Aluminium Foam Produced by the Melt Foaming Route Process, Properties and Applications

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Abstract

Aluminium foams can be produced by several methods. One of these methods is the so-called melt foaming route, developed simultaneously and independently by Alcan and Norsk Hydro in the late 1980's and 1990's. This method implies foam production directly from an aluminium alloy melt (mixed with ceramic particles) by injection of gas through rotor impellers. This way of foam production offers many advantages. The single most important is the possibility for low cost mass production due to the process simplicity and possibility for continuous production. Norsk Hydro has worked with this process for approximately ten years, and the quality of the product has increased substantially over these years. Still, the material has not yet been commercialised by Norsk Hydro. Alcan has now licensed their patent rights to the Canadian company Cymat, who is at present preparing for commercial production.

Aluminium foam has a lot of interesting properties, many of which have been explored by Norsk Hydro and collaborating partners. Based on an evaluation of the properties, two main potential application sectors emerge; energy absorption components for transport applications, and foam for stiffening/strengthening in structural parts such as core for sandwich panels and filling of hollow sections. Norsk Hydro is at the present time involved in three projects funded by the European Commission (METEOR, EAMLIFe, ZEDIS) exploring these potential applications.

1. Foaming process and manufacturing

One of the production methods for aluminium foam is the so-called melt foaming route, developed simultaneously and independently by Alcan and Norsk Hydro in the late 1980's and 1990's. A principle sketch of the process is given in figure 1.

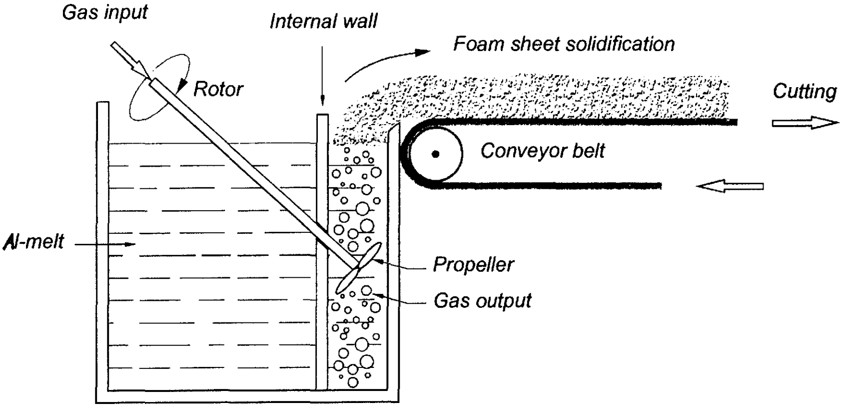

Figure 1. Principle sketch of the melt foaming route employed by Norsk Hydro.

Gas is dispersed into small bubbles in an aluminium composite melt by rotor impellers. The walls of the bubbles created are stabilised by refractory particles, avoiding coalescence between them. The gas bubbles rise to the surface where they accumulate. The accumulated foam on the melt surface is then transferred to a conveyor belt, where it solidifies and cools.

The melt may constitute of different alloys and refractory particles. The most commonly used alloys and particles are given in table 1 below.

Table 1. Typical alloys and particles used for foam production

Base alloy	Particle type	Particle size	Particle amount
AlSi8Mg (or equiv.)	SiC	10-30 μm	10-30 vol%
AlSi8MgCuNi	SiC	10-30 μm	10-30 vol%
AA 6016 (or equiv.)	Al_2O_3	10-30 μm	10-30 vol%

Foam may be produced in densities from 0.1 to 0.5 g/cm^3 by this method. The density is controlled by the process parameters, the most important being the rotor speed, the gas flow through the rotors and the amount of particles in the melt. At the present stage the production is directed towards slabs being typically 8-12 cm thick, 70 cm wide and 200 cm long. A picture showing such a slab is given in figure 2.

From this condition, foam components can be fabricated by machining, stamping and imprinting.

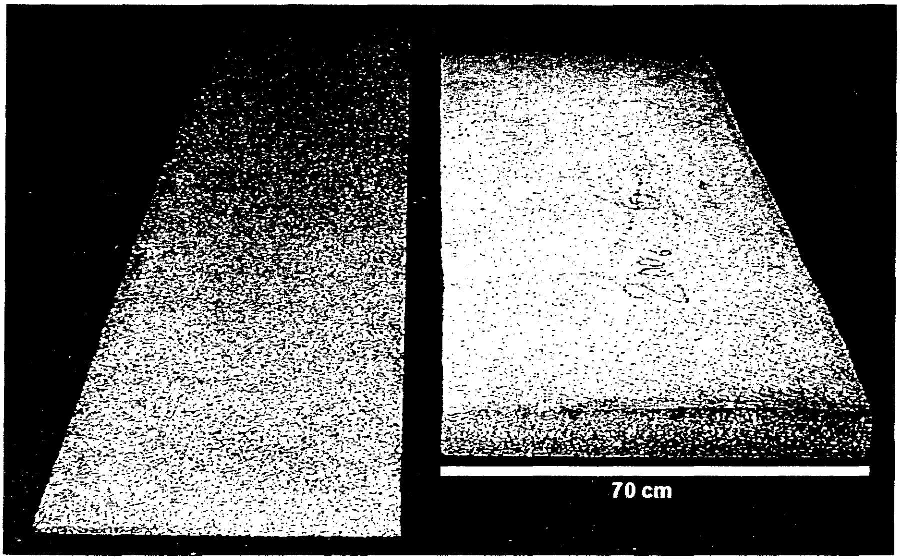

Figure 2. As cast slab with density 0.3 g/cm^3 together with sheet cut to 20 mm thickness by a band saw.

2. Foam properties

A great variety of foam properties have been evaluated. A list of the most important is given below.

Mechanical
Compression (Static/Dynamic)
Shear
Tensile
Bending
Fatigue

Acoustic
Sound absorption
Sound insulation
Elastic modulus

Others
Thermal
Fire
Electrical
Corrosion
Explosion

Almost all foam properties depend strongly on the density of the material, which is the single most important parameter for the foam. There is often power law dependence between the density and a specific property, resulting in property range of more than one order of magnitude within the possible product range. Most of the properties also vary with base material composition (alloy and particles). As an example one could look at the compression strength. Compression strength values in the range from 0.1 to 15 MPa can be obtained, typical values are ranging from 0.5 to 7-8 MPa.

The most desirable properties of aluminium foam are its high stiffness and strength to weight ratio and its compression characteristics. Except maybe for the compression behaviour there is no unique properties of the foam that can not be matched by other materials. For instance, the material has low thermal conductivity compared to most solid construction materials, but far higher than thermal insulators used for instance in refrigerators. This is the case for most non-mechanical properties. Nevertheless, aluminium foam has a *combination* of properties that is unique, which could become decisive in applications where the primary function could be met by several materials. This is probably the key to success in finding adequate applications for this material.

3. Aluminium foam for structural stiffening and strengthening

There seems to be two especially interesting uses of aluminium foam in structural (automotive) applications:

- Foam filled hollow sections
- Sandwich panels

Hollow sections such as extrusions, welded tubes, welded double hat sections etc. are widely used as structural parts in the transport industry (cars, trucks and trains), e.g. pillars in a normal car. The components are usually optimised on weight having constraints on stiffness and strength for various loading conditions. Foam filling can be used in the whole length or as local reinforcements in weak positions of the structure. Weight savings are possible, as a certain reduction of the weight of the section itself may be permissible. Due to the almost isotropic properties of the foam, reinforcements like this are assumed to be rather tolerant towards loading in different directions compared to other solutions. Moreover, bending tests have shown that introducing foam filling in hollow sections alters the deformation course. Instead of having a local bending failure and a global collapse with a corresponding sudden drop in force, the failure develops more gradually over a larger area at more constant load. This would contribute to higher energy dissipation and a more controlled deformation sequence in case of an overload of the structure.

Sandwich panels represent the other large potential use of aluminium foam in structural applications. Typical core types used in sandwich panels today are polymer foams and honeycombs in different materials. As aluminium foam is a material with a high stiffness to weight ratio, it has been proposed as a proper alternative. Aluminium foam in replacement for these materials is not necessarily a better solution if optimised only on stiffness/strength to weight criteria. There are however other properties that make aluminium foam an attractive candidate in real life components such as:

- Better resistance to local indents (compared to honeycombs)
- Easier introduction of load in mountings etc. (compared to honeycombs)
- Added thermal and acoustic insulation (compared to honeycombs)
- Incombustible (compared to polymer materials)
- No toxic fumes from core itself in case of fire (compared to polymer materials)
- Avoids penetration of direct flame (compared to both)
- Relatively easy recycling (compared to polymer materials)
- Price (compared to honeycombs)

Sandwich panels are not off the shelf products, but must be optimised for each application for both its primary function (stiffness and strength) and its secondary functions and constraints. Therefore, the choice of materials to be used will usually be assessed carefully. It would thus be reasonable that the special features offered by aluminium foam will be given attention in various sandwich panel applications.

4. Aluminium foam for energy absorption

The basic property that makes aluminium foam interesting as an energy absorbing material is the behaviour during compression. The material deforms at an almost constant stress plateau over a considerably large relative deformation, by successive collapse of pore layers. The plateau stress level is usually significantly higher than what is seen for polymer foams. An example is given in figure 3a.

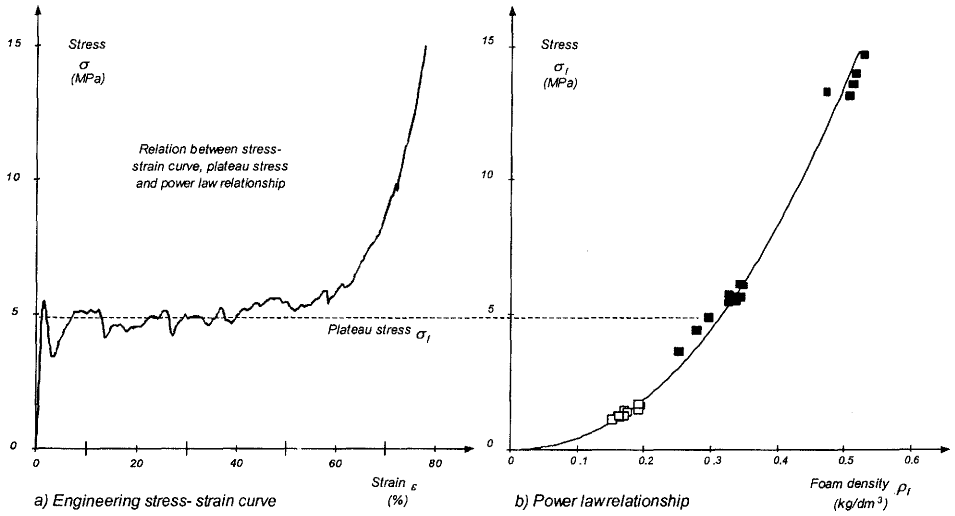

Figure 3. a) Compression curve for aluminium foam with density 0.3 g/cm^3
b) Plateau stress as a function of foam density. /1/

This compression behaviour enables the material to absorb a large amount of energy without high force peaks. As for solid aluminium alloys, the compression behaviour has only minor temperature dependence. Such a material is of course interesting for energy absorption in transport applications. In figure 3b the power law dependence between the plateau stress and the density of the material is demonstrated. As a rule of thumb, the exponent is close to 2 for this relationship. Since the deformation force level is more dependent on density than is the strain to densification, one could take it as a general conclusion that a high density foam has higher mass specific energy absorption potential than a lower density foam. Due to the relationship between density and plateau stress, it is possible to tailor the properties to the appropriate level for specific applications.

There are different intentions for introducing energy absorbing materials in the automotive industry, directed towards both protection of people from injuries and preservation of the car itself in accident situations. First, national and regional legislation demands higher safety standards for passengers and pedestrians, and the car manufacturers actively use safety as a promotion tool. In addition, repair costs after accidents are expected to be smaller if the damage on the car body can be reduced, which in turn will reduce the insurance premiums.

For protection of people in accident situations by direct impact between a person and the vehicle, the allowable impact forces are relatively low. This means that the foam has to be used as a "stand alone" material without structural reinforcement by other materials. Indeed, the foam density also has to be low in order to keep the stress at an appropriate level (typically up to 1 MPa). Aluminium foam is especially interesting in such applications due to its ability to absorb energy even if the direction of impact is oblique and because the properties are stable in different environmental conditions (temperature and humidity).

For the preservation of the vehicles themselves in crash situations, the picture is different. Here the energies to be absorbed are larger, and the vehicles can withstand higher loads. This means higher strength foam is desired, and combination with other materials is often necessary and desirable. One of the most interesting possible products in that respect is foam filled hollow sections (columns) such as aluminium extrusions. Such sections have long been well recognised for their energy absorption capacity in axial compression without foam filler. Norsk Hydro has for some years been supporting a Ph.D. study on axial crushing of foam filled aluminium extrusions at the Norwegian University of Science and Engineering. The results of this work show that foam filled hollow sections have excellent energy absorption capability. An example of the behaviour of axially crushed empty extrusion and aluminium foam filled extrusion is given in figure 4.

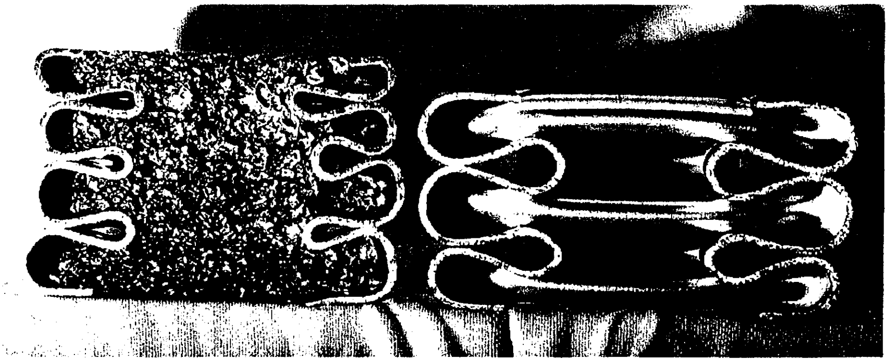

Figure 4. Cut through axially crushed foam filled extrusion and non-filled extrusion. Note the difference in number of buckling lobes. /2/

As can be seen the deformation behaviour has been altered as a result of the foam filling. The foam filler introduces a resistance against inward buckling, thus reducing the effective buckling length of the section walls, and thereby force the extrusion to create more lobes. This change in behaviour influences the force deformation curve of the component in a favourable manner. An example of such a curve is given in figure 5.

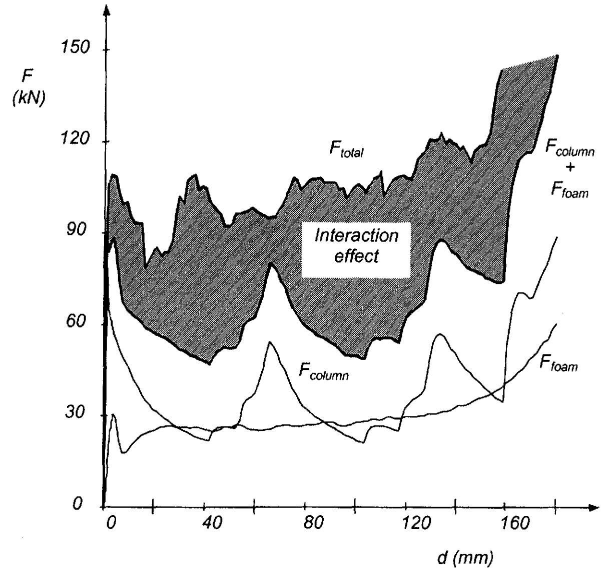

Figure 5. Comparison of force-displacement curves for foam filled extrusion, foam alone, extrusion alone and the added effect of foam alone and extrusion alone. /1/

The increased number of lobes created causes the force level of the foam filled section to be significantly higher than the added effect of the non-filled section and foam alone. This interaction effect causes the effective stroke length to decrease somewhat, but in total it gives a higher energy absorption capacity. Furthermore, the foam filled section exhibits a smoother curve, suppressing the natural force fluctuations of the buckling section, thus increasing the energy absorption efficiency. Yet another advantage with foam filled sections is that the deformation rate sensitivity seen in dynamic compression of non-filled extrusions is less pronounced. The difference in force level between static and dynamic loading evident for a non-filled section is caused mainly by (transversal) acceleration of the section wall. Aluminium foam has no noticeable strain rate sensitivity in the actual velocity range. In a foam filled section having the same force level as a non-filled, the dynamic effect is less due to the fact that a smaller fraction of the force is related to the deformation of the section itself.

Empirical models have been proposed for the average crush force, the maximum crush force and the effective stroke length as a function of the strength of the foam, the strength of the section material and the section geometry. The models are based on an extensive experimental program with a wide span in all parameters. This should secure that the models are robust and able to make precise predictions for a large variety of material strengths and section geometries.

Based on the experimental results the following type of expression was proposed for the average compression force (F_{avg}) and maximum compression force (F_{max}).

$$\mathbf{F_{avg}, F_{max} = F^0 + F^f + \Delta F^i}$$

where F^0 is the crush force of a non-filled section
F^f is the crush force of the foam
ΔF^i is the interaction effect mainly related to the altered deformation of the section

Dividing the total force into three contributions like this is the natural way of addressing this problem. Plots showing the correlation between the experimental values and those derived from the expressions above are given in figure 6. The exact equations are given inside the plots.

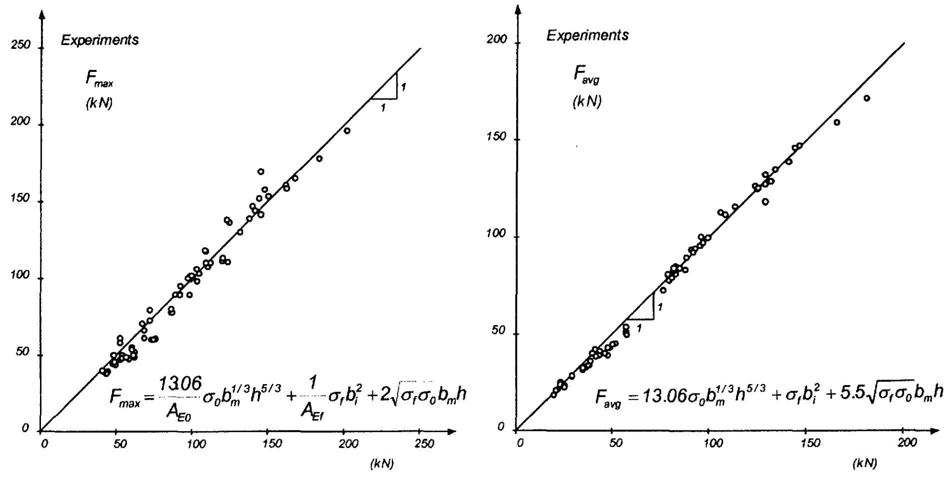

Figure 6. Correlation between the experimental values and the proposed models for average compression force (F_{avg}) and maximum compression force (F_{max}) at 50 % relative deformation /2/. The notations σ_0 and σ_f represents the strength of the section material and the foam respectively, whereas b is the section width and h is the wall thickness of the section. A_E denotes the crush force efficiency.

As seen, there is a fairly good fit between the measured values and the values from the empirical model. The empirical model for the effective stroke length is also tolerably good. This is however a more complicated matter, and a deeper treatment can be found elsewhere /1/.

Anyway, having these models available, it is possible to perform an optimisation procedure for actual problems. By definition of performance criteria such as energy absorption and maximum allowable force, it is possible to determine the combination of extrusion wall strength, foam strength, extrusion wall thickness and component width, that gives the lowest mass provided that specified constraints such as component length and relative deformation are met.

Furthermore, these models have been used to evaluate the feasibility of foam filled sections compared to non-filled section on a minimum mass basis. It can be concluded that significant savings in mass, length and volume can be achieved by utilising foam filler. The results also show that foam filled columns have to have a smaller outer cross section than non-filled columns in order to obtain better energy absorbing performance, which could be advantageous if available space is limited. Together with the other favourable aspects mentioned before (smaller force peaks, sensitivity to dynamic loading), there seems to be positive prospects for the utilisation of foam filled hollow sections as energy absorption components in the transport industry.

5. Concluding remarks

Aluminium foam has had a great deal of attention over the last years. The material has a lot of interesting properties which have been, and still are being explored by different companies and researchers in several national and regional research programs. A number of interesting applications have been identified, but we are still waiting for a broad utilisation as a common construction material. It is reason to believe that applications that employ the high stiffness/strength to weight ratio and/or the energy absorption capacity of the material will be the most probable to succeed.

The success of trying to implement this material in high volume applications depends on several factors. First, the material has to prove its technical feasibility in comparison to other materials, including also the fabrication steps and possibility for recycling. Second, the price of the material must not exceed that of competing solutions. This is becoming increasingly more difficult, as potential high volume markets are getting more and more price-conscious. Additionally, there is a prevailing conservatism in choice of materials for new applications that has to be overcome. Since metal foams is still a young group of materials it is too soon to tell whether it will find its place in this picture. Still, it is important that some successful high volume applications are realised soon, in order to keep both producers and possible users optimistic about the future potential of this exciting group of materials.

References

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