Effective thermal conductivity of metallic foams determined with the transient plane source technique

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Abstract

This article presents experimental results of thermal conductivity in metal foams. The thermal conductivity of cellular solids differs from those of their corresponding dense material. Therefore, the various pore size level effects contributing to the thermal conductivity are comprised by introducing an *effective thermal conductivity*. In this work we investigated metallic foams with various porosities manufactured by the Slip Reaction Foam Sintering (SRFS) Process using a nickel-based powder. For the determination of the effective thermal conductivity at room temperature, we employed the *Transient Plane Source Technique* also known as *Hot Disk*. We verified the influence of the porosity and the thermal conductivity of the solid phase on the effective conductivity and compared the measured values of the effective conductivity with theoretical ones calculated using the thermal conductivity of the solid phase and the solid volume fraction. We present here a simple model that demonstrates the influence of the geometry of the grid elements qualitatively, discuss the applicability of the method to heterogeneous materials such as metallic foams and give an outlook about further investigations at higher temperatures.

1. Introduction

Porous materials play a role of increasing importance in numerous applications such as catalytic converters, solar receivers, porous burners or particle filters. In the context of the study described in this article, porous metal foams are investigated for an application in the combustion chamber of a gas turbine system [1]. In this application a cooling fluid is pressed through the pores of the foam, which is part of the wall of the chamber, with the objective to keep the material's temperature below a critical level. A characterization of the *thermal conductivity* properties of the materials involved is essential to numerically describe the cooling process [2].

Metallic foams generally consist of a solid grid with small open or closed pores filled with air. Consequently, heat transfer in the foam – as in cellular solid in general – may be considered as a composition of single pore size level mechanisms such as thermal radiation from the solid elements to each other, thermal conduction within the solid elements, thermal conduction in the air and solid-to-fluid convective heat transfer [3]. An *effective thermal conductivity* λ_{eff} may then be introduced, which comprises these effects. Mathematically, local thermal temperature averages are taken so that the solution of the general heat transfer problem

$$\frac{\partial T}{\partial t} = \frac{\lambda_{eff}}{\rho c_P} \nabla^2 T \qquad (1)$$

can be performed with the effective thermal conductivity λ_{eff}. The quantity

$$\frac{\lambda_{eff}}{\rho c_P} = \kappa \qquad (2)$$

is denoted as the *thermal diffusivity*.

2. Materials

The materials investigated in the study described were metallic foams manufactured with a powder metallurgy method called SlipReactionFoamSintering (SRFS). In this process, a fine metallic powder with grain sizes of up to 200 μm and a slurry-stabilising dispersant were mixed with a solvent and a certain amount of acid. The slurry foamed at room temperature and after 24 hours of drying, a precast body, called “green sample”, was obtained. The received green sample was stiff enough to be handled. The samples were sintered under reductive hydrogeneous atmosphere between 1120 and 1250 °C, dependent on chemical composition. A laminate silicate was used as the dispersant. The solvent was either water or alcohol diluted with water. The acid was an 85% concentrated phosphoric acid, which was a weak acid. The metallic acid reaction generates gaseous hydrogen, which caused the slurry to foam [4]. For this study Hastelloy B, a nickel based alloy was used as a powder. By varying the quantity of solvent, foam samples of various porosities were manufactured.

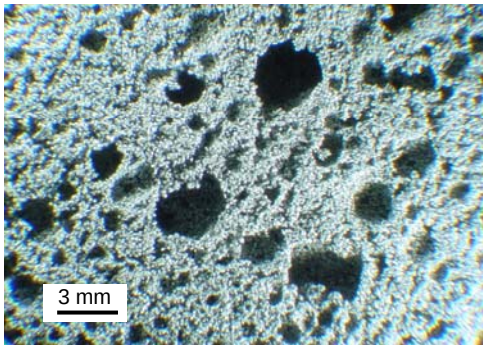

Figure 1: Micrograph of a typical sample of the investigated Hastelloy foams

As an example, Figure 1 presents a micrograph of a typical sample surface. The process generates pores of various magnitude, the largest pores reach a diameter of up to several millimetres. In general there are large pores (primary pores) caused by the chemical reaction and the generation of hydrogen and small pores (secondary pores), which are natural cavities between adjacent particles. For comparison, an additional porous sample has been manufactured without any acid, which only has secondary pores. All manufactured materials have porosity values varying from 0.57 to 0.83. The complete porosity data as well as the measured λ_{eff} values of the samples investigated are provided in Table 1.

3. Experimental Method

The thermal conductivity data presented in this article have been determined with the *Transient Plane Source Technique* also known as *Hot Disk*. The method including its theory has been approved and described in detail in numerous publications [5][6][7][8].

It works with a Nickel double spiral as a sensor, which is placed between two "semi-infinite" samples (Figure 2). The hot disk may be applied at room temperature (with Kapton sensors) as well as at temperatures of up to 1000 K (with Mica sensors, Figure 3). In the latter case the sensors and samples are placed in furnace capable of a precise temperature control.

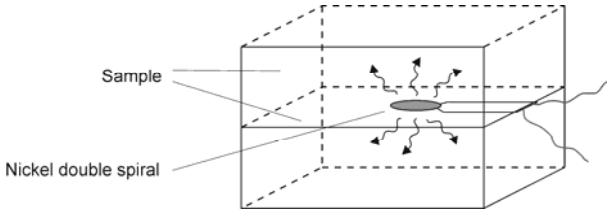

Figure 2: Scheme of measurement principle

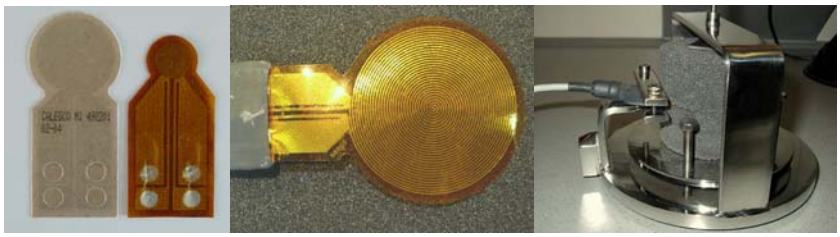

Figure 3: Mica and Kapton sensor of different dimensions (left), Kapton sensor with 30mm diameter (center) and hot disk sample holder with metallic foams specimens (right)

The sensor works as a power source as well as a temperature sensor exploiting the temperature dependent electrical resistance of Nickel. The sensor current is controlled by a separate device which is connected to a computer. This controller allows a variation of the measurement time and power between 2.5 and 640 seconds and between 0.01 and 10 W respectively. The temperature time plot of the sensor is monitored. The one from a metal foam sample is shown in Figure 4 as an example. According to the thermal diffusivity and thermal conductivity properties of the sample the measuring time and power have to be selected in a way that a penetrating of the temperature signal to the edges of the sample has to be avoided (Figure 5).

Solving the thermal conductivity equation theoretically, the time dependent temperature increase $\Delta T_{ave}(\tau)$ can be written as

$$\Delta T_{ave}(\tau) = \frac{P_0}{\pi^{3/2} \cdot a \cdot \lambda_{eff}} \cdot D(\tau) \qquad (3).$$

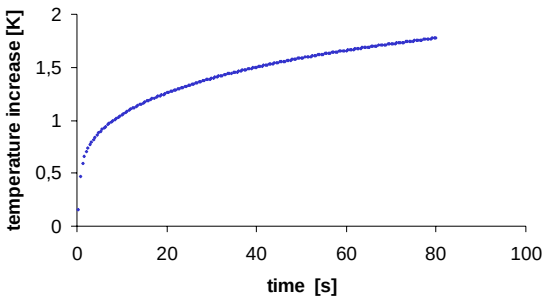

Figure 4: Representative temperature-time plot of a foam sample with a porosity of 0.57

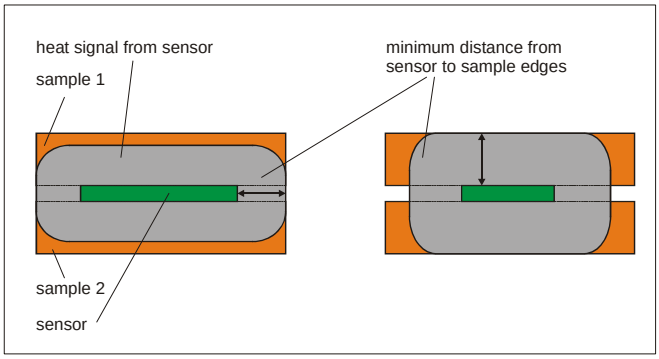

Figure 5: Minimum sample dimensions for the hot disk measurement

In this equation P_0 is the total output of power from the sensor, a is the radius of the disk and $D(\tau)$ is a dimensionless time dependent function with

$$\tau = \sqrt{\frac{t}{\Theta}}. \qquad (4)$$

θ is defined as the *characteristic time*

$$\Theta = \frac{a^2}{\kappa}, \qquad (5)$$

with κ, the thermal diffusivity of the sample. From the temperature data of the measurement λ_{eff} is determined from the slope of a plot $\Delta T_{ave}(\tau)$ as a function of $D(\tau)$ according to equation 3. The characteristic time θ and the thermal diffusivity κ, which are not known before the experiment, are obtained through a process of iteration. So besides λ_{eff}, thermal diffusivity and specific heat are determined in one single measurement.

In the example of Figure 4, the temperature increase has been 1.5 K, which is a typical value for the investigated materials. At different values of thermal diffusivity the temperature increase may be smaller.

At high temperatures the accuracy of the temperature measurement decreases, which leads to higher errors in the measurement of λ_{eff}. At room temperature the overall error may be determined by comparison with standard material samples of known λ_{eff}. However, these materials are commonly conventional dense materials like steel or copper. Here the error is below 4%. For unknown materials, the accuracy may be estimated by comparison of

reproduced measurements. The statistical error comparing reproduced measurements with the same parameters is low (<1%). However, repeated measurements with different sensors and measuring parameters have shown statistical errors of about 7%. A larger scattering of the values plotted in the figures is due to the error in determining the exact amount of porosity in the tested volume.

The *Transient Plane Source Technique* has been chosen for the metal foams investigated, because it allows the use of cylindrical samples of approximately 50-80 mm diameter and 15-30 mm thickness. In contrast to samples used for the *laser flash method,* which are typically 10-15 mm diameter and 2-4 mm thickness, the pores of the metallic foams are distributed homogeneously in the tested volume. The contact sensor/sample was sufficient to enable a heat flow from the sensor to the porous foam material, which is a necessary requirement for the measurement. This is not always the case for porous materials. In case of *ceramic* foam samples, which had been subject of a previous study [9], the measurement failed, because at the edges of the samples the sharp ends of the struts of the foam only represented a point contact to the sensor.

4. Results and Discussion

Firstly, the materials have been investigated at room temperature with the objective to study the influence of the porosity on λ_{eff}. The results are presented in Figure 6 and in Table 1. In Figure 6 the influence of the porosity can be clearly seen. Within the porosity range of 0.73 to 0.83 the thermal conductivity varies between 0.28 and 0.53 W/mK compared to 11.1 W/mK of the dense material. In a first approach the contribution of radiation and convection as well as the one from the conductivity of the fluid are neglected, because only ambient temperatures are considered and the conductivity of the Hastelloy employed in this study is high compared to the one of air (0.025 W/mK) [3]. A simple rule of mixture

$$\lambda_{FOAM} = \lambda_{DENSE} \cdot (1-\varepsilon)$$

suggesting the conductivity being reduced by a factor of (1-ε) would propose thermal conductivity values of the foam of about 2-3 W/mK, a deviation by factor of nearly 10.

The next approach was to take into account the heterogeneous pore structure of the material mentioned in the 2nd paragraph. If the material is considered as a matrix composed out of struts, which itself consist of a secondary pore structure, the influence of the two pore systems on the thermal conductivity properties may be separated. The average thermal conductivity values of the samples from “grid material” (#1990-#1993) with only secondary pores has been λ=0.55, which can be considered as the thermal conductivity of the “matrix”. Defining the primary porosity as

$$\varepsilon^* = (1-\frac{\rho_{FOAM}}{\rho_{MATRIX}})$$

with ρ_{FOAM} and ρ_{MATRIX} being the densities of the foam samples and the matrix material without any primary porosity respectively, the rule of mixture may be applied again. The result is shown in Figure 7. The deviations from the measured data of the foams are small compared to the approach before. For a comparison, the conductivity of air has been taken into account and as expected before, the influence is very small.

Sample ID	Density ρ (g/cm³)	Porosity ε	Primary porosity ε*	Thermal conductivity λ (W/mK)
"dense Hastelloy B"	9.24	0	0	11.1
1990	4.0	0.57	0	0.58 ±0.02
1991	3.9	0.58	0	0.54±0.02
1992	3.9	0.57	0	0.53±0.02
1993	3.4	0.63	0	0.54±0.02
1873	1.2	0.83	0.54	0.32±0.02
1874	1.9	0.8	0.48	0.28±0.02
1875	2.0	0.8	0.47	0.48±0.02
1877	2.3	0.73	0.26	0.53±0.02
1873[1]	1.2	0.83	0.54	0.35±0.02
1873[2]	1.2	0.83	0.54	0.31±0.02

Table 1: Summarized properties and thermal conductivity data (at 20°C) determined for the investigated materials ([1,2] sample 1873 was remeasured after high temperature treatment at 600°C)

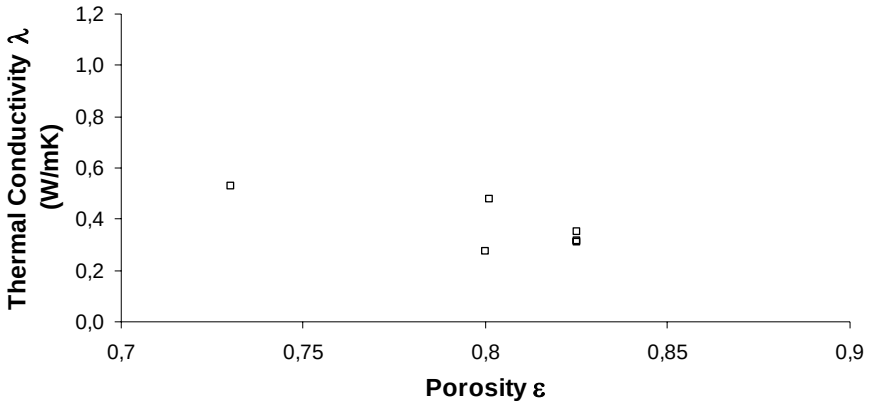

Figure 6: Thermal conductivity of various Hastelloy foams as a function of porosity

Former studies correct the rule of mixture with factors regarding the tortuous shape of the solid matrix [10][11]. This means for the case of the present study, that tortuosity plays a minor role, if primary pores are concerned. However, the thermal conductivity of the matrix material deviates from the one of dense Hastelloy by more than a factor of 10, although the porosity is 0.5-0.7. This shows that for the matrix with secondary pores the geometry of the pores plays a dominant role. This may become more obvious, if the structure of the matrix is considered (Figure 1), which may be compared to a packed bed of single particles, which are linked with small contact points.

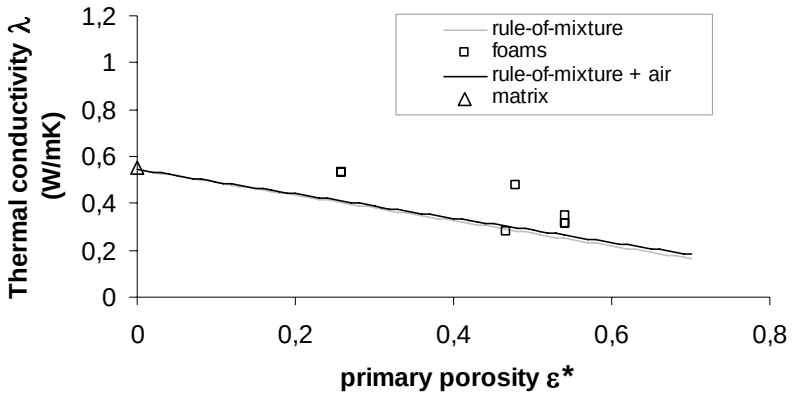

Figure 7: Thermal conductivity of various Hastelloy foams as a function of primary porosity

5. Conclusions and Outlook

It has been shown, that the effective thermal conductivity λ_{eff} of Nickel based foams may be determined with the transient plane source technique at ambient temperature. Compared to dense material the values are smaller by a factor of 20-40 due to the porosity consisting of two types of pores. The influence of the primary pores on λ_{eff} has been described and explained with a simple rule-of-mixture. The secondary pores of the matrix may be compared with the voids of a packed bed consisting of single particles.

Consecutive studies investigate the influence of the secondary pores on λ_{eff}. Furthermore, the investigations are extended to temperatures of up to 700°C and to two more materials, Inconel and Iron.

6. References

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