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Topology optimization of a PCB substrate considering mechanical constraints and heat conductivity

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Abstract

A material mixing method was suggested to obtain an optimal topology for a multiple material structure with multiple thermal criteria, based on Evolutionary Structural Optimization (ESO). To examine the validity of the method, it was applied to a printed circuit board (PCB) substrate. The overall efficiency of material usage in a PCB substrate was measured in terms of the combination of thermal stress and heat flux density by using a combination strategy with weighting factors. A Pareto optimal topology solution having multiple thermal criteria was obtained. The effects of weighting factors for multiple thermal criteria as well as mechanical boundary conditions on optimal topologies were investigated. It was found that as the weighting factor for heat flux density becomes larger, the sizes of holes at the center portion become larger in order to dissipate thermal energy much more efficiently. It was also found that as the magnitudes of the heat conduction are getting larger, a similar tendency of the optimal topologies is obtained to the above. The thermal stress on the clamped four sides is larger than that on the two sides clamped. It is verified that the suggested material mixing method works very well for topology optimization of a PCB substrate for various mechanical boundary conditions with multiple thermal criteria.

Keywords: PCB substrate; Multiple thermal criteria; Material mixing method; Topology optimization; Evolutionary structural optimization

1. Introduction

In the area of MEMS, topology optimization techniques such as homogenization, mass distribution and evolutionary structural optimization (ESO) methods have been actively applied to microactuators [1], compliant mechanisms [2] and printed circuit board (PCB) substrates [3, 4], respectively. They deal with topology optimization of only homogeneous structures. Especially, one of the thermal actuators, microgripper, has been designed by a biomorph structure [5] consisting of two materials with different thermal strains by using the mass distribution method. Also, a material mixing method [6] has been developed to obtain an optimal topology of a multiple material structure with the maximum stiffness under a static load based on ESO [7]. It is based on the concept of gradually removing redundant elements of the low stressed part of the material from a structure to achieve an optimal design. But, a material mixing method has not been suggested to obtain an optimal topology of a multiple material structure with multiple thermal criteria in the thermal optimization problems, which can be applied to PCB substrates and thermal actuators.

In this study, a material mixing method was sug-

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gested in order to obtain an optimal topology of a multiple material structure with multiple thermal criteria in a thermal environment based on ESO. As an example, a PCB substrate was chosen to investigate the validity of the suggested method. Also, the effects of weighting factors for thermal stress and heat flux criteria as well as mechanical boundary conditions and heat conductivity on optimal topologies were investigated. Since thermal performance of a substrate is affected by thermal stress and heat flux, a Pareto topology solution was obtained due to the level of importance by use of weighting factors.

2. Multiple thermal criteria

To estimate the relative efficiencies of material usage of an element, the following two dimensionless factors are introduced [3] as:

efficiency factor of thermal stress: $\alpha_s^e = \frac{\sigma^e}{\sigma^{max}}$ (1)

efficiency factor of heat flux: $\alpha_f^e = \frac{J^e}{J^{max}}$ (2)

where, σ^e and σ^{max} denote the e th element's and the maximum thermal stress, respectively. J^e and J^{max} represent the e th element's and the maximum heat flux densities, respectively.

2.1 Multiobjective optimization

In the case that multicriteria for a structure should be considered, multiobjective optimization should be implemented. In this study, the effect of the thermal stress and heat flux criteria is considered, and those can be represented by Eq. (3).

$$\alpha^e = w_s \alpha_s^e + w_f \alpha_f^e \tag{3}$$

where, w_s and w_f are the weighting factors for thermal stress and heat flux criteria, respectively. The weighting factors provide a means for giving different levels of importance to these two criteria.

2.2 Suppression of checkerboard patterns

Checkerboard patterns are quite common in various finite element-based structural optimization techniques. As pointed out in Sigmund, O. et al., 1998 [8], four node element meshes appear to be locally stiffer than any real material. Shapes and topologies produced with checkerboard patterns may be unacceptable for practical applications. For this reason, the suppression of the checkerboard pattern has attracted considerable attention recently. To correct this, an intuitive smoothing technique [4] was introduced which consists of two basic steps:

(1) Calculate the efficiency factor at each node by using a volumetric weighted average of the efficiency factor for each element connected to this need.

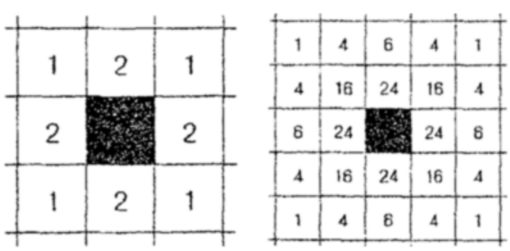
(2) Calculate the new efficiency factor for an element by calculating the average of the efficiency factor for that element.

The weighting factors for each element are shown in Fig. 1, and classified into the first and the second order schemes due to the number of layers surrounding the center element. For a regular rectangular mesh, the efficiency of the smoothed element is calculated from itself and those of eight surrounding elements in the first surrounding layer shown in Fig. 1(a). When necessary, a second order smoothing approach may be applied, in which the smoothed efficiency factors are smoothed further. For a rectangular mesh, the efficiency of the smoothed element is calculated from itself and those of 24 surrounding elements in the first and second layers shown in Fig. 1(b). A new efficiency factor for the center element by applying the smoothing technique can be expressed by Eq. (4), and the following requirement for the sum of the weighting factors, Eq. (5), should be satisfied.

$$\alpha^e = \left(\sum_{i=1}^{m} w_i V_i \alpha_i^e\right) / \left(\sum_{i=1}^{m} w_i V_i\right) \tag{4}$$

$$\sum_{i=1}^{m} w_i = 1 \tag{5}$$

Here, α^e is the multiobjective sensitivity number by suppression, w_i represents the filter parameter, V_i denotes the connection elemental volume, and m



(a) First order scheme (b) Second order scheme

Fig. 1. The filter parameter for the checkerboard suppression.

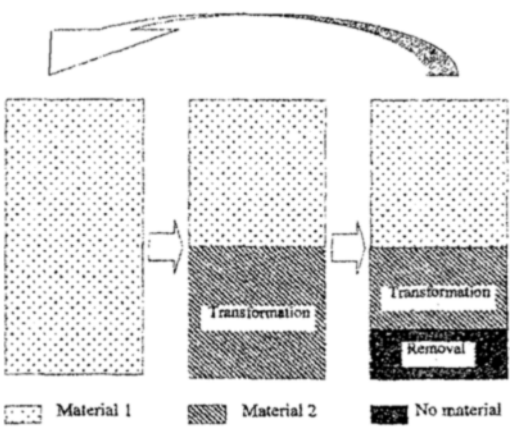


Fig. 2. Procedure of material transformation and element removal.

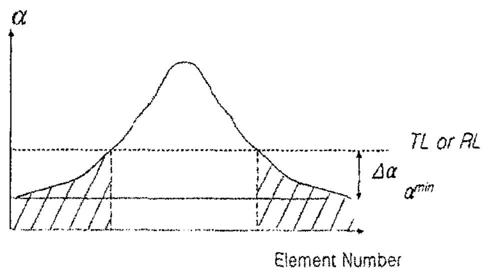


Fig. 3. Transformation and removal lines.

is the number of connected elements. In this study, the second order scheme was implemented.

3. Material mixing method

The explanation of the material mixing method for a bimaterial structure is given here in brief, in the material mixing method for a multiple structure with more than two materials is basically same as for that with two materials. Let the larger and the smaller thermal conductivity and density of the two materials be set material 1 and material 2, respectively. First, consider a design region made of material 1. Apply both the transformation and the removal lines for material transformation and element removal, respectively. As the first step, the elements having lower level of thermal stress and heat flux density than the transformation line are transformed into material 2. As the second step, the elements having lower level of thermal stress and heat flux density than the removal line, which is established as the lower level of thermal stress and heat flux value than the transformation line, are removed. This procedure is shown in Fig. 2.

The transformation line (TL) is defined as Eq. (6). The efficiency factor, α^e, of the thermal stress and heat flux density in each element after thermal analysis is defined as Eq. (4). If α^e of a certain element is smaller than the transformation line, that is, Eq. (7) is satisfied, the element is transformed from material 1 to material 2.

$$TL = \alpha^{\min} + \Delta\alpha \tag{6}$$

$$\alpha^e \le TL \tag{7}$$

where, the threshold ratio $\Delta\alpha$ can be selected as very small value depending on the problem since it controls the range of the elements to be transformed, as shown Fig. 3.

The removal line (RL) is defined as Eq. (8). If α^e of a certain element is smaller than the removal line, that is, Eq. (9) is satisfied, the element is removed.

$$RL = \alpha^{\min} + \Delta\alpha \tag{8}$$

$$\alpha^e \le RL \tag{9}$$

where, the threshold ratio $\Delta\alpha$ can be selected as a very small value depending on the problem since it controls the range of the elements to be removed.

A flowchart of the topology optimization process is shown in Fig. 4. FE analysis for the initial design is performed under the given loads and boundary constraints. Transformation and removal lines are determined from the calculated multiobjective sensitivity number, α^e, for each element. The elements having smaller α^e than the transformation line (TL) are transformed into material 2. After the given convergence constraints are checked and if not satisfied, the elements having smaller α^e than the removal line (RL) are removed. After the given constraints are checked again, and if not satisfied, FE analysis for the obtained topology is performed. This procedure is iterated until satisfying the convergence constraints.

4. Topology optimization for a pcb substrate

One role of the PCB substrate is to dissipate the maximum amount of thermal energy with a limited amount of material while at the same time withstanding the induced thermal stresses. Fig. 5 shows an FEA model of the PCB substrate, which is discretized by 53×33 with 4-node quadrilateral elements [3, 4]. In

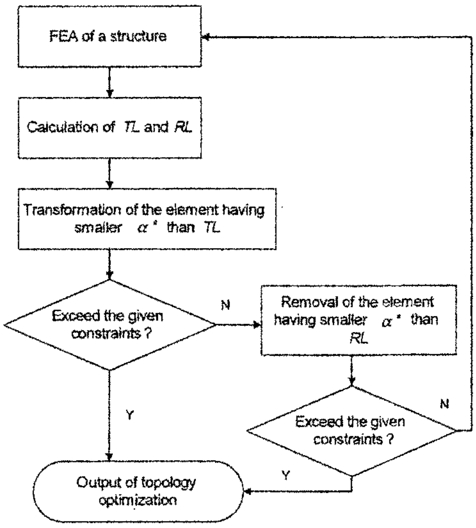


Fig. 4. Flowchart of topology optimization process.

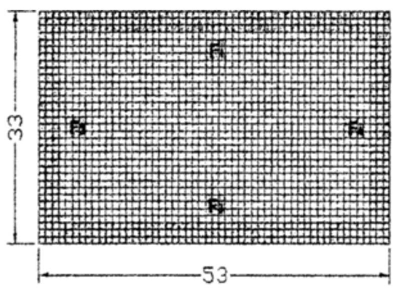


Fig. 5. Initial FEA model of the PCB substrate.

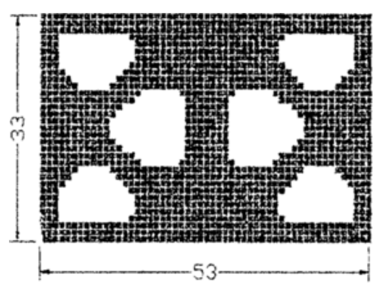


Fig. 6. Topology solution of a PCB substrate made.

Table 1. Material properties.

	Material 1	Material 2-1	Material 2-2	Material 2-3
Young's modulus	210 GPa	210 GPa	210 GPa	210 GPa
Density	2.32 kg /m^3	1.624 kg /m^3	1.624 kg /m^3	1.624 kg /m^3
Heat conductivity	0.045 W/mmK	0.0225 W/mmK	0.045 W/mmK	0.09 W/mmK
Thermal expansion coefficient	1.2×10^{-5}/℃	2.32×10^{-5}/℃	2.32×10^{-5}/℃	2.32×10^{-5}/℃
Poison's ratio	0.3	0.3	0.3	0.3

the model, four steady heat flux inputs, F1, F2, F3 and F4, are set to be 0.2 kW/mm^2. The temperature on the exterior boundary is maintained at 0℃. In this example, the effects of weighting factors for thermal stress and heat flux criteria, and mechanical boundary constraints and heat conductivity on optimal topologies of a PCB substrate with multiple materials, were investigated. The optimal topology of a PCB substrate made of 1 material shown in Fig. 6 in the case of $w_s : w_f = 0.5 : 0.5$ was obtained as very similar to the previous research [3, 4]. Therefore, it is found that the topology optimization scheme is applicable.

Two materials are to be mixed for an optimal topology by the suggested material mixing method. The objective of this study is to obtain a conceptual topology rather than precisely predict the responses of temperature and stress in an actual PCB substrate. By using the materials, the effect of heat conductivity on optimal topology of a PCB substrate was investigated. Heat conductivity and density of material 1 are 0.045 W/mmK and 2.32kg/m^3, respectively. Heat conductivities of material 2 are assumed to be 50%, 100% and 200% of that of material 1. The density of material 2 is assumed to be 70% of material 1. Young's modulus is 210 GPa. Thermal expansion coefficient is 1.2×10^{-5}/℃. Poisson's ratio is 0.3. The material properties are listed in Table 1.

The constraint of the final mass was established as 70% of the initial mass made by material 1 only. Figure 7 shows a Pareto topology solution due to the level of importance of the multiple thermal criteria. From Fig. 7 it is found that as the weighting factor for heat flux density is getting larger, the sizes of holes at the center portion become larger in order to dissipate thermal energy much efficiently. Whereas, as the weighting factor for thermal stress is getting larger, the sizes of holes at the center portion become smaller in order to withstand the thermal stress. The variation of the optimal topologies due to the change of thermal conductivity in the case of the same weighting factors for thermal stress and heat flux criteria was also obtained. It was found that the sizes of holes at the center portion become larger as the magnitudes of the thermal conductivity are getting larger for the same weighting factors as expected.

To examine the effects of mechanical boundary conditions on the optimal topologies, a series of variations of boundary constraints--fully clamped on the four edges, clamped on the top and bottom edges and clamped on the left and right edges--were considered

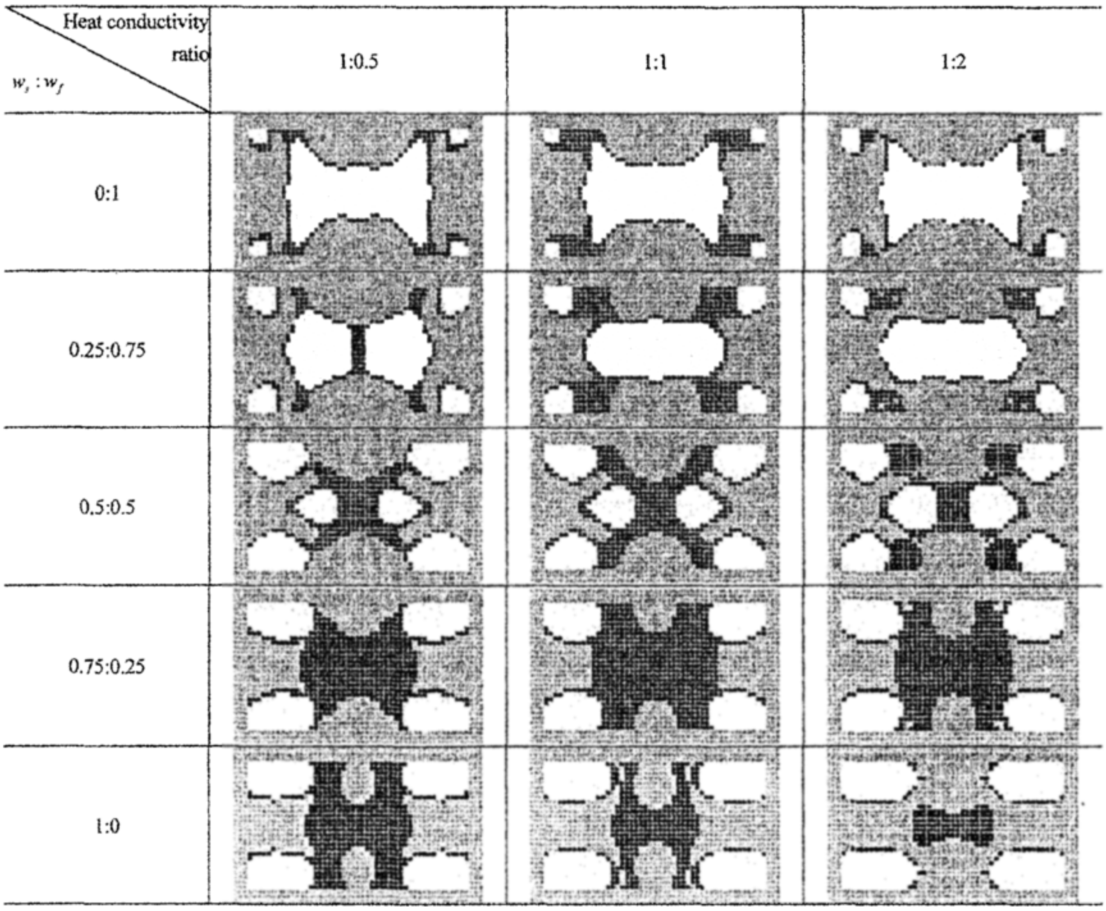


Fig. 7. A Pareto topology solution of a PCB substrate made of 2 materials – fully clamped on the four edges.

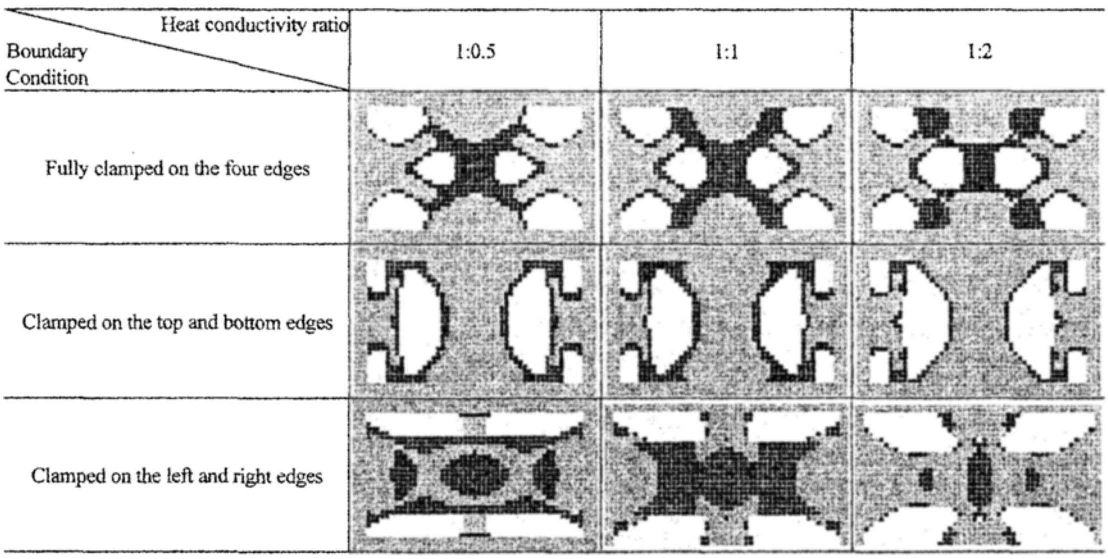
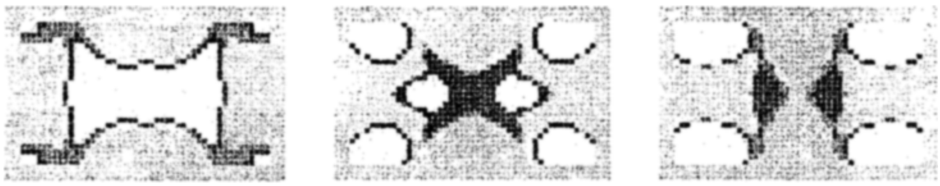


Fig. 8. Optimal topologies of a PCB substrate made of 2 materials due to the boundary constraints and heat conductivity.



(a) $w_s : w_f = 0:1$ (b) $w_s : w_f = 0.5:0.5$ (c) $w_s : w_f = 1:0$

Fig. 9. A Pareto topology solution of a PCB substrate made of 3 materials – fully clamped on the four edges.

Table 2. Material properties.

	Material A	Material B	Material C
Density	2.32 kg/m^3	1.16 kg/m^3	0.696 kg/m^3
Heat conductivity	0.045 W/mmK	0.036 W/mmK	0.027 W/mmK

in this study. The optimal topologies due to the three boundary constraints and heat conductivity were performed. The variation of the topologies shows a similar tendency to those of the fully clamped on the four edges of the PCB substrate. Fig. 8 shows the optimal topologies due to the three boundary constraints and heat conductivity for the same weighting factors of 0.5 only.

For the three materials mixing, the heat conductivity and density of material A are the same as above. Heat conductivities of materials B and C are assumed to be 80% and 60% of material A. The density of material B and C is assumed to be 50% and 30% of material A, respectively. The material properties used are listed in Table B. The constraint of mass was established as 70% of the initial mass made by material A only. The obtained optimal topologies of the PCB substrate made of three materials for the fully clamped on the four edges are shown in Fig. 9. It shows similar optimal topologies to those made of two materials.

5. Conclusions

A material mixing method was suggested to obtain an optimal topology of a multiple material structure with multiple thermal criteria in a thermal environment based on ESO. As an example, a PCB substrate was chosen to investigate the validity of the suggested method. Also, the effects of weighting factors for thermal stress and heat flux criteria as well as mechanical boundary conditions on optimal topologies were investigated.

It was found that as the weighting factor for heat flux density is getting larger, the sizes of holes at the center portion become larger. Whereas, as the weighting factor for thermal stress is getting larger, the sizes of holes at the center portion become smaller. The variation of the optimal topologies due to the mechanical boundary conditions and thermal conductivity for the same weighting factors shows that the sizes of holes at the center portion become larger as the magnitudes of the thermal conductivity are getting larger for the same weighting factors.

It was verified that this method works very well for a PCB substrate as an example made by two or three materials. This method can effectively be used in the thermal microgripper area where thermal stress and heat flux should be considered.

Acknowledgments

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Nomenclature

σ^e	:	e th element's thermal stress
σ^{max}	:	Maximum thermal stress
J^e	:	e th element's heat flux density
J^{max}	:	Maximum heat flux density
w_s	:	Weighting factor for thermal stress
w_f	:	Weighting factor for heat flux
m	:	Number of connected elements
w_i	:	Filter parameter
α^e	:	Efficiency factor of each element
α^{min}	:	Minimum efficiency factor
$\Delta\alpha$	:	Threshold ratio
TL	:	Transformation line
RL	:	Removal line

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