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# Properties of Aluminium Nodules Foamed with Concentrated Solar Energy

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ABSTRACT. Commercial aluminium foam filled structures and sandwich panels are available for structural applications. As alternative to these materials, small granular foamed pieces are proposed to fill structures as well as sandwich panels. On the present work, foam precursors are obtained by Powder Metallurgy (PM) route, using natural calcium carbonate as foaming agent instead of titanium hydride. Extruded precursor bars were cut into small pieces (around 4.5 mm long and 5mm in diameter). Foaming treatment was carried out on two different ways: electrical preheated furnace and by solar furnace. Foamed nodules presented a low cell size, density e.g. 0.67 g/cm$^3$ to 0.88 g/cm$^3$ and a height/diameter ratio between 0.72 and 0.84 as a function of precursor size. These properties depend on the foaming particle size, foaming cycle and precursor dimensions. Carbonate precursors are easily foamed by concentrated solar energy, due to the lower risk of cell collapse than with hydride precursors, resulting from cell stabilization by oxide skin formation into cells and a low degree of foamed nodules bonding.

## 1. INTRODUCTION

Efficiency of automobiles is focused mainly on energy crash, thermal management, lower vibration and a silence ride. On these features, aluminium foams can play an important role since they exhibit unique combination of physical, mechanical electrical and acoustic properties. Close pore aluminium foams increase the level of mechanical and acoustic properties of automobile structures [1]. Crash box, pillars and frames or floor panels are potential applications of closed-pore aluminium foams. The higher crushing resistance of foam filled tubes or structures allowed better security levels.

In order to achieve these metallic foam filled structures, several methods [2] are under development such as PM precursor foamed in a metallic mould, packing hollow metallic spheres (MHS structures), or foaming into small nodules and packing (APM: advanced pore material)[3]. MHS and APM use adhesives to bond nodules or spheres, leading to aluminium foam-polymer composites [4]. Precursor foaming into a mould and foam nodule packing use a precursor obtained by Powder Metallurgy route. However APM structures demostrate an effective processing route, better design flexibility and higher damping properties than mould precursor foaming. Thus, APM foamed nodules are obtained without a mould, since a cuboid precursor granule is heated to melting point. Surface tension of melt leads to its spherical shape, but gravity force modifies its geometry to an ellipsoid-like shape [3]. Heat is transferred directly to precursor when no mould is used. Adhesive coating is a pre-treatment before structure is filled and later warmed to bond the nodules.

Aluminium foam precursor used on APM structures corresponds to titanium hydride foams [3,5]. This is the foaming agent that starts to decompose at over 425ºC. As an alternative, carbonate foams uses $CaCO_3$ as foaming agent [6-8] which starts to decompose at over 700ºC. Natural calcium carbonate are also used, such us marble waste [6-8]. Manufacturing foamed nodules into packing structures (FNPS) is an alternative to APM and MHS structures. In this study, foamed nodules from Al-marble precursors are obtained and characterized prior to their use in filled tubes or structures.

## 2. EXPERIMENTAL PROCEDURE

2.1 Precursor manufacturing. Carbonate precursors were obtained by PM route [9-11]: mixing powders, cold isostatic pressing and hot extrusion into 5 mm diameter bars. As raw materials, elemental aluminium powder (<120 µm, 99%) and marble powder from crushing waste were used. Foaming agent particle size determines the manufacturing conditions and final foam structures. Two particle size ranges were used: 45-65µm and 106-150 µm. In order to obtain aluminium precursors with an adequate dispersion of 10% marble particles, dry and wet mixes were used.

Influence of precursor size and heating time on foaming was studied using a preheated electric furnace at 750ºC in air. Extruded precursor bar was disk precision cut between 4.5 mm to 6.5 mm long. If the precursor were cut using a chopper, it would result in a more irregular shape. Also 5.0± 0.2 mm length Al7SiMg-TiH$_2$ [11] precursor was also foamed as reference material.

2.2 Foaming treatment on solar furnace. Previous works [12] have shown the feasibility to obtain aluminum carbonate foams on a solar furnace. Carbonate precursors were placed on a hot plate (Figure 1). Precursor size was 5± 0.2 mm high. A circular movement of stainless steel hot plate was applied to allow a more uniform heat ($\omega$1, step B, Figure 1). Once foaming had finbished, hot plate speed was increased to improve nodule cooling. ($\omega 2 > 60$ rpm, step C, Figure 1).

Test conditions were: rotary speed ($\omega$1)12 rpm, 10g and 20 g precursor load, solar radiation close to 910W/m$^2$ and 15-20% Shutter aperture. Test times were between 3 and 4 min up to foaming. CCD cameras and two pyrometers were used. Heating cycle was recorded by stainless steel hot plate temperature. A Testo 840 pyrometer was used and focused on the edge of hot plate due to its circular movement. Maximum temperature was lower than what would theoretically be applied to precursor foaming due to the indirect temperature measurement. The hot plate was painted with graphite to avoid aluminum adhesion from foamed nodules as well as improving energy absorption [12]. Heating rates were between 120 to 130 ºC/min.

Foamed nodule density was obtained using the Archimedes method. Also, the nodule surface and fracture were analyzed with scanning electron microscopy (SEM). Wire precision cutting was used to observe the nodule pore structure.

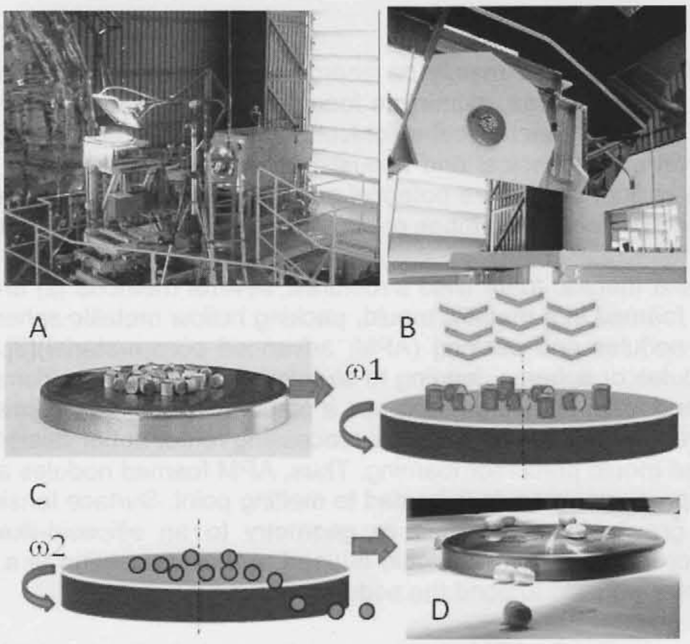

Figure 1. Top: Solar furnace arrangement redirectional mirror and pyrometer device. Bottom: Diagram showing movement of hot plate from test start (A) to finish (D).

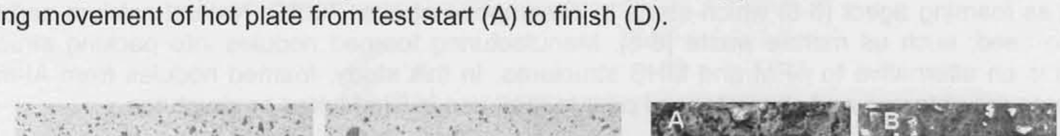

Figure 2. Left: Microstructure of precursor Al + Marble (45-65 µm, dark grey) with agglomerates (A) and free of marble particle agglomerates (B). Right: Fracture of precursor with marble particles (A:45-65 µm and B:102-150 µm, in white color).

## 3. RESULTS AND DISCUSSION

3.1 Precursor foaming behaviour. Final pore nodule structure depends on precursor characteristics and foaming cycle. Microstructure of precursor should be free of marble particle agglomerates (Figure 2, left, sample A) to avoid big pores on final foam structure after foaming on preheated electrical or solar furnace. Wet powders mixing allowed obtaining a more uniform precursor microstructure as it can be seen on precursor fracture (Figure 2, right). As a consequence, a low number of large pores in the foamed nodule will be obtained.

Time dependence of carbonate precursor foaming in preheated electric furnace can be seen in Figure 3, left. At 750°C, 5mm high precursors were placed vertically on hot plate and progressively heated. After 3,5 min foamed nodule was fully developed and its density was close to 0.66 g/cm$^3$. Nodule density (Figure 3), volume and height were dependent on precursor size, but their horizontal or vertical position of precursor on hot plate did not modify the nodule size. Precursor height has a little influence on foam nodule density (Figure 3). However, the shape of nodule was far from spherical (Figure 3, right) when precursor height was 6.5 mm.

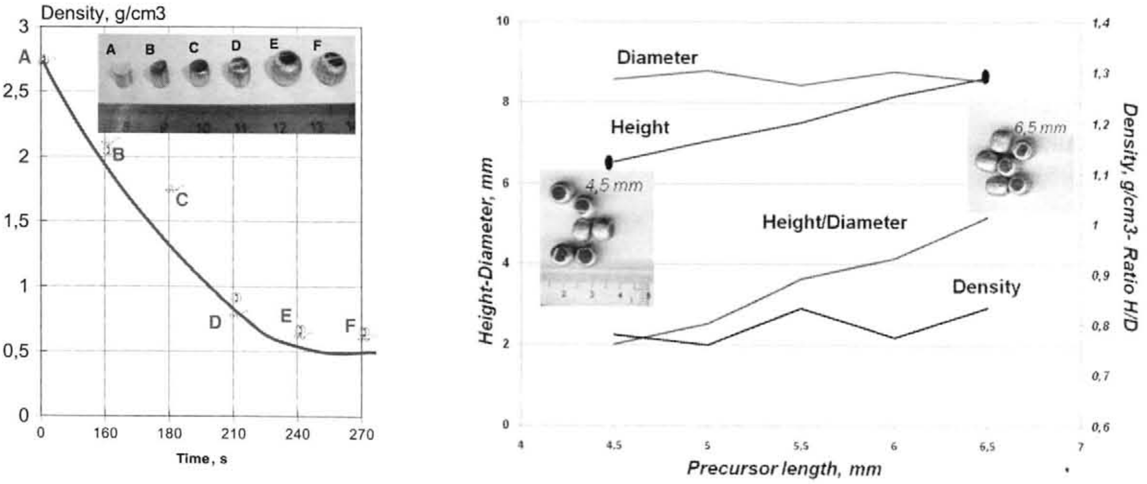

Figure 3. Left: Foaming development (A to F samples) in 5 mm hight precursor as a function of time (s) at 750°C on electrical furnace. Right: Influence of precursor height on foamed nodule size and density

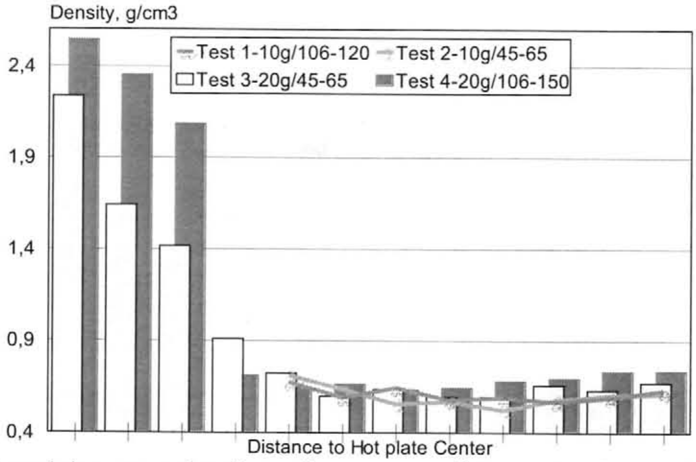

Figure 4. Density of nodules as a function of precursor distance to the centre of hot plate during testing of carbonate precursor (weights: 10g and 20g) with different marble size (45-65μm and 106-150μm).

Surface tension and viscosity of carbonate precursor were not enough to cause the initial cylinder shape (Figure 3). As result of foaming a barrel-like shape was achieved. This allows a high contact angle between granules in a vertical direction. Also, shorter nodules can be vibrated to stand up all of the nodules up on the initial cylindrical precursor axis instead to getting a random nodule alignment. This would be important to get uniform sandwich panels. However, when nodules are used to fill a tube, there is a random nodule alignment and bulk nodule density is close to 0.42 g/cm$^3$, when precursor height was 5 mm [13].

Foamed nodule densities were 0.66 g/cm$^3$ when a fine marble powder was used and 0.70 g/cm$^3$ on average with coarse marble powder. Thus the influence of foaming agent size can be summed up as follows: the finer size decomposes more easily than the coarse size and improves precursor foamability and density [9-11].

3.2 Solar Foaming Treatment. Influence of precursor load and position can be seen on nodule density (Figure 4). Hot plate temperature was higher (close to 550ºC) when a 20 g precursor load was heated instead of a 10g (close to 450ºC), since higher time is needed to complete foaming when test load is increased. On the other hand higher conductivity of titanium hydride precursor and low melting point of Al-Si alloy lead to shorter heating times and lower hot plate temperatures than foaming carbonate precursors.

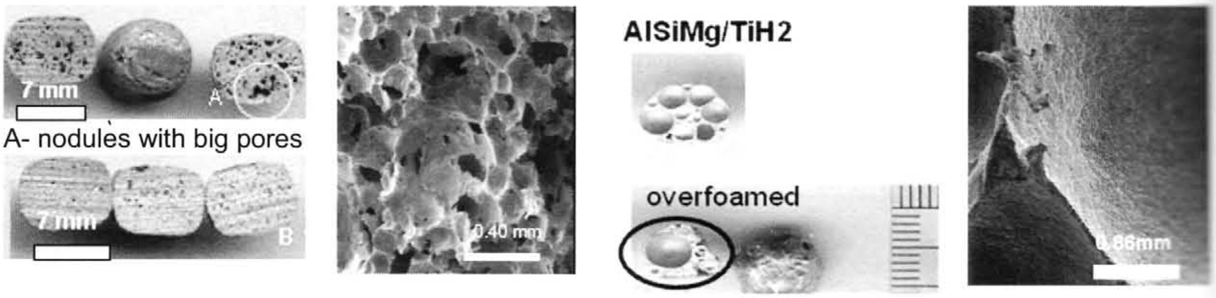

Figure 5. Foamed nodules obtained on solar furnace. Left: nodules from carbonate precursor. Right: nodules from hydride precursor.

According to the hot plate temperature recorded by pyrometers, precursor was also heated by hot plate conductivity as well as by direct concentrated solar energy. Solar furnace treatment using concentrated solar radiation is similar to bulk/3D treatment. However solar heating conditions change with the distance to focus centre and thus, density depended on the distance of precursor from the hot plate centre (Figure 4). Temperature recorded at the hot place center was close to 950ºC during foaming test with a precursor load of 20 g, meanwhile the edge of the hot plate was only 550ºC. Solar heat distribution can be modified to allow the complete foaming of precursors placed close to the edge of the hot place, and the hot table can be displaced to allow complete precursor foaming. Under the conditions used the precursors that were away from the focal point did not foamed and their density was close to 2.4 g/cm$^3$. Meanwhile the nodules placed in the centre, were over-foamed.

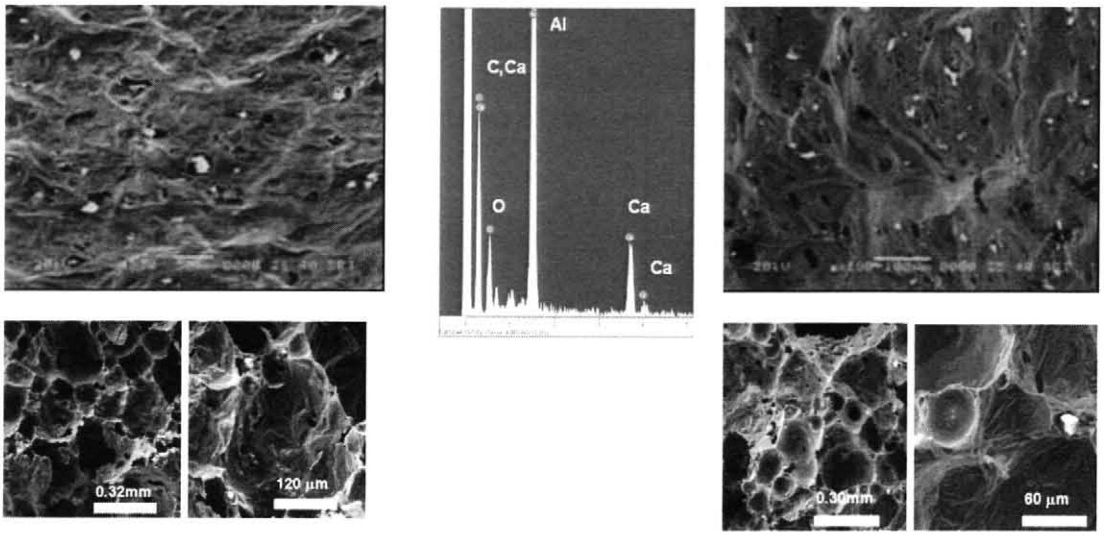

Figure 6. Surface (top) and fracture (bottom) of over-foamed (left) and right foamed nodules (right). White particles represent non-decomposed marble (X-ray microanalysis, centre)

Structure of foamed carbonate nodules showed a smaller pore size (Figure 5, left) than titanium hydride nodules. Some big pores were found in carbonate nodules as a consequence of marble particle agglomerates (Figure 2). An elliptical shape was obtained in titanium hydride nodules as a consequence of gravity [3]. Also pore collapse (Figure 5, right) and high degree of weldability were found on foamed nodules from titanium hydride precursors under the solar conditions used.

When a non-uniform heating was applied, some precursors failed to foam completely while others over-foamed. Thus, a dark grey color, instead a metallic colour, was obtained in nodules placed at the centre of the hot plate (Figure 6). After micro-analysis testing, results showed a high level of oxygen. Then after foaming nodules were oxidized, but over foaming did not lead to pore collapse. Nodule oxidation could lead to lower compression strength. In this case, nodule over-foaming should be avoided.

A smooth surface was obtained on over foamed nodules. Non-decomposed marble particles (X-ray micro analysis, Figure 6) and calcium carbonate particles can be seen on the surface and fracture of foamed and over-foamed nodules. Although carbonate foams are reported to show aluminium drainage [7], the incomplete marble decomposition kept an adequate level of viscosity to avoid Al liquid drainage [8-10].

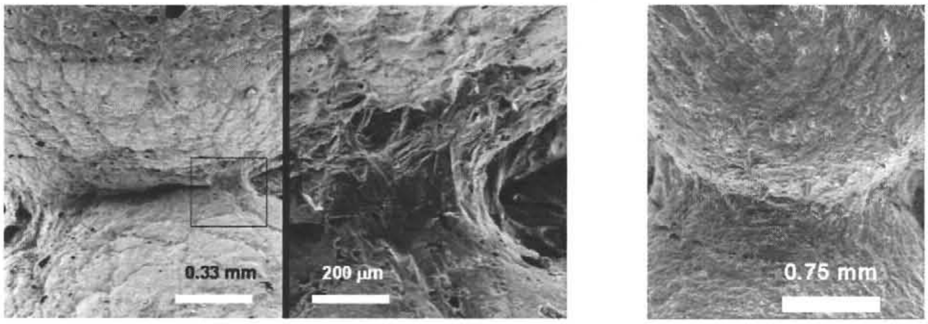

Figure 7. Welding between nodules obtained by concentrated solar energy. Left: carbonate nodules, Right: titanium hydride nodules

A low degree of welding is achieved during bulk carbonate nodule foaming (Figure 7, left) in a solar furnace. Only small necks were obtained between foamed nodules and these bonds are easily broken. On the contrary, Al-TiH2 nodules bonded easily during solar foaming (Figure 7, right) and care needs to be taken with regard to the distance between precursors to avoid this during heating.

Open porosity of carbonate nodules (Figure 6 and 7) could allow good bonding with adhesives. These nodules can be combined in the same way as APM or MHS structures by sintering or adhesive bonding [14]. However when selecting the adhesive a high viscosity adhesive makes filling difficult and decreases the productivity of this method.

## 4. CONCLUSIONS

Although, structures filled or made with aluminum-based foamed nodules are under research, from the perspective of the properties of the nodules, it can be seen that fine marble powder allows for higher decomposition and lower density. However the correct distribution of marble particles in the aluminium matrix was not achieved on dry mixing. As a result, large pores and non-uniform pore distribution were found in the nodules due to powder agglomerates. Powder wet-mixing way solves this problem and nodules obtained from the preheated furnace showed a better pore structure.

Foaming process showed that surface and aluminium melt viscosity controlled the foam expansion. Thus, a spherical shape is not achieved on foamed nodules. On the contrary, a barrel-like shape on foamed nodules was obtained. The height/diameter of foamed nodules depends on the carbonate precursor size but it is independent of heating furnace. Foaming can be carried out with concentrated solar energy where foaming time and hot plate temperature are function of precursor load and composition. Those precursors placed away from the centre of the hot place were only partially foamed due to the heat distribution on the hot plate.

Under the solar furnace conditions used, welding and pore collapse occur when hydride precursors are used. However, carbonate nodules only developed small welding necks during heating and thses bonds are easily broken. No pore collapse was seen in over-foaming carbonate nodules but a high level of aluminium oxidation was observed.

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