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Thermally Powered Soft Gripper Covered with Silver-Coated Nylon Fabric Heater Reinforced with Stainless Steel Yarn

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Soft grippers, generating movement immediately, are generally based on flexible materials actuated by air pressure and comprised of bulky parts, including valves, compressors/pumps, motors, and tubes. In this work, a compact soft gripper with the ability to actuate with a low boiling point liquid (acetone) is presented. SolidWorks 2021 software and 3D printing technology are used to design and manufacture the gripper molds, respectively. The constitutive material of the soft gripper body is highly flexible Ecoflex. A silver-coated nylon fabric (SCNF) heater reinforced with stainless steel yarn (SSY) covering the external surface of the gripper is designed and manufactured using Autocad 2021 and a laser cutting machine, respectively. The idea is inspired by floating the gripper in warm water to provide smooth heat over a large surface area. The available commercial software Abaqus2021 is used to simulate the mechanical deformation of the gripper, and its results are verified with experimental results. The parameter's effect including the voltage and low boiling liquid volume on achievable force and actuating time are investigated. The relation between the electrical, thermal, and mechanical properties of the presented gripper is discussed in detail.

1. Introduction

Pneumatically powered soft actuators (PPSA),[1] for example, silicone-based actuators, worked by pressurized voids,[2–4] are broadly implemented because of their easy and fast actuation, simple operation, and scalable execution. They commonly require thick walls due to their high flexibility, which leads to big unpressurized volumes and restricts their design to small scales, as the bigger structures tend to destroy under their weights.[5] PPSAs can interact safely with brittle objects, move on rough terrain comprising surroundings uncertainty, and appropriately adapt to intricate bodies by having their inherent flexibility.[6] These specifications have enabled them to provide elegant sea creature examples for investigation, help disabled people reach and grasp,[7] and have illustrated usefulness as remote inspection and exploration apparatuses,[8,9] all while implementing relatively easy control methodology and, for some cases, the lack of active feedback mechanisms. These methodologies depend on a portion of control done by their materials. In particular, naturally, soft matter, as well as metamaterials[10–12] can create essential actuation pressure/force that could passively endure both surrounding uncertainty and task-specific.[13,14] These adapt inactively to complicated situations because of their intrinsic compliance, enabling them to interact safely with irregular and fragile things and pass rough terrain.[10,15]

In all previous works, the driving force is the air pressure compressed by the compressor, but in this article, the driving force is the steam pressure created by the boiling of the low boiling point liquid (acetone). Thermally powered soft fluidic actuators (TPSFA) can supply physical force and pressure using the low boiling point liquids easy state transition ability from liquid to gas and vice versa. These low boiling point liquids can be chosen for their boiling point for the application for lesser power consumption and faster response capabilities. For instance, for an actuator used for a wearable device, liquids with boiling points slightly higher than human skin temperature, such as diethyl ether are needed to actuate easily with small amounts of heat applied. If the system must work at room temperature without any hotter object contact, liquids with boiling points between the

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room temperature and human skin temperature are better. Miriyev et al.[16] used ethanol inside silicone pores to create soft artificial muscles. As a different example, Garrad et al. used Novec 7000 liquid to manufacture soft robotic worms.[17] Even though there are studies on TPSFA's in small dimensions with single force direction, soft grippers may also be produced. The capability to manufacture fluid pressure within a soft gripper, and implement a low-cost thermofluidic system based on liquid-vapor phase transition might be implemented to remove the requirement for bulky compressors and motors in conventional fluidic gripping systems.[18–20] By straightly triggering the phase transition using low-voltage tools like gripping systems can be manufactured very portable. However, this technology is still in the preliminary stage, surely, its parameters have not been optimized yet to reach the best actuating performance. Some works used an external thermal for phase transition, which does not work when implementing a straight electric source and is often restricted to small deformation of soft gripper.[21,22] Though there are few studies on electrically driven thermofluidic grippers, they are restricted to tiny membrane enlargements or gradual replying artificial muscle with tiny deformation because of inefficient planar heating systems.[16,23,24]

Finding a significant relationship between parameters related to electrical properties (including electric current, resistance, and voltage), thermal properties (including temperature, heat, specific heat, and melting point), and mechanical properties (including achievable force and deformation) will improve the performance of the actuator whose driving force is the low boiling point liquid. **Table 1** shows these parameters. Relating these properties to achieve better performance has always been an attractive topic for researchers. For example, in the manufacturing process of piezo-resistive sensors, changing mechanical properties such as Poisson's ratio, Young's modulus, and structure geometry to control electrical properties such as sensitivity and gauge factor has always been a subject of interest in recent years.[25–27] To investigate the effect of the sensor structure on its sensory properties, three different auxetic structures including re-entrant,[28] constant Poisson's ratio,[29] and isotropic planar auxetic structures,[30] each of which has a different mechanical behavior, were investigated on the electrical properties of sensor like sensitivity. The results showed that by changing the geometry of the structure, its electrical properties can be controlled. In our previous work,[31] we presented an electromechanical simulation for a piezo-resistive sensor made with the core–shell idea.

Table 1. The relationship between electrical, thermal, and mechanical parameters for designing the actuator powered with low boiling point liquid.

Electrical [input]	Thermal [intermediate]	Mechanical [output]
Electric current	Temperature	Achievable forces
Electric voltage	Boiling point	Deformation
Electric resistance	Specific heat	–
–	Heat	–

In this work, the presented gripper molds were designed and manufactured with Solidworks2021 software and 3D printing technology, respectively. Then, its molding was done using Ecoflex so that the gripper has high flexibility and can work with low pressure. The driving force of this gripper, unlike the previous counterparts that used compressed air pressure by a compressor, is acetone. The boiling point of this liquid is 56 °C, which means that the liquid vaporizes by receiving a little heat and creates pressure inside the gripper. To provide heat, the conductive silver-coated nylon fabric (SCNF) reinforced with stainless steel yarn (SSY) was used as a heater covered 55.3% of the outside surface of the gripper. Here, the effect of the voltage and the amount of liquid used on the actuator's working time and achievable force were investigated. The deformation of the gripper was simulated using Abaqus2021 software and its results were verified with experimental results. The innovation of this actuator can be about its future application. It can be used in the design and construction of the human hand finger by using a liquid with a boiling point close to the temperature of the human body (3M Novec 7000 liquid). With thermoelectric devices, converting the thermal energy of the human body into electrical energy, it is possible to provide an independent energy source from the air compressor equipment. The advantage of using low temperature and high area to produce the required heat for the evaporation of the low boiling point liquid is that it prevents the creation of a high temperature that is harmful to the human body and the process of vaporization and actuation is done faster.

2. Gripper Design and Manufacturing

The construction of the presented gripper consists of three steps. These steps include the following:

2.1. Step 1: Gripper Parts Including Ecoflex, SCNF, and SSY

The Mark10 tensile tester machine was used according to the ASTM D412-06a standard to obtain the Ecoflex mechanical properties with and without the SCNF heater reinforced with SSY. **Figure 1**a shows the mechanical properties of the gripper constitutive material and the gripper bodies manufacturing method. According to Figure 1a, Ecoflex has high flexibility and tears at more than 400% strain, but the Ecoflex with the SCNF heater reinforced with SSY tears at 125% strain. It means that flexibility was reduced by about 320% due to adding the heater. To reduce the flexibility destruction, the heater was glued only around the chambers. In general, the heater covered 55.3% of the outer surface of the actuator. **Table 2** shows the low boiling point liquid (acetone) thermal properties and the SCNF and SSY electrical properties. The actuator's molds including the upper, core, and bottom were designed and manufactured using Solidworks2021 software and a 3D printing machine, respectively. Then, using Ecoflex hyper-elastic material, the parts of the gripper were molded. The upper and core molds are for making the upper part of the actuator, and the bottom mold is for the lid, which is placed on the main part and provides a closed space inside the actuator.

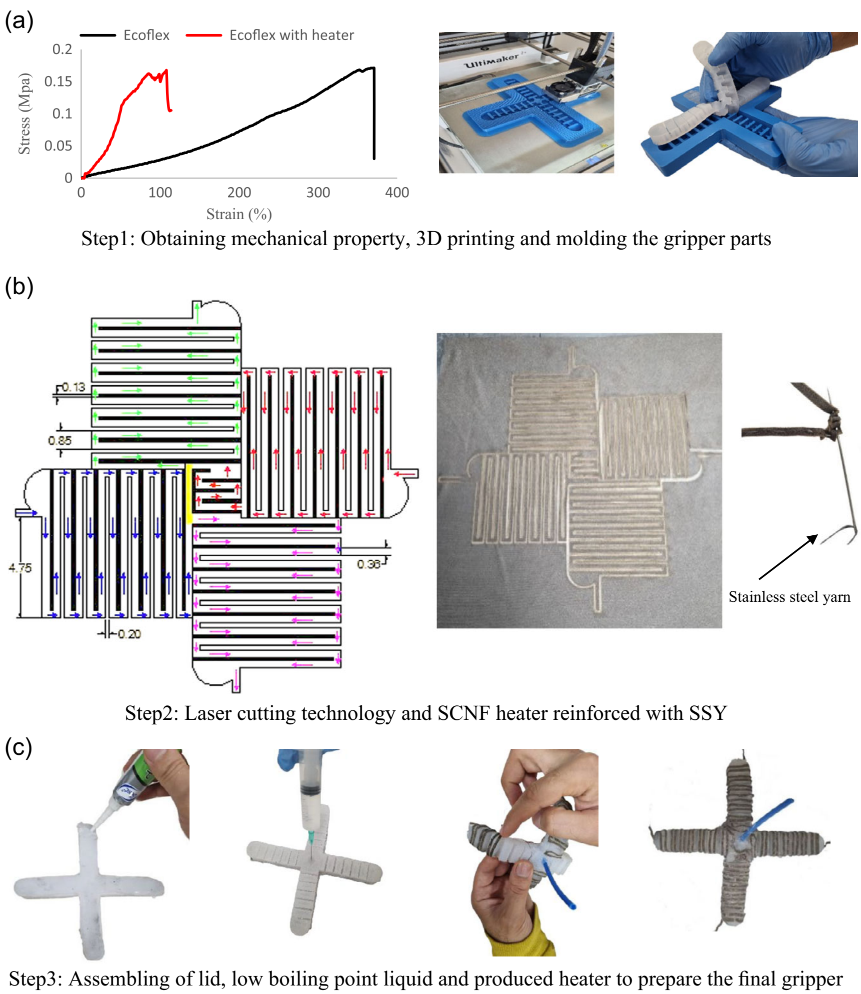

Figure 1. Experiment: a) Stress–strain curve for the Ecoflex with and without the heater and manufacturing method of the gripper body. b) Design and manufacturing of the silver coated nylon fabric (SCNF) heater reinforced with the stainless-steel yarn (SSY). c) Assembling the presented actuator including adding the lid, injection of low boiling point liquid, and using fabric heater in the outside of the gripper body.

Table 2. Thermal property of the low boiling point liquid and electrical property of the SCNF and SSY.

Low boiling point liquid property			
–	Boiling point [°C]	Melting point [°C]	Specific heat [J Kg °C^{-1}]
Acetone	56	−94.8	2160
Heater's parts electric property			
–	Melting point [°C]	Electrical resistivity [Ω m]	Thermal expansion [°C^{-1}]
SCNF	124	1.95×10^{-2}	4.95×10^{-3}
SSY	1400–1450	6.89×10^{-7}	17.2×10^{-6}

2.2. Step 2: Design and Manufacturing of the SCNF Heater Reinforced with SSY

The Autocad2021 software and laser cutting machine were used to design and manufacture the SCNF heater, and then SSY was used to increase the conductivity. Figure 1b shows the design and manufacturing of the heater. Here, SCNF reinforced with SSY was used to manufacture the heater, which can pass electric current and heat. The heater was separated into four parts after being cut by laser, which means that each leg is different from the other legs to prevent its excessive length and to remain electrically conductive. The length of each piece of heater is 1m. The relation between SCNF and SSY is like the relation between yarn and cloth. So, there is no corrosion resistance between them.The details of the heater design will be discussed in Section 4.2.

The SCNF used in the production of the heater can carry a maximum of 1A of electric current. For the heater not to burn out, the current is important, not the voltage applied (of course, the power is the real factor but since the resistance of the SCNF is almost constant, the power becomes directly related to the current). The silicone is not damaged before the SCNF burns.

2.3. Step 3: Assembling of the Gripper Parts

In the assembly part, first, the lid was glued to the base part of the actuator using silicone glue, and then the low boiling point liquid was injected into it. When the low boiling point liquid was injected, the air inside must be first emptied. The reason is that more thermal energy is needed to animate the air, and the presence of air molecules does not allow the quickly evaporating liquid molecules to animate easily. The difference in density of air and liquid was used as the method for air exhaust. The air inside the cell was withdrawn before the fluid was injected with the liquid-filled syringe. The gripper squeezed when the air was removed thoroughly. Of course, trace amounts of air remained. Air went up in the syringe and the liquid stayed down. After adding the low boiling point liquid, the heater was glued to the outer surface and around the gripper using silicone glue. These strips must not touch each other because they cause a short circuit. Finally, the gripper presented in this article is ready. Figure 1c shows the assembling of different parts. Different parts of the actuator are stacked like a layered composite, and therefore the final composite (the presented gripper) has high durability, stability, corrosion resistance, and fatigue resistance. The video of the actuator manufacturing is available in the appendix of the article.

The performance of the acetone solution inside the soft gripper will decrease after it has been put in for a long time. Acetone becomes useless in about one week when it is kept in the fridge while Novec fluids can last more than two weeks even if not kept in the fridge. Novec fluids are much more stable than acetone but of course, acetone is almost free, when the prices are compared.

3. Simulation Procedure

The gripper was designed implementing SolidWorks2021 software and imported into the available commercial software ABAQUS2021 for simulation. For constitutive material model fitting of Ecoflex, Ogden,[32] Darigani,[33] Yeoh,[34] Neo-Hookean,[35] and Mooney–Rivilin[36] were compared. The Ogden model was selected because of the lowest error. The summary of these methods was presented in our previous work.[28] To apply boundary conditions, the upper middle part was fully constrained, and to apply steam pressure, it was applied to all internal surfaces of the actuator. **Figure 2**a shows the boundary conditions applied to the actuator. General static was implemented to solve the finite element algorithm. The type and

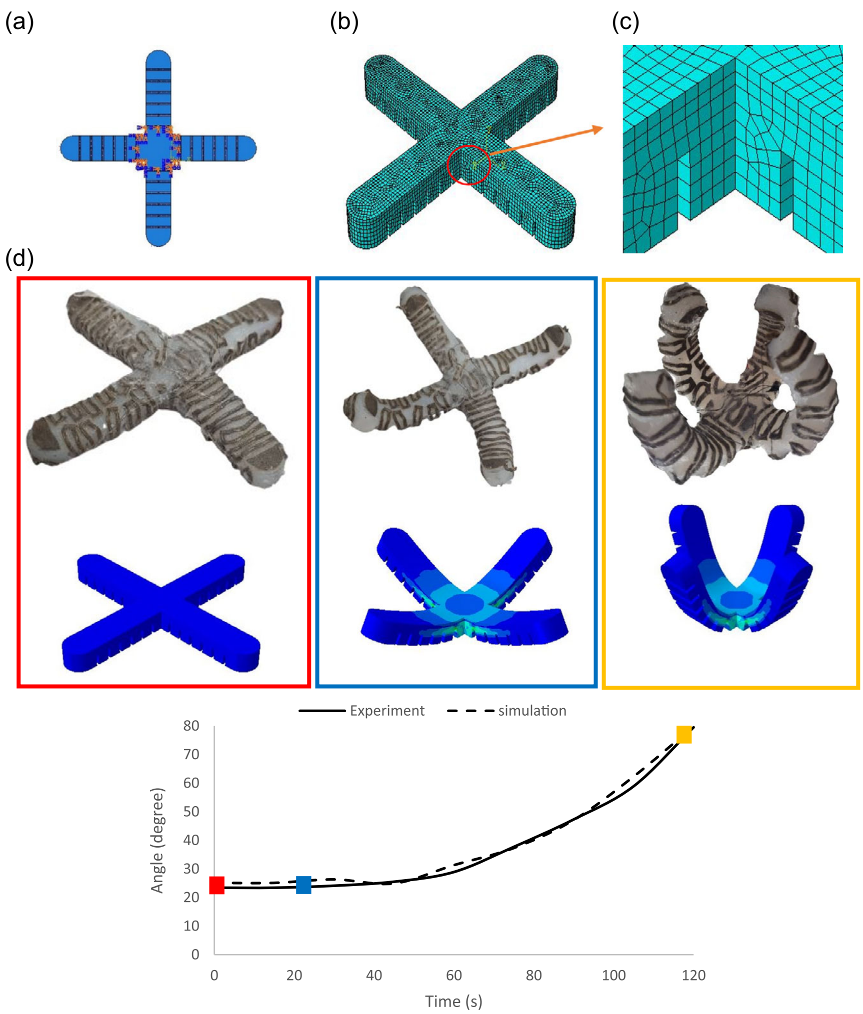

Figure 2. Simulation and verification: a) Boundary condition. b) Mesh of the assembled structure. c) magnified view of the mesh. d) Comparison of the experimental and numerical deformation.

number of mesh are linear hexahedral elements of type SC8R, and 78 000, respectively. Figure 2b,c show the mesh of the model and its magnified view, respectively.

4. Results and Discussion

In this work the relation between electrical, thermal, and mechanical properties was investigated. Equation (1) is the relationship between heat and electrical parameters. Equation (2) and (3) describe the relationship between heat and thermal properties of matter.

$$Q = \frac{V^2}{R} t \quad (1)$$

$$Q = mc\Delta\theta \quad (2)$$

$$Q = mL_f \quad (3)$$

where V, I, and t are the electrical potential difference, intensity of the electric current, and time, respectively in Equation (1). Q, m, and $\Delta\theta$ are the heat, mass of the material, specific heat, and the temperature changes, respectively. L_f is the latent heat of vaporization in Equation (3). According to Equation (1), the produced heat from electric current is related to the second power of voltage ($Q \propto V^2$) and to the first power of time ($Q \propto t$). With the increase of these two parameters, the heat produced increases with the indicated ratios and their limitation is related to preventing the fabric from burning.

4.1. Verification of the Simulation with Experiment

The time parameter is significant here, and to reduce it, the heating area should be increased, and the heat should be transferred to the entire external surface of the actuator. However, the vertical walls are free of the heater to optimize flexibility and heat transfer. Vertical walls have a critical role in the deformation mechanism of the gripper. Here, the comparison between experimental results and numerical results is presented qualitatively and quantitatively. There is good agreement between experimental and numerical deformations. Figure 2d shows the sequence images of the gripper deformation and the graph of the angle in terms of time for the results experimentally and numerically.

This point is interesting in Figure 2d, that initially no angular change occurs inside the actuator and the diagram is like a horizontal line, but with time, the slope of the diagram becomes steeper. This graph trend is consistent with the vaporization behavior of the liquid inside the actuator. Because for a liquid to vaporize, its temperature must first reach the boiling point from room temperature. After reaching the boiling point, it is necessary to receive heat again to carry out the vaporization process. In both steps, the liquid needs to receive heat and spend time. After passing through these stages, the evaporation process accelerates and causes the slope of the graph to be steeper. This will be explained in detail in Section 4.4.

4.2. Inspiration the Idea of SCNF Heater with SSY from the Warm Water

The idea of manufacturing a cover fabric heater was inspired by observing the actuating of the gripper immersed in warm water. The water temperature was 60 °C. The Ecoflex is damaged at a temperature of about 90 °C. When the gripper was immersed in water, the heat of the water is transferred to it through its entire outer surface, causing the liquid inside to vaporize within 2 min (**Figure 3**a). In this article, it has been tried to provide these conditions in the out of water by designing a cover fabric heater. For this purpose, it must provide heat on the surface. Electrons always move in the path of least resistance and are not spread

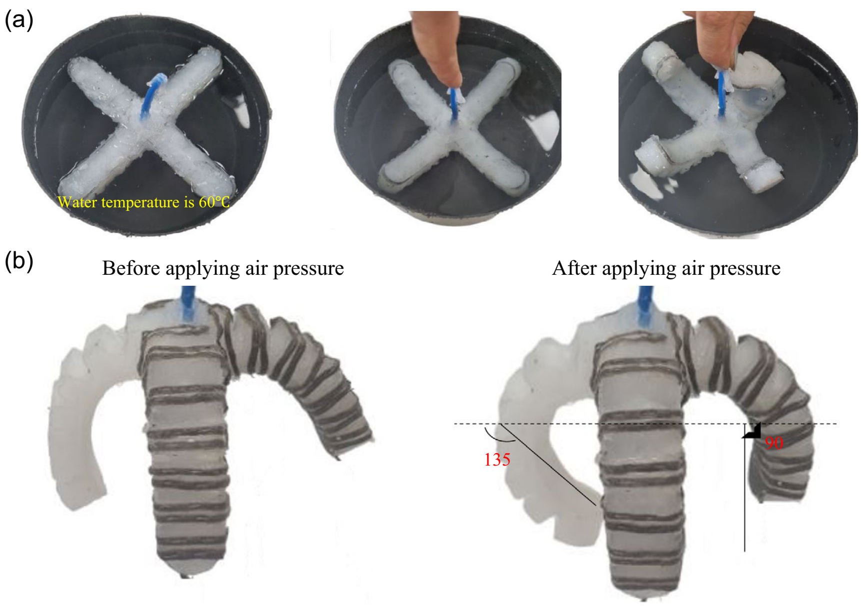

Figure 3. a) The SCNF heater reinforced with SSY was inspired by immersion of the gripper in 60 °C water. b) Adding the heater caused changes of the flexibility of the gripper.

uniformly on the surface. To be able to provide uniform heat on the entire outer surface of the actuator, it is necessary to be able to design the path of the electrons according to Figure 1b. Arrows show the path of electrons. The plus shape covered the behind of the gripper, and each band covered the outer surface of the chambers. Silicone glue was used to assemble this heater on the gripper. The heater consists of four parts, which receive electric current separately. The yellow part was cut after assembling to separate the heater into four pieces. The yellow part was designed to have the monolithic heater and its convenient assembly on the actuator. It is worth noting that adding the heater will affect the gripper's flexibility. Figure 3b shows these changes before and after applying the pressure to the legs with and without the heater. It is not possible to cover the surfaces between the two

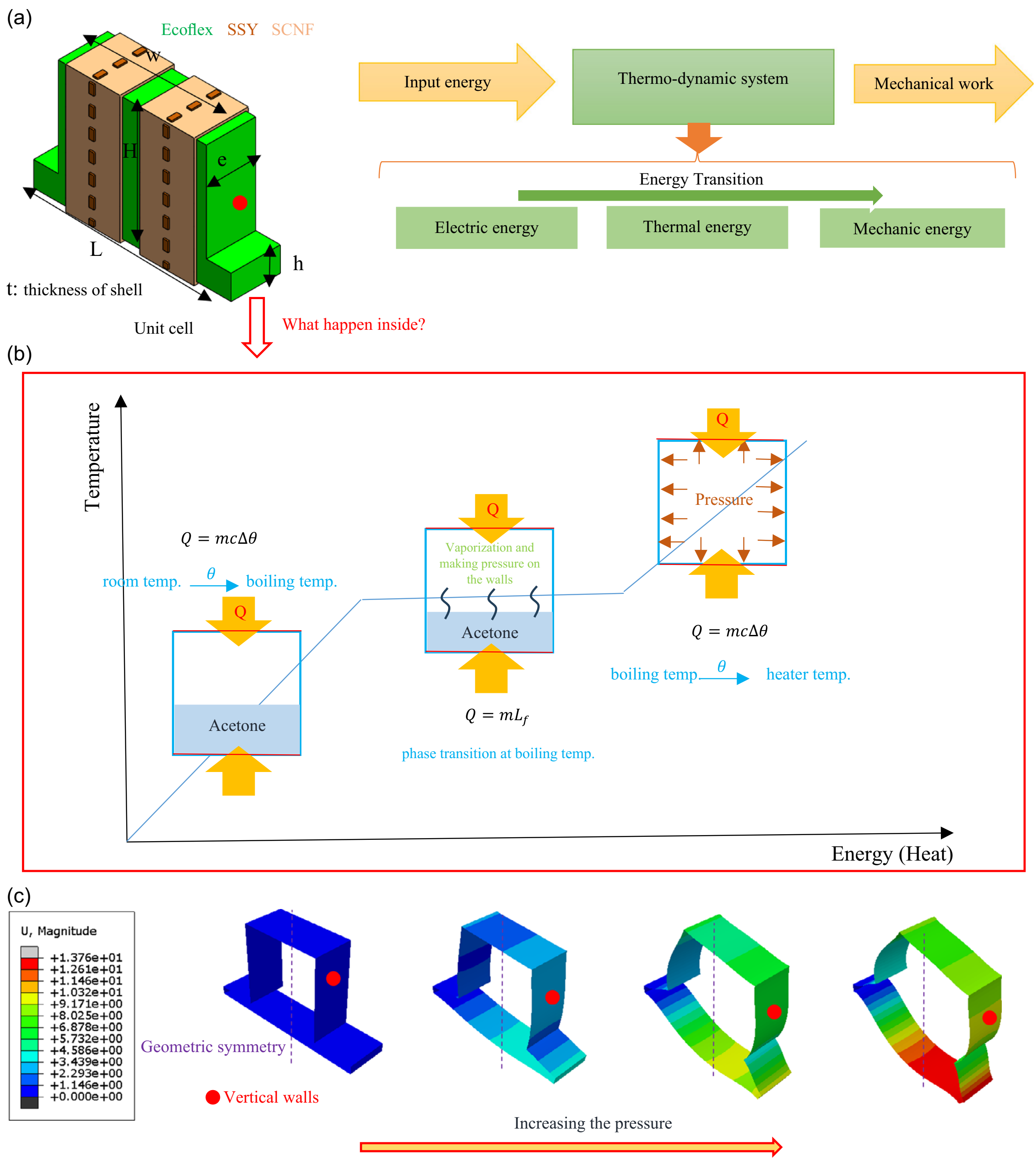

Figure 4. a) The unit cell of the gripper is covered with the heater at the upper and bottom sides. The vertical walls are free of the heater because their instability under pressure has the most effect on the actuator bending. Relation between the electrical, thermal, and mechanical properties. b) The boiling process of the acetone inside the actuator. c) The deformation mechanism of the unit cell during the increasing pressure. The instability of the vertical walls causes actuator bending.

chambers, due to the destruction of the mechanism of actuator bending. Using the relationship between electrical and thermal properties, it was tried to keep the temperature of the fabric heater around 56 °C (boiling point of acetone).

4.3. Flexibility of the Gripper Before and After Adding the SCNF Heater Reinforced with SSY

By assembling the heater, the mechanical properties (flexibility) of the gripper decrease and the optimal mode between flexibility and high heat production should be considered. If the heat production is high, the area covered by the heater must increase, which causes a sharp decrease in flexibility. If the flexibility is high, then it should be reduced from the space covered by the heater, which will slow down the flexibility of the actuator. Figure 3b shows the deformation of two legs including with and without heater before and after applying air pressure. The overall outer surface of the gripper is 20 250 mm^2 and the surface of the heater is 11 200 mm^2, which means that 55.3% of the outer surface of the gripper was covered with heater. As it is clear from Figure 3b, the flexibility of Ecoflex decreased by 45% due to the addition of the heater, although it has been tried to stick the heater in places that do not affect the deformation mechanism of the gripper.

Here, a comparison was done between the flexibility of dog bones presented in Figure 1a and the gripper presented in Figure 3b. This difference in the flexibility of dog bones is about 220%. Because dog bone without SCNF heater reinforced with SSY was broken at 400% strain and dog bone with SCNF heater reinforced with SSY was broken at 123% strain. But for the gripper that contains heater, the flexibility was dropped by 45%. Because the leg without SCNF heater reinforced with SSY was bent 135° due to air pressure, but the leg with SCNF heater reinforced with SSY was bent 90°. It shows that the SCNF heater reinforced with SSY was placed in places to have the least possible effect on flexibility, and these places are around the compartments.

4.4. Actuation by Transforming Energy from Electric to Thermal to Mechanic

Here, a follow-up of energy from electric current to mechanical work was done to investigate the deformation of the actuator unit cell. **Figure 4**a shows the parameters of the unit cell, and the actuator consists of an Ecoflex body covered with a SCNF heater reinforced with SSY. In a thermodynamic system, the input energy of the system is converted into mechanical work. The more energy the system can absorb, the more work it can do. The energy required to perform a certain task determines the type and amount of liquid to be injected into the actuator. Besides acetone, there are other low boiling point liquid options according to **Table 3**. In this research the cheapest liquid with the optimum performance was chosen.

To choose the appropriate type and amount of liquid, the thermodynamic energy parameter can be defined, which is the amount of heat that 1 g of a liquid needs to change from room temperature to steam at 100 °C. The reason why the temperature of 100 °C is considered is that water is included in this comparison. **Table 4** provides the thermal properties of water and acetone. The thermodynamic energy parameter of the water and acetone was obtained at 315.76 and 123.93 using the path presented in Figure 4b. It shows that 1 g of 100 °C water steam has 2.55 times more energy than acetone steam. Therefore, it can be concluded that water has a better capability for providing large forces because water is used in the steam engine. According to the energy required to deform the gripper body, the type of liquid and its amount can be determined. The amount of energy needed to deform the actuator can be obtained pneumatically. To remove the effect of the internal volume of the gripper from these studies, the liquid volume can be expressed as a percentage of the total internal volume of the gripper.

Table 3. Different available liquids for using in the application of thermally powered soft gripper.

Liquid	Boiling point [°C]
Water	100
Acetone	56
Ethanol	78
3M Novec 7000	34
3M Novec 7100	61
½ Novec 7000 + ½ Novec 7100	47
¾ Novec 7000 + ¼ Novec 7100	40

Table 4. Comparison of thermal property of water and acetone.

Parameters	Water	Acetone
C_{Liquid}	4.18 J g °C^{-1}	2.15 J g °C^{-1}
$\theta_{Boiling}$	100 °C	56 °C
L_f	2.26 J g^{-1}	0.52 J g^{-1}
C_{Vapour}	2.04 J g °C^{-1}	1.29 J g °C^{-1}

The cell was filled with the acetone and pulled back some after the actuator started to change its shape. Some free medium is required for the liquid to transform into a gas phase. So, more is not better. In contrast, it is important to note from Figure 4b that if the amount of liquid is large, the start of the vaporization process takes place later, because, in the first stage, the temperature of all the liquid must reach the boiling point to start vaporization.

Despite all the notes mentioned previously, the actuator application plays a more important role in choosing a low boiling point liquid. For example, for the applications of the human body, like an artificial hand actuator, all matters except human health are ignored, and 3M Novec 7000 with a boiling point of 37 °C is the best. It is the best option because higher temperatures will be annoying for humans. When all the liquid is transformed into vapor, then the behavior of all gases follows the law of Equation (4).

$$\frac{P.V}{T} = nR \tag{4}$$

Where P, V, T, and n are pressure, volume, temperature, and the number of mols. R is the universal gas constant ($R = 8.314\ \text{J mol}^{-1}\ \text{K}$). In the next work, we want to investigate this issue in detail for different liquids using molecular dynamics simulation.

Figure 4c illustrates the relationship between electrical, thermal, and mechanical energies in the gripper. When electric current enters the heater, the heater generates heat due to electrical resistance. Heat increases the temperature of the liquid from room temperature to the boiling point, and then at the constant boiling temperature, the acetone liquid turns into acetone vapor, and finally, the temperature of the acetone vapor increases to the temperature of the heater. As a result of the created pressure, the walls of the gripper were bent and instability in the vertical walls caused the actuator to bend downwards. Figure 4c shows the importance of the vertical walls in the deformation of the gripper. So, the heater was not used on this wall avoiding more destruction of the gripper flexibility. Heater optimization depends on the optimization of the gripper structure. The optimization of the heater is related to the location of its attachment so that it was not attached to the vertical walls (see the comparison of the flexibility of the dog bones and the gripper in Section 2). As mentioned in Section 2 the heater covered 55.3% of the outer surface of the gripper.

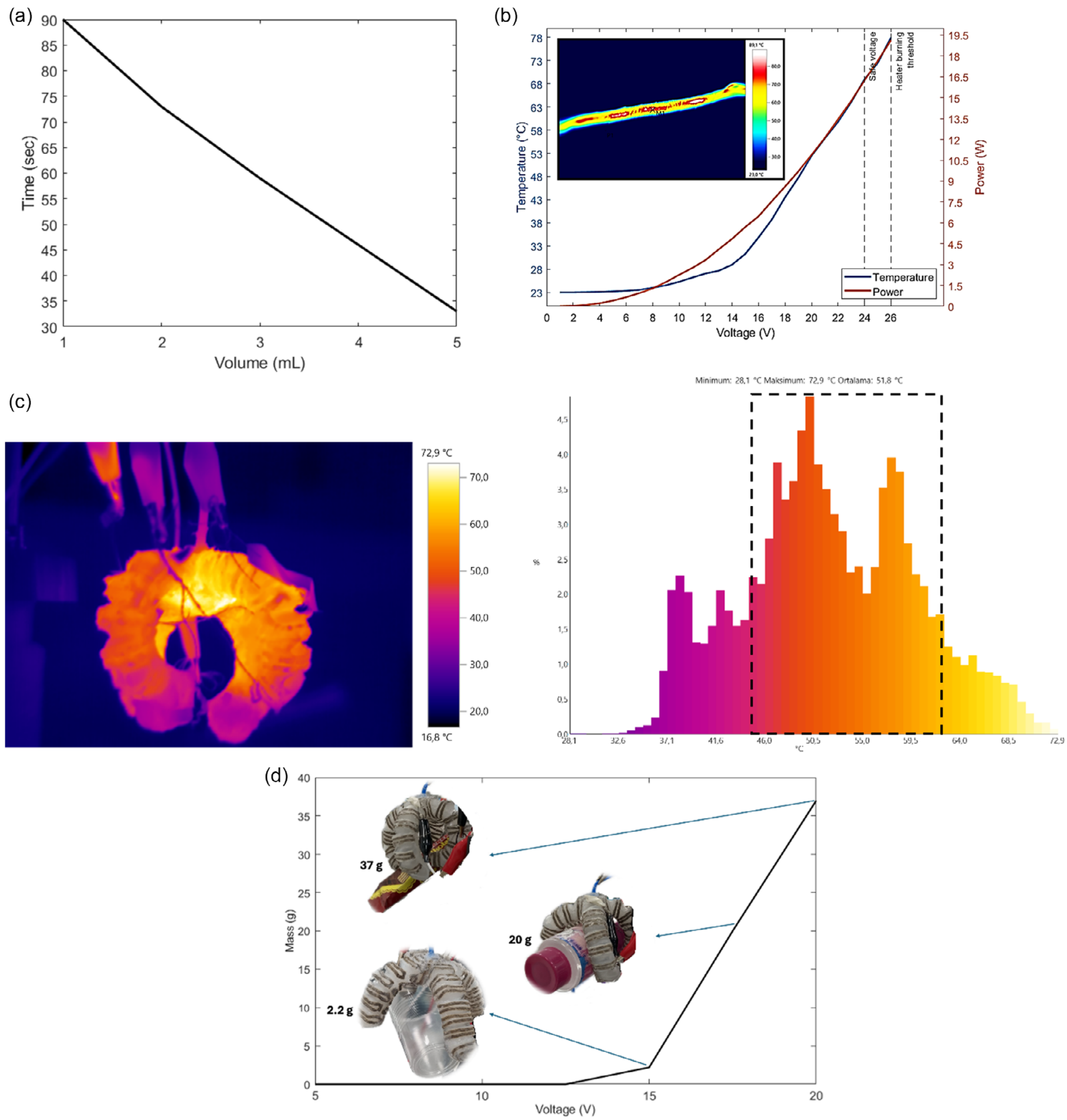

Figure 5. a) Actuating time in terms of the low boiling point liquid volume. b) Temperature in terms of the voltage for the presented heater. c) Generating heat by the presented heater for the gripper. d) Heat distribution histogram for the gripper. e) Mass of gripped things in terms of the voltage.

The geometry and the bending mechanism, according to Figure 4c, of the presented actuator are no different from the PPSAs, only, more precise sealing was done. The main difference is that in the presented actuator, by applying electric current, the pressure gradually increases (transforming liquid into steam) to reach the desired final pressure, but in pneumatic actuators, the final pressure is suddenly applied.

4.5. Parametric Study and Application

In this part, the relationship between the electrical (voltage), thermal (temperature), and mechanical (force) properties of the presented gripper was investigated. Voltage is not directly related to the achievable force provided by the actuator. The voltage causes heat, and it causes steam, and finally, steam pressure provides force. Therefore, to find the relationship between voltage and force, the relationship between voltage and temperature should be investigated. Increasing the voltage up to the voltage corresponding to the boiling point temperature does not provide force due to not having the steam. **Figure 5**a shows the graph of the amount of liquid in terms of the actuating time. As the graph shows, the time decreases linearly with the increase in liquid volume. Figure 5b illustrates the performance (temperature) of the presented heater in terms of the voltage. As can be seen, at first the slope of the graph is low, and after the voltage of 10 V, the slope of the graph increases suddenly. The maximum temperature that Ecoflex can withstand without any damage is 90 °C, and the maximum temperature that fabric can withstand without any damage is 68 °C. To consider the margin of confidence, the maximum applied temperature is 60 °C. A thermal camera was used to take thermal photos.

Figure 5c shows the heat production by the presented SCNF reinforced with SSY. The uniform color of the gripper in Figure 5c indicates its uniform temperature. Considering the temperature of 45–60 °C as the optimal temperature for acetone vaporization, the statistical distribution of temperature (by dividing the area of this area by the total area) for different regions of the gripper shows that 73.4% of the gripper areas are at the optimal temperature. It shows that there is a proper temperature distribution. In this temperature range, the flexibility of Ecoflex is not affected much because the temperature is relatively low and the area that generates heat is large (the idea of generating heat at low temperature and high surface area).

Figure 5d shows the force in terms of voltage. As can be seen, there is no force until the voltage of 13 V, because the temperature resulting from this voltage is lower than the boiling point. At a voltage of 15 V, which corresponds to a temperature of 56 °C, acetone reaches the boiling point and begins to vaporize. As can be seen, the trend of the graph is like the temperature graph in terms of voltage, which increases the force suddenly as the voltage increases.

Apart from the force, the more important parameter is the shape of the object held. In our experiments, it was observed that they fell when an object heavier than the wafer was tried to be held, but other objects with high friction may also be held. The exact model of the holder has not been determined. Still, the linear relationship between tension and voltage for the plastic cup, cologne bottle, and chocolate wafer bar is seen in Figure 5d. For this sample, the chocolate wafer bar is the maximum. To achieve accurate gripping, the shape and friction of the material is very important. Small and round objects cannot be held even if they are very lightweight.

The application of this type of bending mechanism can be in the application of an artificial finger for the human hand as an independent actuator from the compressor. As it was mentioned in sec. 1 about the importance of using low boiling liquid for the design and construction of this type of independent actuator, in the next works, this type of actuator can be used for the human finger, which can provide its energy from the heat of the human body. It is worth mentioning that in the case of using 3M Novec 7000 with a boiling point of 34 °C, it is reasonable to use body temperature to vaporize and create pressure. Obviously, for this purpose, thermoelectric equipment is needed to convert and store the thermal energy of the body into controllable electrical energy.

5. Conclusion

In this work, an Ecoflex-based gripper was presented in which, unlike the previous counterparts worked with the air pressure, the driving force is the low boiling point liquid (acetone). Here, the idea of heating the large outer surface, inspired by immersing the actuator in warm water was used. For this purpose, an electric SCNF heater reinforced with SSY was designed and attached to the outer part of the actuator. This heater covered 55.3% of the outer surface of the actuator. The changes in mechanical properties due to the addition of heaters on the dog bone of Ecoflex and the actuator made of Ecoflex were investigated. By adding the presented heater on the dog bone of Ecoflex, its flexibility drops by 320%. Here, by sticking the heater in the special places of the actuator, this drops in flexibility for the presented actuator became 125%. The relationship between the electrical properties, thermal properties, and mechanical properties of the presented actuator was investigated and their effect on the gripping time was investigated.

Supporting Information

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

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Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Conception: B.T., A.T.A., O.A.; Experimental design: M.F.Ç., M.S.Ç.; Carrying out measurements: B.T., M.F.Ç., M.S.Ç.; Manuscript composition: A.T.A., G.I., O.A.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Keywords

acetone, ecoflex-based actuator, silver coated nylon fabric heater (SCNF), stainless steel yarn (SSY), voltage-temperature-force relation

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