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DESIGN OF MICRO-GRIPPER WITH TOPOLOGY OPTIMAL COMPLIANT MECHANISMS

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ABSTRACT

The objective of this paper describes a new method to design a micro-gripper. In the paper, we use compliant mechanism actuated by micro combined V-shape electrothermal actuator to design a microgripper that the claw can clip the micro object. The compliant mechanism employs flexible to generate movement without any hinge; therefore, it is suitable for MEMS manufacture. The design of micro-gripper is accomplished in compliant mechanism with topology optimum and solved by sequential linear programming (SLP) methods. The design considerations, the analysis method, and the design results are discussed.

KEYWORDS

Microgripper; Topology optimization; Compliant mechanism.

INTRODUCTION

The manipulation of micro object is necessary for micro process, assemblage and position of MEMS (microelectromechanical systems), or micro medical operation. Early work on microgripper study has P. B. Chu[1] present a microgripper using two parallel electrostatic plate clip the object, but it has very high driven voltage about 50~100V. W. Nogimori[2] employ the LASER power to heat the fluid and drive the microgripper mechanism. Although this microgripper could clip about 900 μm but the volume is great and LASER power is expensive. M. Kohl[3] present a microgripper that use electrothermal to change the shape of "shape memory alloy (SMA)", the structure of SMA should be optimum otherwise it would be damage. B. Sebastian[4] employ the micro-pneumatic actuator to drive the microgripper, but its structure and fabrication is so complex. This microgripper have advantages of easy drive and fabrication, compact and optimum structure different from above microgripper.

The compliant mechanisms mean to use flexibility of material to replace the links and hinges of general mechanism. It can act not only as a general mechanism at small movement but also a simple two-dimension structure that made by a pure manufacture. The advantage of compliant mechanism is quite suitable for MEMS fabrication.

The method of design a compliant mechanism is made from the concept of topology optimization. The summary of topology optimization concept defines the "design domain" firstly, and divides the domain into a lot of finite elements. These elements equal to a lot of variables and give the artificial density "material density parameterization". Next, using the optimization theory resolved which elements would remain.

This study uses the Nickel V-shape beam electrothermal microactuator that has 800 μm length, 10 μm width of V-beam and analyses the different performance of microactuator with different apply voltage, amount of buckle beam, width of beam and buckle angle, furthermore. The structure of compliant mechanism uses the SU-8 photoresist to define design domain as 800×800 μm^2, thickness as 50 μm, and discusses the effect for different optimization parameter.

This microgripper uses the compliant mechanisms produce movement when driven by electrothermal microactuator. The design of compliant mechanism employs the topology optimization has the optimum shape and size when the objective function is minimized. The procedures of design methods are shown in Fig.1.

NOMENCLATURE

E_i effective Young's modulus of an element
E_o Young's modulus of the material
F_i external force on i port
SE strain energy
SE_i strain energy of element i
MSE mutual strain energy
MSE_1, MSE_2 output displacement on two tip of microgripper
MSE_i mutual strain energy of element i
u_i displacement on i port
V_C limitation of total volume of each element
$[K]$ global stiffness matrix
$[K_i]$ stiffness matrix of element i
$\{U\}$ global displacement vector
$\{U_i\}$ displacement vector of element i
$\{V\}$ global displacement vector when unit virtual force applied
$\{V_i\}$ displacement vector of element i when unit virtual force applied
$\Delta\rho_i$ variation of design variable
δ_o output displacement on specific port
ε strain field when F_i applied
ρ_i each design variable of artificial normal density

ρ_{i0} initial design variable of artificial normal density
σ stress field when F_i applied
σ_d stress field when unit virtual force applied

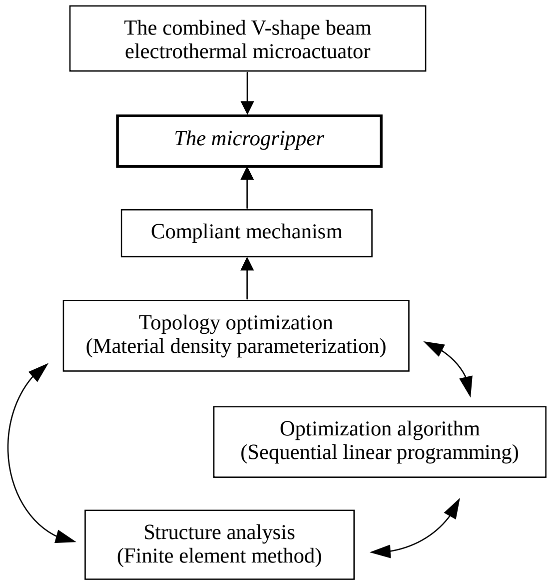

Fig. 1 The flow chart of design methods

COMPLIANT MECHANISMS

The compliant mechanisms are same with the general mechanisms defined by transmit the motion, force, or energy. The differences between then are replaced the links and hinges by flexibility of material. According to G. K. Ananthasuresh and Mary I. Frecker [5], compliant mechanism should be divide into two sorts: one is type of lumped compliant mechanism with small portion flexure application, and analyzed by Pseudo-Rigid-Body; another one is type of distributed compliant mechanism with large portion flexure application, design by topology optimization method. This study chooses the type of distributed compliant mechanism to design the microgripper. The cause of utilizing the compliant mechanism to do this microgripper because it just a two dimensions structure, so suit for micro fabrication. Another reason is it could design by specifics definitions.

TOPOLOGY OPTIMIZATION

The theory of topology optimization of compliant mechanism is to define an unknown design domain. This design domain includes several parameters, such as domains scale, boundary conditions and load location (Fig. 2). The material density parameterization method works as a tool to divide the design domain into n equality elements. The definition of each variable value is artificial normal density ρ_i that defined by artificial normal density (from 0 to 1) as shown in Eq. (1). This variable is related to the new Young's modulus E_i and original Young's modulus E_0 of each element in Eq. (2) [5].

$$\rho_i = \frac{density_{i\,new}}{density_{old}} \tag{1}$$

$$E_i = \rho_i E_o \tag{2}$$

The $density_{old}$ defined by original material density, $density_{i\,new}$ defined by new material density.

Therefore, when ρ approach to 0, the new Young's modulus $density_{i\,new}$ should be less that means the element should be removed. However, when ρ approach to 1 the result is opposite.

THE OPTIMIZATION PROBLEM MODEL

The topology optimization problems can be divided into two sorts: one is the structure supports the load, which should employ the stiffness of structure to optimization, as shown in Fig. 3(a). If the structure concern to the output displacement at specific port, as shown in Fig. 3(b), the optimization problem should employ the flexibility. When an external force F_{in} applied in Fig. 3(a), the problem is just a structure optimization problem. The system stiffness can be expressed by mean compliance in Eq. (3): [6]

$$\text{Mean compliance}=\sum_i F_i u_i \tag{3}$$

F_i: external force on i port
u_i: displacement on i port

Mean compliance is defined as the work done by the applied external force, which can be used as a measure of the stiffness of a structure system. Mean compliance also can be expressed by strain energy (SE) of the system. The SE may be expressed as follows: [5]

$$\text{SE}=\int_V \frac{1}{2}\sigma\varepsilon \,\text{dV} \tag{4}$$

or in matrix form as:

$$\text{SE}=\frac{1}{2}\{U\}^T[K]\{U\} \tag{5}$$

where the σ is stress field, ε is strain field, $[K]$ is global stiffness matrix and $\{U\}$is global displacement vector when F_i applied, as shown in Fig. 3(b).

When the problem demanded the output displacement at specific port, the optimization should employ the mutual strain energy (MSE) to define flexibility. The MSE can be presented as follows [6] .

$$\text{MSE}=1\cdot\delta_{out}=\int_V \sigma_d \varepsilon \,\text{dV} \tag{6}$$

or in matrix form :

MSE= $\{V\}^T\{K\}\{U\}$ (7)

where the σ_d is stress field, $[K]$ is global stiffness matrix and $\{V\}$ is global displacement vector when the unit virtual force is applied, as shown in Fig. 3(c).

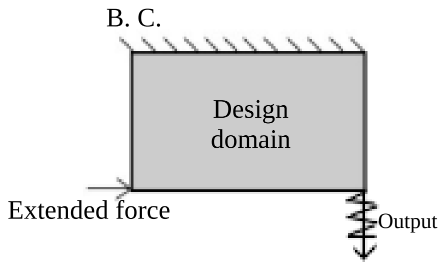

Fig. 2 Design domain

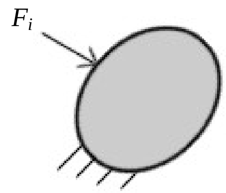

Fig. 3 (a) The structure supports load

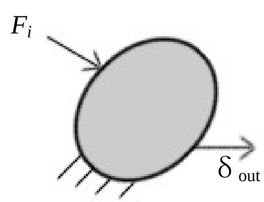

Fig. 3 (b) The structure supports the load and defines an output δ_{out} at specify port

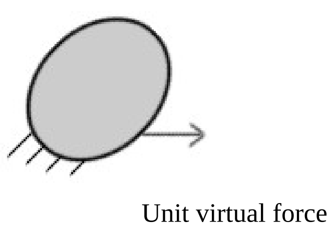

Fig. 3 (c) A unit virtual force at output port

For obtaining a optimization solution of the system, the gradient of SE and MSE is necessary [6].

$$\frac{\partial SE}{\partial \rho_i} = -\{U_i\}^T \frac{[K_i]}{\rho_i}\{U_i\} = -\frac{SE_i}{\rho_i} \quad (8)$$

$$\frac{\partial MSE}{\partial \rho_i} = -\{V_i\}^T \frac{[K_i]}{\rho_i}\{U_i\} = -\frac{MSE_i}{\rho_i} \quad (9)$$

The SE_i and MSE_i are the strain energy and mutual strain energy of every element in Eq. (8) and Eq. (9), respectively. For desiring most stiffness of the structure is applied the load, the optimization problem is just a single object function for minimum SE. Therefore, when the structure not only desire most stiffness but also need to generate displacement at specific port, the optimization problem must be multi-criteria object function of minimum SE and maximum MSE. This study desires the output displacement at two specific ports. Consequently, this study combines the criteria of two desire output post, and the optimization problem numerical model was shown as following：

$$\text{minimize：} \varphi(\rho_i) = \frac{SE}{MSE_1 + MSE_2} \quad (10)$$

subject to：

$$g_1(\rho_i) = -\rho_i \le 0 \quad (11)$$

$$g_2(\rho_i) = \rho_i - 1 \le 0 \quad (12)$$

$$h(\rho) = \sum_{i=1}^{n} \rho_i v_i - V_C \le 0 \quad (13)$$

where the SE is the strain energy while the external force applied. The MSE_1 and MSE_2 are the mutual strain energy while the unit dummy load applied at output ports. The ρ_i are design variable, v_i are the volume of every elements, and V_C is the limitation of total volume of each element.

The optimization result would be artificial material density ρ_i ($0< \rho_i <1$) that means which elements should be removed. Therefore, the optimal topology configuration would be appeared. This optimum structure will transform the motion and force at specific input and output port. We call it mechanism. This optimal topology compliant mechanism has optimal design between the flexibility and stiffness. In other word, this compliant mechanism not only can generate larger displacement at specific ports but also has enough stiffness while it supported the load.

The optimization problem model of Eq. (10), (11), (12) and (13) is nonlinear form. In here, we uses the Sequential Linear programming (SLP) to resolve it. The main concept of the SLP is to use first-order linear terms in the Taylor's series expansion to approximate the original nonlinear problem. The problem can be expressed as : [7]

$$\text{minimize：} \sum_{i=1}^{n} \frac{\partial \varphi(\rho_i)}{\partial \rho_i} \Delta\rho_i \quad (14)$$

subject to：

$$\bar{g}_{1i}(\rho_i) = g_{1i}(\rho_{i0}) + \frac{\partial g_{1i}(\rho_i)}{\partial \rho_i} \Delta\rho_i \le 0 \quad (15)$$

$$\bar{g}_{2i}(\rho_i) = g_{2i}(\rho_{i0}) + \frac{\partial g_{2i}(\rho_i)}{\partial \rho_i}\Delta\rho_i \le 0 \quad (16)$$

$$\bar{h}(\rho_i) = \sum_{i=1}^{n} h(\rho_{i0}) + \frac{\partial h(\rho_i)}{\partial \rho_i}\Delta\rho_i < V_C \quad (17)$$

The new variables are $\Delta\rho_i$ while the nonlinear problem transformed into the linear problem. To solve this linear problem, we should give an initial value ρ_{i0} for the system. Then we can find the new variables $\Delta\rho_i$. Let us definite ρ_{i0} updated by $\rho_{i0}+\Delta\rho_i$, and then substituted the new ρ_{i0} to the problem to solve the $\Delta\rho_i$ again. Repeating above iterations until the $\Delta\rho_i$ is smaller than a given limited value, consequently the problem converged. The solution procedures of the optimization problem can show as in Fig. 4.

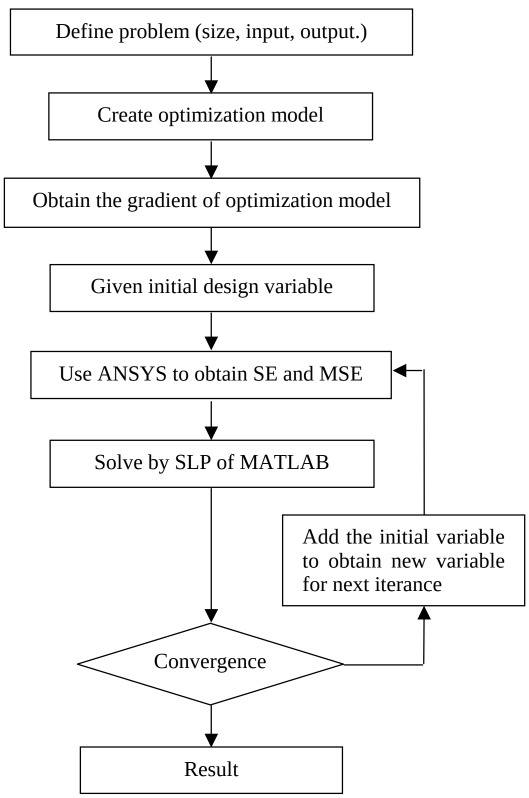

Fig.4 The solution procedures of optimum problem

DESIGN THE MICROGRIPPER

The design procedures of this microgripper include deciding which part material of the system would be used, defining the microgripper scale and design domain, and determining the actuator type and specification. Inn this study we used two V-beam numbers, and buckle angle 4° microactuator that has about 5.5μm displacement, 6000μN forces when two voltages are applied.

The design domain of topology optimization means to define an unknown domain that what configuration of mechanism in the domain is unknown. The definitions of design domain include boundary conditions, domain scale, finite elements size by divided, input port by force applied, output ports number and direction, spring constants k_s. The definitions of design domain for microgripper show in Fig. 5. The domain defined symmetry by single input and two outputs, and other detail definitions show in Tab. 1.

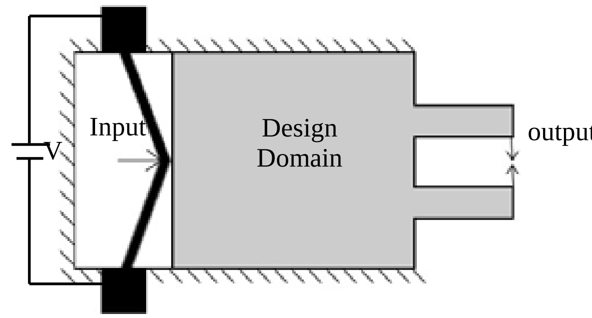

Fig. 5 The design domain scheme of microgripper

Tab. 1 Design domain specifications

Domain size	Clips size	Divided size
800X800 μ m^2	100 μ m	20 μ m

Spring constants	Actuated force
50N/m	6000 μ N

TOPOLOGY OPTIMIZATION OF MICROGRIPPER

After defining the design domain and deciding the microactuator specification, we should solve the optimization problems Eq. (10 - 12) to obtain the topology optimization solution. In order to simplify fabrication, we need to provide enough flexibility and thickness for compliant mechanism of this microgripper. We choose the SU-8 photoresister to make it. The SU-8 has Young's modulus E=4.4 GPa and the Poisson's ratio ν =0.22.

According to above definitions of design domain, the topology optimization result after about forty times iteration shows in Fig. 6. The SE and MSE of object function at output spring constant 50N/m shows in Fig. 7 and Fig. 8. The convergence value of SE is about 3600 and MSE1, MSE2 equal about 6.

The color of every element presents different artificial normal density 0 to 1. When the color approaches to white that means the artificial normal density of element more approach to 0, this element is soft and should be removed. The color of element approaching to black is opposite from above. After obtaining the topology optimization contour, the finite element commercial software, ANSYS, was used to build this result model and to simulate it. The simulation result of this topology optimization shows in Fig. 9, the clip tip would move in y-direction about 20 μ m and force about 600 μ N at input force 6000 μ N without output spring.

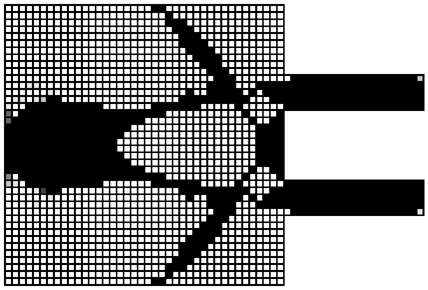

Fig. 6 Ttopology optimization result

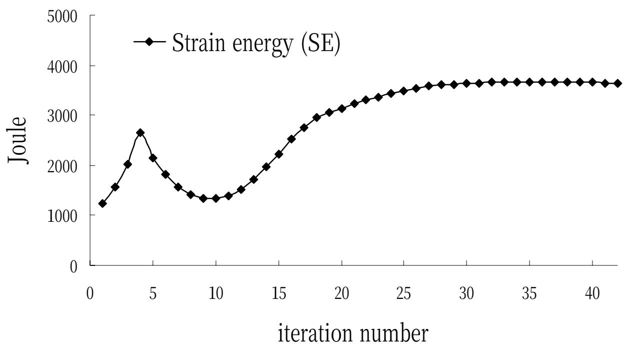

Fig. 7 The variation of SE

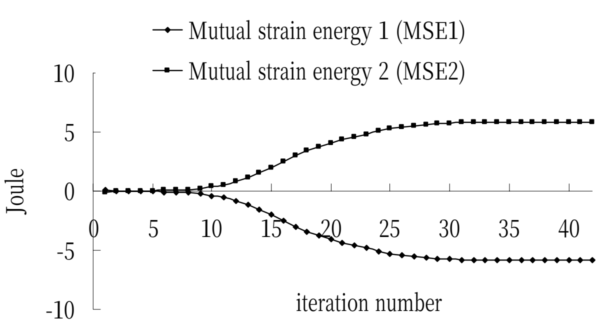

Fig. 8 The variation of MSE1 and MSE2

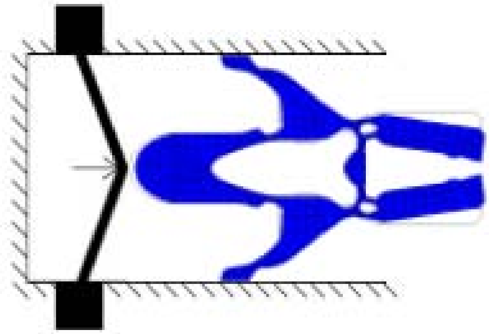

Fig. 9 The simulation of microgripper

DISCUSSION

This paper describes a new way that using the topology optimization of compliant mechanism to design the microgripper. This microgripper has advantages of easy driven, optimum structure and is suitable for MEMS fabrication. In the topology optimization problem that has many parameters would affect the topology optimization result, such as output port spring constant, the thickness of design domain and material constrain.

The effect of topology optimization with different output port spring constant K parameters shows in Fig. 10. The MSE curve of Fig. 10 is decreased with large spring constants, but the decreased amount of MSE is smaller than increased amount of spring constants. The output force of microgripper should be increased with large spring constant. Consequently, the spring constant mainly determines the material amounts of clips, in other words, it determines the stiffness of two clips of gripper to affect the output force. The output force would be invariable at 600 μN when the K is greater than 100N/m, because the stiffness of clips would be the upper value. The SE curve of Fig. 10 is increase with large spring constants, because the larger K makes the more stiffness in clips. The left portion of gripper that support the input force would be decrease the stiffness. The more stiffness means the smaller SE, therefore the microgripper would have more output displacement (see Fig. 11). Therefore, the different output requirement of microgripper could be reached with different spring constant for topology optimization (Fig. 12).

The SE and MSE with different thickness of design domain show in Fig. 13. The thick microgripper that have more stiffness therefore the SE would decrease with thick microgripper. According to statement, the left portion of microgripper has more stiffness, but the MSE of microgripper would be decreased. Therefore, the lesser MSE with same spring constant at output port means the output force would be decreased and the more SE means the output displacement would be decreased (Fig. 14). The Fig. 15 shows the topology optimization result with different thickness of design domain.

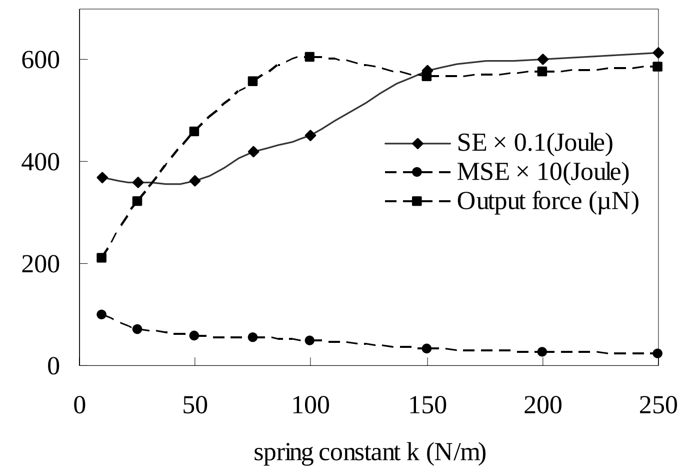

Fig. 10 The effect of topology optimization result with different spring constant

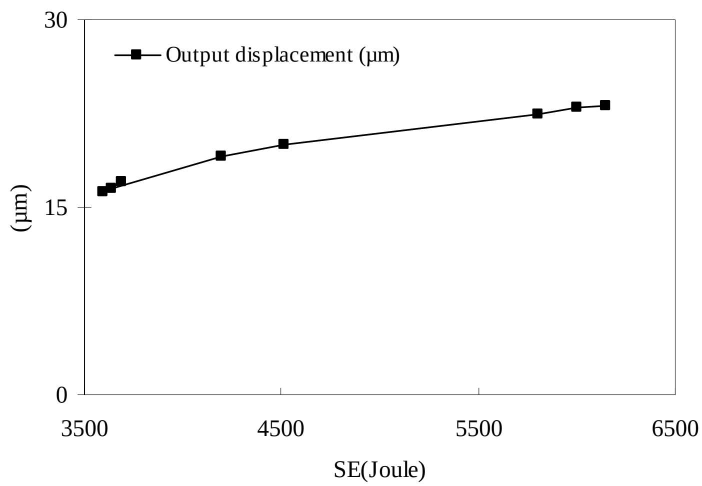

Fig. 11 The force-displacement of microgripper

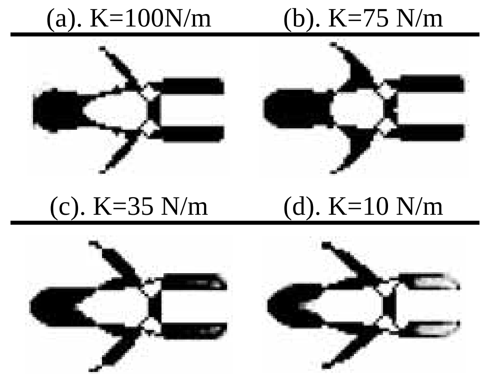

Fig. 12 The optimization result with different spring constant

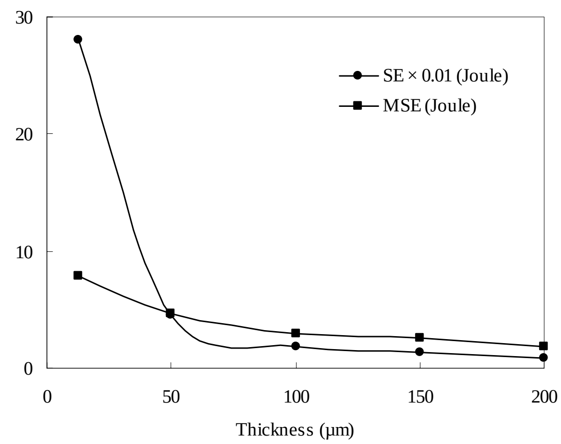

Fig. 13 The result with different thickness

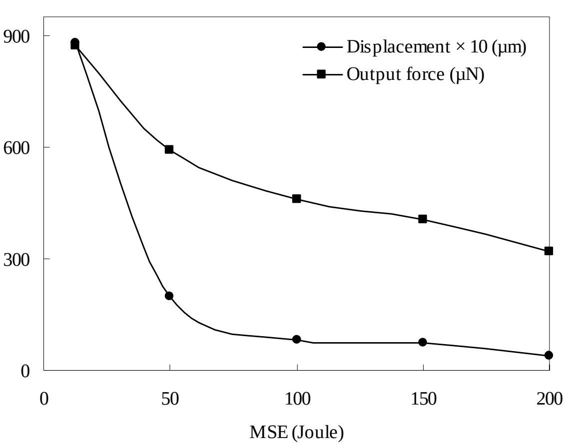

Fig. 14 The result with different MSE

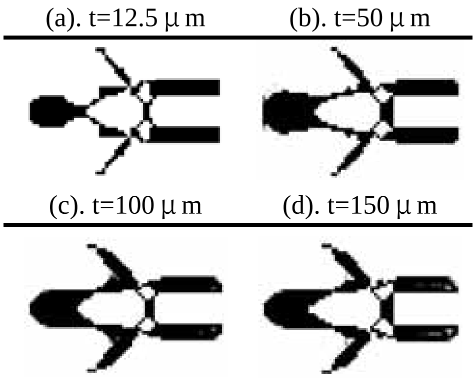

Fig.15 The optimization result with different thickness of design domain

CONCLUSION

This study designs a microgripper that employs the electrothermal microactuator to drive a topology optimization of compliant mechanism. The electrothermal microactuator used the material of Nickel, and compliant mechanism uses the SU-8 photo resister. This microgripper could produce about 20 μ m output displacements and forces about 600 μ N when two voltages were applied with output spring constant K=100N/m.

In the other analysis, the effect of electrothermal microactuator performance with different parameters that includes the combined beam numbers, buckle beam angle, applied voltage and beam size. When we added the combined beam numbers, buckle beam angle, applied voltage and beam size, the force of microactuator would be amplified. But adding the buckle angle and beam size would decrease the output displacement.

The effect of topology optimization with different optimum parameters also would be discussed. The larger output spring constant that has more output force and displacement, but the stiffness of microgripper would be decreased. Although the output force and displacement would be increased with large spring constant, but the failure of material should be considered. The thickness of microgripper also should be discussed. The thicker microgripper that has lesser output force and displacement, but the stiffness of microgripper would be increased.

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