STRUCTURE AND PROPERTIES OF INDUSTRIAL ALUMINUM FOAMS

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Abstract

Metallic foams represent an emerging family of materials that could have significant application in many fields of industry. In the past, the production of this material was limited to small samples produced by batch processing. The situation has changed considerably, as large size aluminum foams are now being manufactured by various producers using a number of different approaches.

One of the most important benefits in using aluminum foam is weight savings in structural applications. Other potential benefits include the energy absorption, structure-borne noise and vibrational damping, fire resistance and isotropic load response. For other applications the low thermal conductivity is of interest as well. In all cases, the properties can be varied with foam density.

A description of the fabrication processes used to create aluminum based foams will be provided. In addition, an evaluation of properties based on possible fields of application was performed. The interdependence between foam density and structural behavior was investigated and will be discussed in this paper.

Introduction

Aluminum foam can be considered for several applications. Certainly the primary advantage of the material is its low density with improved temperature capability. As an example, aluminum foam has higher temperature capabilities and improved environmental resistance relative to some polymer-based foams. In addition to a potential advantage in lightweight structural applications, the aluminum foam has other performance advantages. Aluminum foam has high structure borne and airborne damping capacities, considerable specific stiffness, high thermal insulative properties as well as high energy absorption properties. Aluminum foam is isotropic, which could be a significant performance advantage relative to honeycomb which are highly anisotropic. Finally, some foaming processes allow for direct fabrication for three-dimensional, near net foam shapes. Therefore it is possible that manufacture of aluminum foam products could be cost competitive with traditional materials and processes while offering unique performance advantages. There is currently high interest for automotive, railway, aerospace and other industrial applications where weight reduction and improvement in comfort and safety are demanded.

There are several suppliers for foams made of different materials who have utilized alternative production approaches which are listed in Table 1. Some of those are in a production and others in a pre-production, or developmental stage.

PRODUCTION FOAMS

Company	**Process**	**Composition**
Shinko Wire Co, Japan	Batch casting	Al
Alcan Int. Ltd, Canada	Semi-continuous casting	Al w/particles
ERG Inc, USA	Directional solidification	Al
Hogan Industries, USA	Fine powder, sinter	Cu, Ni

DEVELOPMENTAL/PREPRODUCTION FOAMS

Company	**Process**	**Composition**
Norsk Hydro, Norway	Semi-continuous casting	Al w/particles
Frauenhofer Institute, Germany	P/M hydrides	Al
Frauenhofer Institute, Germany	Electrodepostion	Zn
Austrian Metal AG, Austria	P/M hydrides	Al
Georgia IT, USA	Oxide reduction	Ni
Lawrence Livermore, USA	P/M hydrides	Be-Li
Academy of Sciences, Ukraine	Sintered powder	Ti-Mo
DMI, Ukraine	Directional solidification	Various

Table 1: World wide supplier base and process routes of foam products

The herein described investigations on aluminum-foams are focused on material manufactured by the batch casting, the semi-continuous casting and powder/metal hydrides processes.

A batch casting process (used by Shinko Wire to manufacture their product with the trademark, Alporas[R]) is based on establishing the proper viscosity of the molten alloy during casting to stabilize pores that are created by a forming agent. Metallic calcium is used to adjust the viscosity, and titanium hydride is added as a foaming agent. As the hydride dissolves, bubbles are created. The product is sold in a limited range of densities and cell size. "Construction grade" is a close-cell foam, while the "sound proof grade" is an open-cell foam.

The semi-continuous casting process is based on aeration of aluminum melt containing ceramic particles (SiC, MgO). These particles stabilize the pores of the liquid foam on top of the melt to such an extend that it can be drawn off onto a moving belt and solidified (Fig.1). The material can be produced in a wide range of densities (0.1 g/cm³ - 0.5 g/cm³). At present the available maximum length and width is 3 m x 0.75 m produced by Alcan International Ltd. Both Alcan and Norsk Hydro have patented this process. Data indicates that aluminum foam manufactured by this technique is about 2 times more expensive, on a weight basis, than the bulk material.

By either of these processes, a semi-finished material can be produced. Secondary forming of the product is possible to a limited extend.

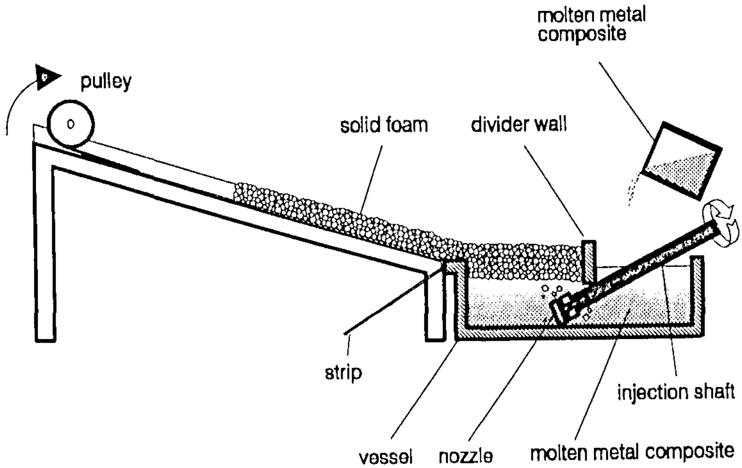

Fig.1: Schematic for semi-continuous casting process

Finally, the possibility of direct fabrication for three-dimensional, near net foam shapes parts is offered with the third production route, based on powder metallurgy (P/M) processes (Frauenhofer and Austrian Metal process and patent). Alloyed powder is blended with metal hydride, such as titanium hydride, which acts as a foaming agent. This mixture is either cold or warm compacted and then rolled or extruded. This semi-finished product is then placed in a die which is heated up near to the melting point of the powder alloy. The hydride dissolves, releasing gas which creates the pores (Fig. 2). The content of hydrides in the blend controls the density. Aluminum foam is 5 to 8 times more expensive, on a weight basis, than the bulk material.

The P/M manufacturing approach has two important advantages. First, it is more flexible in utilizing a wide range of initial alloy compositions. As with the other processes, the foam strengths would be dependent on the alloy composition. Second, it allows for direct manufacture of complex three-dimensional shapes. Direct manufacture of aluminum foam core sandwich structures and foam filled tubular structures have been demonstrated.

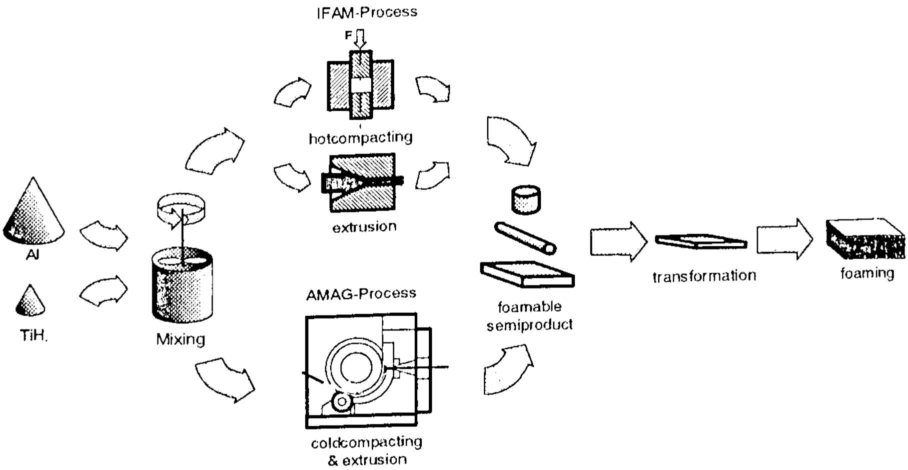

Fig. 2: Schematic for powder metallurgical process

Properties

Significant testing has been performed to evaluate the properties of aluminum foam as a function of foam density. Properties measured included compressive yield strength, Young's-modulus, and energy absorption coefficients. Where possible, results of this test program have been compared with supplier data.

Compressive yield strength has been determined on foam manufactured by the semi-continuous casting route (Alcan). Fig. 3 shows the data for the yield strength of the Alcan foam, normalized by parent material yield strength, plotted against the relative density. Gibson and Ashby [1] express the relationship between strength and density as

$$\frac{\sigma_{foam}}{\sigma_{parent\ solid}} = C \cdot \left(\frac{\rho_{foam}}{\rho_{parent\ solid}} \right)^{x} \qquad (1)$$

Where C is a constant, found empirically to be 0.3 for open-cell polymer and ductile metal foams and the exponent is 3/2, from fundamental theory. Analyses of the test results in this program suggest that the Alcan aluminum foam behaves similar to theory. The dashed line represents a best fit of the current test data to the Gibson and Ashby relationship, with C = 0.7 and x = 1.9. The data also agree with other published data for open-cell polymer and metal foams [2]. There is a close interdependence between density, mechanical and physical properties, though these properties decrease more rapidly than the density itself [3, 4].

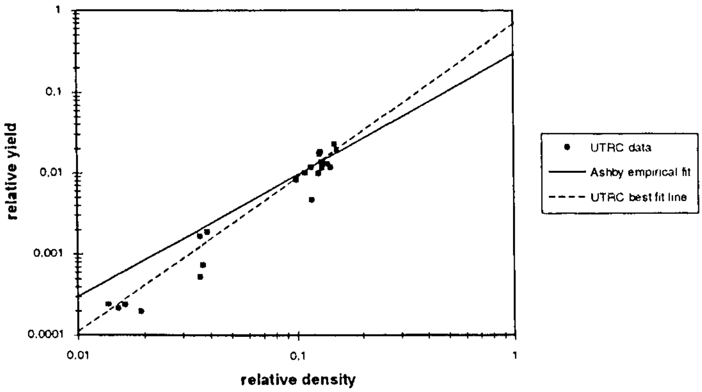

Fig. 3: Yield strength analysis

Fig. 4 compares measurements of Young´s modulus for different aluminum foams. Note that the values for the Alcan foam measured at UTRC and DBAG are consistently higher than the Alcan vendor supplied literature. Results of DBAG internal test program show that a single power law relationship between density and modulus is accurate for all types of foam investigated. Discrepancies between test results are most propably due to different test techniques. DBAG determined his values by means of a four point bending test. UTRC performed axial compression tests and reported strain based on crosshead displacement. Even by comparing all tests parameters no satisfying explanations for these significant differences have been found.

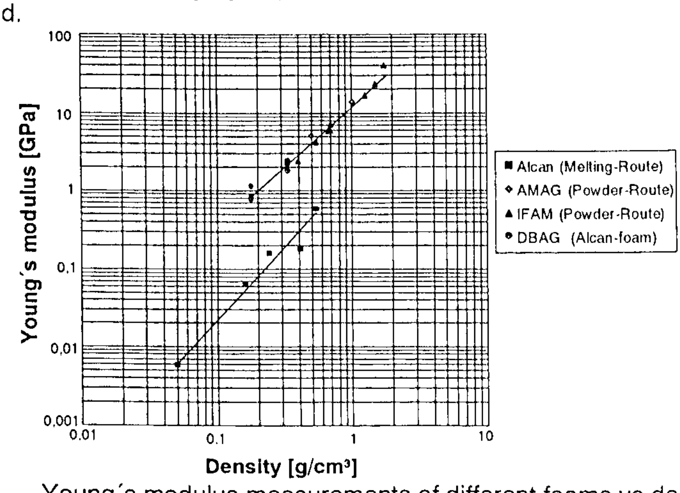

Fig. 4: Young´s modulus measurements of different foams vs density, comparison to supplier data

Dynamic compression tests have been performed at high strain-rates varying from 5 to 40 km/h. Compressions from 23 - 93 % were measured. The results indicate that aluminum foam is an effective energy absorbing material. Even though additional tests are necessary for confirmation, the results show that at high strain-rates the energy absorption capacity may increase with increasing strain-rate (Fig. 5).

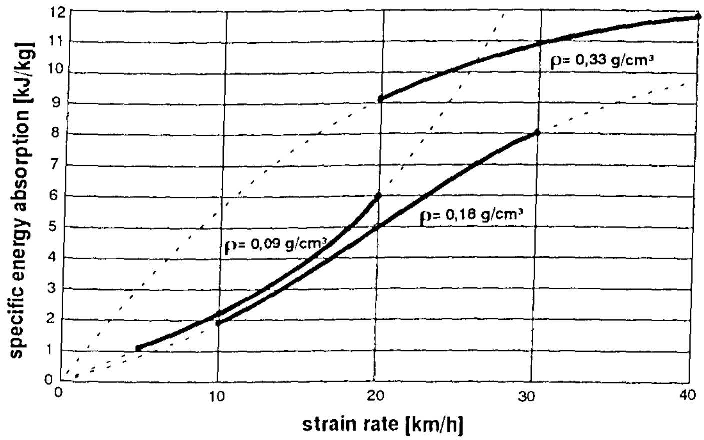

Fig. 5: Specific energy absorption of different foam densities vs strain rate

Benefits in acoustic damping are generally achieved only with open cell foams. A comparison of the sound absorption coefficient data from suppliers (AMAG, Shinko Wire) is shown in Fig. 6. The suppliers data indicate that aluminum foam, with the proper cell structure, has about the same behavior as polyether foam. For aluminum foams, the maximum sound absorption occurs at approximately 2000-3000 Hz, a lower frequency than for glass fiber materials.

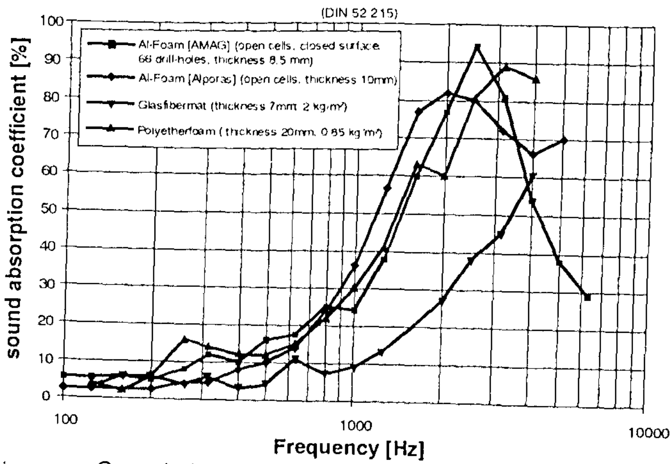

Fig 6: Sound absoption capacity of open cell foams from different suppliers compared to polyether and glassfiber materials

Applications

Aluminum foam may be important in a number of applications because of its unique combination of properties and the inherent ability to optimize performance through design of the cell structure and density. In this way it appears possible to create final products with anhanced capability. Multiple benefits, reduced weight, reduced noise or reduced vibration, for example, may be realized through the implementation of the material. A less obvious advantage is the aluminum foam´s ecological "friendliness". Reduction in waste costs through improved recycleability may be a significant factor in substituting aluminum foam for some polymer-based foams.

A japanese supplier (Shinko Wire) has sold significant volumes of aluminum foam for use in commercial applications. This foam has been incorporated into sound-proofing structures for highway roadsides and bridged decks as well as for wall panels to reduce interior building noise in a shopping mall. Lightweight sandwich panels with foam cores are used for removable floor panels, temporary building structures and bases for plotters. It has also been reported that aluminum foam was utilized as a firewall in a 1992 Toyota concept vehicle.

A simple analysis can be performed to assess the merit of aluminum foam as a direct replacement for a number of different construction materials, a potential, very-high volume application. Fig. 7 compares a variety of materials with the same stiffness. A 0.1 g/cm^3, 10 mm thick aluminum foam sheet was selected as the basis for comparison. The necessary sheet thickness of a traditional material can be calculated with the following equation

$$t_{parent\ solid} = \sqrt[3]{\frac{E_{foam} \cdot t_{foam}^3}{E_{parent\ solid}}} \qquad (2)$$

This particular relationship is derived from the bending of a sheet with one end fixed and the free end loaded. An aluminum foam with 0.1 g/cm^3 density and 10 mm thickness has only 1/7th area density of a 0.8 mm thick steel sheet of the same stiffness. The same foam has about 2/3rd area density of a 2.2 mm oak wood often used for floor panels and 3/5th area density of a 1.1 mm carbon fibre reinforced plastic of the same stiffness.

In general, this is a relatively new and unique class of materials and its importance is just beginning to be assessed by various industries.

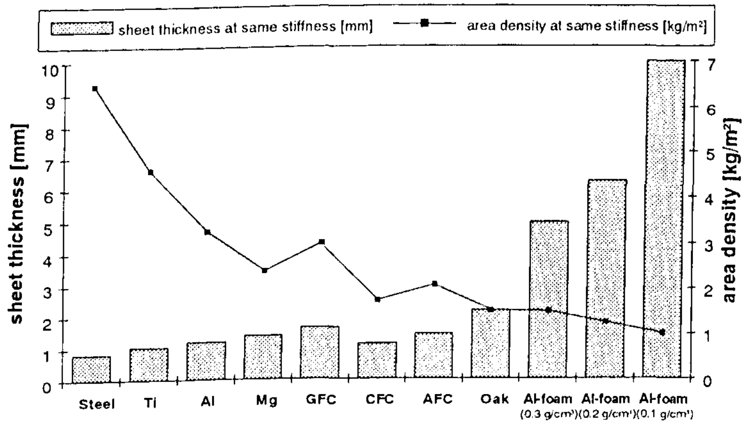

Fig. 7: Sheet thickness and area density for different materials at constant stiffness compared to a 10 mm aluminum foam sheet (0.1 g/cm³)

Conclusions

Three different approaches for manufacturing aluminum metal foam have been discussed. The advantages and disadvantages of each technique have been briefly described. Direct fabrication for three-dimensional, near net foam shapes parts using the powder metallurgical process may be particularly important.

Properties of various aluminum foams have been described. Aluminum foams are lightweight materials with high stiffness, high energy absorption capacity, acceptable specific strength, low thermal conductivity and excellent heat resistance. Open-cell foams are also sound absorbing. Foams are relatively isotropic.

Aluminum foam is a candidate replacement for polymer foams where higher temperature capability or where improved environmental performance (e. g. recycleability, off-gassing, flame, smoke, toxicity) is required. Aluminum foam is although a candidate replacement for structural and non-structural applications. It is expected that aluminum foam will find application in product which fully utilizes its unique characteristics. Several generic possibilities have been identified.

References

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