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Microgripper: Design, Finite Element Analysis and Laser Microfabrication

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Abstract

This research is focused on new and innovative design, finite element analysis, precision laser microfabrication, and performance evaluation of a microgripper. The design of the microgripper with overall dimension of 1.4(W)x2.8(L)mm is based on a pair of cascaded structures oriented in a face-to-face direction, to act as microtweezers. Each cascaded structure is formed by connecting several basic actuation units in series. Each actuation unit consists of a constrainer and two semi-circular-shaped actuation beams. The actuation principle is based on the electro-thermal effect. On application of electrical potential, the output displacement and the force are generated from the summation of all basic actuation units in these cascaded structures. Finite element analysis (FEA) is applied to simulate dynamic performance of the microgripper and to choose proper operational voltage parameters. Thin nickel foil of a thickness of 12.5 micrometers was used in the laser microfabrication of these prototypes. Dynamic performance of the prototype device was evaluated within 0-1.9 voltage range. The maximum tweezing displacements of up to 30 micrometers were recorded for nickel microgripper prototype. Larger displacements are feasible through the optimization of design parameters.

1. Introduction

Microgripper is one of the key elements in microrobotics and microassembly technologies for handling and manipulating microobjects, such as, micro mechanical parts, electrical components, biological cells, micromaterials *etc* without damage. An essential component of all microgrippers, as of any micro-electro-mechanical systems (MEMS) and micro-opto-electro-mechanical systems (MOEMS), is an actuator, which provides the required grasping motions and generates applied force to make the device operate as a gripper or tweezers. Although various actuation methods have been reported in the literature [1,2], including electro-thermal, electro-static, piezoelectric, electro-magnetic, pneumatic and shape memory alloy effects, each method has its own distinguished specifics, which depend on the design and the fabrication process. Electro-thermally driven actuators are more compact as compared to others, can provide high output force, but have a more complex geometry and high-aspect dimensional ratio between the local elements and the overall device dimensions. On application of electric potential, the conductive elements (usually made from metal) produce Joule heating (resistive heating) and thermal expansion of the entire structure. The objective of the actuation structure design is to direct thermal expansion in the desired direction to produce motions by applying non-uniform resistive heating. It is therefore necessary to note that the choice of material, the design and the fabrication processes are interrelated. Laser microfabrication technology is a one of the modern technologies to produce high precision miniature parts with complex 2D/3D geometries with high-aspect dimensional ratio between local elements and overall dimensions [2-5]. Almost all light absorbing materials can be machined using photon energy available from this cost-effective, non-contact laser microfabrication technology.

The objective of the present work is to design, fabricate and test a new and innovative structure to act as a microgripper for microrobotics and microassembly applications. Finite element analysis was applied to model, simulate and predict microgripper's dynamic performance. Laser micro material removal technology was used to fabricate the nickel microgripper prototype.

2. Design

Figure 1 illustrates the geometrical design of the microgripper prototype requiring no post assembly. The monolithic structure of the design significantly reduces the overall dimensions of the microgripper to 1.4(W)x2.8(L)*mm*. As stated before, the actuation principle is based on the electro-thermal effect. The design utilizes multi-cascaded approach [5,6] based on a pair of cascaded actuators oriented in a face-to-face direction, to act as microtweezers. Each actuator is formed by connecting five actuation units in series. Therefore, on application of electrical potential, the output displacement and the force are generated from the summation of all the basic actuation units in these cascaded actuators. Each actuation unit consists of an internal constrainer and two semi-circular-shaped actuation beams. Since the thin actuation beams are of $25\mu m$ width and have higher electrical resistance, they heats up more than the wider constrainer, which has a width of $50\mu m$ and correspondingly lower electrical resistance. As a result, the actuation beam thermally expands more than the wider constrainer. Also, the constrainer plays an additional important role in the performance of the microgripper. When an actuation unit is electrically heated, actuation beam tends to expand in all directions evenly. The constrainer will expand lesser than the actuation beam and suppresses the expansion of the actuation unit in the vertical direction and allows the primary displacements in the desired horizontal direction. Microactuators tweeze jaws, shown in Figure 1, are supported by vertical levers to hold the object.

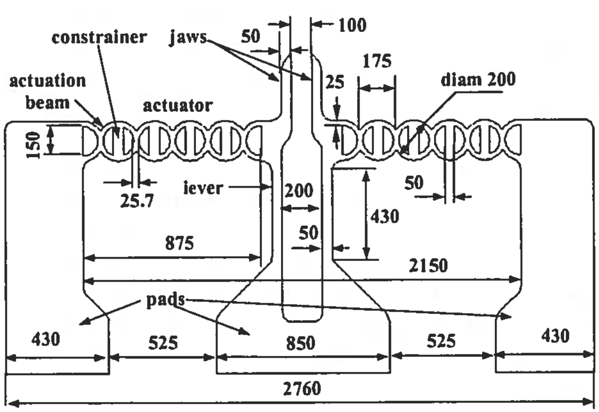


Figure 1. Geometrical design (dimensions in μm)

3. Finite element analysis

The finite element model of the microgripper was created and its dynamic performance was simulated using ANSYS - the finite element analysis software. The electric-thermal-structural analysis was performed using the element SOLID98 (a 10-node Tetrahedral Coupled-Field Solid). This element is capable of handling six degrees of freedom (x/y/z-displacements, temperature, voltage, and scalar magnetic potential). Another reason for choosing this element is that the tetrahedral shape is more suited to irregular shape models; that is ideal for the design of the circular shape of the actuation units.

After the model was meshed, the load was applied to the lower portion of the microgripper model (pads). In electric-thermal analysis, voltage potential of 1, 2, and 3V was applied between the outer and inner arms of the microgripper, and the initial temperature for each of the arms was set to 20 degrees Celsius. In large-deflection structural analysis, as a constraint, the pads were fixed in x/y/z-directions, allowing only the top portion to expand from the joules heating effect generated from the applied voltage.

The finite element analysis provided results on displacement, temperature, and voltage distribution as a function of input voltage. As an example, Figure 2 shows simulated displacement distribution of the nickel microgripper prototype with $2V$ applied voltage. Analysis of displacement distribution allows model and prediction of overall dynamic performance of the fabricated microgripper prototype and the maximum achievable tweezing displacements. The results of the finite element analysis with respect to tweezing displacements and maximum working temperature are listed in Table 1.

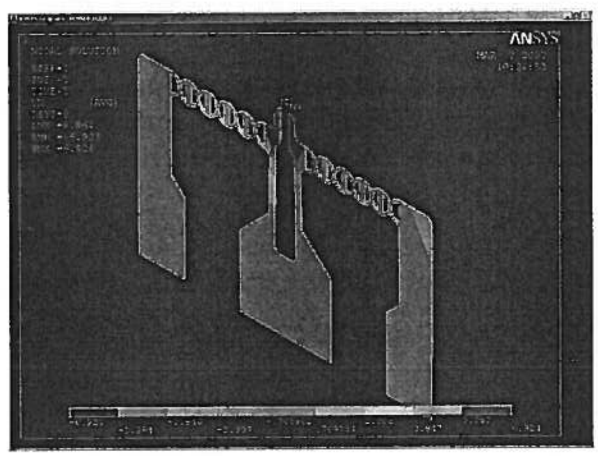


Figure 2. Simulated displacement distribution of the nickel microgripper prototype

Figure 3 shows the simulated temperature distribution of the nickel microgripper prototype with $2V$ applied voltage. Working temperatures of the tweezing jaws can be simulated and predicted using temperature distribution results. Also, the relationship between tweezing displacements and working temperatures, shown in Figure 4, is important for practical application, because working temperature provides limitation for handling objects made from thermo-sensitive materials.

Table 1. Results of FEA		
voltage	tweezing displacement	*max* temperature
1V	4.14μm	166.3°C
2V	13.84μm	575.1°C
3V	30.02μm	1256.2°C

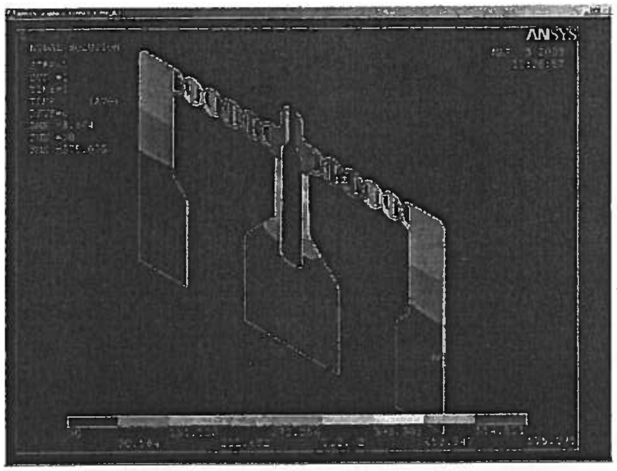


Figure 3. Simulated temperature distribution of the nickel microgripper prototype

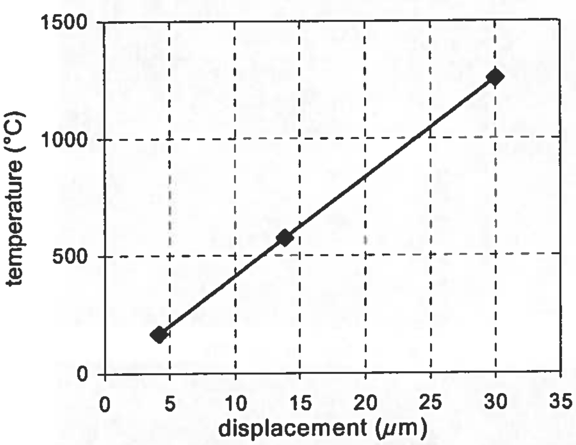


Figure 4. Tweezing displacement vs. *max* working temperature

4. Laser fabrication

Thin nickel foil with a thickness of 12.5μm was used in this study to fabricate the microgripper prototype using direct-write laser micromachining technology and employing the in-house developed laser processing system. The system is equipped with a Q-switch diode pumped solid state Nd:YAG laser with an appropriate optical beam delivery system and a three-axis CNC-based positioning system. The positioning accuracy of the motion system was in the order of 0.5μm in the X and Y axes. Both the laser and the motion system were controlled and synchronized using the in-house developed software to set up the optimized process parameters and control required for the generation of toolpath trajectory. An optical microscope ("Olympus" model SZX12) coupled with a VisionGauge® software from VISIONx Inc. was used to measure the gripper prototype geometry within an accuracy of 0.1μm.

5. Geometry evaluation

The microgripper's design has a complex geometry with five actuation units on the each side. Each actuation unit has a pair of semi-circular-shaped actuation beams. Complexity of the microgripper's geometry consists of a large number of combined geometrical features, such as, arcs, radii, lines, curvatures, segments and pockets, with high-aspect ratio in dimensions, e.g., thickness of the actuation beams is 25μm with respect to microgripper's overall dimension of 1.4(W)x2.8(L)mm.

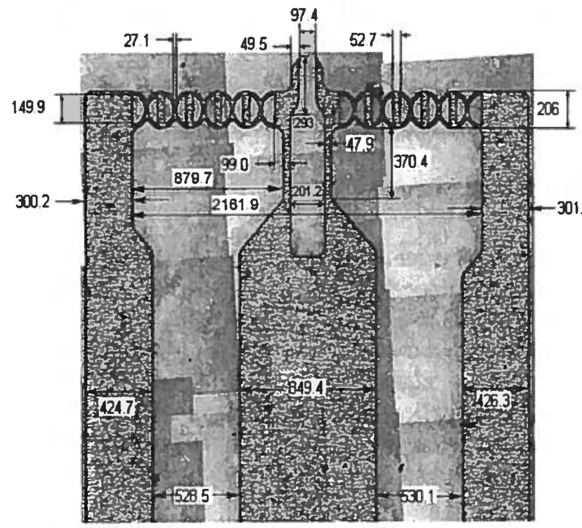


Figure 5. Fabricated nickel prototype (dimensions in μm)

Figure 5 shows fabricated nickel microgripper prototype. Table 2 summarizes the desired and machined dimensions. Absolute accuracy is also calculated. Although achieving the highest accuracy and precision was not the objective of this study, some dimensions of the fabricated prototype were machined within sub-micron accuracy, for example, the width of the jaws has an accuracy of 0.5μm and the length of the constrainer has an accuracy of 0.1μm due to high positional accuracy. On the other hand, it is necessary to note that some dimensions, such as, the diameter of the actuation unit (200μm), the length of the five actuation units (875μm) and the total length of all actuation units and jaws (2150μm), have relatively large deviations, such as, 6.0μm, 4.9μm, and 11.9μm, respectively, the reason being that these deviations represent the accumulative results of the fabrication process due to dynamic accuracy of motions.

Table 2. Geometry evaluation

Desired dimension, μm	Machined dimensions, μm	Absolute accuracy, μm
25.7	27.1	1.4
50.0	49.5	0.5
50.0	47.9	2.1
50.0	52.7	2.7
100.0	97.4	2.6
150.0	149.9	0.1
175.0	172.0	3.0
200.0	206.0	6.0
200.0	201.2	1.2
429.3	426.3	3.0
430.0	424.7	5.3
525.0	528.5	3.5
850.0	849.4	0.6
875.0	878.2	3.2
875.0	879.9	4.9
2150.0	2161.9	11.9

5. Performance testing

The experimental testing of the performance of the nickel microgripper prototype was carried out by using an optical microscope ("Mitutoyo" model 400) and VisionGauge® software. In particular, the microgripper prototype was placed under the microscope and DC voltage was applied between the pads. The time-space motions of the microgripper were video recorded and tweezing distances were measured from the recorded images.

Figure 6 shows typical performance test results as a function of tweezing distance in time with respect to the applied voltage and current. Approximately ten tweezing movements were recorded and measured for each of applied current. Complete dynamic performance of the microgripper prototype was analyzed at six different current levels {0.32A, 0.39A, 0.52A, 0.60A, 0.74A, 0.84A}. Figure 7 illustrates tweezing motions of the microgripper prototype before (Figure 7a) and after (Figure 7b) the actuation for 1.9V and 0.84A, achieving a tweezing displacement of 26.6μm. The results of all performance test experiments are illustrated in Figure 8, which includes the calculated mean value and min/max values of achieved tweezing motions for each applied current. It is quite obvious that tweezing distance widens with the increase in applied current until the temperature of the actuation beam will reach its melting point. Fabricated nickel prototype was able to produce maximum tweezing displacements of 28.8μm under applied 1.9V and 0.84A. It is also necessary to note that the repeatability of the tweezing motions is higher for lower applied current level.

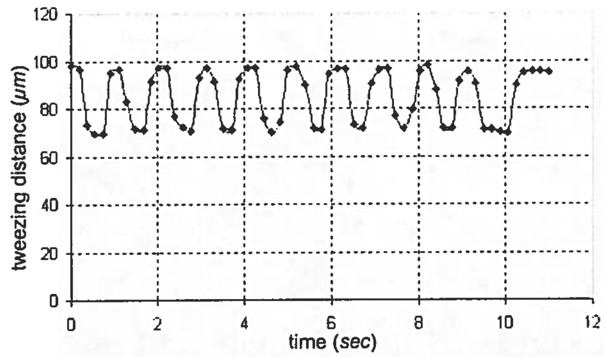
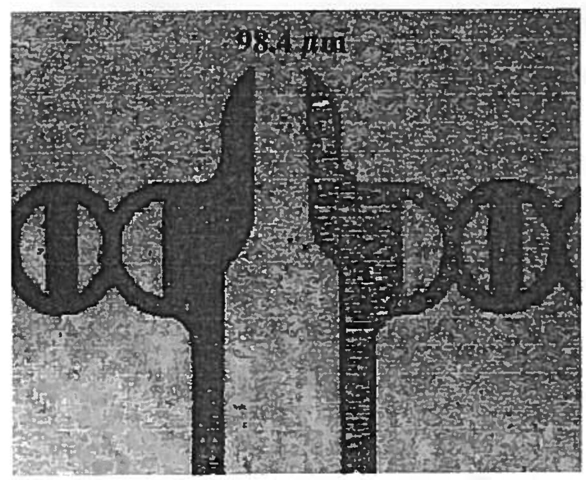
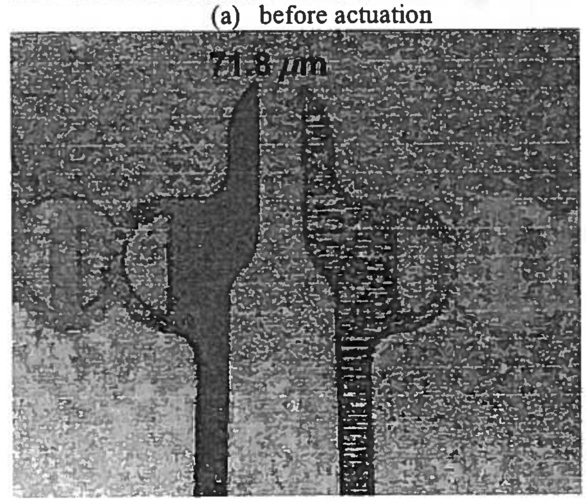


Figure 6. Performance testing of the nickel microgripper prototype (1.9V, 0.84A)



(a) before actuation



(b) after actuation

Figure 7. Motions of the nickel microgripper prototype (1.9V, 0.84A)

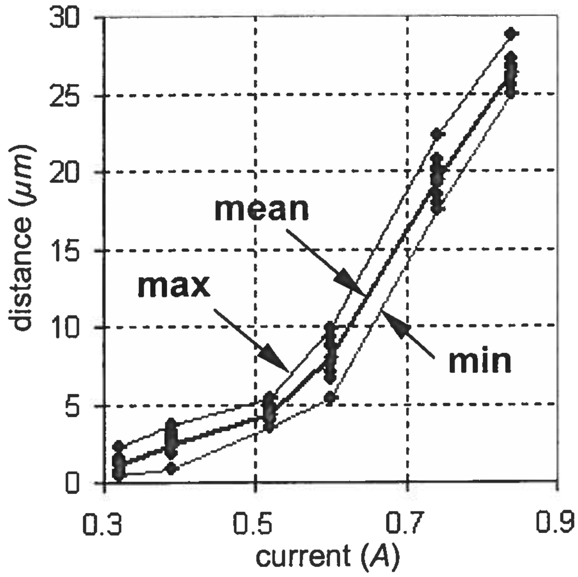


Figure 8. The test results of the nickel microgripper prototype

6. Summary and conclusions

A novel monolithic prototype structure with cascaded actuation units and semi-circular shape actuation beams to act as an electro-thermally driven microgripper with overall dimension of 1.4(W)x2.8(L)x0.0125(H)*mm* was designed, fabricated using nickel foil, and its performance evaluated. Finite element analysis was applied to simulate and predict dynamic performance of the designed microgripper. Fabricated prototype exhibited tweezing displacements from 0.8*μm* to 28.8*μm* for applied current variation from 0.32*A* to 0.84*A*. The following conclusions could be drawn from these studies:

1. The nickel microgripper prototypes have successfully demonstrated the ability to produce high gradient up to 34.29*μm/A* tweezing displacements up to 28.8*μm* under low input voltage (1.9*V*) and applied current (0.84*A*) conditions. A typical response time is 200*ms* for 1.6*W* electrical driving power.
2. The use of high-precision laser fabrication technology allowed to fabricate the microgripper prototype from a thin (12.5μm) nickel foil with high dimensional accuracy (down to 0.1μm). The final accuracy of the fabricated microgripper geometry is a result of a complex combination of the positional accuracy and dynamic accuracy of motions.
3. The microgripper prototype provides an inexpensive and compact solution for micromanipulating and microhandling operations in biological, medical, chemical and electro-opto-mechanical applications.

7. Acknowledgements

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