voltage was suddenly applied to the actuator at the room temperature of 26 ℃, and the bottom surface temperature of the inextensible layer was measured via a Pt100 platinum thermistor which was stuck to the bottom surface. The temperature values were transmitted to the PC by the intelligent communication meters via the RS485 communication interface. The melting speed was measured under three currents (4A, 6A, and 8A) for this experiment.

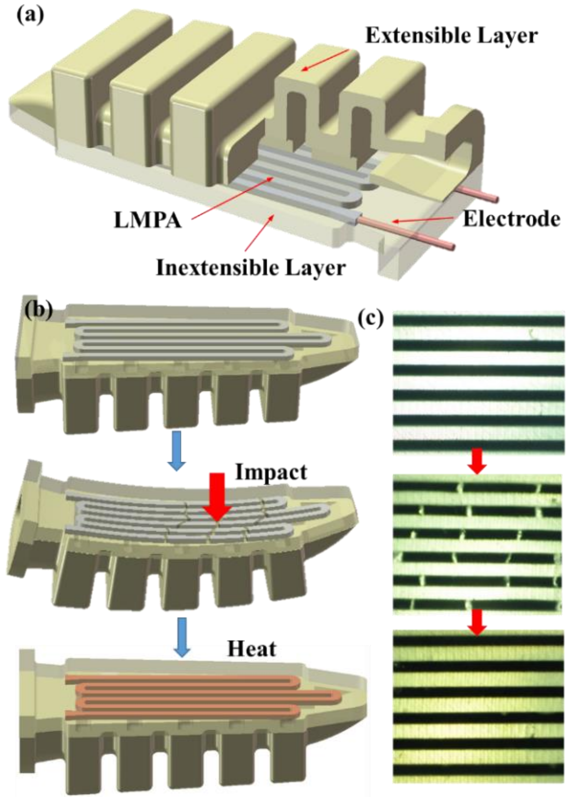

Figure 1. (a) The structure of the soft actuator embedded with LMPA. The actuator consists of two parts: the top extensible layer and the bottom inextensible layer. LMPA, which is heated by the electrode, is injected into the channel of the inextensible layer. The section size of the channel is 1.4 mm X 1.4 mm. (b) The self-healing property of the soft actuator. When the actuator sustains huge impact, the LMPA will break into pieces. However, it will recover by heating the actuator at the temperature of 60 ℃ for 2 min and 30 sec. (c) The photographs showing the self-healing process of the actuator.

2.3 Experimental setup for the self-healing property test

Because the molten alloy can recrystallize itself after melted, it is possible to self-heal the cracks. As Fig. 1b shows, the LMPA part of the actuator was broken into pieces when the actuator suffers the large impact. However, by heating it to the molten state and recrystallizing again, the actuator recovered its intact state and the mechanical properties. To test the self-healing property of the soft actuator, we fabricated three samples and tested the tensile strength of them. Because it is very difficult to clamp the whole actuator in the test platform and the self-healing property mainly exists in the inextensible layer of the actuator, the tested samples only contained the inextensible layer embedded with LMPA. For each sample, we first measured its tensile strength for the intact state (as upper panel shows in Fig. 1c), then we broke the LMPA in the sample into pieces without tearing up the silicon rubber of the cover layer (shown in the middle panel of Fig. 1c). After a melting and refreezing process, the tensile strength of the healed sample (showed in the lowest panel of Fig. 1c) was tested again. The tensile strength was tested under a universal material testing machine (exceed model E44, MTS, America). As Fig. 2a shows, the sample was fastened by the two clamps of the machine; then the upper clamp was moved upwards at the speed of 0.5 mm/s until the sample was broken. The force and the displacement values were recorded at the sample rate of 20 Hz, and the data was smoothed via a median filter with the window width of 5 samples.

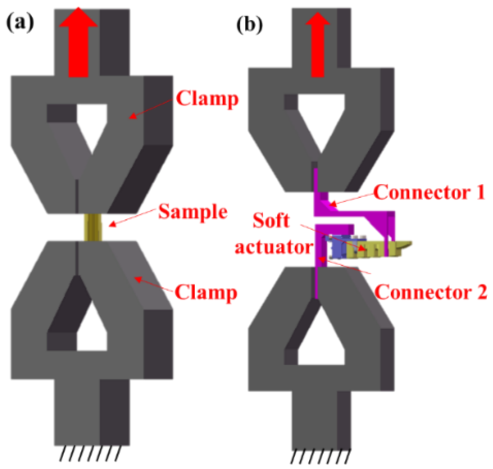

Figure 2. (a)The experiment setup for the self-healing property test of the soft actuator. For this experiment, we first test the tensile strength of the sample before fracture, then break the LMPA into pieces and test the tensile strength of the healed sample after heating. (b) The setup for the bending stiffness test. For this experiment, three samples were conducted for each state of the metal (solid state and liquid state). For each test, we fixed the sample to the connectors and fastened the connectors to the clamps of the machine. Both of the experiments were conducted using the universal material testing machine (exceed model E44, MTS, America).

2.4 Experimental setup for characterizing the bending stiffness of the actuator and load capacity of the gripper

The bending stiffness of the actuator is a significant criterion to determine the load capacity of the actuator. To test the enhancement for bending stiffness of the actuator when embedded with LMPA, we conducted a comparison experiment to test the bending stiffness of the actuator when the LMPA was in solid state and liquid state separately. In this study, the bending stiffness was defined as

$$k=\frac{\partial F}{\partial x} , \tag{1}$$

where F is the force applied to the actuator and x is the deflection resulted by F. Fig. 2b shows the experimental platform. The actuator was fixed to connector2, which was fastened to the lower clamp of the universal material testing machine. One end of the connector1 was fixed to the upper clamp, while the other end was contacted to the actuator at a distance of 30 mm from the base of the actuator. During the test, connector1 was dragged upwards by the upper clamp at a speed of 1mm/s, causing the actuator to bend upward. The force and the displacement along the moving direction were transmitted to the computer at the sample rate of 20 Hz and were smoothed the same way as the self-healing experiment. For this experiment, we tested three samples for each state of the LMPA (liquid state and solid state).

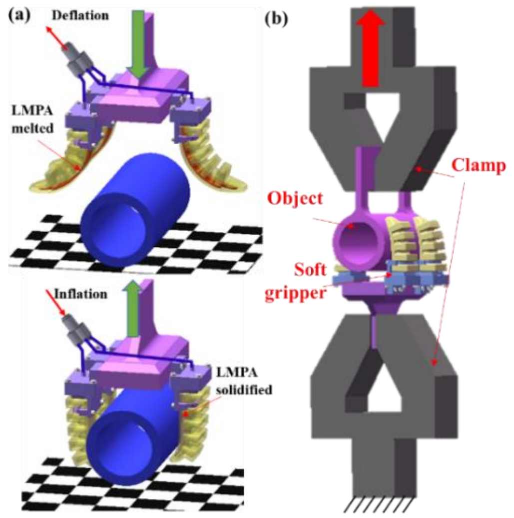

Figure 3. (a)The gripping strategy of the soft gripper. After heating the LMPA to the molten state, deflate the soft gripper and approach the object. When grasped, inflate the soft gripper and wait for the LMPA to recrystallize, then lift the object. (b) The experiment setup for pull-off force test of the soft grippers when the LMPA in solid state and liquid state. The experiment process was similar to those of the actuator. For the gripper works in the solid state, we first melted the alloy, then inflate the soft gripper to grasp the object. After about 3 minutes, the alloy was entirely refrozen, and the object was pulled upwards.

By applying three variable stiffness actuators to a base, we fabricated a soft gripper with variable stiffness and proposed a grasping approach for gripping objects (as Fig. 3a shows): first, melt the LMPA and deflate the actuators to open the grasping space and approach the object. Then inflate the actuators to contact and conform the object. Finally lift the object after the metal was recrystallized, which will take about two and a half minutes. We hypothesize that the load capacity of the variable stiffness gripper will be improved significantly if the metal is in the solid state. To test the load capacity of the gripper, we conducted an experiment to compare the pull-off forces of the gripper when the LMPA was in solid state and liquid state. Three trials were conducted for each of the states. As Fig. 3b shows, the gripper was fixed to the lower clamp of the universal material testing machine, while the object with a cylinder shape was fastened to the upper clamp. For the soft gripper with metal in liquid state, we first reset the force, and the displacement values of the machine then inflated the gripper with a constant pressure of 20 kPa. After that, the object was moved upward at the speed of 1 mm/s. The force date was recorded at the sample rate of 20Hz. After smoothing the data through the same filter mentioned above, the maximum force obtained was regarded as the pull-off force of the gripper. For the gripper works when the metal is in the solid state after the force and displacement were reset, the metal was melted before the chamber was inflated to grasp the object. Then the chamber was inflated to grasp the object. Finally, the object was pulled upwards after 3 minutes to ensure the metal was refrozen.

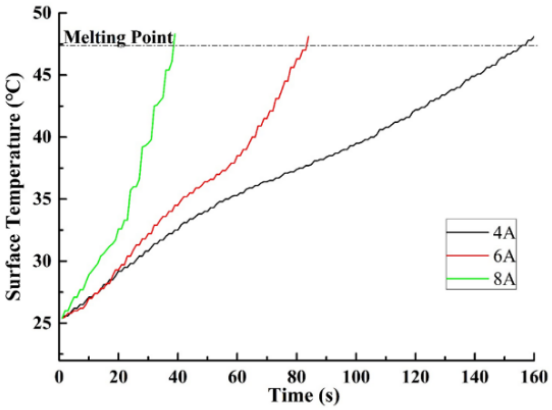

Figure 4. The results of the melting time with the relation of the electric current. Because it is very difficult to measure the inner temperature of the LMPA, we measured the surface temperature at the bottom of the actuator. As the figure shows, with the increase of the current, the melting time decreases drastically.

3 Results and Discussion

3.1 Thermal and self-healing properties of the actuator

Fig. 4 shows the melting speed of the LMPA with the relation of applied currents. It should be noted that the real melting times is shorter than those measured, for the temperature was measured at the bottom surface of the actuator. As the results show, with the increase of the current, the melting speed increases dramatically. When the current was 4A, it took about 160 seconds to heat the metal from 26 ℃ to 48 ℃. Increasing the current to 8A, the melting time from 26 ℃ to 48 ℃ diminished to 37 seconds, about a quarter of the time for 4A. The higher the current, the faster the melting speed. However, higher current needs more powerful power supply and safer heater circuit, which may result in other unexpected problems. According to the first law of thermodynamics, the energy needed to melt the metal for a given structure could be estimated as

$$P\cdot t = m\cdot c\cdot \Delta T + m\cdot L, \quad (2)$$

where P is the power of the heater, m is the mass of the metal, c is the specific heat capacity, ΔT is the temperature difference between the room temperature and the melting point and L is the latent heat of the metal. If we melt the metal by direct joule heating, the P could be written as

$$P = R\cdot i^2 , \quad (3)$$

where R is the resistance of the metal while i is the current. According to Eq. (2) and Eq. (3), we can see that the melting speed is not only related to the current but also related to the structure of the metal. For the structures with the same mass of the metal, the energy needed to melt the metal is the same. However, if the structure has a smaller sectional area, for example, the width of the channel to embed the metal reduces by half, the area will reduce by half, and the length of the channel will elongate two times. Consequently, the resistance of the metal will increase by four times and the melting time will be reduced to a quarter theoretically. However, the strength and the stiffness of the structure will be affected. For the actual application, we must balance the melting speed and the structure design of the LMPA. It should be better that the metal has a small sectional area together with a multilayer structure to accelerate the melting speed without diminishing the strength too much. Fig. 5 shows that there is no significant difference between the tensile strength of the pre-fractured sample and the fractured sample after a reheating-refreezing circle, which means that the actuator has a great self-healing property. And the mechanical properties of the actuator in the solid state will be restored too. This merit is impossible for the jamming stiffness enhancement [20], by which the structure will be damaged permanently under huge impact.

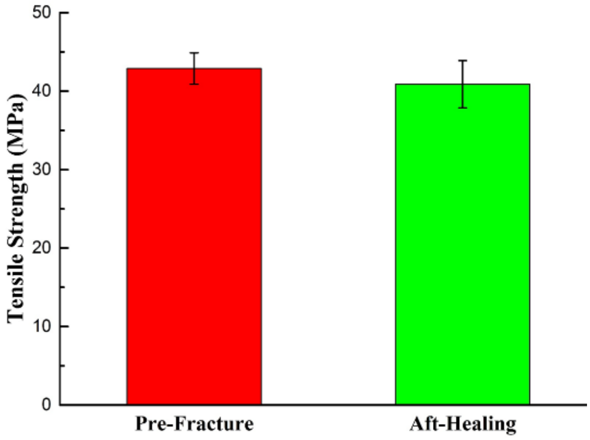

Figure 5. The results of the self-healing experiment. As the figure shows, the tensile strengths of the samples under pre-fracture and aft-healing state are similar, which means the broken soft actuator can maintain the mechanical property after self-healing.

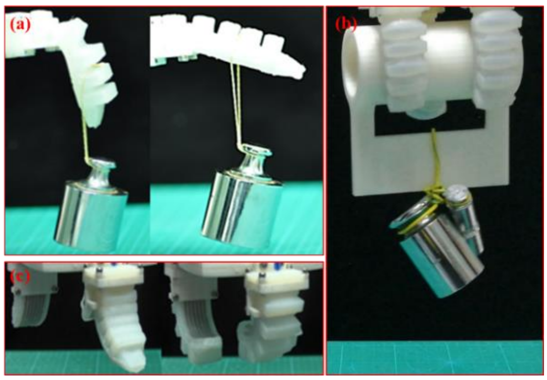

Figure 6. (a) When the LMPA was molten, the actuator would directly bend into 90° when a 200 g weight was added to it (left). When the LMPA was in the solid state, the actuator can sustain the weight with a small deflection (right). (b) With stiffness enhancement, the gripper can easily grasp the object with the weight about 780 g. (c) The bidirectional motion of the soft gripper when the LMPA was molten.

3.2 Bending stiffness and load capacity

With the help of the LMPA, the bending stiffness of the actuator and the load capacity of the gripper have a significant increment. As Fig. 6a and Fig. 6b show, with the LMPA, the actuator can sustain a 200 g weight and the gripper can grasp the object weighing about 780 g, which is impossible if there is no LMPA. Besides, the metal has no influence on the motion flexibility of the gripper. As Fig. 6c shows, the gripper can easily bend towards two directions when the LMAP was molten. Fig. 7 shows the bending stiffness comparison between the two states of the metal. As Fig. 7a shows, the force has a linear relationship with the deflection distance for both of the states. However, the force of the actuator with the LMPA in the solid state is much bigger than that in the liquid state under the same deflection distance. After calculating the bending stiffness using Eq. (1), we got the results of Fig. 7b. As the results show, the bending stiffness of the actuator with the metal in the solid state is about 3.5 times of that in the liquid state. By combining the soft actuator with LMPA, the bending stiffness had a great improvement. And the load capacity of the gripper was also improved significantly, which could be validated based on the results of Fig. 8. Thanks to the LMPA, the pull-off force of the variable stiffness gripper with the metal in the solid state increased by about 6.5 times compared to that with the metal in the liquid state. These kind of effects are insurmountable by using other variable stiffness materials such as SMP [17] and jamming ground coffee [21] under the same structure volume. But the metal material also has a drawback: it is friable, so it cannot sustain very big bending forces. That is why the pull-off force increased 6.5 times, but the bending stiffness only increased 2.5 times. However, the bending stiffness is also important for the gripper, for the gripper will bend to hold the object, especially those with a rectangular shape. To improvement the bending stiffness, we shall improve the structure design of the actuator.

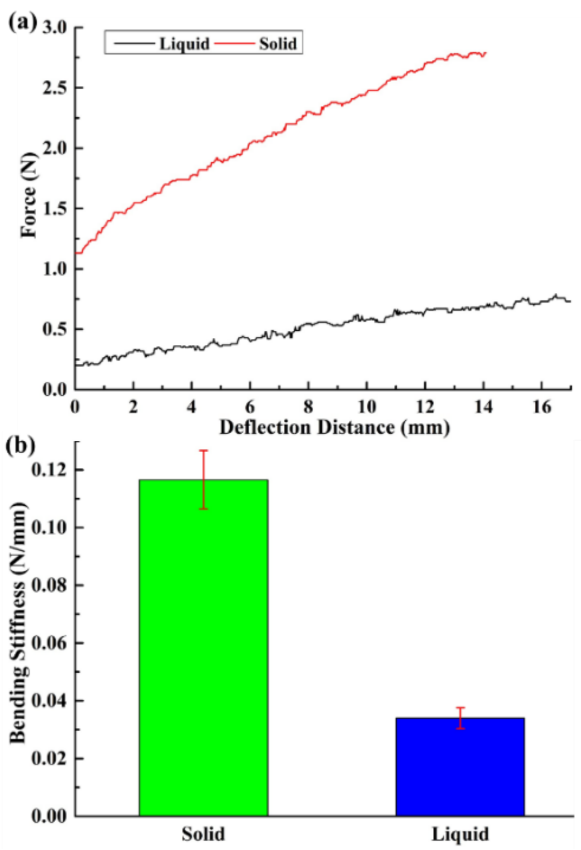

Figure 7. (a) The force as the function of the deflection distance for the bending stiffness experiment. “Solid” means the LMPA was in the solid state, while “Liquid” means the LMPA was in the liquid state. (b) The bending stiffness comparison of the actuator when the LMPA was in solid state and liquid state.

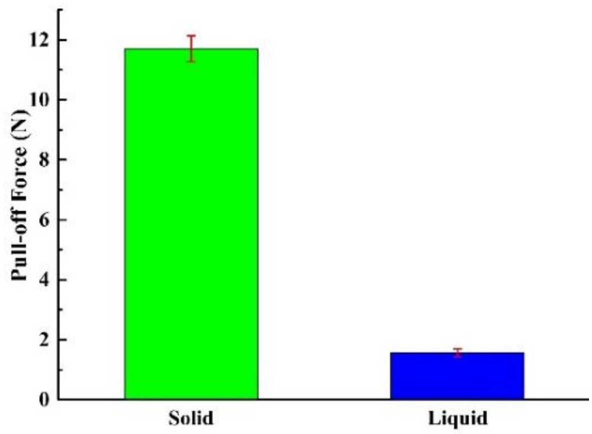

Figure 8. The pull-off force comparison of the two grippers. “Solid” means the average value when the LMPA was in the solid state while the gripper grasped the object, while “Liquid” means the average value when the LMPA was in the liquid state for gripping.

4 Conclusion

In this paper, a variable stiffness actuator embedded with Low-Melting-Point alloy was demonstrated. The thermal behavior, self-healing property and bending stiffness of the actuator were studied. By adding three actuators to a base, a variable stiffness gripper was fabricated and the load capacity was tested. The broken structure of the actuator, as well as the mechanical property of the actuator, could be cured after a reheating-refreezing circle. This self-healing property opens a new door for the soft robotic research. One can imagine that a dead soft robot under unexpected attacks will be reborn after the self –healing process. Due to the LMPA, the bending stiffness of the actuator and the load capacity of the gripper had significant improvements, which may exceed the threshold of soft robots. The combination of soft robots and LMPA is a great option to overcome the drawback of the soft robots, such as the light load capacity, poor stiffness for some strength needed situations.

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