Production, Properties, and Applications of Alulight® Closed-Cell Aluminum Foams

P. Schaeffler and W. Rajner
Alulight International GmbH, Lach 22
5282 Ranshofen, Austria
p.schaeffler@alulight.com

D. Claar, T. Trendelenburg, and H. Nishimura
Alulight of America L.P.
9 Innovation Way – Suite 100, Newark, DE 19711 USA
dclaar@msn.com

Abstract

After nearly 15 years of R&D, closed-cell aluminum foams are emerging as a new class of lightweight engineering materials that are being evaluated for a broad range of applications. These novel materials can provide multi-functionality because of their unique combination of properties, such as very high specific stiffness, crash energy absorption under compressive loading, shock wave attenuation, blast mitigation, vibration damping, fire resistance, and noise reduction. Results will be presented on several studies that were conducted to demonstrate the behavior and performance advantages of aluminum foams. These case studies include such applications as crash energy management in transportation systems, lightweight composite integral armor systems for ballistic protection of military vehicles, and fire protection structures. The advantages of utilizing aluminum foams in combination with other conventional materials of construction will be presented. The current status of manufacturing scale-up of the Alulight® powder metallurgy process for closed-cell aluminum foams will also be discussed.

Keywords: *aluminum foam, energy absorption, fire resistance, shock attenuation, ballistic armor*

1. Introduction

An extensive amount of research has been performed on the processing and properties of lightweight metal foams since the early 1990's. Most of this work has been conducted on metal casting [1,2] and powder metallurgy-based foaming processes [3,4]. The results of these R&D efforts have demonstrated that aluminum foams exhibit a unique combination of materials properties that can be tailored to produce multi-functional materials.

The key properties of aluminum foams include the following:

- Low density for ultra-lightweight and buoyant structures
- High degree of homogeneous and tailorable closed-cell porosity
- Very high specific stiffness
- Effective energy absorption from impact, crash, and explosive blasts
- Fire resistance
- Enhanced mechanical damping compared to bulk aluminium
- Good sound insulation characteristics
- Reduced thermal and electrical conductivity
- Tailorable properties through selection of alloy, foam density, and heat treatment
- Shielding of electromagnetic interference (EMI)
- Good machinability (drilling, sawing,turning, milling)
- Joining by adhesive bonding, soldering, active brazing, mechanical inserts, advanced welding methods
- Amenable to re-cycling for environmental friendliness

This paper will focus on the versatile powder metallurgy process originally developed by the Fraunhofer Institute for Manufacturing and Advanced Materials (IFAM). This process has been further developed and scaled-up for manufacturing and commercialization by Alulight International GmbH. Alulight® closed-cell aluminum foams are currently being manufactured in Ranshofen, Austria, where installation of a new plant is underway for scaled-up production. It will provide an overview of (1) the powder metallurgy process for production of Alulight® closed-cell aluminum foams, (2) key properties and attributes of foams that make them attractive for a broad range of applications, and (3) results of several case studies performed for potential applications in the areas of vehicle crashworthiness, hybrid lightweight ballistic armor systems, and fire protection.

2. Production of Alulight® Closed-Cell Aluminum Foams

The powder metallurgy process for production of Alulight® aluminum foams is shown in Figure 1. Atomized aluminum alloy powders are blended with titanium hydride (TiH2) foaming agent to produce a uniformly mixed powder blend. This mixture of Al alloy and TiH2 powders is then consolidated into a dense body of foamable precursor material. The consolidation of powders into foamable precursor can be achieved by a combination of cold isostatic pressing (CIP) into a semi-dense billet, followed by extrusion into plates, bars or rod-shaped precursor. More recently, Alulight has developed a more cost-effective one-step powder consolidation process based on an advanced extrusion technology. The compacted foamable precursor is then placed inside a mould having the shape of the desired foam part. The foam parts can be either simple flat plates or more complex three-dimensional shapes. The mould containing the precursor is heated to a temperature near the melting point of the aluminum alloy. The foaming agent decomposes, forming a gas that is trapped inside the compacted powder body. The expanding gas bubbles create voids within the expanding body of semi-molten metal and are retained during solidification to create the cellular metal foam. The process results in a lightweight material with a high degree of closed-cell porosity. The density of aluminum foams can be controlled within the range of 0.3 to 1.2 g/cm3.

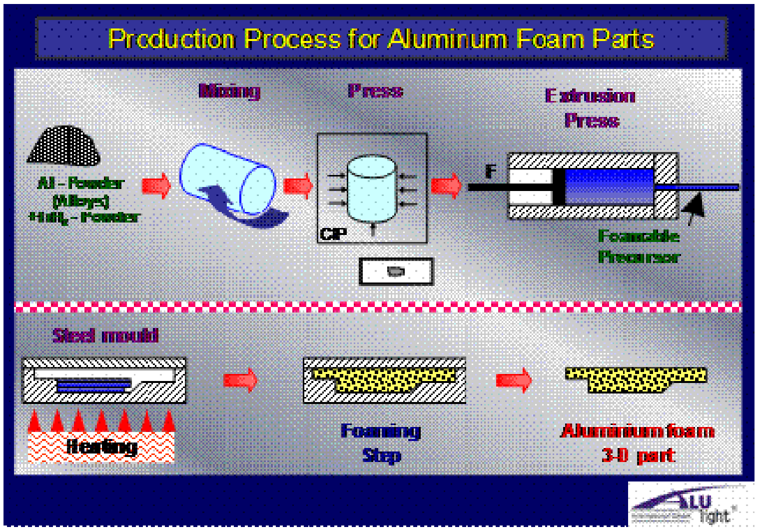


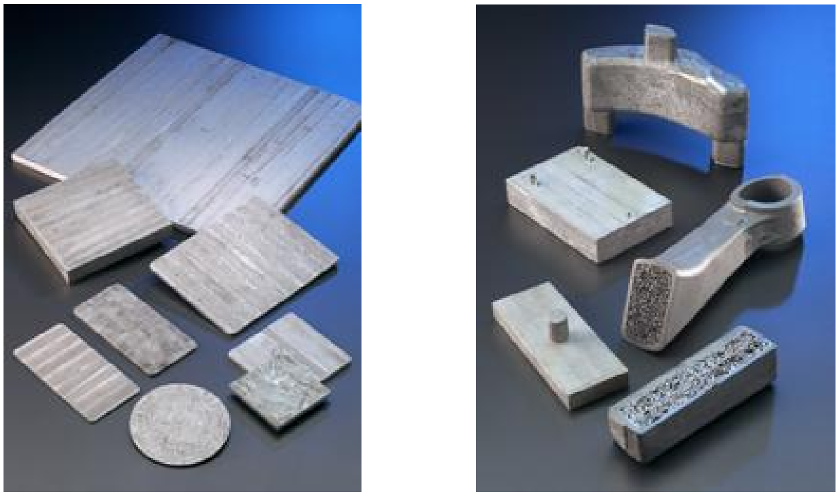
Figure 1. Schematic diagram of the Alulight® aluminum foam production process

2.1 Production of Aluminum Foam Shapes

Alulight operates a pilot-scale plant for production of aluminum foam as either flat plate or 3-D shaped parts. Figure 2(a) shows flat plates of aluminum foam produced in sizes up to 625 x 625 mm and thicknesses ranging from 8 to 30 mm. Figure 2(b) shows 3-D shaped aluminum foam parts used as cores for lighter weight aluminum castings. Alulight is currently in the process of constructing a new manufacturing facility for production of larger size panels, with the goal of producing sizes up to 1.0 x 1.5 m.

3. Applications of Aluminum Foams

Closed-cell aluminum foams possess a unique combination of properties such as low density, high stiffness, strength and energy absorption that can be tailored through design of the microstructure. When combined with other materials of construction, aluminum foams can be utilized to create multi-functional components with a broad range of potential military, industrial, and commercial applications [5]. Case studies of several promising applications of aluminum foams are discussed in the following sections.



(a) (b)

Figure 2. Aluminum foam parts produced as (a) flat plates and (b) 3-D shapes for use as cores in lightweight aluminum castings

3.1 Crash Energy Management in Vehicles

Low-density aluminum foams have a demonstrated ability to absorb significant amounts of energy during compressive deformation. This behaviour suggests their use as crushable energy-absorbing elements for crash energy management in automobiles, trucks, trains, aircraft, ships, air-drop containers and other transportation systems. Aluminum foams may be used as inserts in rails, pillars, or other vehicle components, as well as energy-absorbing seat structures in autos, trains, and aerospace vehicles.

An extensive study was performed on the energy absorption behaviour of 6063-T6 aluminum alloy and Type 304 stainless steel tubes with aluminum foam inserts. The outer metal tubes had a rectangular cross-section of 75 mm x 75 mm x 3 mm walls. Inserts of Al-7Si alloy foam with a density of 0.5 g/cm3 were inserted into 305 mm (12 in.) long metal tubes either by mechanical force-fitting or adhesive bonding. Both empty and Al foam-filled tubes were tested in quasi-static compressive loading to the point of 177 mm crush length (58% compressive strain). The resulting compressive load vs. deformation curves were analyzed to calculate the amount of energy absorbed in each test specimen. At least three replicate axial compression tests were conducted on each type of empty and Al foam-filled 6063-T6 Al and 304 stainless steel tubes, in order to quantify the specific energy absorption value for each type of specimen. Figure 3 shows the outer tube surface and cross-sectioned surface through a typical specimen of Al-7Si foam-filled 304 stainless steel tube after testing to 58% compressive strain. This photogragh shows the extensive amount of densification that occurred in the foam insert, as well as the deformed convolutions in the outer stainless steel tube. The significant extrusion of Al-7Si foam outward into the SS wall convolutions, which also contributed to the energy absorption, is also observed in this photograph.

Figure 3. Stainless steel tube with adhesively bonded aluminum foam insert, tested in axial compression to 58% strain

Analyses of the specific energy absorption during deformation of the various types of specimens, summarized in Table 1, indicated the significant improvement in crush energy aborption of Al foam-filled tubes vs. empty tubes.

The results in Table 1 indicate that the 0.5 g/cm3 Al-7Si foam inserts increased the specific energy absorption (S.E.A.) of the 6063-T6 alloy tubes by 25 to 32 % compared to the empty tubes. The foam inserts increased the S.E.A. of the 304 stainless steel tubes by 33 to 38%. It was also determined that the adhesive bonded foam inserts provided 5 to 7% absolute improvement in S.E.A. compared to the mechanically force-fit foam inserts.

Table 1. Specific energy absorption of empty and aluminum foam-filled tubes of aluminum and stainless steel tested in axial compression

Specimen Geometry	**Specific Energy Absorption (S.E.A.), kJ/kg**	**Improvement in S.E.A with Al-7Si foam inserts**
6063-T6 Al extruded tubes - Empty	21.6 ± 0.32	6063-T6 Al Baseline
Al-7Si foam insert – Force-fit	26.9 ± 2.13	+25%
Al-7Si foam insert - Adhesive bonded	28.6 ± 1.25	+32%
304 SS welded tubes - Empty	24.3 ± 0.31	304 SS Baseline
Al-7Si foam insert - Force-fit	32.3 ± 2.46	+33%
Al-7Si foam insert - Adhesive bonded	33.6 ± 2.44	+38%

3.2 Lightweight Ballistic Armor

Military agencies in the U.S. and other countries are conducting extensive R&D on development of lighter weight and more effective ballistic armor. In a study performed with the U.S. Army Research Laboratory, aluminum foam has been shown to provide several performance advantages in lightweight armor [6]. Composite structural armor panels containing an intermediate layer of low-density closed-cell aluminum foam were impacted with 20-mm fragment-simulating projectiles (FSP). A photograph of a cross-section through one of the ballistic panels containing an Al foam intermediate layer and impacted with a 20 mm FSP projectile is shown in Figure 4.

During ballistic impact, the foam exhibited significant non-linear deformation and stress wave attenuation. The experimental ballistic results were compared with one-dimensional plane strain finite element analyses (FEA) of stress wave propagation. This combination of experimental/analytical analyses correlated well with the experimental observation that aluminum foam can delay and attenuate stress waves associated with the ballistic event.

Figure 4. Cross-section through lightweight composite integral armor using layer of aluminum foam

It was found that the dynamic deformation of aluminum foam started at the ceramic impact face and propagated through the thickness until complete densification. The cellular structure of aluminum foam acts as tiny wave-guides and geometric dispersion of stress waves takes place. The shock stress wave was not able to effectively propagate through aluminum foam until after complete densification occurred. If the foam densification is partial, it can act as a stress wave filter. The time required for complete densification appeared as a time delay in stress transfer to the layer (backing plate) behind the foam layer, and was found to be a linear function of foam thickness.

In comparison to the baseline armor design of the same areal density - but without foam – the armor with an intermediate foam layer showed superior performance. The Al foam-containing armor provided improved ceramic fracture characteristics, less separation of the polymer layer covering the entire armor layup, localized aluminum foam deformation, less dynamic deflection of the backing plate, less volumetric delamination of the backing plate, and no debonding at the ceramic-foam interface. The superior performance and unique attributes of this novel aluminum foam integral armor adds a new dimension to armor design. It is a significant step forward to lighter and more damage-tolerant composite integral armor for the next generation of lightweight armored vehicles.

3.3 Fire Protection Structures

The fire-resisting qualities of aluminum foams are of significant interest for potential applications as lightweight components in ships, trains, tunnels, and other engineered structures. Metal foams are also being considered for use in fire training and protection systems. Fire tests were designed and conducted on panels of aluminum foam and bulk aluminum alloy plate using the Harmathy test method. This test method specifies that a representative sample of the construction material be exposed on one side to the atmosphere of a specially built gas flame test furnace. The flame temperature is controlled to follow a prescribed curve simulating the flame and temperature conditions in a burning room. The other side of the test part remains in contact with the cooler ambient atmosphere at all times. The test specimen is considered to have failed if the temperature on the cool side rises above a pre-set temperature or if the wall ceases to function structurally as an effective barrier against the spread of fire.

The first fire test was conducted on a single piece of solid 6061 aluminum alloy plate while, the second test was on two 18 x 18 inch panels of Al-7Si foam joined together with a 90° step joint and having approximately the same thermal mass as the bulk plate. The dimensions were 18 x 36 x 0.5 in. for the 6061 Al plate and 18 x 36 x 2 in. for the aluminum foam panel. The test apparatus consisted of a concrete test oven chamber, 35 x 16 x 16 in. open on one side, fired with a propane torch. Three thermocouples were installed: one in the test chamber near the exposed side of the test sample, and two affixed to the top, unexposed surface of the sample.

Figure 5 shows the measured temperatures of the gas flame and the outer surface of the Al foam test panel. Thermocouple TC3 measured the flame temperature inside the fire box; TC2 measured the Al plate or foam temperature at the outer surface about 1/3 distance along the direction of the propane flame; and TC1 measured the test panel outer surface temperature about 2/3 distance along the direction of the propane flame. Also shown in Figure 5 is the excellent condition of the Al foam panels after 90 minutes of testing at a flame temperature of 1380 to 1480°F. Only a small area of minor incipient melting of the Al-7Si alloy foam on the inner surface was observed at the point of maximum flame temperature. By contrast, the bulk 6061 Al plate having the same thermal mass experienced melt-through of a 6-inch diameter hole at the hottest point of the gas flame. Neither the Al-7Si foam nor the 6061 alloy plate showed any tendency for burning in these tests. The formation of a thermally insulating aluminum oxide layer due to oxidation of the high surface area provided by the foam cell walls – combined with the significantly lower thermal conductivity of the Al-7Si alloy foam vs. the dense 6063 Al plate – appeared to provide superior flame resistance and high temperature behaviour of the Al foam. However, additional instrumented flame tests under well-controlled conditions are necessary to better understand the very good flame resistance of Al foams. This improved understanding is necessary in order to optimize the performance Al foams under high-temperature flame conditions.

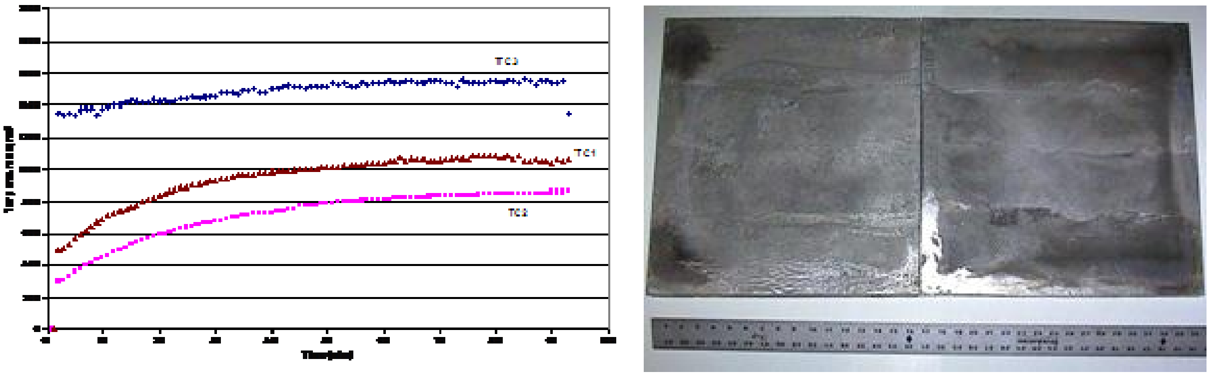


Figure 5. Temperature vs. time traces of the fire test on Al-7Si alloy foam panels (left) and excellent condition of inner surfaces of foam panels after 90 minutes of testing in 1380-1580°F flame (right)

4. Conclusions

- Closed-cell aluminum foams have demonstrated potential as ultra-lightweight, multi-functional engineering materials in a range of military, industrial, and commercial applications.
- Aluminum foams used as inserts inside metallic tubes increased the specific energy absorption by 25-32% for 6063-T6 aluminum and 33-38% for 304 stainless steel tubes. Additional crashworthiness studies using aluminum foams are in progress for seats in military vehicles.

- The performance of lightweight armor for military vehicles can be enhanced by use of Al foam. The foam increases the effectiveness of ceramic armor tiles, delays and attenuates the ballistic shock wave, and reduces backplate deflection and damage to the fiber-reinforced polymer composite backplate.
- The observed attenuation of ballistic shock waves suggests that aluminum foams may be effectively utilized in military vehicles for protection against mine blasts and improvised explosive devices (IED's).
- Al foam panels successfully survived exposure to a propane flame at 1380-1580°F for over 90 minutes, indicating great promise for use in fire protection systems.

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