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Research paper

An experimental study on mid-high temperature effective thermal conductivity of the closed-cell aluminum foam

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HIGHLIGHTS

- Effective thermal conductivity (ETC) of aluminum foam is measured from 100 to 500 °C.
- Differences exist in cell wall thermal conductivity (CWTC) among tested foams.
- ETC is product of CWTC, relative density and reciprocal of squared tortuosity.
- Tortuosity is weakly dependent on density in concerned density range.
- ETC and CWTC decrease with temperature increasing.

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ABSTRACT

In this work, the Effective Thermal Conductivity (ETC) of closed-cell aluminum foams was measured in the temperature range of 100–500 °C. Analyses showed that the ETC is proportional to the relative density as well as the cell wall thermal conductivity, and is inversely proportional to the square of the tortuosity. Differences in the cell wall thermal conductivity were found among the foam samples. As the thermal conductivities of Al, $Ti_2Al_{20}Ca$ and Al_4Ca in the cell wall decrease with temperature and hydrogen-related phase transition occurs, the measured ETC decreases with temperature.

1. Introduction

Due to the particular mechanical, thermal, electric and acoustic properties [1,2], metallic foams draw increasing attention from both the academic and industrial fields. A lot of works discussed the dependence of the mechanical properties on the structural parameters [3–7] and properties of the cell wall material [8,9]. It has been revealed that the closed-cell aluminum foam has excellent mechanical properties, especially the energy absorption characteristic. Besides, efforts were made to simulate the heat transfer process based on either regular geometries [10,11] or Computed Tomography (CT) images [12–15]. The closed-cell aluminum foam was found to have low thermal conductivity, thus could be used in thermal insulation. Lu [10] and Lázaro [16] revealed that the closed-cell aluminum foam showed good fire retardance performance at high temperature. In view of these findings, the closed-cell aluminum foam is promising to be used in some high temperature situations, acting as both load-bearing and thermal insulation components. Thus, in addition to the mechanical properties, it is extremely important to systematically study the heat transfer behavior of the aluminum foams.

The ETC of the aluminum foams has been measured with different methods [17–21]. With a transient plane source method, Solórzano [17] measured the ETC over a wide density range. As the structure of the aluminum foam is complex, it may be difficult to prepare paired samples of similar characteristics as this method requires. Paek [18] measured the ETC with a steady-state comparative method, and pointed out that the experimental error was dominated by the contact condition between the thermocouples and the foam surfaces. In another application of the comparative method, Sadeghi [19] extrapolated the temperature of the foam from that of the reference sample and found that the thermal contact resistance between the foam and adjacent layers could be significantly large. Therefore, the ETC could have been underestimated by Abramenko [20] as the foam surface temperatures were taken as those of the adjacent layers. The experimental works

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above all focused on the ETC at room temperature. Babcsán [21] measured the ETC of the foam from room temperature to 500 °C, with a test bench similar to the one used by Sadeghi [19]. The foam temperatures were measured with thermocouples inserted in the drilled holes on the foam. The results showed that the ETC of the closed-cell aluminum foam increased with both density and temperature [21].

Although quite a few experimental works were done on measuring the ETC of the closed-cell aluminum foam, most of them focused on the room temperature property, and revealed the difficulty in accurately measuring the foam temperature. Besides, the reported works seldom analyzed the experimental results with consideration of the foam structure parameters and the cell wall material property. In this work, we have measured the ETC of the closed-cell aluminum foam from 100 to 500 °C and discussed the effects of the density, the tortuosity and the cell wall thermal conductivity.

2. Experimental

2.1. Material

The closed-cell aluminum foam used in this work was produced by Osenter Metal Composite Materials Co. Ltd. (Shanghai, China) using a liquid state processing with TiH_2 as a foaming agent. The processing was similar to that of Alporas (Shinko Wire) foam [22]. The relative density ρ_r is defined as the ratio of the density of the foam to that of the metal matrix. In this work, the density of the metal matrix is conventionally taken as that of the pure aluminum, 2.7 g/cm^3. Six samples were machined with a wire-electrode cutting facility, with a relative density range of 0.072–0.172. The samples were numbered from 1 to 6 in a density-increasing order as shown in Table 1. The size of the samples was 230 mm × 230 mm × 40 mm.

2.2. Measurement of effective thermal conductivity

A steady-state comparative method was used to measure the thermal conductivity, as shown in Fig. 1. Heat from the electrical heater transfers through the sample stack and is finally brought away by the cooling water. A carborundum plate (10 mm in thickness, 87 W/(m K) in thermal conductivity) is used as a heat spreader to sustain a uniform temperature on the top surface of the sample. Between the sample and the granite, a thin aluminum plate (5 mm in thickness, 231 W/(m K) in thermal conductivity) with grooves is used to place the thermocouple wires (0.4 mm in diameter). In order to decrease the thermal contact resistance, a piece of soft silicone pad (1 mm in thickness, 2 W/(m K) in thermal conductivity) is laid between the granite and the copper plate. With comparatively low thermal conductivity, the granite 603 reference sample could lower the cooling load. The insulation consists of fibrous insulation and firebrick. The fibrous insulation layer has a thickness of 25 mm in the horizontal direction, and the thermal conductivity is 0.05 W/(m K). The firebrick layer has a thickness of 150 mm in the horizontal direction, and the thermal conductivity is 1 W/(m K).

Due to the good thermal insulation and the large size of the sample, when the system reaches a steady state, the heat flux remains the same through the central area of the stack. Thus we have

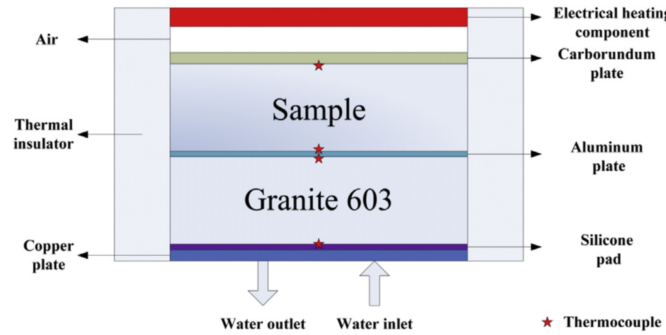

Fig. 1. The schematic of the steady-state comparative method.

$$\frac{k_s \Delta T_s}{L_s} = \frac{k_r \Delta T_r}{L_r} \tag{1}$$

where L, ΔT and k are the thickness, the temperature difference and the thermal conductivity, respectively. The subscripts "s" and "r" denote the sample and the reference material (the granite), respectively. Eq. (1) can be rewritten as:

$$k_s = k_r \frac{L_s}{L_r} \frac{\Delta T_r}{\Delta T_s} \tag{2}$$

The values of k_r at different temperatures were calibrated with the conductometer QTM-500 (KEM) with an accuracy of ±5% as listed in Table 2. k_r at other temperatures were obtained by linear interpolation. With cold ends immersed in mixture of water and ice, K-type thermocouples were used to measure the temperatures. The temperatures of the granite were measured with thermocouples located in the drilled holes on the granite surfaces.

In order to verify the accuracy of the method, we tested stainless steel 304 of which the thermal conductivity is close to that of the aluminum foams [17]. The temperatures of the steel were measured with thermocouples located in the drilled holes on the surfaces. Table 3 shows that the maximum deviation between the measured and reported [23] values is less than 3%. The results confirmed the high accuracy of the comparative method used in this work.

As for the aluminum foam, the measurement of the foam surface temperatures requires careful manipulation. Simply laying the thermocouple on the foam surface [18] or adjacent layer [20] could lead to large errors. In this work, the thermocouples were carefully welded onto the foam surfaces with a kind of aluminum solder. The foam material at the welding spot was molten during welding and finally joined with the solder, as shown in Fig. 2(a), implying that welding the thermocouples onto the foam is adequate to ensure the accuracy of the foam temperature measurement.

By taking logarithm and differential of Eq. (2) successively, one can obtain the following equations:

$$\ln k_s = \ln k_r + \ln L_s - \ln L_r + \ln\Delta T_r - \ln\Delta T_s \tag{3}$$

$$\frac{dk_s}{k_s} = \frac{dk_r}{k_r} + \frac{dL_s}{L_s} - \frac{dL_r}{L_r} + \frac{d\Delta T_r}{\Delta T_r} - \frac{d\Delta T_s}{\Delta T_s} \tag{4}$$

Table 1
The relative density of the aluminum foam samples.

Number	1	2	3	4	5	6
ρ_r	0.072	0.106	0.113	0.115	0.126	0.172

Table 2
The thermal conductivity of granite 603 calibrated with QTM-500.

Temperature/°C	100	300	500
k_r/W m^{-1} K^{-1}	2.153	1.579	1.348