Vol. 46 No. 3 SCIENCE IN CHINA (Series E) June 2003

Constructs of highly effective heat transport paths by bionic optimization

CHENG Xinguang (程新广), LI Zhixin (李志信) & GUO Zengyuan (过增元)

Department of Engineering Mechanics, Key Lab of Enhanced Heat Transfer and Energy Conservation of Education Ministry, Tsinghua University, Beijing 100084, China

Correspondence should be addressed to Li Zhixin (email: lizhx@tsinghua.edu.cn)

Received September 9, 2002

Abstract The optimization approach based on the biological evolution principle is used to construct the heat transport paths for volume-to-point problem. The transport paths are constructed by inserting high conductivity materials in the heat conduction domain where uniform or nonuniform heat sources exist. In the bionic optimization process, the optimal constructs of the high conductivity material are obtained by numerically simulating the evolution and degeneration process according to the uniformity principle of the temperature gradient. Finally, preserving the features of the optimal constructs, the constructs are regularized for the convenience of engineering manufacture. The results show that the construct obtained by bionic optimization is approximate to that obtained by the tree-network constructal theory when the heat conduction is enhanced for the domain with a uniform heat source and high conductivity ratio of the inserting material to the substrate, the high conductivity materials are mainly concentrated on the heat outlet for the case with a uniform heat source and low thermal conductivity ratio, and for the case with nonuniform heat sources, the high conductivity material is concentrated in the heat source regions and construacts several highly effective heat transport paths to connect the regions to the outlet.

Keywords: bionic optimization approach, heat conduction optimization, constructs of high conductivity material.

With the rapid progress of microelectronic and microprocessing technology, how to remove the heat from the packages becomes one of the main bottlenecks that hinder the further miniaturization of the devices such as micro electronic components, biochips and micro-machines[1−3]. The routine method of convection cooling generally includes both heat conduction and convection. Only enhancing the convection is not enough to meet the requirements of increasing density of integration. One way to channel the generated heat out of the package is to enhance the conduction by constructing high heat transport path with high conductivity material[4]. Optimizing the construct of the high conductivity material will reduce the material and the manufacturing cost, and suit for further miniaturization. Such an optimization problem is also to be found in many other engineering fields, such as heating or cooling the chemical reaction and biological fermentation in the big space[5], cooling food in food industry[6] and increasing the thermal conductivity of energy storage media by inserting carbon fibers[7].

The fundamental problem in the above-mentioned cases is the volume-to-point problem, that is, how to effectively conduct the heat generated in a finite-size volume to a small patch (point) located on the boundary. It is clear that highly effective conduction paths need to be constructed by inserting high conductivity material into the domain. To solve the volume-to-point problem, Bejan[8] presented the tree-network constructs based on the constructal theory. The optimal tree-networks are available for the rectangle domain with uniform heat sources and high conductivity ratio $\bar{k}$ of high conductivity material to the substrate. Xia et al.[9] reported the bionic optimization approach based on biological evolution, in which the high conductivity material is regarded as a being alive, the thermal environment and thermal boundaries are the environment, the evolution of the high conductivity material gradually constructs the optimal construct according to the uniformity principle of temperature gradient.

Based on the bionic optimization approach, the heat transport paths are simulated for the cases of the heat conduction domains with uniform/nonuniform heat sources, and different thermal conductivity ratios of high conductivity material to the substrate, and the constructs are effectively regularized for the convenience of engineering manufacture in this work.

1 Bionic optimization of heat conduction

The bionic optimization of heat conduction imitates the evolutionary processes in nature to seek the optimal construct of the high conductivity material. In the bionic optimization, the high conductivity material is regarded as a being alive. The physical conduction space and the physical feature, such as the geometric structure, the thermal boundary condition, the heat generation in the conduction domain, and the thermal conductivity of the substrate material are all defined as the natural environment for the being alive. Controlled by the natural selection, the being alive gradually evolves its shape to the optimal heat transport paths for heat conduction enhancement.

The evolution of the high conductivity material can be divided into generation process and degeneration process. In the generation process the high conductivity material grows at the locations with the largest temperature gradient in the conduction domain. On the contrary, in degeneration process, the parts responsible for the smallest heat transfer flow rate (in other words, the temperature gradient is the smallest) are removed. Therefore, the evolution process of generation or degeneration will both make the temperature gradient field in the conduction domain more uniform. According to the uniformity principle of temperature gradient, the generation and degeneration processes can be effectively simulated numerically.

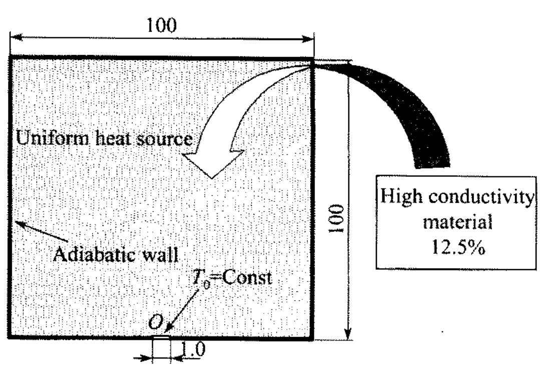


Fig. 1. Volume-to-point problem with uniform heat sources.

2 Heat transport paths for the domain with uniform heat source

A 2D volume-to-point problem is considered (fig. 1). In the square domain with uniform heat sources, the heat outlet is at constant temperature, T_0. The other boundaries at the wall surface are adiabatic. The volume of the high conductivity material to be inserted is 12.5% of the total volume.

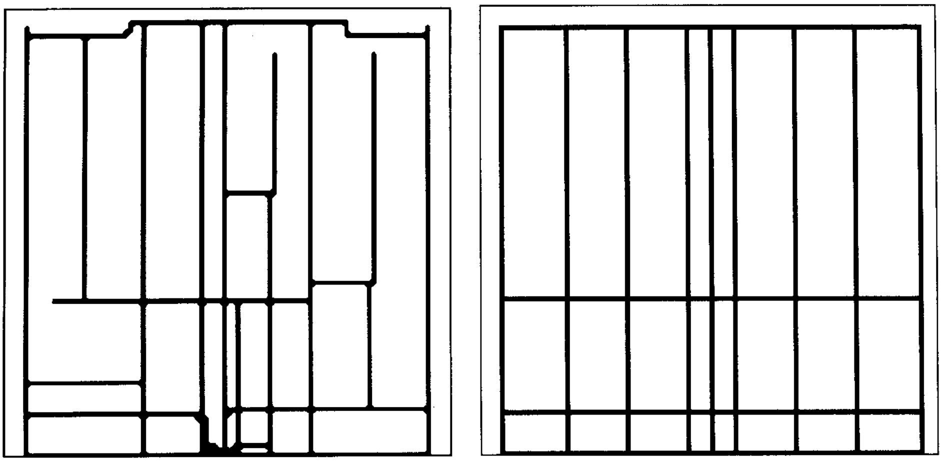
2.1 Effective heat transport paths for high conductivity ratio

According to the numerical method of bionic optimization[9], the constructs of high conductivity material with conductivity ratio $\bar{k}$ of 400 is shown in fig. 2(a). The structure features of the effective heat transport paths are

(1) the construct is mainly composed of the slender bars;

(2) the directions of the bars are either horizontal or perpendicular;

(3) the high conductivity material spreads all over the square domain, and in the region near the heat outlet (point O), the material is a little more concentrated.



(a) (b)

Fig. 2. The constructs obtained by bionic optimization (uniform heat sources, $\bar{k} = 400$). (a) Numerical result; (b) regularized construct.

The construct is irregular so that it is not easy to manufacture. According to the structure features, the construct can be regularized as the one shown in fig. 2(b).

The numerical simulation results of the heat transfer show that the regularized construct (fig. 2(a)) is approximate to the irregular one (fig. 2(b)) in heat transfer performance. The maximum temperature difference in the domain with the irregular construct is 1.2% that in the domain without any high conductivity material. Correspondingly, the maximum temperature difference in the domain with the regularized construct decreases 98.7%. Obviously the regularized one is much more convenient for engineering application. Therefore, the effective heat transport path can be constructed as shown in fig. 2(b) when the conductivity ratio of the high conductivity material to the substrate is 400.

In the bionic optimization approach, the effective heat transport paths are constructed in two steps. Firstly, the irregular optimal construct is obtained by the numerical simulation based on the uniformity principle of temperature gradient; secondly, the optimal construct is regularized according to the structure features, and the regularized construct should be of almost the same heat transfer performance as the irregular one.

The tree-network constructal theory is fit for 2D heat conduction optimization of a square bar with uniform heat source and the thermal conductivity of the inserted material should be high. The tree-network is assembled by several order constructs in steps; that is, each order construct contains several constructs. For the 2D volume-to-point problem shown in fig. 1 and the conductivity ratio of 400, the tree-network constructal theory presents an optimized construct of high effective transport paths shown in fig. 3, which contains two first order constructs and every first order construct consists of four elemental volumes. The volume of the high conductivity material is also 12.5% of the total volume.

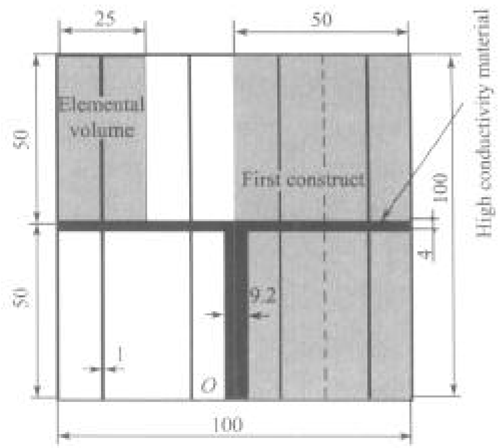


Fig. 3. Construct optimized by tree-network constructal theory.

Comparison of fig. 2 with fig. 3 shows that the tree-network construct is similar to that given by bionic optimization in structure features. Table 1 lists the maximum relative temperature differences in the domain for both cases, where DT_0 is the maximum temperature difference in the domain without high conductivity inserts. The maximum relative temperature differences in the domain with constructs given by bionic optimization and constructs given by tree-network contructal theory are 0.013 and 0.016 respectively, which indicates that for this case the constructs given by bionic optimization and tree-network constructal theory are similar not only in shape, but also in heat transfer performance.

Table 1 The maximum relative temperature difference in the domain (uniform heat source, $\bar{k} = 400$)

Construct	Bionic optimization (fig. 2(b))	Tree-network constructal theory (fig. 3(b))
$\Delta T_{max}/\Delta T_0$	0.013	0.016

In fact, rectangular domain, uniform heat source and high conductivity ratio are required for tree-network constructal theory, and the bionic optimization approach has not any limits. Therefore, for one rectangular domain with uniform heat source and high conductivity ratio, both the tree-network constructal theory and the bionic optimization approach are suitable to optimize the effective heat transport path. However, for the domains with nonuniform heat sources and relatively low conductivity ratio, only bionic optimization approach is feasible.

2.2 Effective heat transport path for low conductivity ratio

The 2D volume-to-point problem is shown in fig. 1, with the thermal conductivity ratio of 3 (much less than 400), and the effective transport path obtained by bionic optimization is shown in fig. 4. Fig. 4(a) is the simulation result of bionic optimization and fig. 4(b) is the regularized one for engineering application. Different from the case with high conductivity ratio of 400 (fig. 3(a)), the high conductivity material in fig. 4(a) is concentrated in the region near the outlet where the heat flux is the maximum in the domain. The reason is that the insert with lower thermal conductivity ratio has less influence on heat transfer. In the extreme, if the heat flux distribution has almost no variation after the high conductivity material is inserted in the domain, the high conductivity material should be continuously inserted in the highest heat fluxes position near the outlet.

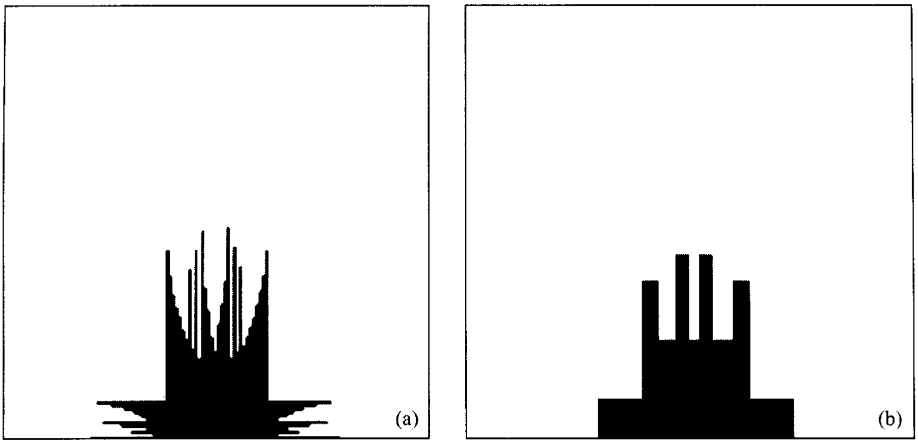


Fig. 4. Constructs obtained by bionic optimization (uniform heat sources, $\bar{k}=3$). (a) Simulation result; (b) regularized construct.

The numerical simulation results of heat transfer indicate that the temperature distributions in the domain with high conductivity inserts shown in fig. 4(a) and 4(b) are similar and the temperature gradient with either constructs is more uniform than that without high conductivity material construct. Table 2 gives the maximum relative temperature differences in the domain, where DT_0 is the maximum temperature difference in the domain without high conductivity inserts. The maximum relative temperature differences in the domain with irregular and regularized constructs are 0.522 and 0.526. Therefore, the regularized construct is valid and convenient for engineering application.

Table 2 The maximum relative temperature difference in the domain (uniform heat source, $\bar{k}=3$)

Construct	Simulated construct (fig. 4(a))	Regularized construct (fig. 4(b))
$\Delta T_{max}/\Delta T_0$	0.522	0.526

3 Effective heat transport path for the case with nonuniform heat sources

2D volume-to-point problem shown in fig. 5 is analyzed. The square domain with nonuniform heat sources has one heat flow outlet at constant temperature, T_0, The other boundaries are adiabatic. The volume of the high conductivity material insert is 12.5% of the total volume.

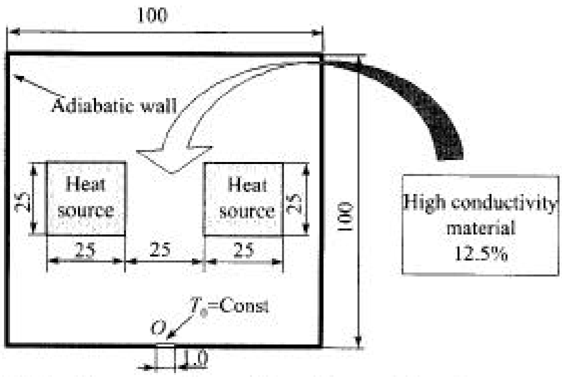


Fig. 5. Volume-to-point problem with non-uniform heat sources.

In the above analysis of a domain with uniform heat sources, the bionic optimization is proved to be fit for both high and low thermal conductivity ratios. Therefore, only high conductivity ratio is considered here. According to the procedure of bionic optimization, the construct with conductivity ratio of 300 is shown in fig. 6. The simulation result in fig. 6(a) indicates that the high conductivity material is concentrated in the regions with heat sources and some heat transport paths connect the regions to the heat flow outlet. The construct of numerical simulation is also irregular. And the regularized one is shown in fig. 6(b).

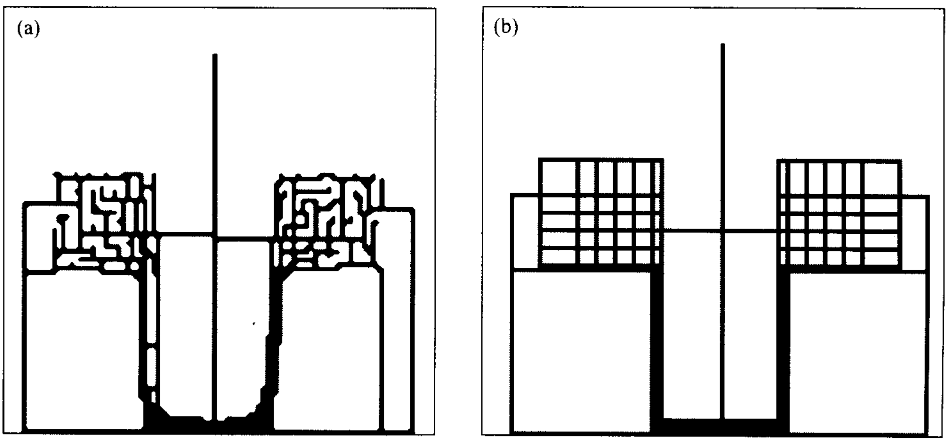


Fig. 6. The optimization for the domain with nonuniform heat sources ($\bar{k} = 300$). (a) Simulation result; (b) regularized result.

The validity of the regularized construct in fig. 6(b) is also proved by numerical simulation on heat transfer. Both the constructs shown in fig. 6 do enhance the heat conduction. The maximum relative temperature differences in the conduction domain are only 1.2% and 1.3% of the case without high conductivity inserts (table 3). Therefore, the effective heat transport path can be constructed into the structure shown in fig. 6(b) for the 2D heat volume-to-point problem with nonuniform heat sources shown in fig. 5 and for the conductivity ratio of 300.

Table 3 The maximum relative temperature difference in the domain (nonuniform heat source, $\bar{k} = 300$)

Construct	Simulated construct (fig. 6(a))	Regularized construct (fig. 6(b))
$\Delta T_{max}/\Delta T_0$	0.012	0.013

4 Conclusions

(1) The bionic optimization based on the principle of biological evolution enables us to optimize the construct of high conductivity material with high or low thermal conductivity ratio to substrate material and the domain with uniform or nonuniform heat sources.

(2) In the bionic optimization, the irregular construct is obtained via numerical simulation. For the convenience of engineering application, it can be regularized based on structure feature analysis. The regularized construct has almost the same heat transfer performance as the irregular one.

(3) If the thermal conductivity ratio is high and the conduction domain has a uniform heat source, the construct obtained by bionics optimization is similar to that obtained by the tree-network constructal theory both in structure features and heat transfer performance.

(4) For the case of low thermal conductivity ratio and the domain with uniform heat source, the high conductivity material is mainly concentrated in the region near the heat flow outlet. The high conductivity material will be concentrated in the regions with heat sources, forming some heat transport paths to connect the heat source regions to the heat flow outlet when the heat source is nonuniform.

Acknowledgements This work was supported by the National Key Fundamental R&D Program of China (Grant No. G20000263).

References

1. Aung, W., Cooling Technology for Electronic Equipment, New York: Hemisphere, 1988.
2. Tien, C. L., Chen, G., Challenges in microscale conductive and radiative heat-transfer, Journal of Heat Transfer, Transactions of the ASME, 1994, 116 (4): 799—807.
3. Guo, Z. Y., Frontier of heat transfer- microscale heat transfer, Advance in Mechanics, 2000, 30(1): 1—6.
4. Bejan, A., Constructal, theory network of conducting paths for cooling a heat generating volume, International Journal of Heat and Mass Transfer, 1997, 40(4): 799—816.
5. Coulson, J. M., et al., Chemical Engineering, 3d ed., New York: Pergamon Press, 1994.
6. Ketteringham, L., James, S., The use of high thermal conductivity inserts to improve the cooling of cooked foods, Journal of Food Engineering, 2000, 45(1): 49—53.
7. Fukai, J., Kanou, M., Kodama, Y. et al., Thermal conductivity enhancement of energy storage media using carbon fibers, Energy Conversion & Management, 2000, 41(14): 1543—1556.
8. Bejan, A., Shape and Structure From Engineering to Nature, Cambridge: Cambridge University Press, 2000.
9. Xia, Z. Z., Li, Z. X., Guo, Z. Y., Heat conduction optimization: high-conductivity constructs based on the principle biological evolution, Heat transfer 2002, in Proceeding of the Twelfth International Heat Transfer Conference, Grenoble, France, Vol. 2, 2002, 27—32.