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Performance Characterization of Alcoa Aluminum Foam Products

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The low density aluminum foam product developed at Alcoa Technical Center can now be manufactured at commercial production rates of 1,500 kg/hour. The product is continuously cast as a wide, thin plate and cut to length for applications in the architectural, transportation and defense sectors. Through the controlled decomposition of carbonate powders within a molten aluminum-magnesium alloy, a stable, foamable suspension is created. This suspension allows for production of aluminum foam with a relative density as low as 25% of the parent alloy, and resists both coalescence and drainage. In this presentation, the manufacturing challenges and performance requirements of aluminum foam panel products will be discussed. The performance of foam panels in both laminated and unlaminated conditions will be characterized, with emphasis given to those characteristics most critical in architectural applications. The physical and mechanical performance of the product under multiple stress states will be related to its microstructural and mesostructural characteristics. Corrosion resistance in both the coated and uncoated condition will be discussed. Product properties following one year exposures to high humidity and salt water environments will be presented, as will a comparison of the effectiveness of different fastening systems following simulated service exposures.

Keywords: *Aluminum, Foam, Cellular, Corrosion.*

1. Introduction

The physical and mechanical properties of metallic foams offer a unique set of performance solutions in a number of applications. Closed-cell aluminum foams in particularly provide an attractive combination of high specific rigidity, low density and resistance to heat and fire which make them ideal candidate materials in building and construction, defense and transportation applications. As a relatively new class of materials, however, achieving significant market success can be challenging. Not only must the product be competitive to incumbent materials in categories such as price and service performance, but it must also be compatible with accepted methods of joining, coating, and lamination so that the entire system offers an attractive solution to customers.

In this paper, the process and product development for Alcoa Aluminum Foam will be discussed as it relates to the meeting these challenges. The development of a low cost continuous casting process for the manufacture of wide aluminum foam panels will be described, as will the material characteristics achievable using this technology. The physical and mechanical performance of the material itself, along with the performance of fabricated products manufactured from this material, are described for the case of architectural panels.

2. Manufacturing Method

True solid foams are formed on the solidification of liquid foams. Liquid metal foams, like all liquid foams, are inherently unstable and subject to degradation through the mechanisms of coalescence, wall thinning and gravitational drainage. In the Alcoa Aluminum Foam process, stabilization is accomplished through the creation of a solid-gas-liquid suspension initiated by the addition of carbonates into an aluminum-magnesium alloy melt [1,2]. Under the proper processing conditions, this action initiates a cascade of chemical reactions within the melt to create a foamable suspension capable of resisting natural decay. In the current manufacturing process, a suspension is formed within an Al-2Mg-1Si melt through the addition of calcium carbonate. Under conditions of aggressive agitation, the carbonate decomposes within the molten metal to form CaO solids and the reactive gas CO_2. The gas bubbles formed within the molten metal are ruptured and fragmented, exposing more of the reactive gas to the molten metal. This gas reacts vigorously with the aluminum-magnesium melt, forming CO gas and *in-situ* formed Al_2O_3, MgO and other mixed oxides, as detailed below:

$$CaCO_3(s) \rightarrow CaO(s) + CO_2(g) \quad (1)$$
$$CO_2(g) + 2/3Al(l) \rightarrow 1/3Al_2O_3(s) + CO(g) \quad (2)$$
$$CO_2(g) + Mg(l) \rightarrow MgO(s) + CO(g) \quad (3)$$
$$CaO + xAl + yMg \rightarrow Al_xMg_yCaO \quad (4)$$

The generation of carbon monoxide, CO, within the melt initiates an additional sequence of chemical reactions resulting in the formation of solid particles within the liquid metal. CO reacts with liquid Al to form graphite; and graphite can further react with liquid Al to form aluminum carbide (Al_4C_3):

$$CO(g) + 2/3Al(l) \rightarrow 1/3Al_2O_3(s) + C(s) \quad (5)$$
$$C(s) + 4/3Al(l) \rightarrow 1/3Al_4C_3(s) \quad (6)$$

The CO and CO_2 gas bubbles, as well as the metallic oxide phases and other solids, act to stabilize the liquid metal suspension by modifying the viscosity and surface energy of the molten metal [3,4]. The unreacted portion of the CO_2 gas is vented along with the CO reaction product. The CO is safely flamed off at the surface of the agitated melt. The result is a viscous molten metal suspension containing fine gas bubbles and a dispersion of unreacted calcium carbonate particulates. This partially foamed product is continuously transferred to a moving mold, allowing for the production of a continuous plate of aluminum foam. Through control of the thermo-mechanical flow path, panels of aluminum foam are manufactured over a range of widths, thicknesses and densities. Typical specifications for the panel produced at a 19 mm gauge are given in Table 1.

Table 1: Specification Properties for Alcoa Aluminum Foam

Density	***Minimum***	***Maximum***	***Average***	***Units***
Gauge	18.4	19.7	**19.0**	mm
Gauge Variance	-	2.5	**0.64**	mm
Bow	-	1.65	**0.48**	mm
Width	912	917	**914**	mm
Length	2436	2441	**2438**	mm
Absolute Density	0.65	0.92	**0.79**	g/cm^3
Panel Solid Fraction	26%	32%	**29%**	%
Panel Area Weight	13.3	16.4	**15.0**	Kg/m^2
Panel Weight	30	37	**33**	Kg
Compressional Strength	9.7	16.6	**13**	MPa
Bend Rupture Strength	9.7	16.6	**13**	MPa
UTS	5.5	11.7	**6.9**	MPa
Comp. Modulus	3.5	4.8	**4.1**	Gpa
Tensile Modulus	3.5	4.8	**4.1**	GPa
Bend Modulus	3.5	4.8	**4.1**	GPa

While the data shown is specifically for an alloy matrix of the Al-2Mg-1Si, laboratory studies have shown that aluminum foams with similar properties can be produced using a broad range of alloy compositions. As the process has shown a wide tolerance for a range of traditional alloying additions to aluminum (Si: 0% to 8%; Mg: 2% to 8%; Cu: 0% to 4%; Zn: 0% to 3%, for example), the manufacturing process accommodates a variety of mixed alloy scrap streams. This flexibility in metal sourcing provides the potential not only for lower cost, but also allows for higher recycle content, a key element in the US Green Building Council's LEED® certification [5] for products used in architectural applications.

3. Performance in Architectural Applications

3.1 Rigidity and Area Density

Though architectural panels are not the primary load bearing structures in commercial buildings, as wind and rain screens the facades must possess sufficient rigidity and bend strength that they can withstand heavy wind loads in vertical mountings, and both snow and maintenance personnel loads in horizontal or angular mountings. Alcoa Aluminum Foam panels with relative densities between 24% and 35% of the parent alloy were subjected to three and four point bend tests per ASTM standards [6,7]. All specimens were tested in the as-fabricated condition: the surface skin (formed on contact with the mold) was left intact and the alloy was retained in the as-cast condition [8]. Fig. 1 shows the testing fixture, here being loaded with 5-ply marine plywood for comparison. As seen in Fig. 2, the bend modulus (here plotted with the tensile and compressive moduli) for foam is seen to have a strong relationship to the density of the foam, with a power law dependency of the modulus with the density.

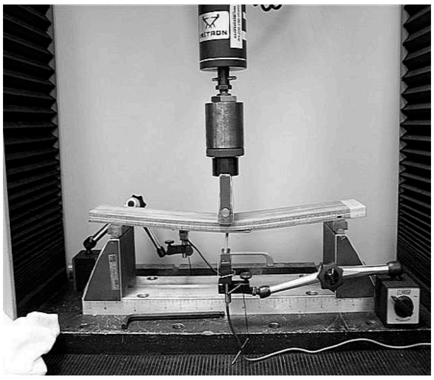

Fig. 1: Photograph of 3-point bend test apparatus. A 5-ply standard of marine plywood is used as a standard

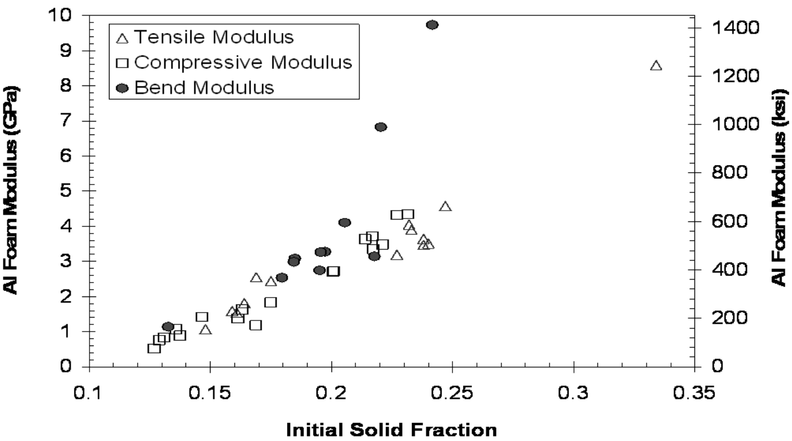

Fig. 2: Modulus of Alcoa Aluminum Foam as a function of density measured in compressive, tensile and bending stress states.

Knowing the effect of lamination on the flexural properties of composites, specimens were prepared with AA3105 aluminum face sheets on both the upper and lower surfaces of the aluminum foam. In this product configuration, the aluminum foam functions as a core material, as in other architectural products such as aluminum composite materials (ACMs) and aluminum honeycomb panels, both of which are manufactured using polymeric cores. The specific bend properties for two such laminated products are shown in Fig. 3, along with the unlaminated foam and those of two grades of marine plywood. As can be seen in the figure, while the specific modulus and specific rupture strength of the unlaminated product lie below such laminated products as 5 or 7 ply marine plywood, when the foam material is used as a core in the sandwich product, the specific properties increase by up to a factor of four. Owing to this significant increase in rigidity and rupture strength, and the aesthetic options available through the use of roll-coated aluminum sheet, this all-aluminum architectural panel is currently being tested for architectural applications which demand such fire-resistant products.

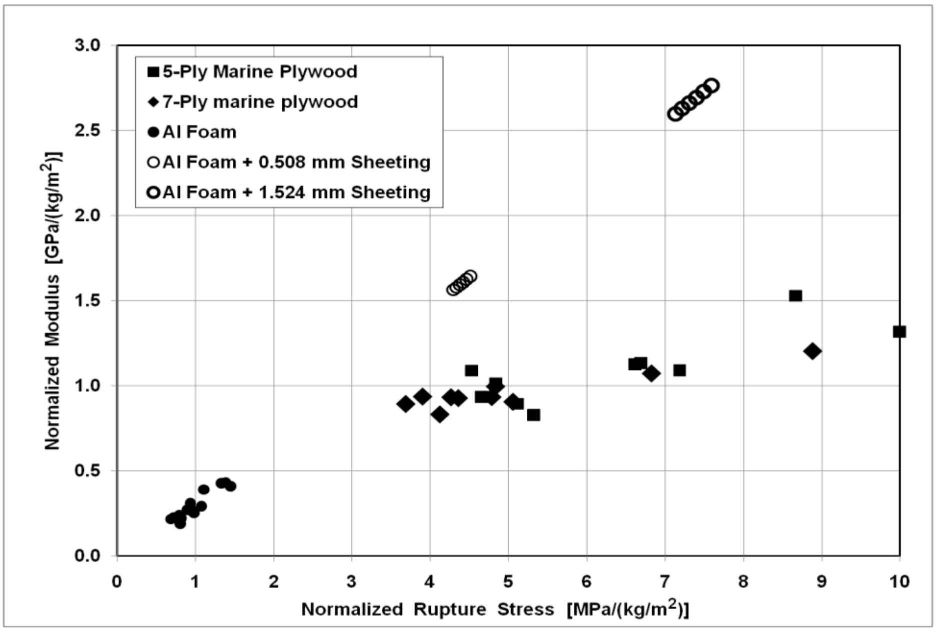

Fig. 3: The modulus and rupture strength have been normalized by areal density and plotted against each other for five panel products: two grades of marine plywood, unlaminated aluminum foam, and two model composite panels incorporating two gauges of AA3105 sheet sandwiching an aluminum foam core.

3.2 Corrosion Resistance

As architectural panels are exposed to all weather conditions, extended tests were conducted to determine the effects of extended exposure to aggressive environments. As a porous product, however, aluminum foam cannot be reliably tested using the methods used with monolithic aluminum. Mass loss, a common measure in many prolonged exposure tests, may well be misleading as the open structure of aluminum foam acts to retain any corrosion products. For this reason, compression testing was performed on all specimens to compare the strength before and after exposure. Specimens were subjected to a series of exposure tests for up to twelve months:

- high humidity (90% relative humidity at 50°C)
- post-exposure high humidity (4 hours immersion in a 3.5% NaCl solution followed by 90% relative humidity at 50°C)
- alternate immersion (cyclic treatments of 10 minutes in an aqueous solution of 3.5% NaCl followed by 50 minutes in air of 45% relative humidity at 27°C)

The results are plotted as a function of relative density in Fig. 4. Though the data show a significant amount of scatter (most likely due to the small specimen sizes used), no net loss of compressional strength was noted even after one year in these conditions. Additional corrosion tests were conducted with coated products, using foam samples painted with either powder coat technology (an attractive method for aluminum foam, as its electrically conductive nature allows for electrostatic coating methods) or traditional spray coating technology. Fig. 5 shows a typical test using a powder coating method incorporating a vapor phase image transfer. The specimens are scratched and subjected to a cyclic acetic acid salt spray as a test for filiform corrosion susceptibility [9]. As shown in the figure, paint adhesion was good and no evidence of filiform corrosion was seen after 21 days of testing.

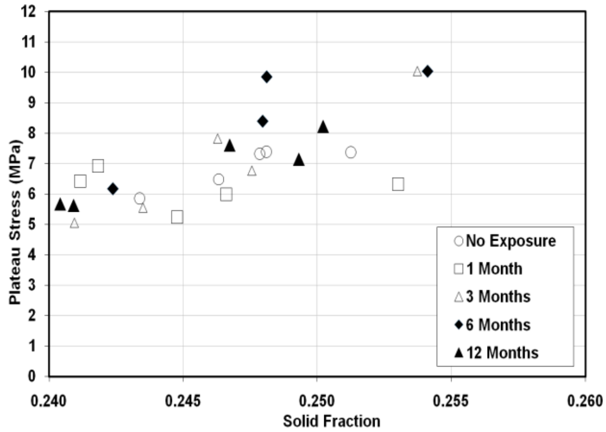

Fig. 4: Compressive strength of Alcoa Aluminum Foam following up to 12 months of alternate immersion in 3.5% NaCl solution.

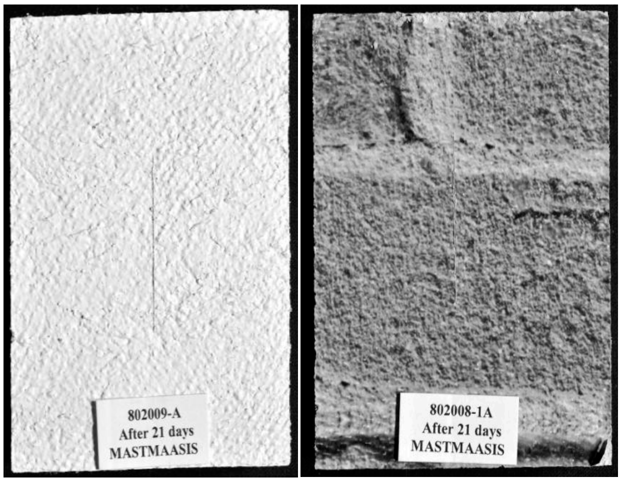

Fig. 5: Standard test for filiform corrosion on painted aluminum applied to powder coated aluminum foam

3.3 Fastener Testing

One of the perceived advantages of aluminum foam architectural panels, as opposed to polymeric core or honeycomb core architectural panels, is the ease of fastening such panels to the building structure. As the face sheets on all three panels are thin, attachment must generally be through the panel (which mars the beauty face) or into the core. While honeycomb panels can have attachment points built into them on site, this involves routing out the core and back-filling with various thermo-set polymers which adds considerably to the installation cost. As Alcoa Aluminum Foam is uniform and small celled (average cell size is 0.70 mm), traditional screw attachment to the core can be made. A series of tests were conducted with six different screw types (self-tapping, self-drilling, thread-cutting, etc.) and the pull strengths tested [10]. The data, shown in Fig. 6, show a marked dependency of the pull-out strength with density, as predicted, with wood screws and thread-forming screws showing the highest pull-out strength of those tested. The average pull-out strength of 180 kgf is comparable to that of most softwoods traditionally used in building and construction.

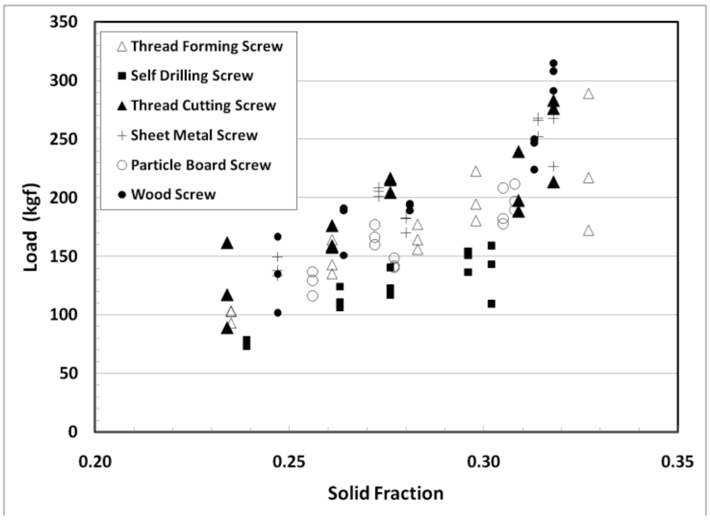

Fig. 6: Screw pull-out strengths for six different screw types in Alcoa Aluminum Foam.

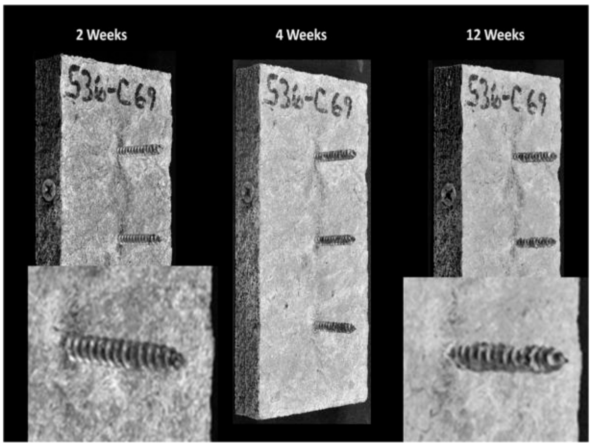

Fig. 7: While strength loss was minimal, use of galvanized screws with aluminum foam resulted in corrosion build up.

The appearance of such fasteners after simulated environmental exposures was also tested. Here a single screw geometry was tested, and screws were procured in four materials to test compatibility: bare steel, galvanized steel, aluminum and stainless steel. Specimens were then subjected to 12 weeks of either alternate immersion in 3.5% NaCl solution or 12 weeks in simulated acid rain conditions (pH 3.5 to pH 4.0; 1000 ppm NaCl). The results are shown in Fig. 7. As expected, bare steel displayed the worst performance, producing substantial rust stains within several weeks. While neither aluminum nor stainless steel displayed any signs of degradation during the tests, galvanized steel showed surprisingly poor corrosion resistance. While such galvanized fasteners are successfully used in both wood and polymeric panels in architectural applications, the inherent hardness of the aluminum foam structure appears to remove much of the zinc coating from the screws, subjecting them to rapid corrosion.

4. Conclusions

A method of manufacturing aluminum foam has now been brought to commercial production levels. Through the injection of calcium carbonate into a molten aluminum alloy, a stabilized suspension of liquid, gas and solids has been created with is largely resistant to cell coalescence, cell wall thinning and gravitational drainage. A continuous casting process provides for production of aluminum foam panels of widths out to 1000 mm and gauges between 12 mm and 25 mm. In targeting the product for architectural panel applications, the lamination of the foam core was found to deliver substantial benefits in aesthetic finish, flexural rigidity and rupture strength. With the recent conclusion of long term exposure tests in both salt water immersion and high humidity, the product was seen to display the corrosion resistance similar to the 6xxx series alloy from which it was cast. Fastener tests showed pull out strength comparable to standard wood products used in construction, though either stainless steel or aluminum fasteners are recommended for attachment.

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