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THE TRANSIENT PLANE SOURCE TECHNIQUE (TPS) TO MEASURE THERMAL CONDUCTIVITY AND ITS POTENTIAL AS A TOOL TO DETECT IN-HOMOGENEITIES IN METAL FOAMS

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Abstract – A collection of AlSi7 closed cell foams of densities between 500 kg/m^3 and 1300 kg/m^3 were produced following the powder metallurgical route [1,2]. On the one hand, thermal conductivity of the samples has been measured by means of the transient plane source (TPS) technique [3,4]. Values obtained showed the increase of thermal conductivity values with density. On the other hand, the TPS technique has been tested as a tool to detect in-homogeneities derived from the manufacturing process. The results obtained have proved the ability of this method to detect these in-homogeneities, and its possible use as a non – destructive quality control method.

Keywords: TPS, metal foams, in-homogeneities, quality control method.

1. INTRODUCTION

The development of different manufacturing techniques to produce metal foams has increased greatly last years [5,6]. These technologies are able to produce foams of different densities and from different alloys. However, the foams produced have, in general, defects and in-homogeneities in their cellular structure, such as big pores, presence of a thick skin, etc. Due to this reason a quantitative characterization of the microstructure and internal architecture of the foams is needed. Some investigations [7,8,9] have been performed exploring different non-destructive techniques (micro-computed tomography, microscopy, ultra small-angle neutron scattering, X-ray tomography), to obtain information about the internal structure of the foam.

Another possible way to detect in-homogeneities is to measure the thermal conductivity. The method that is described in this paper is based on thermal conductivity measurements using the transient plane source technique (TPS). This novel method offers some advantages such as fast and easy experiments, wide range of thermal conductivities (from 0.02 to 200 W/m K), no sample preparation and flexible sample size.

2. TPS THEORY

Measurements of thermal conductivity are possible by means of the TPS method. In this method, the transient plane source (TPS) element behaves both as temperature sensor and heat source.

The TPS element consists of an electrical conducting pattern of thin nickel foil (10 μm) in the form of double spiral, which resembles a hot disk, embedded in an insulating layer made of kapton (70 μm). (Figure 1)

Fig 1. Schematic diagram of TPS sensor.

Two samples of the same material are brought in contact with the flat sides of the sensor. A constant electric power is supplied to the sensor and the increase in temperature $\Delta T(t)$ is calculated from the variation in the sensor resistance with time R(t) by using the equation:

$$\Delta T(\tau) = \frac{1}{\alpha}\left(\frac{R(t)}{R_0} - 1\right) \qquad (1)$$

where R_0 is the hot-disk resistance in the beginning of the recording (initial resistance), α is the temperature coefficient of resistance of the nickel foil, and $\Delta T(\tau)$ is the temperature increase of the sensor expressed in terms of an only variable τ, defined as:

$$\tau=(t/\theta)^{1/2} \quad , \quad \theta=a^2/k \qquad (2)$$

where t is the measurement time, θ is the characteristic time, which depends both of parameters of the sensor (a is the

sensor radius) and the sample (k is the thermal diffusivity of the sample).

Figure 2 shows the sensor temperature variation in a typical transient heating.

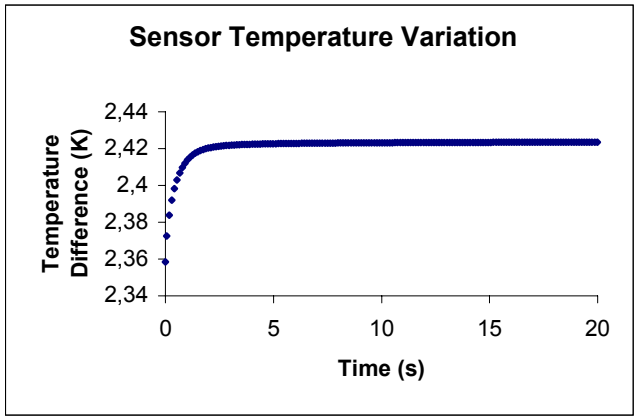


Fig 2. Sensor temperature variation during a TPS measurement.

Assuming the conductive pattern to be in the Y-Z plane of a coordinate system, the temperature rise at a point (y,z) at time t due to an output of power per unit area Q is given by the expression:

$$\Delta T(y,z,t) = \left(8\pi^{3/2}\rho c\right)^{-1}\int_0^t dt'\left[k(t-t')\right]^{-3/2}\int_A dy'dz' \times Q(y',z',t')\exp\left\{-\left[(y-y')^2+(z-z')^2\right]\times\left[4k(t-t')\right]^{-1}\right\} \quad (3)$$

where ρ is the density of the material (kg/m^3), c is the specific heat of the sample (J/Kg K) and k is the thermal diffusivity (m^2/s).

Previous expression can be simplify taking $k(t-t')=\sigma^2a^2$:

$$\Delta T(y,z,t) = \left(4\pi^{3/2}a\lambda\right)^{-1}\int_0^\tau \frac{d\sigma}{\sigma^2}\int_A dy'dz' \times Q(y',z',t')\exp\left\{-\frac{\left[(y-y')^2+(z-z')^2\right]}{4\sigma^2a^2}\right\} \quad (4)$$

where $k = \lambda/\rho c$ and λ is the thermal conductivity.

In the case of a disk geometry, consisting of m concentric ring sources, an exact solution of equation (4) is possible. The average increase of temperature is:

$$\Delta T(\tau) = P_0\left(\pi^{3/2}a\lambda\right)^{-1}D(\tau) \quad (5)$$

where P_0 is the total output power and D(τ) is a geometric function given by the next expression:

$$D(\tau) = \left[m(m+1)\right]^{-2} \times \int_0^\tau \frac{d\sigma}{\sigma^2}\left[\sum_{l=1}^{m} l\left\{\sum_{k=1}^{m} k\cdot \mathrm{Exp}\left(\frac{\left(-l^2+k^2\right)}{2\sigma^2m^2}\right)L_0\left(\frac{lk}{2\sigma^2m^2}\right)\right\}\right] \quad (6)$$

in which L_0 is the modified Bessel function.

Thermal conductivity can be obtained by fitting the experimental data to the straight line given by equation (5), and thermal diffusivity is calculated from equation 2 taking into account the τ value determined in the previous fit. Finally, heat capacity is derived from previous values using the relation $k = \lambda/\rho Cp$ where ρ is the sample density.

3. SAMPLE PREPARATION

Al foam precursor material containing 7 wt.-% Si and 0.5 wt.-% TiH_2 has been produced according to the powder compact melting route. Foaming took place in a batch furnace in a steel mould (200x65x65 mm^3) between 630ºC and 730ºC. Different foaming temperatures and exposure times lead to different densities. Three specimens were cut from each foam sample with dimensions of 60x65x65 mm^3, namely a, b and c. Figure 3 illustrates this process and relates directions of measurement to the geometry of the original foam body. Four of the specimens' faces retained their solid skin, while it was cut off on the others. In general, two samples were used for each measurement. The sample's average density is shown in table 1. Figure 4 shows an overview of the samples.

Samples	Foaming Temp. (ºC)	Foaming Time (min)	Average density (kg/m^3)
1a/c	730	23	564
2a/c	690	28	684
3a/b	730	23	753
4a/c	730	23	852
5a/b	690	28	1001
6b/c	630	51	1339

Table 1. Foaming conditions and density of the samples under study.

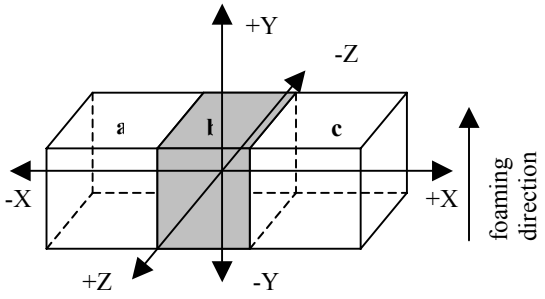


Fig. 3. Directions of the analysed samples

Since foaming temperatures and times differed among samples, a qualitative evaluation of microstructure was performed. It showed that melting of the powder compact and formation of an alloy occurred in all samples.

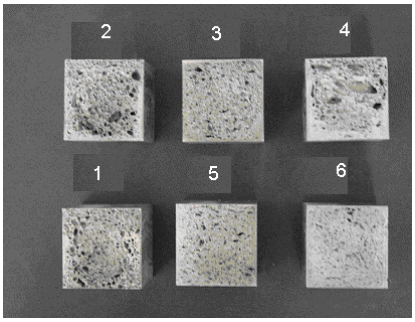
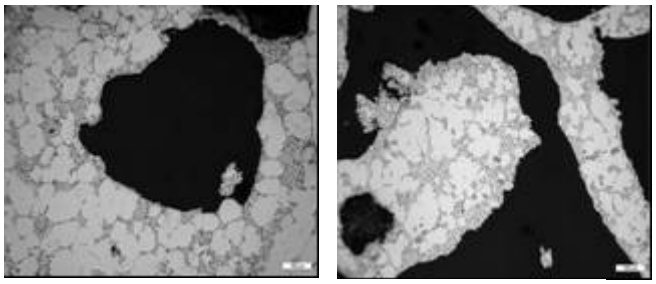


Fig 4. Overview of the samples produced.

Figure 5 shows the microstructure of some of the samples. No obvious differences in grain sizes exist, and variation in microstructure is limited to a slightly finer eutectic in the lowest density sample.



a) b)

Fig 5. SEM micrographs of some of the samples.
a) Sample 2a b) Sample 5a

4. EXPERIMENTAL SET-UP AND RESULTS

To perform the experiments, the TPS sensor was embedded between two samples of the same material, as shown in figure 6. Measurements include, on the one hand, experiments in X direction on the cut faces of the samples (results in section 4.1). In these tests the sensor is located between sample faces perpendicular to the X axis. On the other hand, an investigation on the in-homogeneities produced in the metal foams was carried out performing several experiments in which the sensor was sandwiched between a single AlSi7 foam sample and a reference material (results in section 4.2)

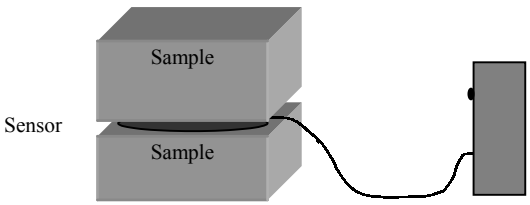


Fig. 6. Experimental set-up for the measurements of thermal conductivity

4.1 Measurements in X-direction

A sensor of radius 9,719 mm was chosen. Output power was fixed at 0.4 W and total measurement time (t) varied between 16s and 25s. It is important to remark that the temperature difference on the sample surface is related with the thermal conductivity measured. Only this discussion is possible if the output power remains constant in all over the measurements. Figure 7 shows the thermal conductivity obtained and the surface temperature difference parameters plotted against density. As it can be observed a higher temperature difference results in a lower conductivity.

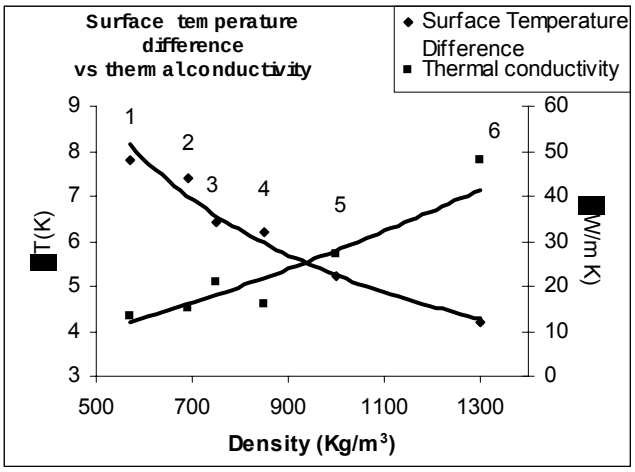


Fig. 7. Comparison between thermal conductivity and surface temperature difference of AlSi7 foam samples.

Figure 8 shows the thermal conductivity values plotted against density. As expected, thermal conductivity increases with foam density. Values are between 10 and 50 W/m K, a reduction of 3 to 10 times compared to a solid alloy of similar composition ($\lambda_{AlSi7Mg0,3}$≈151 W/m K, determined using the same technique). The measured values are slightly different from those given by Abramenko et al [10], who found conductivities of 2.1 to 8.8 W/m K for porosities between 0.69 and 0.79, and Babcsán et al [11], who measured thermal conductivities of 6 to 20 W/m K for porosities between 0.82 and 0.93, both using a monotonic heating method on an AlSi type alloy.

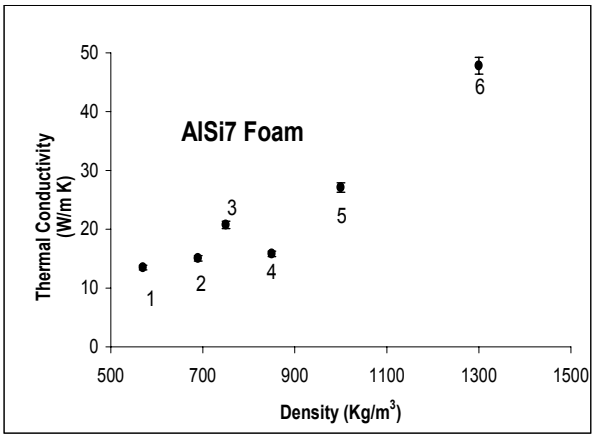


Fig. 8. Thermal conductivity values measured vs density.

4.2 Sample + Reference Material Measurements

Measurements were performed with the sensor embedded between the sample under study and a reference material. The measurements were carried out in all the surfaces of the samples.

In the present work, three reference materials were tested, covering a large range of thermal conductivities:

a) Solid bulk low density polyethylene ($\lambda \cong 0.2$ W/m K).
b) Mild steel ($\lambda \cong 13$ W/m K).
c) AlSi7Mg0.3 solid alloy ($\lambda \cong 151$ W/m K)

It is an important aspect to maintain constant the average temperature of the samples because the sensor can detect small room temperature variations, which could distort the experiment. In this study a temperature of 23±1ºC was used for all the experiments.

AlSi7 solid alloy was finally chosen as reference material due to the high temperature differences detected in the measurements in comparison with the experiments performed using mild steel as reference material. Moreover, experiments carried out using low density polyethylene also showed appreciable differences in temperature, but the use of this material as reference was neglected due to its low thermal conductivity, which could cause local heating of the TPS sensor, and as consequence it would be necessary to wait for a longer time between measurements.

The measurements were carried out using a TPS sensor of radius 9.719 mm, whereas output power was fixed at 0.2 W and measurement time was set-up at 10s for all the measurements. Six samples were tested, and measurements were carried out in each face with closed outer skin. Table 4 shows the samples studied.

Sample	Density (kg/m^3)
1a	546
2a	700
3b	728
4a	826
5a	944
6c	1300

Table 4. Samples studied in the single sample – reference material experiments.

One measurement was performed in each face and the temperature difference was registered by the sensor. In samples where an acceptable homogeneity was observed, a neutral Z direction was chosen to perform the experiments. Table 5 show the values obtained in the measurements performed. All the values are given in K.

As seen in table 5, the values obtained in the measurement vary greatly in different directions of some of the samples. For example, in sample 4c, +Z, +Y and –Z directions show higher temperature difference than -Y direction. This could be related with the presence of a thick layer of metal at the bottom of the sample, as shown in figure 9.

Sample	Density kg/m^3	ΔT +Y	ΔT -Y	ΔT Z	ΔT -Z	ΔT +Z
1a	546	1.64	2.06	2.30	---	---
2a	700	1.03	1.79	---	2.03	1.94
3a	728	1.84	1.81	1.90	---	---
4c	826	1.52	1.09	---	1.51	1.72
5a	944	2.73	2.08	1.95	---	---
6b	1300	1.09	0.99	0.88	---	---

Table 5. Temperature difference detected in sample + AlSi7 solid alloy measurements.

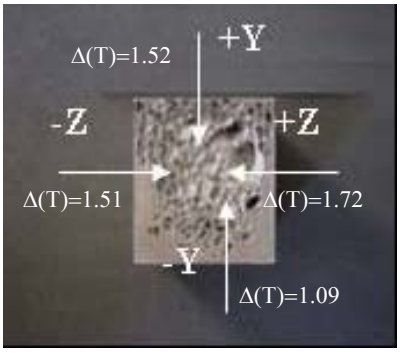


Fig. 9. Structure of the sample 4c showing the temperature differences detected in each direction.

On the other hand, sample 6b shows no great variations in the values obtained, which could be due to the homogeneous structure of this sample, showed in figure 10.

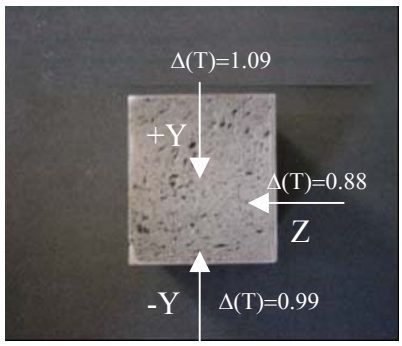


Fig 10. Structure of sample 6b showing the temperature differences detected in each direction.

From previous figures, it can be seen that the structure of the sample is related to the temperature difference measured. By this reason, a comparison between the values obtained in the different experiments carried out could inform about the internal structure (presence of big pores, thick bottom layer of metal, etc) of the sample.

5. CONCLUSIONS

Thermal properties of AlSi7 foams have been investigated using the TPS technique. Temperature difference values were found to be sensitive to the direction of measurement, which is directly related to in-homogeneity induced during the foaming process. Several measurements have been carried out testing different reference materials, AlSi7 solid alloy seems to be the best election to perform the experiments. The results have proved qualitatively the ability of this technique to resolve such variations relating the temperature difference obtained to foam's internal structure. For these reasons, the TPS technique has demonstrated promise to become a tool for further studying these phenomena, and a possible means for quality control in metal foam production.

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