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Procedia Materials Science 4 (2014) 121 – 126

Procedia Materials Science

www.elsevier.com/locate/procedia

8th International Conference on Porous Metals and Metallic Foams, Metfoam 2013

Effect of processing parameters on morphology and plateau stress of AlSi and AlSiMg foams

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Abstract

In this work, aluminium foams produced by the powder metallurgy route are evaluated. This kind of aluminium foams have a high potential in weight-sensitive construction parts. The aim of this study is to evaluate the properties (in terms of foam morphology and plateau stress) and to optimize three control factors chosen: temperature, precursor material and mean of cooling. AlSi10 and AlSi0.6Mg1commercial foamable precursors are the starting materials. Different set of samples are realized following the DoE approach; manufactured samples have been morphologically and mechanically analyzed to evaluate what level of each parameter better influences the final quality of the foam. Temperature and mean of cooling have a great influence on the mechanical behavior of the foamed structure.

Keywords: Aluminum foam; Repeatability; Morphological Characterization; Compressive test; Plateau Stress

1. Introduction

Metal foams are cellular materials obtained by the dispersion of a gas in a plastic solid material. Many processes have been developed to realize metal foams, according to the state in which the metal is processed. Metal foam structures can be used to reduce the weight of machinery without compromise the mechanical behavior. The stiffness

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doi:10.1016/j.mspro.2014.07.613

to weight ratio is the main criteria for material selection in light-weight design (Surace et al. (2007)). So, it is interesting to study the morphology and the mechanical behavior of foamed samples produced with different process parameters. In this work, foamed samples are produced by a method developed at the Fraunhofer Institute in Bremen (Germany), known as "powder metallurgical route". The process leads to foamed structures, because it involves the decomposition of particles that release gas in semisolid. The reference technique was first applied in 1963 by Allen et al. In this work, commercially available precursors are used, thus the production of the metal foamable compacts is avoided; circular and rectangular profiles are used for the experimental part. The porous structure of aluminium foams, manufactured through foaming of precursors containing blowing agent, is stochastic in nature, usually with a random distribution of pores of different size and shape, creating difficulties in the modeling and prediction of foam properties (Nosko et al (2010)). This process allows the production of near net-shaped parts with complex geometries, as well as 3D-shaped sandwich structures with a foamed core layer (Baumgartner et al (1999)). Nowadays, a huge number of studies on the process are available (Banhart et al. (2001), Mukherjee et al. (2010), Campbell (2003), Mukherjee et al. (2010)), but the knowledge of correlations existing between the final properties of the foamed parts and the process parameters is still not complete. The aim of this study is to evaluate the properties and to optimize the process parameters of this powder technique by means of a statistical approach.

2. Experimental Approach

The process is based on foaming of aluminium foamable precursors, in particular of AlSi10 and AlSi0.6Mg1 alloys containing titanium hydride (0,8 % of TiH_2) as blowing agent, followed by morphological and mechanical analysis of the obtained samples. The foaming process takes place in a furnace at different temperatures and then the samples are cooled in water or in calm air.

2.1. Materials and Processing

The three parameters chosen for the experimental part are foaming temperature, precursors material and mean of cooling of the foamed samples. The chosen parameters are considered responsible for influencing the quality of the final product and they are tested during screening. In particular, the temperature of the chamber influences the time of permanence of the precursors in the furnace and the internal structure, the material of which the precursor is constituted affects the melting point and the heterogeneity of the bubbles obtained and, finally, the cooling rate has an influence on the level of morphological defects and cell size non-uniformities (Nosko et al (2010)).

The precursors used are rectangle of 2x4 cm or cylinders with 1 cm of diameter and the same length of the rectangular ones. The aim is to investigate how the chosen process parameters influence the morphological and the mechanical behavior of the foamed structures, in order to optimize the choice of the most relevant parameters. As the authors asserted in a previous work (Marinzuli et al. (2011)), a mould in which precursors complete their foaming is necessary; when foaming is performed inside a closed mould and the foaming time is set appropriately, a foam of reproducible volume – that of the mould – and density can be obtained. Moreover, to obtain perfectly cylindrical samples a series of opening moulds is created. Hollow steel cylinders, in which the precursors can expand, are longitudinally cut; then they are joint by a tie as shown in Fig. 1. In this way, after foaming, samples can be extracted without damaging their shape. The authors have verified the effects of three reference main factors on cells area, circularity parameter, density and plateau stress.

Fig. 1. Opening steel cylinder and mould used for foaming.

Table 1. Parameters and levels of the factorial plan.

FACTORIAL PLAN	
PARAMETERS	LEVELS
Temperature [°C]	700
	800
Mean of cooling	Air
	Water
Precursor material	AlSi10
	AlMg1Si0,6

The adopted standard approach for Design of Experiments (DoE) is used for the design of a full factorial method (TABLE I). Two levels for each factor are chosen: 700°C and 800°C for the temperature, air cooling or water cooling for the solidification and AlSi10 or AlSi0.6Mg1 for the precursors material. Other useful parameters, not included in the factorial plan but fixed during screening, are starting dimensions of the precursors, that are used to calculate the expansion curve of the foamed sample and to ensure the production of the same foamed volumes, material and dimensions of the steel mould. Also the initial location of the foamable precursors in the mould and its anisotropy have a significant effect on the structure of the aluminum foam, which is different for a given precursor distribution due different heat conduction and pore formation. Symmetric heating of precursors is required to obtain foam with a relatively uniform structure. Three replications for each combination of the factorial plan are made, so 24 samples are produced for the investigation. Another set of 24 samples is manufactured for the mechanical characterization, to investigate the effects of the same process parameters on the mechanical behavior of the aluminium foams manufactured. Some samples resulted damaged after foaming: in this experimental work, a sample is discarded if after three further replications it still resulted damaged. The discarded samples received the lowest score in the statistical analysis.

3. Results and Discussions

3.1. Morphological characterization

Morphological characterization is carried on in two phases: a qualitative inspection and a quantitative evaluation of pore features. The visual inspection focuses on the main defects of a foamed structure: heterogeneity, drainage, coalescence, corrugation and collapse of the cell walls. These defects can be avoided by reducing the stress applied to the foam immediately after solidification and by reducing the rate of cooling. Anyway, in presence of cell wall corrugation, both the axial stiffness and the flexural rigidity of the curved or corrugated structural member are reduced (Simone et al. (1998)) up to a 70% drop in the modulus and strength below the values estimated for planar cell walls (Grenestedt (1997)). Longitudinal sections of the samples prepared for morphological investigation are showed in Fig. 2. An important value to investigate bubble sphericity in the quantitative evaluation is the circularity parameter. It is expressed by:

$$\text{Circularity parameter} = 4\pi A/P^2 \quad (1)$$

where A and P are respectively area and perimeter of bubbles. The circularity is defined to be shifted from 0 to 1 when the structure of pore is closer to spherical from irregular shape. The values of the equivalent diameter and circularity parameter have been determined after pores area measurements. Each section, after the qualitative inspection, receives a score, according to the quality of the internal morphology. The score assigned shifts from 0 to 4 (TABLE II). There is no great matching between circularity parameter and the score assigned; this could indicate that the perfect shape of each bubble does not ensure a good dispersion of the same bubbles in the foamed sample and that bubbles circularity does not necessarily correspond to the perfect bubbles sphericity. After these considerations, the element that seems to characterize better closed cell foams, especially from a mechanical point of view, is the good dispersion of the pore and low heterogeneity. The authors note that a foam with all little regular pores and few big pores has a worst mechanical response than a foam with all the pores almost of the same dimensions: the pores that leave the central trend have to be considered as defects in the structure.

Using the scores assigned to each cross section, Main Effect and Interaction Plot graphs are diagrammed (Fig. 3 and 4). Main Effects graph points out that the temperature of 700 °C gives the best results in term of morphology. It is a partially unexpected data because in previous works (Mukherjee et al. (2010)) 800°C gave the best results. Actually, in this case two different precursors materials are used; since the alloy composition influences the melting point of the precursor, a different optimal temperature in comparison to test conducted on one precursor material only is reasonable. About the mean of cooling, there are not great differences between air or water and, finally, AlSi0.6Mg1 show best results as precursor material.

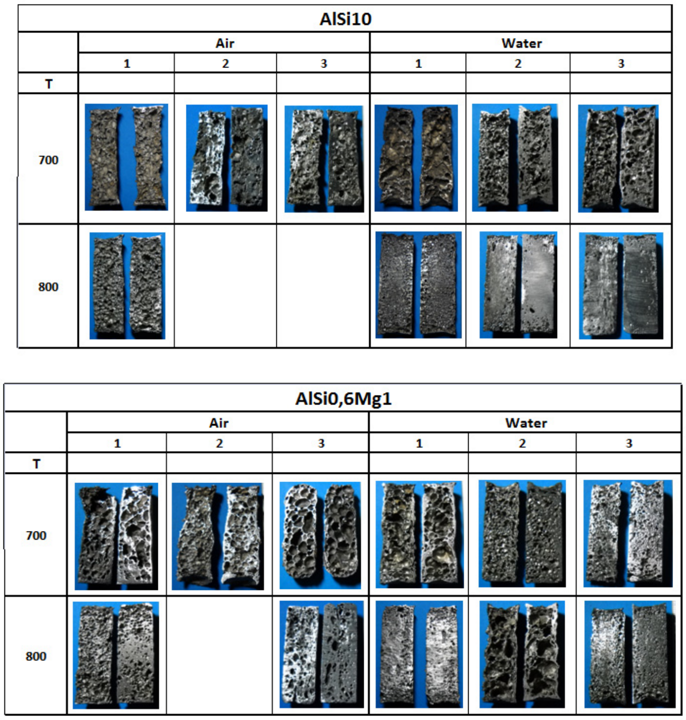

Fig. 2. Cross section of samples prepared for morphological analysis.

Table 2. Scores scale chosen for samples.

SCORES	
0	Discarded sample
1	Poor sample
2	Sufficient sample
3	Good sample
4	Optimal sample

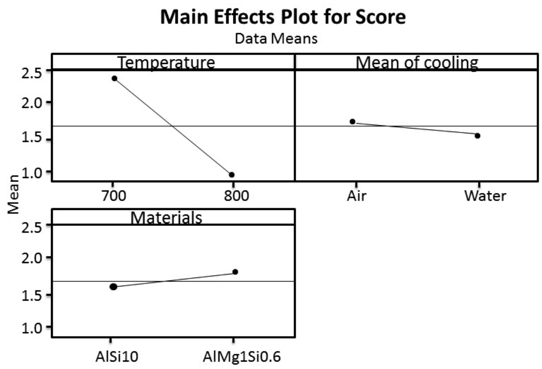

Fig. 3. Cross section of samples prepared for morphological analysis.

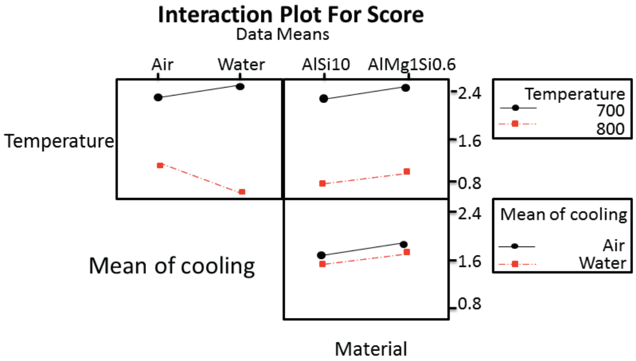

Fig. 4. Interaction Plot for Score.

3.2. Mechanical characterization

For the mechanical characterization, another set of 24 samples is realised. Compressive strength has been evaluated following the statements of the standard test method of the UNI 558-85, on the compressive test on metallic materials at room temperature. The standard UNI 558-85 states that the dimension of the sample have to respect the following relation: L0/D0 = 1,5. The foamed samples used for tests were 45 mm long and they had a diameter of 30 mm. Flat surfaces of foam specimens are prepared.

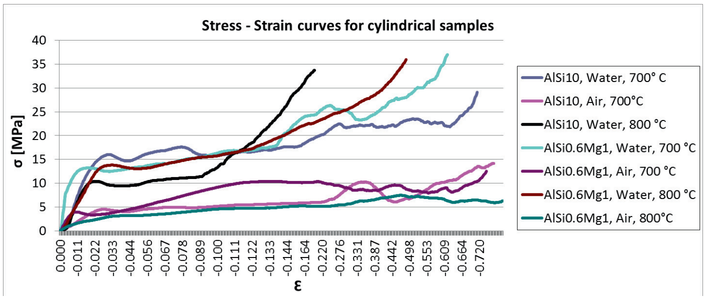

Fig. 5. Stress –strain curve for each combination of parameters and levels of the factorial plan.

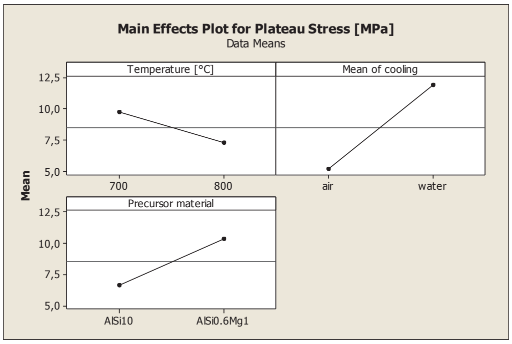

Fig. 6. Main Effects for Plateau Stress.

Before doing compressive tests, samples are weighed with a precision balance to calculate their density and to compare it from density value of samples manufactured for the morphological investigation. Repeatability is found also in samples density, because samples obtained with the same process parameters have almost the same density. Moreover, a better mechanical response is expected from those samples with a lower density: they should present the typical trend of stress – strain curve for the cellular metal in which a long plateau zone is present. So, higher plateau stress values are expected form those samples with low density. Mechanical tests, only loading ones, are carried on by mean of an INSTRON 4485 machine. The control software was set up on the following specifications:

- Speed = 1 mm/min. (quasi static conditions);
- Sampling speed = 1 Hz;
- Limit load = 200 kN (Static Load Cell of 200 kN, with a maximum load of the plates of 300 kN).

The compressive force is parallel to the foaming direction of the precursors material and the samples are deformed of the 70% beyond the initial thickness, to point out the densification phase, in which the load rises strongly. Each test is interrupted when the graph, built by the control software, shows an asymptotic growth. Load and displacement are the output data of the compressive machine: from such data couples acquired, stress – strain values are calculated. Fig. 5 shows some stress – strain curve for each combination of parameters and levels. Plateau stress value is identified in each graph at a fixed deformation of 5% and it constitutes the new score for each sample compressed. Plateau stress is used to understand how the chosen process parameters influence the mechanical behavior of the realized foam. Main Effect (Fig. 6) and Interaction Plot graphs for plateau stress are realized. The higher is the value of the plateau stress the longer the foam undergoes an elastic strain. So that the graphs put in evidence the parameters that well affect this value. Main Effects graph shows that mean of cooling particularly influences stress and water cooling allows the production of foams with high plateau stress. Temperature of 700°C and AlSi0.6Mg1 are the other parameters that allow to have aluminium foams with good mechanical characteristics. A low content of silicon maybe influences better cell morphology and also the mechanical response of the foam, because high silicon content increases heterogeneity of the foam.

4. Conclusions

In this work effects of process parameters on the morphology and on the mechanical behavior of an aluminum foam are investigated. The selected parameters are related to the process and to the material chosen for the precursors: temperature of the furnace, mean of cooling of the foamed structure and composition of the foamable precursor seem to have the greatest influence on foam quality. After the statistical investigation, temperature results the more influent parameter on foam morphology. About the mechanical characterization, water cooling seems to be the most relevant parameter for gaining high plateau stress values; a lower temperature matched with a low content of silicon also influences the mechanical response of the foamed structure. Future works foresee the possibility to verify how the foam reacts to heat treatments, in particular to annealing and ageing, from a morphological and a mechanical point of view. Then, an attempt to fill boxes will be made to verify if the geometry of the mould influences the characteristics investigated in this work.

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