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Mechanical and functional properties related to porous structure of recycled aluminium sponges

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The present study describes mechanical and functional properties of open-cell metal foam associated with structural morphology and metal nature. Aluminium sponges were manufactured by melt infiltration of a pattern of NaCl with a recycled aluminium alloy using vacuum pressure followed by solidification, and finally the NaCl preform is removed by dissolution in water. The open-cell aluminium foams manufactured had a fully open interconnected porosity and a relative density around 0.33. Mechanical and functional properties associated with structural morphology and metal nature were evaluated. According with the test, several foam samples with pore size from 2.0 mm to 500 μm were studied. Uniaxial compression test was performed to determine the porous structure influence on plasticity and damage accumulation in the metal sponges. The standing wave tube method was used to determine the sound absorption coefficient in samples with 30mm diameter and 10-20mm thickness. To evaluate the permeability, pressure drop tests was carried out to have an understanding of the interaction of the fluid with the cell walls in the aluminium sponges. It is showed that sound absorption behaviour is affected by the pore size and an increase in strength with reduction in cell diameter was observed by uniaxial compression. The influence on the permeability of pore connectivity, pore size and sample thicknesses of the porous material have been reported. Several characteristics of the porous material have a notable impact on the energy absorption capacity, permeability and sound absorption behaviour without take into account the metal source to produce the sponge.

1 Introduction

According to the connectivity of cells, metallic foams can be categorized as either closed or open-celled. For functional applications such as filtration, separation, heat exchange, and sound insulation and energy absorption, the cells need to be open, but, the majority of metal foams in the market are closed-cell aluminium foams manufactured by powder metallurgy technologies or by casting foaming processes [1-2]. The aluminium foams produced by these methods are either too expensive due to the high production costs or too poor in quality due to poor controllability in pore structure and porosity. Because of this fact, there has been a growing need for developing cost effective manufacture technologies. Melt routes are popular, since they are economically attractive and can utilize a range of raw materials. In this case, the casting of metals and alloys around a filler material has recently attracted a lot of interest, because it is potentially a very economic way to create cellular structures of a wide range of metals and porosities [3-4].

One of the earliest of this kind casting process utilize NaCl particle to form a preform that can be removed by simply dissolving in water. The metallic foam cellular structure resulting is a shape replication of the starting NaCl particles, and due to that, the structure parameters like cell size, cell shape and porosity are determined to a large extent by the space-holder. Apart of this, the use of recycled aluminium alloy instead certified aluminium alloy leads to a diminishing the cost of raw materials and manufacturing. This paper describes a casting and infiltration process for manufacturing open cell aluminium foams and characterizes the porosity, microstructure, compressive property, sound absorption and permeability of the foams produced, and the influence of the use of recycled aluminium is examined as well.

## 2 Experimental procedure

2.1. Preparation of the Al alloy sponges

The materials used for manufacturing the open cell metal foam (named sponges), were NaCl or common salt and, an AlSiMg recycled aluminium alloy, which composition (before and after the infiltration process) was obtained by atomic absorption spectrometry and the results are showed in Table 1. The recycled aluminium was supplied by a local high voltage energy transmission company. Sodium chloride was sieved to obtain particles of controlled size, the particles of 2.0 mm, 1.2 mm and 0.5 mm sizes was used in this article. Preforms were infiltrated at 700°C with molten aluminium alloy under vacuum pressure to 33 kPa. The resulting Al/NaCl composites were then machined into cylinders with measurements depending of the test. The salt was subsequently removed by dissolution in distilled water, leaving cylindrical samples of recycled aluminium sponges (RAS).

Recycled alloy	Al	Si	Mg	Fe	Cu	Mn	Others
Raw material	88.4	11.3	0.49	0.28	0.14	0.02	balance
Metal matrix sponge	87.8	10.5	0.41	0.37	0.14	0.02	balance

Table 1. Chemical composition of the recycled aluminium alloy

The particle size of the NaCl needs to be selected according to the intended cell size of the final sponge. In this case, NaCl had an irregular morphology such as is showed in Figure 1.
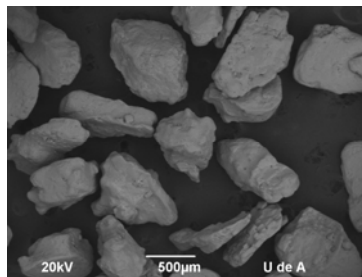
Figure 1. SEM image of salt particles of irregular morphology

The structure of the RAS, including cell morphology and microstructure of the metal strut, was examined by optical microscopy and a JEOL JMS-6490LV scanning electron microscope (SEM). For the microstructural examinations, the pores of the samples were filled with epoxy resin before polishing. Energy dispersive X-ray analysis (EDX) was also carried out to identify the composition of second phase precipitates present in the compression fracture region. The porosities of sponge were determined using a picnometer device.

2.2. Measurements and tests

The compression tests of the specimens were conducted on an Instron 5582 materials testing system at a crosshead speed of 0.5 mm/s. The specimens for the compression tests were 20 mm in diameter and 20 mm in height. It was used three specimens for each pore size. The measurement of acoustic properties of metal sponges was carried out using the impedance tube method [5]: the sound absorption coefficient measures the fraction of the energy of a sound wave which is absorbed when it is incident on the surface of a material. The test frequency range was 300–6400 Hz. In this case, the air gap layer between the sample and the rigid wall is zero. The sound absorption properties of materials have been expressed by sound absorption factor α. The sound absorption test samples were 29 mm in diameter and the thickness was 20 mm.

The experiments for permeability measurements were conducted using a system that consists of a middle flange assembly where the aluminum sponge specimens were securely assembled, a pressure transducer, a velocity meter, a pressure vessel and a settling chamber. The velocity meter and pressure transducer data were acquired using a data acquisition device connected to a PC. The permeability testing samples were 50 mm in diameter and 20 mm in height. The permeability was measured by flowing liquid at steady state through the sponges and the liquid used was distilled water.

3. Results and discussion

3.1. Cellular structure and metal microstructure

The RAS exhibit open cells uniformly distributed and well-interconnected. The pore morphology and pore size represent the characteristics of the original NaCl particles. The aluminium sponges have average porosity of 67% and cell sizes of 2.0 mm, 1.2 mm and 0.5 mm. The relative density of the RAS produced by the present method is in the range of 30~38% and is related proportionally to the size pore. SEM and optical images of the macrostructure and microstructure of the RAS manufactured are shown in Fig. 2.

The Fe concentration in the metal matrix of the sponges was higher than that of the raw material. It is possible that some interaction between iron crucible and the aluminum alloy had occurred during metal melting and infiltration process. The microstructural images confirmed the Fe content on metal matrix, since several β-AlFeSi particles were observed in the metallographic samples (Fig. 2b). In general, the RAS consists of dendrites of a α-Al, coarse Si particles (dark grey plates and plates with like-coral morphology), Mg_2Si precipitates (black Chinese script) and, α-AlFeSi (light grey Chinese script) and β-AlFeSi (intermediate grey needles) second phase particles.
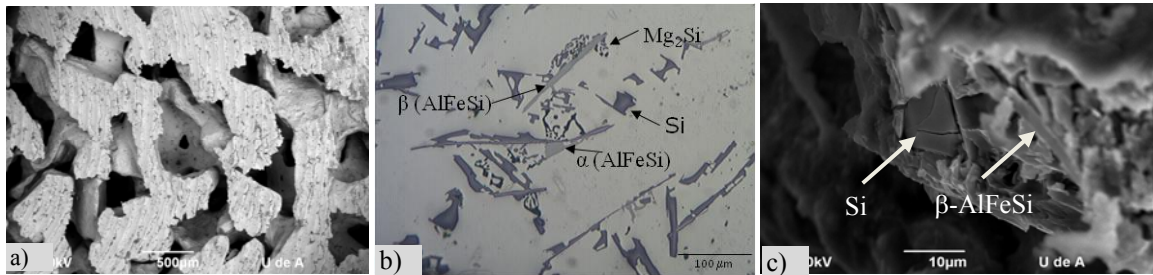
Figure 2. Macrostructure and microstructure of the sponges manufactured: a) SEM images of macrostructure, b) optical image of metal matrix microstructure, c) SEM image of Si and β-AlFeSi particles over compressive fracture surface

From point of view of the process, second phase particles formation (α or *β*) during solidification and the particle size will depend on the cooling rate and the chemical composition of the aluminum alloy. It has been suggested that high iron content together with high content of Si and slow cooling rate of the Al/NaCl composite have a strong influence on the formation of β-AlFeSi. In the similar way, the size of particles of Si and AlFeSi increases with slow cooling rates [6-7]. In addition, the present study suggests that the Si particles with like-coral morphology are a consecuence of the NaCl-Al alloy interaction during the casting process [8]. Additional studies focused in this subject must be done.

3.2. Mechanical properties of the foams

The variations in compressive stress–strain as a function of pore size and relative densities are shown in Fig. 3. The curves are typically characterized by an initial elastic region, followed by a deformation plateau region with a nearly constant flow stress up to a large strain around to 50 to 60% and finally a transition where the flow stress rapidly increased because of sample densification. This trend of the RAS is similar to those of other metal foams [9].

One of the characteristics of the RAS is a very homogeneous behavior in the stress-strain curve for each pore size of the sponge. It was observed that the stress at the macroscopic yield point and the subsequent plateau stress at a certain strain increase with increasing relative density. Moreover, it should be noted that the RAS with the smaller pore size 0.5 mm showed a higher flow stress than that with the greater pore size of 2.0 mm.

In the other hand, compressive fracture surfaces observed by SEM images in Fig. 2c. show coarse particles of β-AlFeSi and Si. It is known that Si and β-AlFeSi phases are brittle particles with plate and needle morphologies, respectively, and both present a sharp interface boundary which may have induced significant stresses in the aluminum matrix acting as a potential site for crack initiation and propagation. Amsterdam et al. [10] indicated an intergranular fracture caused by AlFeSi precipitates in Duocel aluminum foams. EDX measurements confirmed the iron content in the found AlFeSi particles.
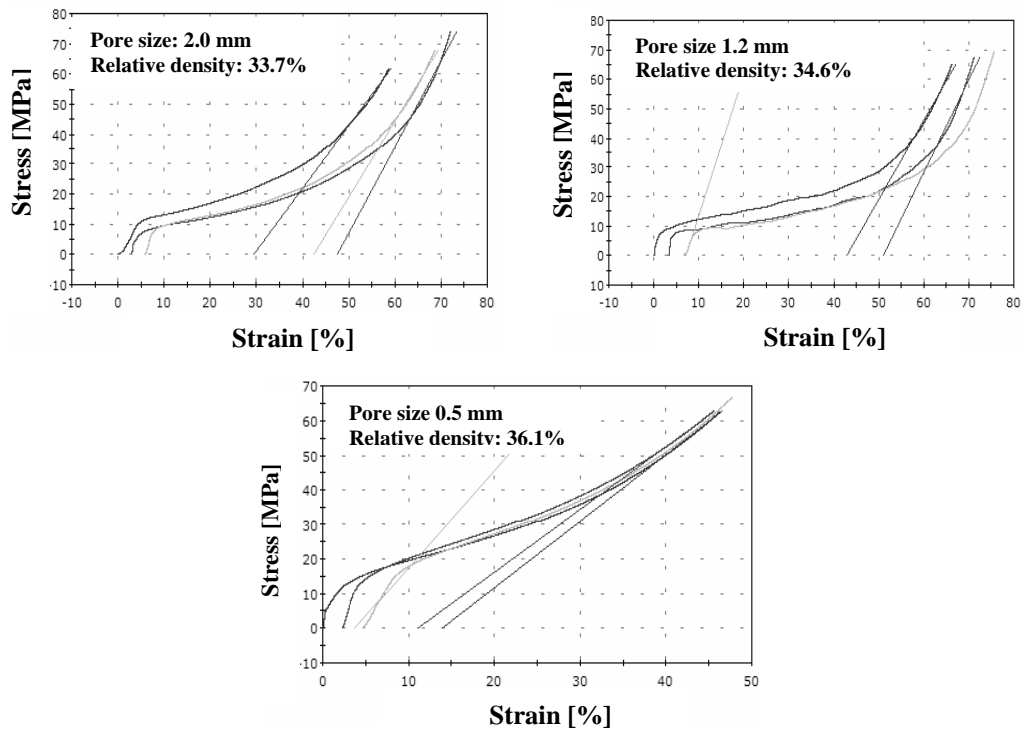
Figure 3. Compressive stress–strain curves of the RAS in function of pore size and relative density: a) 2.0 mm (33.7%), b) 1.2 mm (34.6%) y c) 0.5 mm (36.1%).

3.3. Sound absorption capacity α

The curves of normal sound absorption coefficient α of RAS samples are shown in Fig. 4 over the frequency range of 500-6500 Hz for three pore sizes. It was noted that sponges with smaller pore sizes tend to absorb more sound than sponges with higher pore sizes. The absorption coefficient peaks were shown at resonance frequencies of 2200 Hz (α= 0.87), 2900 Hz (α= 0.80) and 3000 Hz (α= 0.63), for pore sizes of 0.5 mm, 1.2 mm and 2.0 mm, respectively. It is considered that RAS with small pores have good sound absorption properties because of their open porous structure which leads to efficient absorption of vibration energy [11].
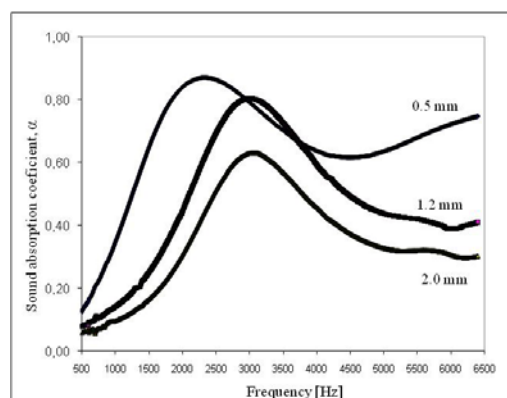
Figure 4. Sound absorption coefficient – frequency curves in function of pore size

3.4. Permeability

Pressure drop results show that the flow through RAS samples is in agree with Darcy's law [12]. Resulting values for permeability, K, depending on pore size and relative density, are given in Table 2. The permeability is significantly affected by pore size and porosity. For the sponges evaluated, the effect of pore size on the permeability indicates that K increases with the increasing of pore. In similar way, it was demonstrated that permeability increases as porosity of sponges increases.

Pore size [mm]	Relative density [%]	Permeability [m^2]
0.5	36.7	1.76×10^{-10}
1.2	34.1	1.84×10^{-10}
2.0	32.4	2.36×10^{-10}

Table 2. Values of permeability K obtained for recycled aluminium sponges

Conclusion

Recycled aluminum sponges were processed by infiltration process under vacuum pressure using NaCl as perform and recycled aluminum as metal matrix. The use of recycled aluminum leads to a more economical process without cause a detrimental effect in physical properties, however, in order to do not generate second phase precipitates that could affect the mechanical properties, more careful must be taken with respect to Fe and Si content, and Al/NaCl composites cooling rates. The microstructure observations revealed Si particles with like-coral morphology, likely due to a possible NaCl-Al interaction during metal casting and infiltration process. The compressive strength of the RAS were partially affected for the presence of brittle second phase particles β-AlFeSi. In spite of this, it was found that the sponges showed a good mechanical behavior and the stress-strain relation was in agreement with others cellular aluminum.

Acknowledgment

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