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On the foamability of AlSi12 precursors prepared by high velocity compaction

Daniela Negri[a,*], Valerio Mussi[a], Simone Vezzù[b], Andrea Trentin[b], Silvano Rech[b], Michele Monno[c]

[a]*Machine Tools and Production Systems-MUSP Laboratory,Via Tirotti 9, 29122 Piacenza, Italy*
[b]*Veneto Nanotech, Laboratori Nanofab, Via dell'Industria 5, 30175 Marghera, Venezia, Italy*
[c]*Mechanical Engineering Department - Politecnico di Milano, Via La Masa 1, 20156 Milano, Italy*

Abstract

High Velocity Compaction (HVC) has been proposed as a cost-effective method to prepare foamable precursors and the feasibility of the process has been demonstrated. The impact energy results a key parameter to control the final precursor density. Increasing values of impact energy leads to a continuous enhancement of performances in terms of maximum expansion and stability of the foam up to values comparable to those of commercial Alulight® precursors.

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Keywords: Al foam; HVC; precursor; densification; porosity

1. Introduction

Aluminum foams can be considered suitable as filling reinforcement material for structural applications: they can be used in vehicles as energy absorbers in case of a crash or as vibration dampers in machine construction. In order to use metal foams to fill hollow parts the powder metallurgy (PM) route is an interesting process due to its ability to produce near-net shape components. It starts from a solid compacted precursor made by mixing a metallic powder and a gas releasing one. The foam forms in a second step through the gas releasing from the blowing agent as the temperature of the precursor rises up to above its melting point. The precursor densification has a fundamental role

* Corresponding author. Tel.: +39 0523 623190; fax: +39 0523 645268
E-mail address: daniela.negri@musp.it

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for the achievement of high quality final products. One major factor for successful foaming by PM route is to ensure that the precursors have a density close to the theoretical value as shown by Kennedy (2002), that is, with a little residual porosity after compaction. The blowing agent has to be uniformly embedded in a metal matrix densified up to the solid density in order to ensure that the gas leads to bubbles formation and does not escape during the foaming process through existing interconnected pores.

An automated foaming line using the Conform Technology was adopted by Alulight International (Schäffler et al. (2007)) and hot or cold uniaxial pressing processes are often used for test series in laboratories (Asavavisithchai et al. (2006), Bonaccorsi et al. (2006), Helwig et al. (2009)). Non-conventional compaction procedures, starting from machined chips, have also been proposed by Kanetake et al. (2008) and Hohlfeld et al. (2011) in order to reduce the production cost of foamable precursors. Densification process plays a fundamental role on the quality of the final product and on the production cost of foamable precursor and justifies the efforts to simplify this step in powder metallurgical route process. Among the different PM routes, High Velocity Compaction as shown by Cocks (2001) seems to possess the key features that allow the production of high quality precursors for aluminum foams. This method, which allows compacting at low temperature, is useful to process temperature sensitive materials as confirmed in the case of polymer powders compaction by Azhdar et al. (2005). Relative density higher than 99 % can be achieved preventing the oxidation of the feedstock powders as recently reviewed in the case of titanium-based materials by Yan et al. (2011). Aim of this work is to explore the feasibility of HVC process for the production of aluminum foam precursors. A preliminary experimental investigation, which considers some operating parameters, has been performed on AlSi12 powders (TiH2 as blowing agent). The foamability of HVC precursor was compared to that of commercial Alulight cold compacted and hot extruded precursors. Maximum expansion during foaming, circularity of the expanding precursor and stability of the foam were considered as quality parameters. Macroscopic features of the foam were correlated to the microstructural characterization of the compacts and morphological appearance of the foam.

2. Experimental

Commercially available powders were used as raw materials. Table 1 reports powder's characteristics while SEM micrographs (Figure 1) highlight their morphology. In Aluminum Silicon powders, produced by atomization, the geometry is mainly elongated with the presence of some agglomerates and fine particles. For crushed titanium hydride powders, the powder geometry appears angular and shaped. The particles size is according to powders specifications and in particular it is possible to observe a large fraction of fine powders with a mean size of approximately 4-6 μm. Concerning AlSi12 powders D10, D50 and D90 are respectively 10 μm, 35 μm and 65 μm. Apparent density evaluated by ISO 3923/1 of aluminum silicon powders is 0.94 g/cc. The blend were prepared by mixing AlSi12 with 0.75 % wt. of TiH2 in a T2F Turbula (Willy A. Bachofen). Powders were then compacted within 24 h after mixing in order to avoid the separation between the different components and oxidation.

The precursors were prepared by High Velocity Compaction using a Hydropulsor HYP35-7 high-velocity compaction machine (mould diametr: 30mm). During high-velocity compaction, the impact energy can be adjusted by varying stroke length of the hammer following the relation $E = Fh$, where E is the impact energy, F is the force applied on the hammer by the hydraulic system and h is the stroke length, which is the distance between starting position and impact position of the hammer. For the employed high-velocity compaction machine, F is 74,182.5 kN. Five different impact energy, from 371 J up to 1854 J, were employed in order to investigate their effect on final density of the compacted precursors and on their foaming ability (Table 2).

Table 1. Raw materials employed for the production of foaming precursors.

Material	Supplier	Composition	Grain size (μm)
Al12Si	ECKA Granules	12 ± 1 % wt Si, Al bal.	< 75
Ti Hydride	Metal polveri	TiH_2	< 63

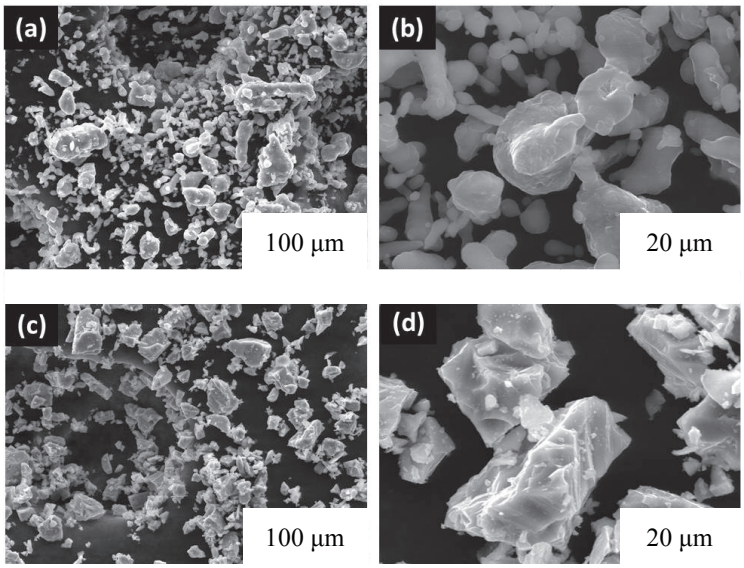

Fig. 1. SEM micrographs of (a)-(b) Aluminum Silicon and (c)-(d) Titanium Hydride powders employed for the preparation of the precursors.

Table 2. Compaction parameters employed for the production of foaming precursors. Mean value of relative density, standard error of the mean and number of samples are also reported.

Sample ID	Stroke Length [mm]	Impact Energy [J]	Relative Density [%]	Mean SE	n	Mass [g]
ID 1	5	371	0.86	0.002	10	9.79
ID 2	10	742	0.94	0.002	10	9.74
ID 3	15	1112	0.96	0.004	6	11.61
ID 4	20	1484	0.97	0.002	5	10.97
ID 5	25	1854	0.98	0.001	10	11.44
ID 6			0.963	0.0008	10	4.08
ID 7	15	1112	0.96	0.001	3	9.53
ID 8	20	1484	0.97	0.001	3	9.70
ID 9	25	1854	0.98	0.001	3	12.34
ID10			0.963	0.0024	3	4.00

Table 3. Maximum value of A/Ao, circularity at the maximum expansion and stability time for the analyzed curves. Table also report the standard error of the mean and the number of samples.

Sample ID	A/A_o	Mean SE	n.	circularity	Mean SE	n.	Stability Time (s)	Mean SE	n.
ID2	2.71	0.114	5	0.66	0.043	5	91.2	10.33	3
ID3	4.30	0.205	6	0.82	0.006	6	92.6	9.53	3
ID4	4.14	0.094	5	0.86	0.019	5	93.0	11.85	4
ID5	4.29	0.127	6	0.87	0.015	6	109.2	15.96	4
ID6	5.10	0.078	12	0.92	0.001	1	283.3	65.97	3
ID7	4.58	0.105	3	0.82	0.017	3	27.6	4.48	3
ID8	5.23	0.437	3	0.84	0.010	3	29.3	5.04	3
ID9	4.15	0.173	3	0.83	0.030	3	102.3	10.74	3
ID10	5.59	0.152	3	0.92	0.001	3	65.00	12.50	3

The density of the precursors was determined geometrically (Table 2). Alulight samples (ID6-ID10) of composition AlSi10 were cut by abrasive water jet in cylindrical shape, of around 20 mm diameter and 5 mm thickness, from a bar. They were considered as a foamability benchmark. Observation direction parallel to the extrusion direction was considered. The density of the precursors, determined by buoyancy method, is reported in Table 2. Consolidated precursors were placed on a thin steel sample holder and were foamed in air in a convection heating furnace pre heated to 650 and 700 ^{o}C. The thermal evolution with time was followed by a thermocouple T_s in the sample. A uEye camera (1600x1200 pixels UXGA Camera with 1/1.8" CCD Sensor) equipped with a

precision lens (focal lens 25 mm) recorded the blowing behavior of the precursor in the furnace. A filter for infrared radiation to improve the contrast between the foam and the background was used. The process was observed at one frame per second (1 fps). A quantitative analysis of foam expansion was performed using the ImageJ (Rasband) software for image analysis. The foaming behavior was evaluated by the relative projected area expansion, A/A_o defined as the ratio between the projected area of precursor during foaming and the initial projected area of the precursor.

Geometrical and morphological analysis were performed on foamed precursors extracted from the furnace at key instants on the temperature vs time curve, related to remarkable steps of the foaming process. Each sample was cut along a vertical cross section cold encapsulated to avoid the rupture of the weak pore walls and prepared for microscopy observation. Light optical microscopy by using a Leica DM6000M Microscope allowed observing the foam morphology. The whole cross section, along the diameter, was investigated by image analysis (Cocks (2001)). Porosity, pore circularity and aspect ratio were calculated and compared as a function of foaming time and precursor properties.

3. Results and discussion

Statistical analysis gives evidence of the dependence of the relative density ($\rho_{rel}= \rho_{comp}/\rho_{alloy}$) of the compacted precursor to the height of the hammer (Table 2). Relative density and thus densification increases as the height increases. Samples ID5 are characterized by ρ_{rel} values around 98%, which are considered suitable for good foaming (Asavavisithchai et al. (2006), Bonaccorsi et al. (2006)). Figure 2 reports the foam expansion, A/A_o, the circularity and the temperature in the sample versus time for samples that are able to expand. The represented curves are the mean curve of each set of process parameters. Some pictures representative of important steps of the process highlight how the precursor's expansion depends on the process parameters. Samples characterized by relative density higher than 94% are able to expand. The maximum of A/A_o is higher for samples compacted from higher height up to values comparable to that of commercial precursor (ID6). All the samples exhibit the maximum expansion when the eutectic phase transition is completed. Samples ID3, ID4 and ID5 begin to expand during the phase transition, when the precursor is in the semisolid state. The expansion of commercial precursor begins at the beginning of the plateau corresponding to the eutectic. As highlighted in expanding samples' figures, in HVC precursors, the expansion starts on the lateral surface and then extends to the whole sample. Commercial precursors exhibit more isotropic expansion characterized by high values of circularity and higher stability in time. Since using foam as filling material requires maintaining it stable during the filling process, a "stability time", defined as the time spent by a specimen above 90% of A/A_o max, was calculated. It increases with height but remains lower than in commercial precursors (Table 2). A nearly linear correlation between the precursor ρ_{rel} and the maximum expansion A/A_o confirms the requirement to obtain very compact precursors and to reduce the porosity between particles that allows hydrogen escape during the foaming process. Figure 3 highlights that the Alulight benchmark shows a better behavior leading to excellent area expansion with relative density around 96 % and that comparable performance characterizes HVC precursors with 97 % relative density. A possible reason for this behavior could be related to the different origin of the precursor porosity. Precursors obtained by HVC show typically a combination of closed porosity and interconnected porosity due to a lack of cohesion and metallurgical bond among adjacent particles. This porosity is critical because it allows the hydrogen to escape following a path along the border of the compacted particles. On the other hand, the porosity in extruded precursors is mainly closed.

The evolution of the internal geometry and microstructure of the foamed specimens confirmed that the density of the precursor is the key parameter to maximize the area expansion as well as the quality of the foam. High density of precursor maximize circularity of the internal pores, minimize the aspect ratio and mean diameter of the pores. The quality of the foam increases progressively with the area expansion reporting its highest value close to the maximum foaming efficiency. ID4 and ID5 samples show circularity values close to 0.8, while the mean pore size was 7.8 and 5.1 mm in case of ID4 and ID5 samples respectively. Similar values (circularity 0.8 and mean pore size 5.2 mm) have also been obtained on commercial samples, ID6. Foaming tests highlighted that foams obtained starting from HVC compacted precursors show a skin that avoids or limit the foaming at the top and bottom surfaces of the precursor.

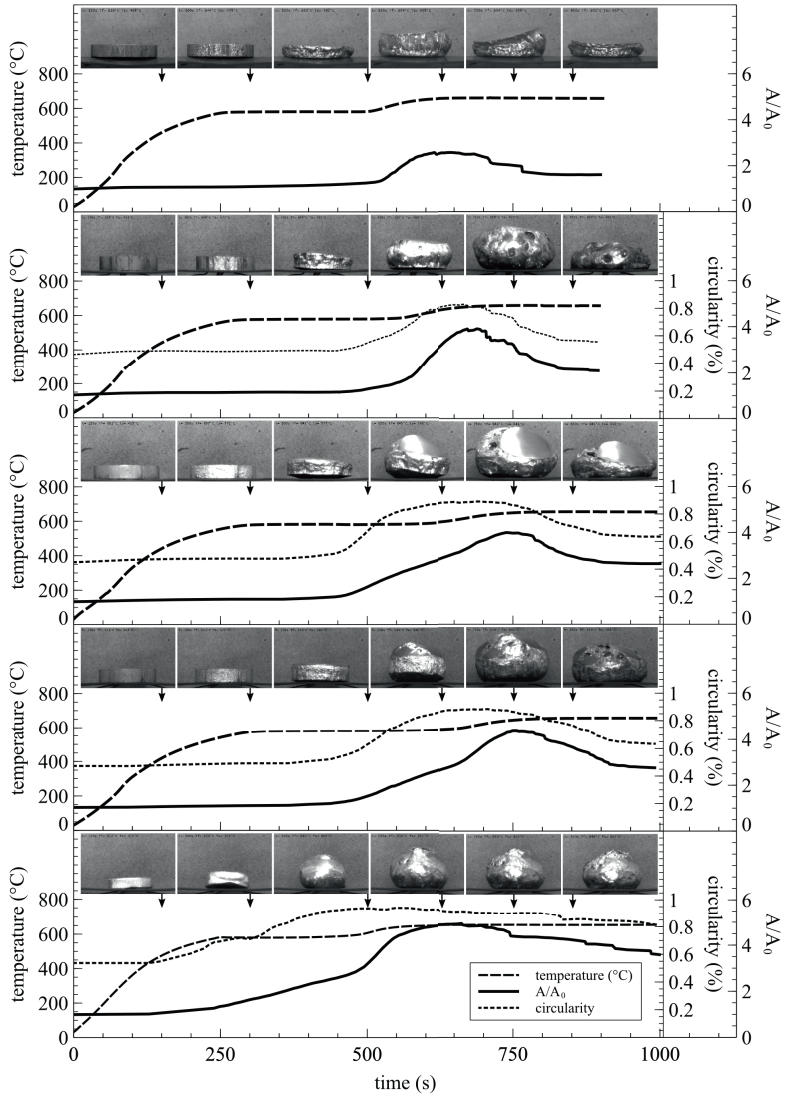

Fig. 2. Evolution of A/Ao, temperature in the sample and circularity vs time. From top to bottom: ID2, ID3, ID4, ID5, ID6.

The result is a compact aluminum boundary that encloses the foam that could be critical when multiple precursor pieces are used to fill a wide volume. Figure 4 shows the microstructure of specimens of various ID extracted at the maximum foaming efficiency. It suggests that the skin effect is strongly dependent on initial precursor density. Moving from panel 4a to panel 4d the thickness of the external boundary thins enough to be fractured by the growing foam.

As the thickness of the boundary seems to depend on hydrogen mobility and ability to escape, some test experiments were performed at higher foaming temperature (700 °C) in order to speed up the kinetic of the process (ID7-ID10). They show (Table 3) that the foaming expansion does not improve a lot at higher temperature but ID9 foam is very stable, with stability time value higher than commercial ID10. The skin thins with increasing impact energy but the external boundary is not always fractured. It should be mentioned that these are preliminary result and that the statistic has to be improved.

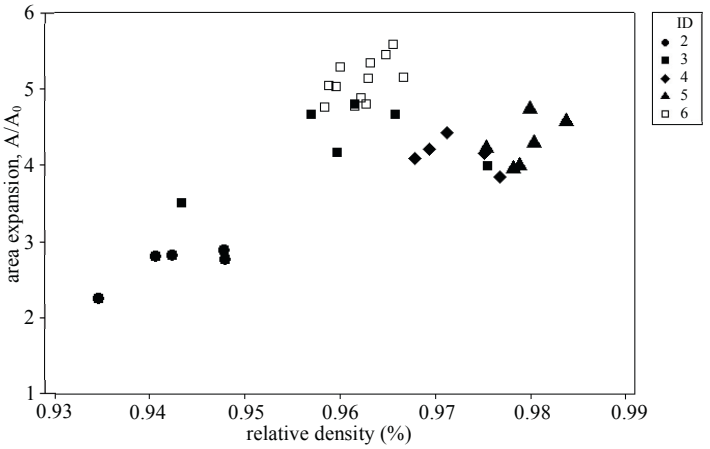

Fig. 3: Scatter plot of area expansion, A/A_o vs relative density

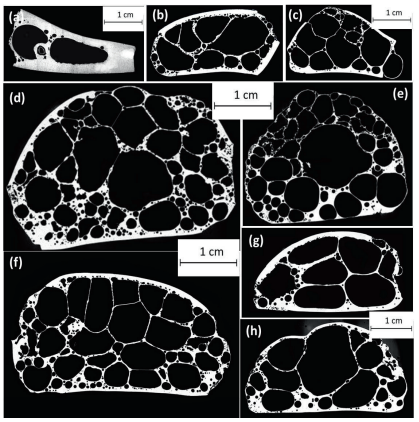

Fig. 4. Microstructure of specimens of various ID extracted at the maximum foaming efficiency. Each specimen is identified by compaction energy and furnace temperature: (a) 742 J/650°C (b) 1112 J/650°C (c) 1484 J/650°C (d) 1854 J/650°C (e) Alulight/650°C (g) 1112 J/ 700°C (f) 1484 J / 700°C (g) 1854 J / 700°C.

4. Conclusion

This work proved that HVC is a promising and cost-effective alternative to extrusion in the production of Al foamable precursors. Relative densities and thus densification increase as the impact energy increases. Stroke height of 25 mm (1854 J) allows obtaining precursors with $\rho_{rel} \approx 98\%$, which give rise to foams characterized by $A/A_o \approx 5$. Foam's morphology is comparable to that of Alulight foam but its stability is lower. Future work will be devoted to improve quality and stability of the foam using ceramic stabilizers and metal matrix with wider melting ranges. HVC will be very useful in the production of compacted precursors of different shapes to fill complex structures when a random disposition of precursor pellets is required.

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