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Metallic microgripper with SU-8 adaptor as end-effectors for heterogeneous micro/nano assembly applications

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Abstract This paper presents design, fabrication, and characterization of easy-to-handle electroplated nickel microgrippers with SU-8 adaptors for heterogeneous micro/nano assembly applications. Two distinctive designs of microgrippers as end-effectors of micro/nano assembly applications have been developed in this work. The first design is 200 μm thick electroplated nickel microgripper with a plastic mechanical displacement amplifier that is driven by a piezoelectric actuator. The piezoelectric actuator is capable of creating ~5 μm displacement which is amplified to ~10 μm by the plastic mechanical amplifier and finally such displacement generates 50–139 μm microgripper tip displacement. The second design is 20 μm thick electroplated nickel microgripper embedded in SU-8 adaptor for easy-to-handle operation. The second design is electro-thermally actuated using a set of joule-heated bent beams. With applied actuation voltage in the range of 2–4 V, the microgripper generates tip displacement of 4–32 μm. Extensive thermal and mechanical finite element modeling have been carried out and measurement results were compared with the simulation results. Such developed easy-to-handle microgrippers can be used for micro/nano pick-and-place assembly applications.

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1 Introduction

The development of manufacturing systems that are able to integrate a variety of micro devices into a single, heterogeneous system will trigger major advances in the achievable complexity and functionality of microsystems. One promising approach is to equip existing robotic systems with specialized end-effectors so that they are better suited to precisely handle and manipulate micro components. Many efforts have been made in the research and development of a variety of microgrippers and their applications in MEMS, micro-optics and biological sample manipulation [Kim et al. (1992), Suzuki (1996), Lumina et al. (1999)]. Recent developments in microsystems indicate a growing interest and need for three-dimensional manipulation of micron-sized structures to form specialized, microrobotic systems. This requires research efforts in the area of microsystem integration, particularly in the area of microassembly [Hunter et al. (1999), Cohn et al. (1998), Nelson et al. (1998), Huang et al. (2003)]. However, the current approaches in such manipulation have been limited by time consuming manual assembly and poor yield [Ellis et al. (2002)].

Pick-and-place robotic micro/nano assembler and manipulator systems which use conventional computer-based macroscopic control yet capable of micron scale assembly have been developed at Zyvex Corporation (Richardson, Texas, U.S.A.) [Huang et al. (2003), Ellis et al. (2002)]. In such micro/nano assembler and manipulator systems, one of crucial components is microgripper as an end-effector. Silicon microgripper was commonly used for such an application [Ellis et al. (2002)]. In this work, two types of metallic microgrippers were investigated which can be used as end-effectors for such micro/nano assembler and manipulator applications.

2 Design and simulation

Two distinctive designs of metallic microgrippers were investigated in this work. The first design is a relatively thick (~200 μm), large scale (~15 mm in length), and uses mechanically amplified piezoelectric actuation. The second design is relatively thin (~20 μm), smaller scale (~1.5 mm in length), and uses direct electro-thermal actuation using joule heating of rmultiple number of bent-beams.

The design 1 has three different types of electroplated nickel microgripper structures as shown in Fig. 1. This design is based on the previous work on the poly-silicon microgripper at Zyvex [Ellis et al. (2002)]. The

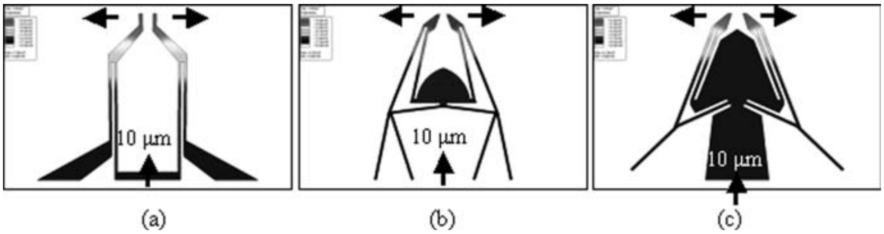

Fig. 1a-c. In-plane displacement simulation results for the design 1; **a** type A, **b** type B, and **c** type C microgrippers

microgripper tip opens when a force is applied at the bottom of the microgripper as shown in Figure 1. The overall size of the microgripper is approximately 15 mm by 13.5 mm and 200 μm thick. Mechanical finite element analysis (FEA) was carried out using ANSYS (ANSYS, Inc., Canonsburg, Pennsylvania, USA) with an assumption that the electroplated nickel obeys Hook's law. The Young's modulus and Poisson's ratio of electroplated nickel used were 130 GPa and 0.31, respectively.

The type A microgripper shows relatively large tip opening of the microgripper but more prone to out-of-plane displacement which is undesirable. Type B and C show relatively smaller tip opening of the microgripper but less prone to out-of-plane displacement due to the addition of significant mass in the middle of the microgripper. Figure 1 shows amounts of the in-plane displacement of the three different types of microgrippers with a mechanical displacement of 10 μm at the bottom of the microgripper. Type A shows 160 μm tip opening while the type B and C show 108 and 124 μm tip opening, respectively.

The design 2 as shown in Fig. 2 is based on the mechanically amplified microfabricated bent-beam structures [Huang et al. (2003), Ellis et al. (2002)]. Again, electroplated nickel was used as the microgripper structural material. The primary difference of this design from the design 1 is the use of massive SU-8 structures as an adaptor for easy-to-handle operation. The SU-8 adaptor provides mechanical support and electrical isolation for the electroplated nickel microgripper. In addition, it is shaped to be compatible with micro/nano pick-and-place robotic systems to allow precise alignment. This enhancement will allow us to make one step closer to the realization of a system which is capable of massively parallel assembly and manipulation in micro/nano scales using robotic pick-and-place system. In this design, a mesh is implemented to promote attachment strength between nickel microgripper structure and SU-8 adaptor. The overall size of design 2 microgripper is approximately 1.5 mm by 1.7 mm and 4 mm by 8 mm for the SU-8 adaptor. The thicknesses of the electroplated nickel microgripper and the SU-8 adaptor are 20 and 170 μm, respectively. The microgripper tip consists of three separate square contact areas having a slight inclination at rest, which provides parallel gripping surfaces when used with designed object dimensions.

Electro-thermo-mechanical FEA for the microgripper design 2 was performed using ANSYS. Figure 3 shows the 3-dimensional mesh used for the FEA. Fine meshing was used for critical areas such as bent-beams and microgripper arms and relatively coarse meshing was used for SU-8 adaptor and nickel pad area.

In this FEA, we assumed that electroplated nickel microgripper and SU-8 adaptor obey Hook' s law and material properties of electroplated nickel and SU-8 do not change as a function of temperature. In addition, we assumed that there is no residual stress in the electroplated nickel and SU-8. The properties of electroplated nickel used for simulation are as follows: Young's modulus of 130 GPa, thermal expansion coefficient of 13.1 ppm/°C, Poisson's ratio of 0.31, resistivity of 6×10^{-8} Ω-m, and thermal conductivity 60.7×10^{6} W/μm °C [Davis et al. (1991), Fritz et al. (2000)]. The properties of SU-8 used for the simulation are as follows: Young's modulus of 4.4 GPa, thermal expansion coefficient of 50 ppm/°C, Poisson's ratio of 0.22, nearly infinite resistivity of 10^{44} Ω-m, and thermal conductivity 0.2×10^{6} W/μm °C.

Figure 4a and b show the design 2 microgripper ANSYS FEA simulation results for the temperature distribution and in-plane displacement, respectively when a voltage of 3 V is applied. With an applied voltage of 3 V, the induced

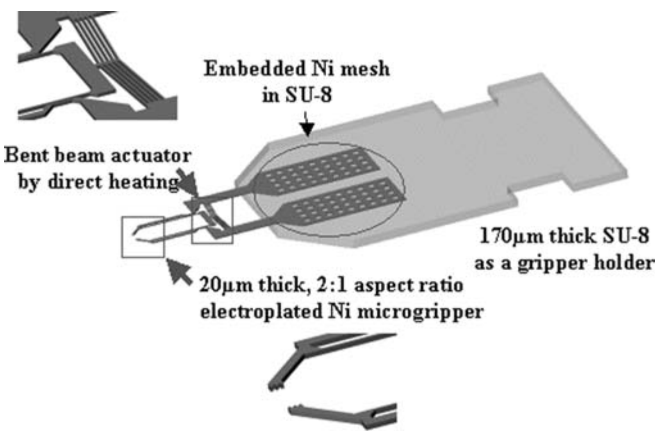

Fig. 2. Schematic diagram of an integrated metallic microgripper with SU-8 adaptor

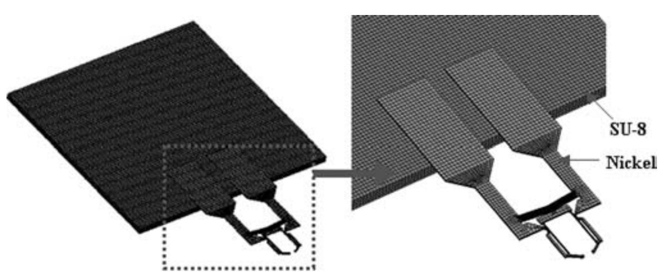

Fig. 3. Three-dimensional finite element mesh diagram for the design 2

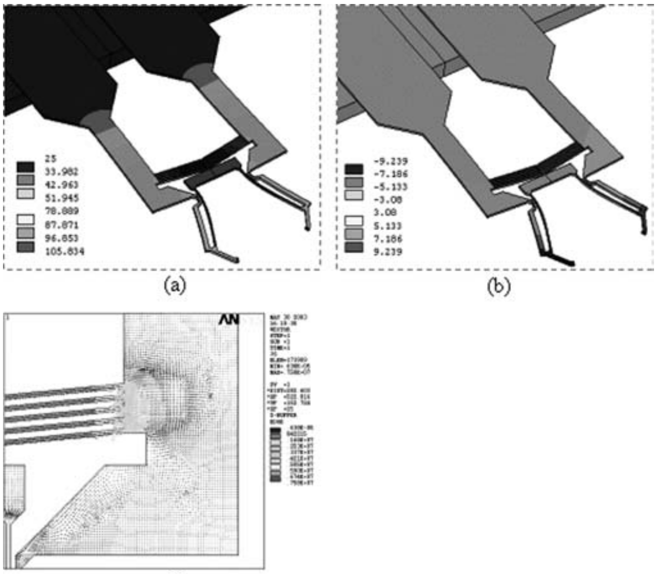

Fig. 4a-c. ANSYS FEA simulation results of the design 2 with an applied voltage of 3 V. **a** temperature distribution; **b** in-plane displacement; **c** induced current density distribution

current is 14.04 mA and the maximum current density is approximately 12×10^6 pA/μm^2. Maximum temperature of 106 °C occurs at the bent-beam structures and the balancing mass in the middle of the microgripper and thin arms of the microgripper are also substantially heated near to the maximum temperature. We can notice that the majority area of the SU-8 polymeric adaptor and the nickel pad area embedded in the SU-8 adaptor are maintained at low temperature. Maximum in-plane outward displacement for each tip is approximately 9.239 μm, yielding a tip opening of 18.478 μm for the microgripper when 3 V is applied. Gripper tips also moves −3.55 μm in the length direction and out-of-plane displacement is found to be negligibly small (−0.02 μm for each tip). Figure 4c shows the induced current density distribution near the bent-beam, and as expected the primary current path is through the bent-beams.

3 Fabrication

The fabrication sequence for the design 1 was started with thermal oxidation of silicon substrate or spin casting of SU-8 as a sacrificial layer. Metallic seed layers were deposited and a 220 μm thick SU-8 2075 layer was spin coated. The wafer was soft-baked at 95 °C for 90 min, exposed with an energy dose of 650 mJ/cm^2, followed by post-baking at 95 °C for 20 min. After development, the wafer was cleaned by reactive ion etch (RIE) which is followed by nickel electroplating through developed SU-8 mold. A nickel sulfamate electroplating bath was used and the current density was set at 10 mA/cm^2. Average growth rate of electroplated nickel was approximately 25 μm/hour. After the completion of the electroplating, SU-8 was completely dry etched using RIE with O_2 and CF_4 gas mixtures. Finally, the sacrificial oxide or SU-8 layer was etched and microgrippers were released from the substrate. Figure 5 shows scanning electron microscope (SEM) photomicrographs of batch fabricated three different types of electroplated nickel microgrippers of the design 1.

The fabrication sequence for the design 2 is shown in Fig. 6. Silicon substrate was thermally oxidized to form an oxide sacrificial layer. A 50 Å chromium adhesion layer and a 300 Å gold seed layer were deposited using electron-beam evaporation. A 25 μm thick SJR 5740 (Shipley) photoresist was spin coated and patterned. A 20 μm thick nickel was electroplated in a 55 °C nickel sulfamate bath with mechanical agitation. Next, the SJR 5740 photoresist mold was removed and the seed/adhesion metallic layers were etched away.

In order to create SU-8 adaptor, approximately 50 μm thick SU8–2025 was spin-coated which was followed by an evacuation process to remove air trapped in the trenches between the electrodeposited nickel structures. After the 1st SU-8 layer deposition, surface of SU-8 shows surface topology of the nickel microgripper. The 1st SU-8 layer was baked and the 2nd SU8 layer (120 μm thick SU8–2075) was spin coated to create a planarized polymeric adaptor for the microgripper. The double-layer SU–8 were baked and patterned, resulting in nickel microgripper structures partially embedded in SU-8 adaptor structures. Finally, batch microfabricated metallic microgrippers with SU8 adaptors were released by etching of the 2 μm SiO_2 in buffered HF solutions.

Figure 7 shows SEM photomicrographs and optical photomicrographs of the released design 2 microgrippers. The microgripper has an initial tip opening of 170 μm at rest and the tooth of the tip is 10 μm in width and 20 μm in height resulting in an aspect ratio of 2:1. The grippers were picked up manually with tweezers using the patterned notches in the SU-8 adaptors from a set of microgripper (Figure 7d and e).

4 Characterization

The design 1 microgrippers were mounted on a test station (Fig. 8a) in which a piezoelectric actuator was installed at

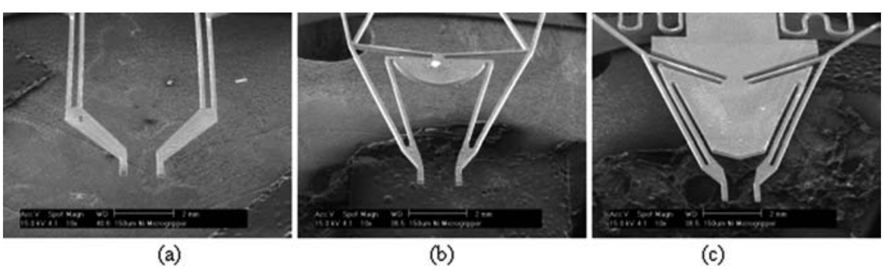

Fig. 5a-c. SEM photomicrographs of design 1 microgrippers: **a** type A; **b** type B; **c** type C

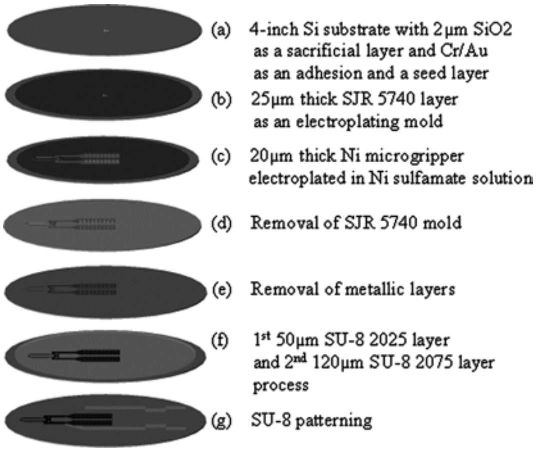

Fig. 6. Fabrication sequence of Ni microgrippers integrated with SU8 adaptors

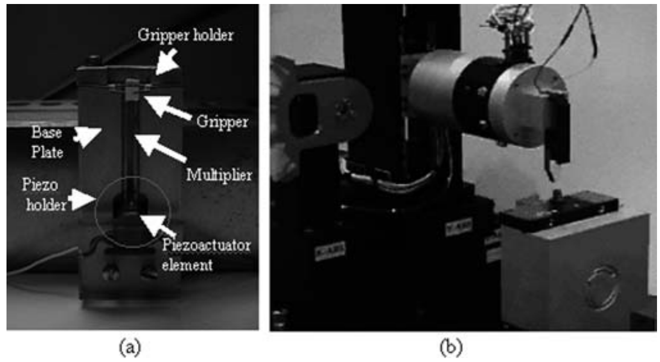

Fig. 8. **a** Design 1 microgripper test station, **b** microgripper installed on a robotic pick-and-place tool

the bottom of the vertical column and a plastic mechanical displacement amplifier connects the microgripper and the piezoelectric actuator. A maximum of 5 μm displacement was generated at the piezoelectric actuator and such displacement was mechanically amplified by the plastic intermediate piece. At the top end of the plastic, the displacement became a maximum of 10 μm.

Such amplified displacement directly applied to the microgripper in a manner as shown in Fig. 1. The amount of the tip openings were in the range of 135–165 μm for type A, 52–108 μm for type B and C. The wide variation of the measurement values is due to the difference of the alignment quality between the microgripper and the mechanical amplifier for each sample since the microgripper was manually mounted. The maximum deviation between the average value of the measured data and the simulation results is ~31% for type B and C. Figure 8b shows an optical photomicrograph which shows a microgripper installed on a macroscopically controlled robotic micro pick-and-place tool.

The design 2 microgripper was tested using a probe station by directly applying voltage between nickel pads. Applied voltage in the range of 2–5 V, frequency in the range of 0–5 Hz sawtooth and pulsed waveform were used to drive the microgripper. Figure 9 shows in-plane outward displacement of the tip of the microgripper as a function of the applied voltage. Up to applied voltage of 3.5 V, reproducible displacements were observed and there are good agreement between the ANSYS simulation results and measurement results for various types.

As the applied voltage increased beyond 3.5 V, the measured displacement became greater than the simulation results. Such a deviation was getting larger as the applied voltage continually increased. This could be explained by the plastic deformation of electroplated nickel microgripper due to excessive heating. For various types of the design 2 microgrippers, thermal deformation and complete failure of the microgripper by bent-beam burning occurred typically at around 4.5–5 V. Figure 10 shows optical photomicrographs of burning nickel bent-beams (Fig. 10-a) and completely burnt microgripper (Fig. 10b) with excessive heating.

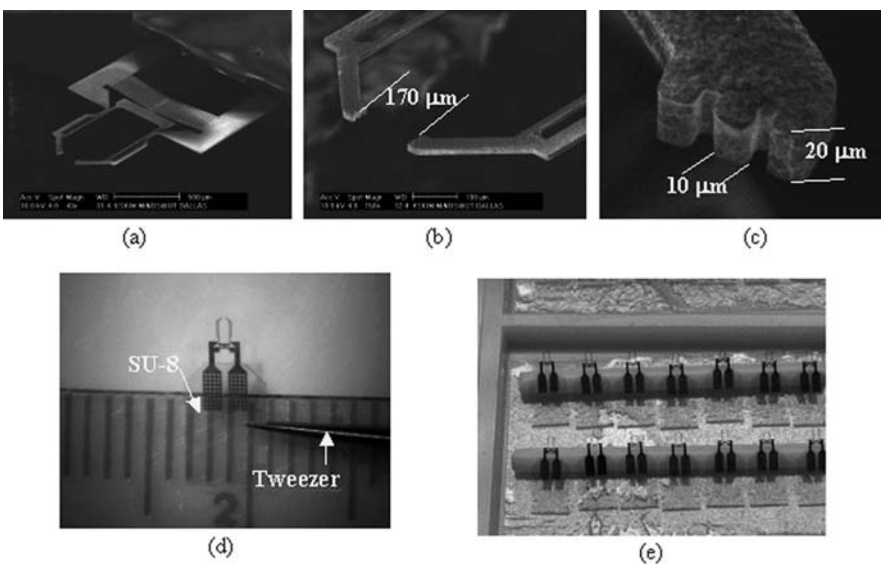

Fig. 7a-e. SEM and optical photomicrographs of design 2 micrgrippers. **a** A microgripper; **b** close-up view of a microgripper tip; **c** close-up view of the teeth of the tip; **d** a microgripper manually picked-up at the SU-8 adaptor notch by a tweezer; **e** a set of a microgripper

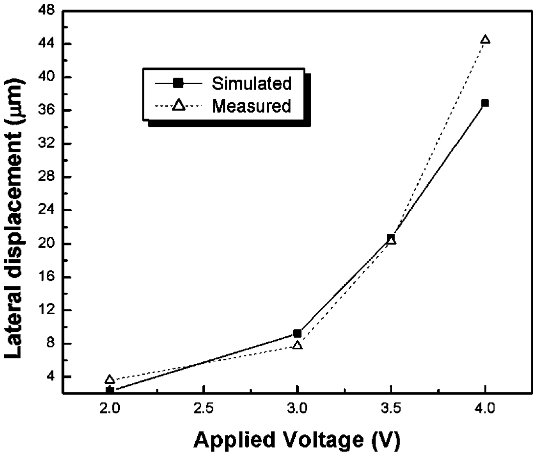

Fig. 9. Outward in-plane displacement of the tip of the design 2 microgripper as a function of the applied voltage

Fig. 10a,b. Optical photomicrographs of the design 2 metallic microgrippers with excessive voltages applied (> 4.5 V). **a** A burning microgripper; **b** a completely burnt and structurally disintegrated metallic microgrippers

5
Conclusion

Electroplated nickel microgrippers were designed, fabricated, and characterized to be used as end-effectors for micro/nano assembly applications. Two distinctive designs were developed: the first design was a relatively large scale microgripper with mechanical amplification of piezoelectric actuation; the second design was a relatively small scale microgripper which was electro-thermally actuated by direct heating of bent-beams and integrated with a novel SU-8 adaptor for easy-to-handle operation. Operations of both designs were successfully demonstrated. A part of the study showed that manual alignment of a microgripper on a conventional robotic tool can cause significant deviation of microgripper operation from one to another. Easy-to-handle, packaging friendly microgripper design could greatly decrease such errors. Failure mechanism of electro-thermally actuated bent-beam nickel microgripper was preliminarily studied. Investigation on the cause of the failure for electroplated metallic microstructures is rare and much study is needed.

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