

Design, numerical simulation and experimental investigation of an SU-8 microgripper based on the cascaded V-shaped electrothermal actuators

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Abstract. This paper presents the numerical simulation results and the experimental investigations of a polymeric microgripper designed using the cascaded V-shaped electrothermal actuators. The microgripper was simulated using electro-thermo-mechanical finite element method (FEM) based on Coventorware 2014 software in order to check the performance of the gripper. As structural material of the microgripper, the SU-8 biocompatible polymer was used during the fabrication process. The metallic micro-heaters were encapsulated in the polymeric actuation structures of the microgrippers to reduce the undesirable out-of-plane displacement of the gripper tips, to reduce the mechanical stress and to improve the thermal efficiency. Experimental testing has been performed to determine the openings of the microgripper tips as function of electrical current. A displacement of the tips of more than 50 μm can be obtained at an electrical current of around 25-26 mA. Over 27-28 mA the heaters are still working but a softening and a damaging status in the polymer were observed.

1. Introduction

Microgrippers used as end-effectors are important tools for handling, pick and place fragile objects. The multiplicity of the microgripper's applications includes biological micro-manipulation such as cells, blood vessels and tissues, micro-assembly of Microelectromechanical Systems (MEMS) and MOEMS components (lenses, fibers) and micro-robotics.

The actuators play a significant part of MEMS that are used for energy conversion, motion generation and force production [1-3]. The V-shaped actuators are widely used for grippers, micro-valves, micro-pumps and other devices. V-shaped electrothermal actuators have the advantages of generating a large force (up to several hundred mN), the simple structure design, a lower drive voltage and a large deformation. Que et al. [2] developed single and cascaded V-shaped electrothermal actuators and present the experimental results. Shen et al. [3] present an analytical model for cascaded V-shaped actuators bringing a complete description of the mechanical performance. Usually the structural material is silicon, polysilicon or aluminium.

A variety of microgrippers have been studied using the SU-8 based electrothermal actuators designed on different configurations such as, U-shape or V-shape. This is proving the interest in the bio-micro-manipulation domain [1, 4-19]. SU-8 is a highly crosslinked epoxy-type photo-patternable polymer which has been used extensively as the preferred polymer material for fabrication of biocompatible devices. The SU-8 polymer has a relatively large coefficient of thermal expansion (CTE) of 52 ppm, good mechanical strength with a modulus of elasticity of around 4.02 GPa and a good thermal stability



with a glass transition temperature of 210°C [15] which make it a good polymer material for fabrication of electrothermal actuators. The polymer V-shaped actuators are preferred for the better performance in aqueous medium [4].

In this work, we report the design, numerical simulation results and the experimental investigations of an SU-8 polymeric microgripper designed using the cascaded V-shaped electrothermal actuators. The SU-8 microgripper can be used for bio-manipulation and assembly applications. The microgripper was numerically investigated using the coupled electro-thermo-mechanical simulations based on finite element method (FEM) and using the Coventorware 2014 software in order to confirm the performance of the microgripper. In this paper an improved technological process was realized in order to fabricate the microgripper using a sandwich structure actuator. As structural material of the microgripper, the SU-8 biocompatible polymer was used during the fabrication process. The metallic micro-heaters were encapsulated in the polymeric actuation structures of the microgrippers to reduce the undesirable out-of-plane displacement of the gripper tips, the mechanical stress and to improve the thermal efficiency. Experimental testing and characterisation have been performed to determine the openings of the microgripper tips as function of electrical current. A displacement of the tips of more than 50 μm can be obtained at an electrical current of around 25-26 mA. Over 27-28 mA the heaters are still working but a softening and a damaging status in the polymer were observed.

2. Design

The polymer microgripper was designed using the principle of the cascaded V-shaped electrothermal actuators. The gripper is designed with an initial opening of 50 μm (figure 1). When the gripper is electro-thermally actuated, the tips will close and can handle a micro-object. The total length of the gripper arms used to grasp an object is of 920 μm . The arms were designed with a width of 20 μm . A metallic micro-heater is implanted between two SU-8 layers. The heater wires have a width of 10 μm and were designed to be fabricated using Cr/Au/Cr materials.

The optimized design consists of symmetrically disposed of three material layers. A metallic layer for the heater is implanted between two SU-8 based structure layers having the same thickness, as described previously [17-20]. The thicknesses of the Cr/Au/Cr films were 30 nm/300 nm/30 nm. For each SU-8 layer we obtained a thickness of 9 μm . The details of the fabrication work have been reported also previously in [20].

The microgripper was designed symmetrically with encapsulated metallic micro-heaters in the structural material of the grippers, the SU-8 polymer, in order to reduce the undesirable out-of-plane displacement of the gripper, to obtain the electrical isolation of the heaters and to reduce the mechanical stress that can occur in the structure.

3. Simulation

Finite element modeling using Coventorware was performed to optimize the microgripper design and to evaluate the performance in air. Coupled electro-thermo-mechanical simulations were completed using the MemMech simulator. A simplified 3D microgripper model (figure 2) was meshed using hexahedral elements (Extruded bricks). The number of volume elements was optimized choosing the proper size of the mesh elements using the Split and Merge algorithm.

The materials properties and the surface boundary conditions were set for the simulations. The initial temperature of the whole structure and the temperature of the environment were considered to be $T_0=27^\circ\text{C}$, with respect to the Coventorware settings requirements for such kind of analyses. The radiation losses from the device are negligible in comparison with the heat loss by convection to the surrounding media [4], since the maximum temperature reached in the microgripper, in order to operate, is lower than 800°C. The air convection coefficient was set to 250 $\text{W}/\text{m}^2\text{K}$ [4]. The Young's modulus of the SU-8 were measured with the nanoindentation technique and set for a value of 4.6 GPa. The thermal coefficient of expansion was set at 52 (ppm/°C) and the thermal conductivity at 2×10^5 $\text{pW}/\mu\text{mK}$. For the gold layer we used a Young's modulus of 77 GPa reported for thin films. For the thin Cr/Au/Cr films, a temperature coefficient of resistance (TCR) of 0.0014/°C was used [20].

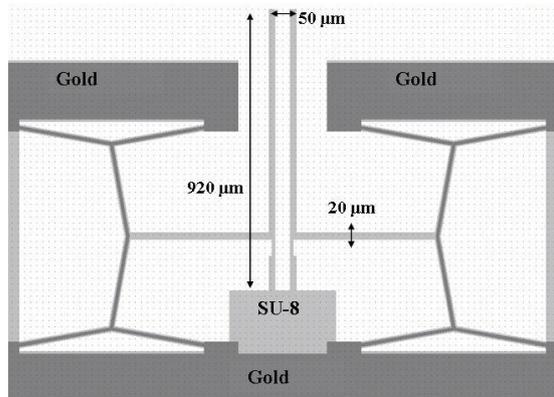


Figure 1. Schematic design of the SU-8 microgripper.

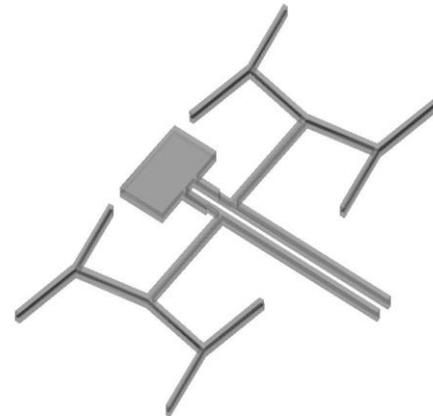


Figure 2. The simplified 3D model of the microgripper with encapsulated heaters in SU-8 polymer: the layers sandwich structure used in FEM simulations (Coventorware2014).

The simulated values of the temperatures reached on the arms and the in-plane deflections of the tips as function of electrical current were presented (figure 3 and 4). The simulation results show that the gripper can work up to a maximal temperature of 160 °C reached in the actuation area, when a complete closing tips is occurred. The gripper can continue to work up to 205 °C in order to obtain a higher displacement or a higher pressure on the gripped micro-object. The simulation results indicate that the polymer microgripper can work at low operation temperatures of the tips and with high in plane displacement. A displacement of 25 μm for each microgripper polymeric arm was obtained for a current value of 25 mA. At 25 mA a complete closing tips was observed. The tips temperatures remain at 30-35 °C nearby the initial temperature settings of the media. The microgripper can be optimized by increasing the initial opening.

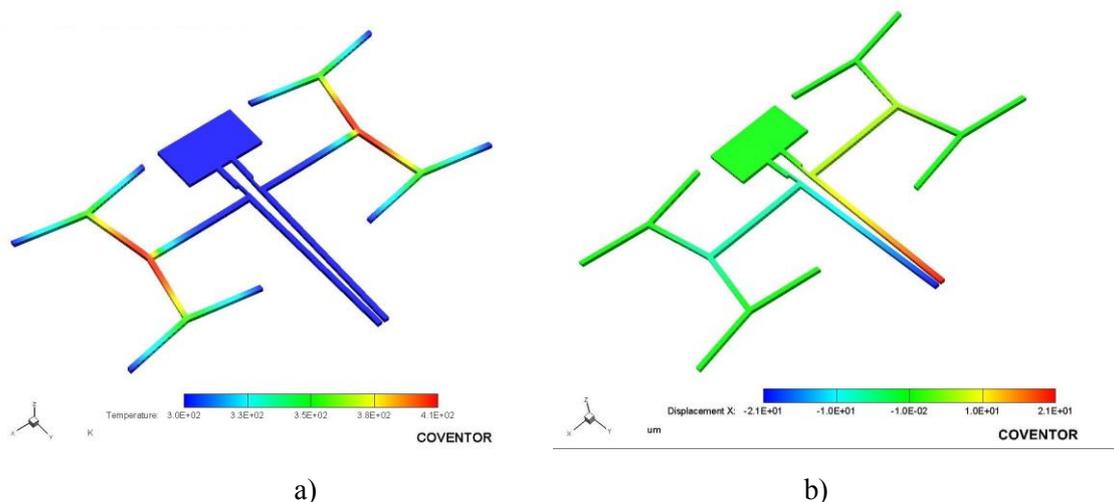


Figure 3. FEM coupled electro-thermo-mechanical simulations results: a) The temperatures distribution in the microgripper at 22 mA; b) The in-plane deflections at 22 mA (Coventorware 2014 simulation).

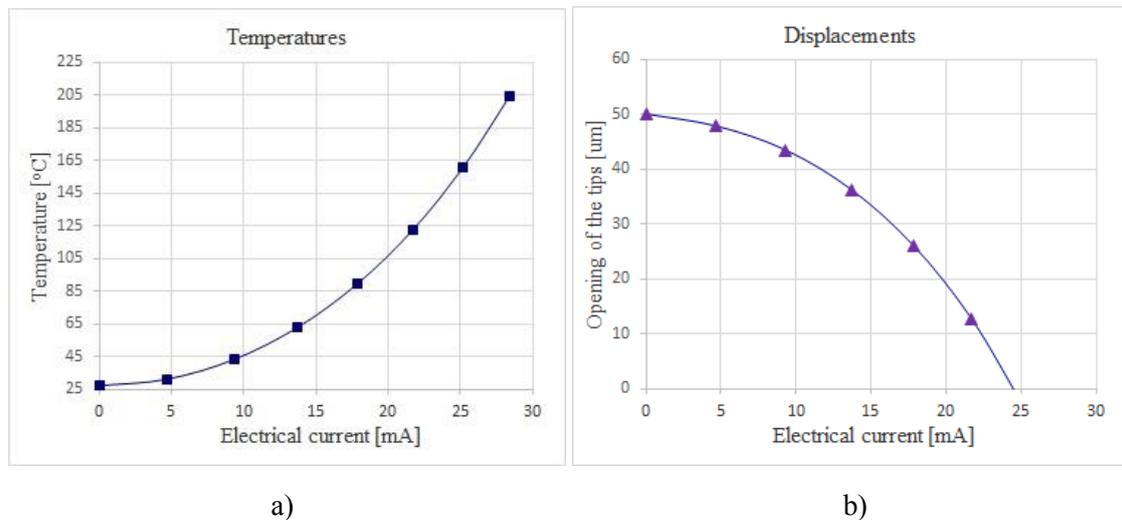


Figure 4. Simulation results: a) The temperature values versus electrical current; b) The jaw displacement versus electrical current;

4. Fabrication and experimental investigations

4.1. Fabrication

For fabrication of the microgrippers we used a 3 mask process and the OmniCoat stripper (MicroChem) in order to completely release the final structures [20].

A thin layer of Omniccoat was deposited on a silicon wafer by spin-coating and baked at 200°C on a hotplate. Then the SU-8 (MicroChem) polymer was deposited by spinning on the wafer in order to obtain a thickness of 9 μm. The wafer was soft-baked at 65°C and at 95°C. The SU-8 layer was then exposed using the first mask. After the exposure, the wafer was post-baked at 65°C and at 95°C and then developed. The polymer structure was hard-baked at 185°C in order to complete cross-linking of the SU-8 polymer. The metal layer consists of a sandwich of Cr/Au/Cr films of 30nm/300nm/30nm thicknesses. The metals were evaporated and the heater and pads were obtained using a lift-off process based on AZ photoresist. The second SU-8 layer was obtained using the same conditions as for the first layer. In this step the access to the metallic pads was created using the third mask for SU-8. The final thermal process of the polymer in this step was the hard-baking for cross-linking of the SU-8 polymer. To release the microgripper structures the Omniccoat layer was developed. Figure 5 shows an optical picture of the fabricated microgripper.

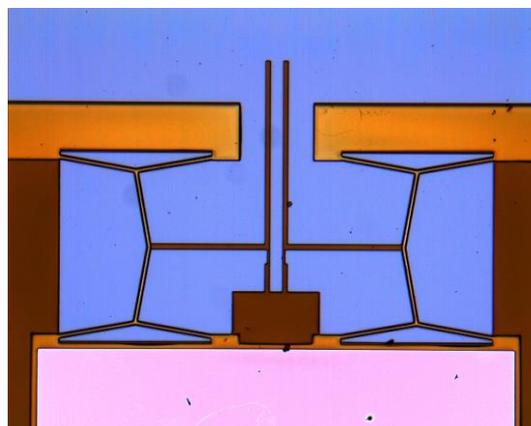


Figure 5. Optical microscope picture of the fabricated electrothermal SU-8 microgripper

4.2. Experimental Testing

In order to validate the model, the experiments were performed in air. Each structure was fixed manually on a silicon substrate. The in-plane deflection change with drive current was observed with an optical microscope and a camera with the associated viewing software. For each actuation step, the displacements of the gripper tips were measured using the optical images. Figure 6 shows the first and the last stage of the opening-closing tips of the microgripper. The out-of-plane displacement is not observed during experiments and due to the simulation results is less than 54 nm. Over 27-28 mA the polymer SU-8 becomes softer and the device is damaged due to the increased temperature over T_g of 210 °C (figure 7).

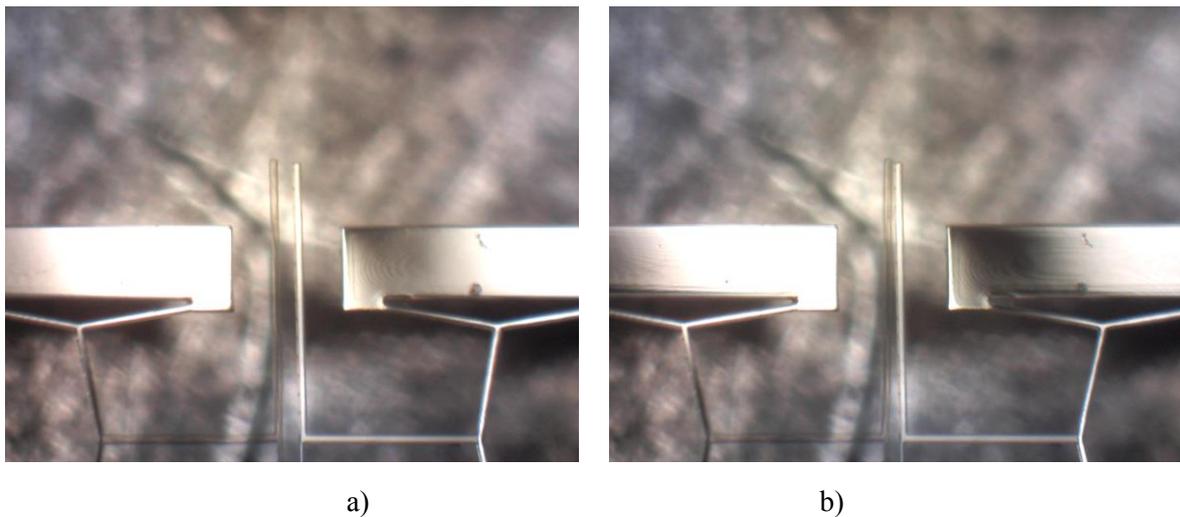


Figure 6. Optical images of the actuated microgripper and the tips in the open and close stage: a) the initial stage of the microgripper tips with the initial opening of 50 μm ; b) closing tips stage at 24 mA.

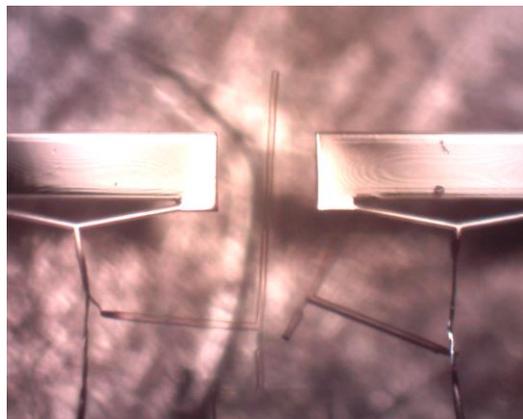


Figure 7. Optical image of the damaged SU-8 microgripper at 28 mA.

5. Conclusions

An SU-8 electrothermally actuated microgripper based on a cascaded V-shaped configuration was designed, numerically and experimentally investigated. The results show that the microgripper can work in air in its maximal stage for an electrical current of 25-26 mA and for a highest temperature of the tips of 35 °C. Over 27-28 mA the device is damaged due to the SU-8 transformations over the glass transition temperature reached in the structure. Further investigations will be the comparison between the simulation results and the measurements.

Acknowledgments

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