# THERMAL PROPERTIES OF CLOSED-CELL ALUMINUM FOAM WITH CIRCULAR PORES

by

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*The thermal property of closed-cell aluminum foam is studied numerically and the effects of the distribution of the circular pore on the thermal property are studied theoretically. When the convection and radiation are ignored, the effects of porosity, cell size, and distribution forms of pore on the apparent thermal conductivity are investigated. Moreover, the effects of air in the pore on the thermal property are analyzed as well. Simulation results show that apparent thermal conductivity linearly increases with the increase of porosity, while the cell size and the distribution have negligible effects on the thermal property. By comparison, thermal conductivity of air has slight effect on thermal property of foamed aluminum in the context of small size pore.*

Key words: *apparent thermal conductivity, close-cell aluminum foam,*
*circular pore, finite element method*

## Introduction

Metal cellular materials [1], because of its special structural character, are known to have many interesting combinations of physical and mechanical properties and are wildly used in the field of industry such as aerospace, civil engineering, energy engineering, *etc*. The typical uni-axial compressive stress strain response of porous cellular materials consists of linear loading followed by a long stress plateau region, after which, the stress increase with increasing strain [1]. This is a good character for energy absorption. There are a large number of science and technology workers focus on the static and dynamic mechanical behavior of metal foams, such as the strain rate effect [2, 3], the energy absorption mechanism of deformation mode [4, 5], crack propagation, and so on. Most of these articles focused on room-temperature behavior for most of the foam's applications exist only at room temperatures. But porosities means high surface area and large volume of interconnection which makes metal foams can be used in environments where high temperatures and stresses are involved as. For example: in the transpiration cooled rocket nozzles, in the cooling system, in the burning chamber of gas and steam turbines, and heat shielding for aircraft exhaust [6-9]. Those made the researches on the high temperature mechanical properties of metal cellular material are increasingly valued. So obtaining some information concerning the effects of foam's density,

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temperature as well as the applied stress on the mechanical properties of foams at high temperatures, thermal conductivity should be given intensive attention. Closed-cell aluminum foams exhibits excellent resistance to fire, but the reason is still unclear. Rayleigh [6] firstly tried to give the mathematical approximate solution on the effective thermal conductivity of foam materials. Using the steady-state conduction solution method developed by Tien *et al.* [7, 8] the effective thermal conductivity can be gotten and used in the energy equation.

Lu *et al.* [9, 10] investigated the effect of geometric imperfection – irregular shape, fractured cell edges, missing cells, and cell size variations by using two-dimensional Voronoi model. They also carried out the experimental and numerical research to get the equivalent coefficient of thermal conductivity based on hollow spherical shell's uniform distribution character of the foam's structure. Hosseini *et al.* [11] study the coefficient of thermal conductivity of the foams which have the different space filling or the polyhedron space filling structure. They consider the effect of relative density. Fiedler *et al.* [12] discussed the thermal conductivity of two structure one has uniform hollow metal sphere structure, and the other has the periodic unit of heterogeneous adhesion embedded structure. They focus on the different hollow sphere structure (*i. e.* the original cube, body centered cubic and face-centered cubic) effect on the effective thermal conductivity.

For the diversity style of the porosity and the space filling state, the foams will have versatile thermal transport properties. To explore the underlying mechanism on the thermal transportation we study the effect of the relative density, geometric dimension of the unit cell and distribution forms of pore on the apparent thermal conductivity using finite element methods. The effects of air filled in the unit cell on the thermal transport character are also discussed.

## Calculation model of heat transfer

### *Finite element model*

Foam has a pore structure which is very complicated and the distribution and combination of the cell unit have a lot of the randomness and irregularity. These foam properties are related to their cellular structure. Complicated architecture of foams make it is difficult to get the enough information of morphology of foams. Statistical methods are used to give the regularity of the microstructure. Zhang *et al.* [13] using digital image processing technology and software, IMAQ Vision Builder, obtain the statistical distribution feature of the main microstructure parameters of foam which can predict the macro-behaviors of foamed aluminums. They gave the statistical distributions of the aperture and porosity. Their results show that the aperture size range between 0.2 mm to 2.4 mm, and the pore size of 0.4 mm to 1.4 mm are major part which accounts for about 89% of the total. According this aperture probability distribution, we compile C program to produce random pore radius and center point co-ordinates. The python command was used to read these data to generate the finite model of ABAQUS which has the random character of pore size and center point distribution. The model was shown as fig. 1. Through the C program we can control the porosity. Figure 1 is a kind of stochastic finite element model which has the porosity of 52.4%. According to the aluminum

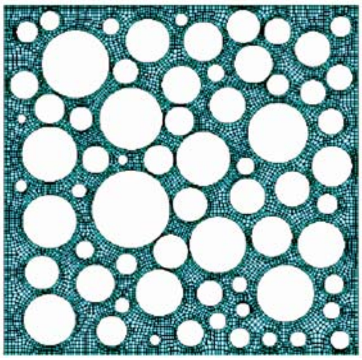

**Figure 1. Stochastic finite element model with porosity of 52.4%**

foam aperture probability figure [13], the highest probability distribution of seven aperture size, 0.8 mm, 1.0 mm, 1.2 mm, 1.4 mm, 1.6 mm, 1.8 mm, and 2.0 mm are selected out to study the effect of the pore size and porosity on the coefficient of thermal conductivity. We construct two kinds of finite element models to investigate the effect of pore size and the porosity. One (model I) has the same pore size and different porosity. The other (model II) has same porosity and different pore size. The effect of natural convection of air within the cells is negligible even in the case of low-conducting polymer foams and the effect of thermal radiation are negligible even at relatively high temperatures (~600 °C) [9]. We do not consider the convection of the gas filled in the pore and the thermal radiation. The heat transfer element of ABAQUS is used. There are a total of 7067 heat transfer elements including 16966 nodes.

The concrete parameters of model I and model II are shown in tabs. 1 and 2. Although the contribution of gaseous conduction is not significant [9], we consider it in our finite element model and construct air model element filled in the pore. The thermal mechanical parameters of the aluminum are density (2710 kg/m$^3$), heat conductivity coefficient (236 W/mK), expansion factor (0.0000232 °C$^{-1}$), and specific heat capacity (902 J/kgK). The same parameters for air are 1.165 kg/m$^3$, 0.0267 W/mK, 0.003676 °C$^{-1}$, and 100.5 J/kgK.

**Table 1. Parameters of the model with different pore size and same porosity [mm]**

| Pore size | 0.8 | 1.0 | 1.2 | 1.4 | 1.6 | 1.8 | 2.0 |
|---|---|---|---|---|---|---|---|
| Wall thickness | 0.2 | 0.25 | 0.3 | 0.35 | 0.4 | 0.45 | 0.5 |
| The model size | 5 | 6.25 | 7.5 | 8.75 | 10 | 11.25 | 12.5 |
| Porosity | 50.26% | | | | | | |

**Table 2. Parameters of the model with same pore size and different porosity [mm]**

| Porosity | 5% | 10% | 15% | 20% | 30% | 40% | 50% | 60% | 70% | 80% | 90% |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Wall thickness | 3.9 | 2.52 | 1.8 | 1.38 | 0.87 | 0.56 | 0.35 | 0.2 | 0.14 | 0.08 | 0.02 |
| The model size | 26.5 | 19.6 | 16 | 13.9 | 11.3 | 9.8 | 8.75 | 8.0 | 7.7 | 7.4 | 7.1 |
| Pore size | 1.4 | | | | | | | | | | |

### *Boundary conditions and solving types*

In the absence of forced convection, the transport of heat across cellular foam having either open or closed cells is dominated by conduction along the solid cell walls and the thermal radiation amongst the cell walls. For the foam having open cells the convection of gas may be important and it will be small and can be negligible for the foam with closed cells. In our model the conductivity of the base material and gas filled in the pore are considered. The convection of the gas inside the cell and the radiation do not be considered. The tie constrain is used between the elements of air and the cell wall. Using steady-state thermal analysis solver, only the boundary condition should be given: the constant temperature of 40 °C is set on the top boundary and 30 °C on the bottom side. Adiabatic boundary is set on the other sides. From the simulation results we can get the heat flow intensity and using the Fourier's theorem the effective thermal conductivity can be gotten through:

$$k_y = \frac{q_y L_y}{T_2 - T_1} \tag{1}$$

where $T_2$ is the top side temperature, $T_1$ – the down side one, $q_y$ – the heat flow intensity on the thermal transfer direction, and $L_y$ – the distance of two boundaries.

## Simulation results and discussion

### *The influence of porosity on the effective thermal conductivity*

Figure 2 shows relationship of the effective thermal conductivity and the porosity when aperture size keeps constant and the effects of the air filled in the pore are compared by considering the air or unconsidering the air in the simulation model. $k_y/k_0$ means the ratio of the equivalent conductivity coefficient to the thermal conductivity of the aluminum matrix.

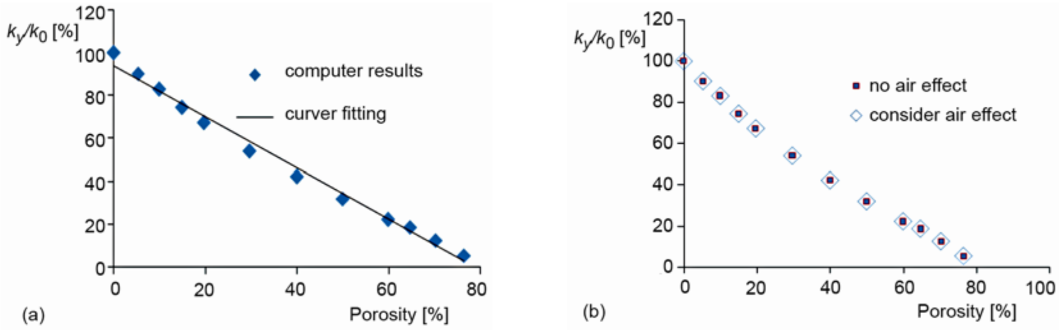

**Figure 2. Relationship of the effective thermal conductivity and the porosity when aperture size keeps constant and the effects of the air filled in the pore**

From the figure we can see that the equivalent conductivity coefficient decreased linearly with the increasing void content. Through curve fitting methods we got the eq. (2)

$$k_y/k_0 = 94.41 - 1.95\varphi, \quad R = 0.9899 \tag{2}$$

where $\varphi$ is the porosity, and $R$ – the dependency number.

Figure 2(b) shows the effects of the air on the relationship of the effective thermal conductivity and the porosity when aperture size keeps constant. There are tiny differences between the results of considering and un-considering air conductivity. It is because that the conduction of gaseous is about 10000 times smaller than that of aluminum. The heat transfer is mainly by the shell wall of foams.

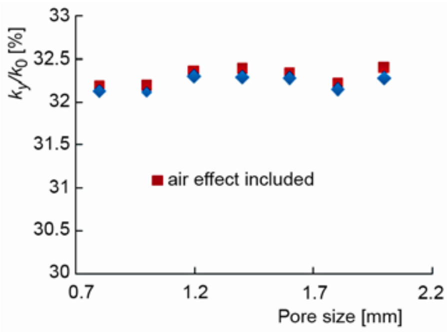

**Figure 3. Relationship of the effective thermal conductivity and the pore size**

### *The influence of pore size on the effective thermal conductivity coefficient*

Figure 3 shows relationship of the effective thermal conductivity and the pore size when porosity keeps constant and the effects of the air are also considered and compared.

It can be seen that the equivalent coefficients of thermal conductivity do not change greatly with pore size changing when the porosity keeps constant. In our simulation condition the relative equivalent coefficient maintained at around 32.29%, and the tolerance of fluctuations is about 0.5%. The porosity is the main influence factor on the equivalent coefficient of the foams. The pore size has little effect on the equivalent coefficient. When the effect of the air's conductivity was considered there is about 0.1% increase on the equivalent coefficient of thermal conductivity. So the effect of the gas on the equivalent coefficient is very weakness and can be ignored.

### *The influence of the pore size distribution model on the effective thermal conductivity*

Figure 4 shows the relationship between the effective thermal conductivity and porosity which are given by three kinds of aperture random distribution model. We can see that the effective thermal conductivities are very close whether the aperture distribution is random or homogeneous. The deference is smaller than 5%.

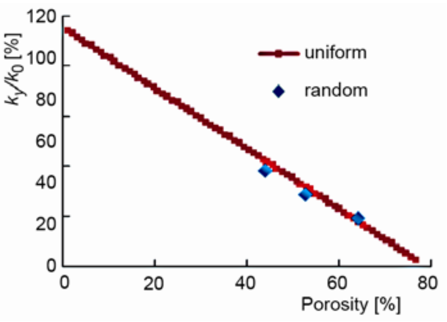

**Figure 4. The relationship of equivalent coefficient of the thermal conductivity and different aperture distribution model**

## Conclusions

This article use two-dimensional finite element numerical model to get the equivalent coefficient of the thermal conductivity of aluminum foams with different aperture distribution model.

- the effective thermal conductivity of foams is linear decrease with the increase of porosity when the pore size unchanged.
- the effect of pore size and the topological distribution of pore on the effective thermal conductivity is very small, even can be neglected.

To sum up, the effective thermal conductivity of closed-cell foam aluminum materials under low temperature coefficient was mainly affected by the porosity.

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