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TECHNICAL MANUAL FOR CYMAT
SmartMetal™

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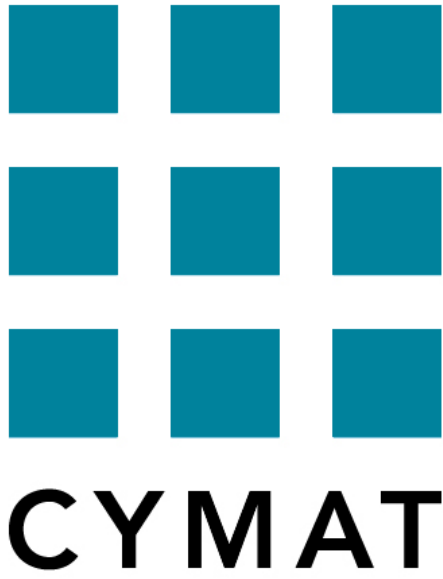
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INTRODUCTION

1 INTRODUCTION

Cymat Technologies Ltd is a materials technology company with exclusive worldwide rights to the technology to manufacture Stabilized Aluminum Foam (SAF). It is a public company that is listed on the Toronto Stock Exchange (TSX) under the symbol CYM.

SAF is a closed cell aluminum foam that can be produced in flat sheets or as 3-D shapes as shown in Figure 1.1.

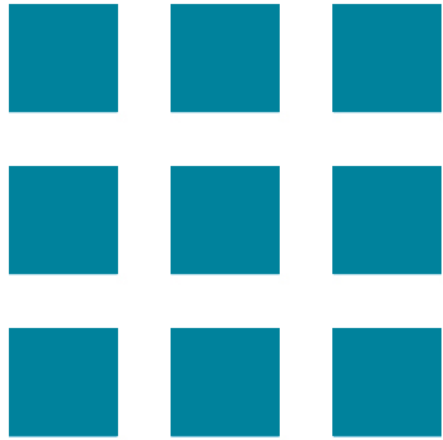
Some of the many advantages of SAF are listed below:

- High strength and stiffness-to-weight ratio
- Strain rate insensitive (the speed of loading does not affect the strength)
- Notch insensitive (holes do not affect material strength)
- Constant properties over time, temperature and moisture range
- High mechanical energy absorption in all directions
- Not flammable or susceptible to environmental degradation
- Electromagnetic insulation properties
- Acoustic and thermal insulation properties
- Recyclable
- High performance-to-price ratio

These properties make SAF valuable in automotive, transport, and military and civil defence applications. The unique appearance of the material also makes it suitable for architectural surface applications for which it is sold under the Alusion™ brand name. Please visit the corporate website at www.cymat.com or the Alusion™ website at www.alusion.com for more information.



Figure 1.1. Examples of Stabilized Aluminum Foam (SAF) in panel form and as a 3-D casting.



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TERMINOLOGY AND CONVENTIONS

2 TERMINOLOGY AND CONVENTIONS

2.1 General

Density – There are two methods for reporting density. The first is the standard mass/volume value in units of g/cc, kg/m³, lb/ft³, etc. The second method common to cellular materials is *relative density* that directly compares the density of the foam to the density of the parent material. For example, if a block of SAF has a density of 0.27 g/cc and the density of aluminum is 2.7 g/cc the SAF can be said to have a *relative density* of 10%. This is an important measure since many of the mechanical properties of Cymat’s SAF scale with relative density.

Table 2.1. Conversion of common SAF densities

g/cc	kg/m ³	lb/ft ³	relative (%)
0.1	100	6.24	3.7
0.2	200	12.50	7.4
0.3	300	18.73	11.1
0.4	400	24.97	14.8

Metal Matrix Composite (MMC) – A composite material with at least two constituent parts, one being a metal. The other material may be a different metal or another material, such as a ceramic or organic compound

Stabilized Aluminum Foam (SAF) – The term for foam produced by introducing gas bubbles into a melt of metal matrix composite (MMC). The hard ceramic particles in the aluminum alloy stabilize the bubbles allowing the foam to be formed into its final shape.

2.1.1 Mechanical Properties

Numbering Convention – Due to the production method, SAF sheets have a natural directionality in the final product. For the remainder of this document the numbering convention shown in Figure 2.1 is followed.

Elastic Modulus (Compression) - There are two elastic moduli that can be measured for SAF in compression: *loading* and *unloading*. Due to very early onset of plastic yielding in foam, the loading modulus appears much lower than the unloading modulus (Figure 2.2). Both are reported in the data sheets.

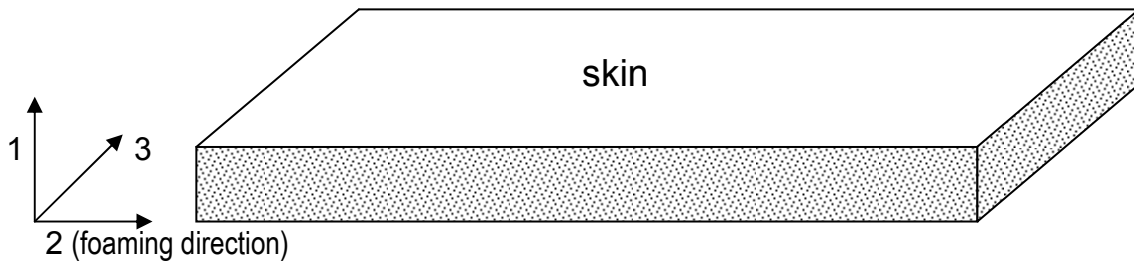


Figure 2.1. Numbering convention of material directions in SAF foam.

Upper Yield Point – When SAF is compressed in the 1 direction it exhibits an initial peak in the stress-strain curve. This is the upper yield point (Figure 2.2a).

Lower Yield Point – The first trough in the compressive stress-strain curve in the 1 direction (Figure 2.2a).

Compressive Strength – In the 2 and 3 directions there is no obvious upper and lower yield points, rather the stress-strain curve exhibits a flat plateau (Figure 2.2b).

Densification Strain – The strain at which the foam is completely crushed and there is a sharp increase in the slope of the stress-strain curve (Figure 2.2).

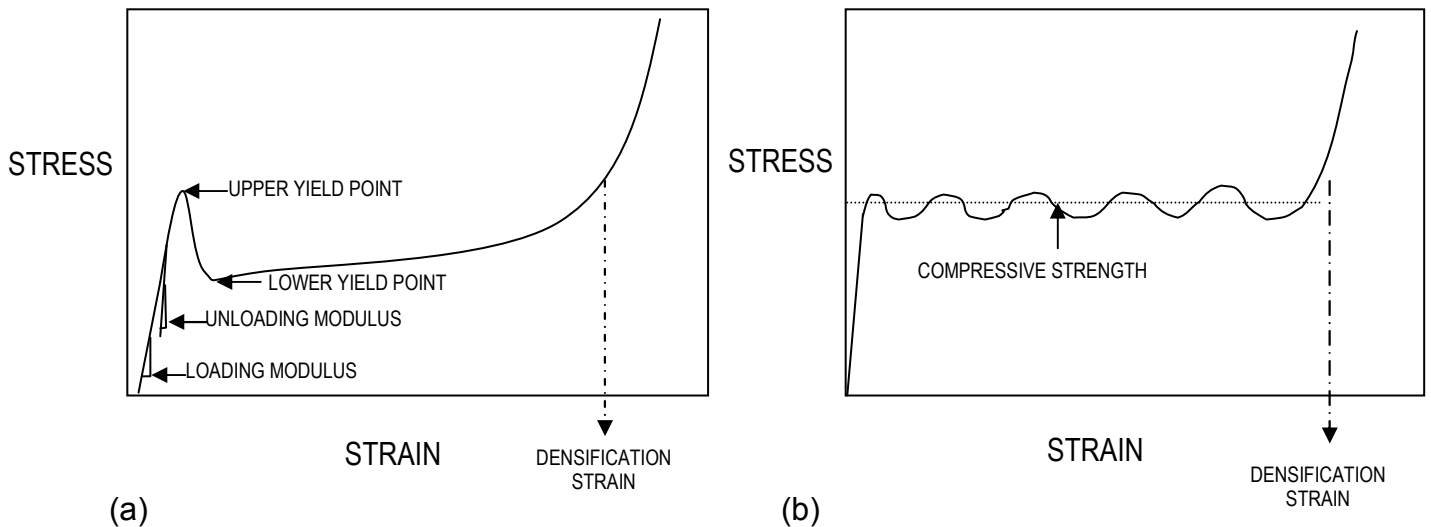
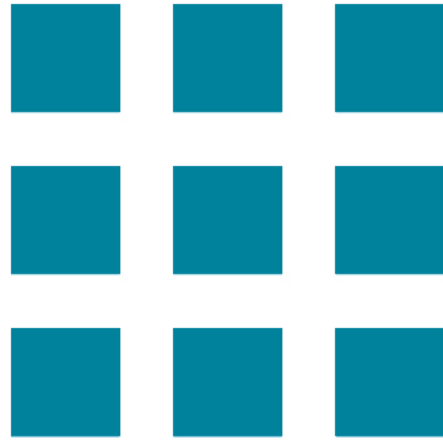


Figure 2.2. Schematic of the compressive stress-strain curves in the a) 1 direction and b) 2 and 3 directions.

Tensile Strength – Failure load of SAF in tension.

Shear Strength – Failure load of SAF in shear.



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PROCESSES AND PRODUCTS

3 PROCESSES AND PRODUCTS

There are two processing routes to produce Stabilized Aluminum Foam (SAF): 1) horizontal continuous casting (flat panels), and 2) low pressure casting. Each process along with its capabilities and its end products are discussed here.

3.1 Processes

3.1.1 Horizontal Continuous Casting

The patented process for producing SAF flat panels starts with a metal matrix composite - an aluminum alloy that has ceramic particles added. Once melted, the MMC is poured into a foaming box. By injecting gas in a controlled fashion through a rotating impeller, bubbles are created. The bubbles rise through the liquid MMC and create a foam structure. The foam collects on the surface of the molten material where it can be continuously drawn off to form a sheet. The foam structure is predominantly closed cell. The cell size can be controlled by varying the operating conditions of the injection system. The rate and means by which the gas is introduced can be varied to produce foams with densities varying from 5% to 25% of the density of solid aluminum (i.e. 97.5% to 80% air). Because many of the mechanical and physical properties of SAF vary with density, cell size and parent material, SAF can be tailored to suit a specific application. A schematic of the horizontal casting process is given in Figure 3.1.



Figure 3.1. The SAF horizontal continuous casting system.

3.1.2 3-Dimensional Low Pressure Casting

3-D SAF shapes are made via Cymat's modified low pressure casting process which is similar to an aluminum low pressure casting process, which is commonly used to make aluminum wheels. In Cymat's process molten MMC is injected into

a mould. Gas is then introduced through a rotating nozzle and the resultant bubble rise and displace the molten MMC in the mold forming the foam shape. Similar to the flat panel process the density and therefore the properties of the final product are controlled by the cell structure and density of the material. This process is also capable of filling steel and aluminum parts with foam. Low Pressure Casting is capable of producing relative densities of between 15%-30%.

3.2 Products

3.2.1 Standard Panels

The following sheet thickness and densities are available from Cymat. A standard sheet measures 8'x4' (2.44m x 1.22m).

Table 3.1. Standard sheet sizes.

Density lb/cu. ft. (g/cc)	Sheet thickness Inches (mm)	lb/sq. ft. (kg/m ²)	Weight/ sheet lb (kg)
33.7(0.54)	0.5 (12.7)	1.4 (6.9)	44.9 (20.4)
25.6 (0.41)	1.0 (25.4)	2.13 (10.4)	68.2 (31.0)
16.9 (0.27)	0.5 (12.7)	0.7 (3.4)	22.5 (10.2)
	1.0 (24.5)	1.4 (6.8)	45.0 (20.4)
8.7 (0.14)	1.7 (43.0)	1.2 (6.0)	39.4 (17.9)

For energy absorbing applications for the Automotive and Defense and Security industries, panels can be customized to the needed density subject to minimum volume requirements. Please consult the graph in Figure 3.2 for possible density/thickness combinations. Please contact the sales office for application assistance, pricing and lead time information.

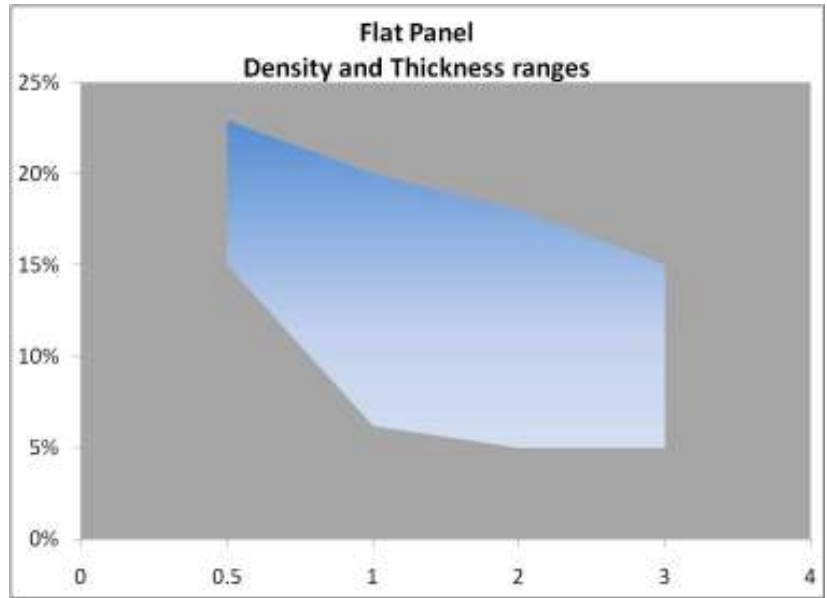


Figure 3.2. Possible range for density/thickness combinations.

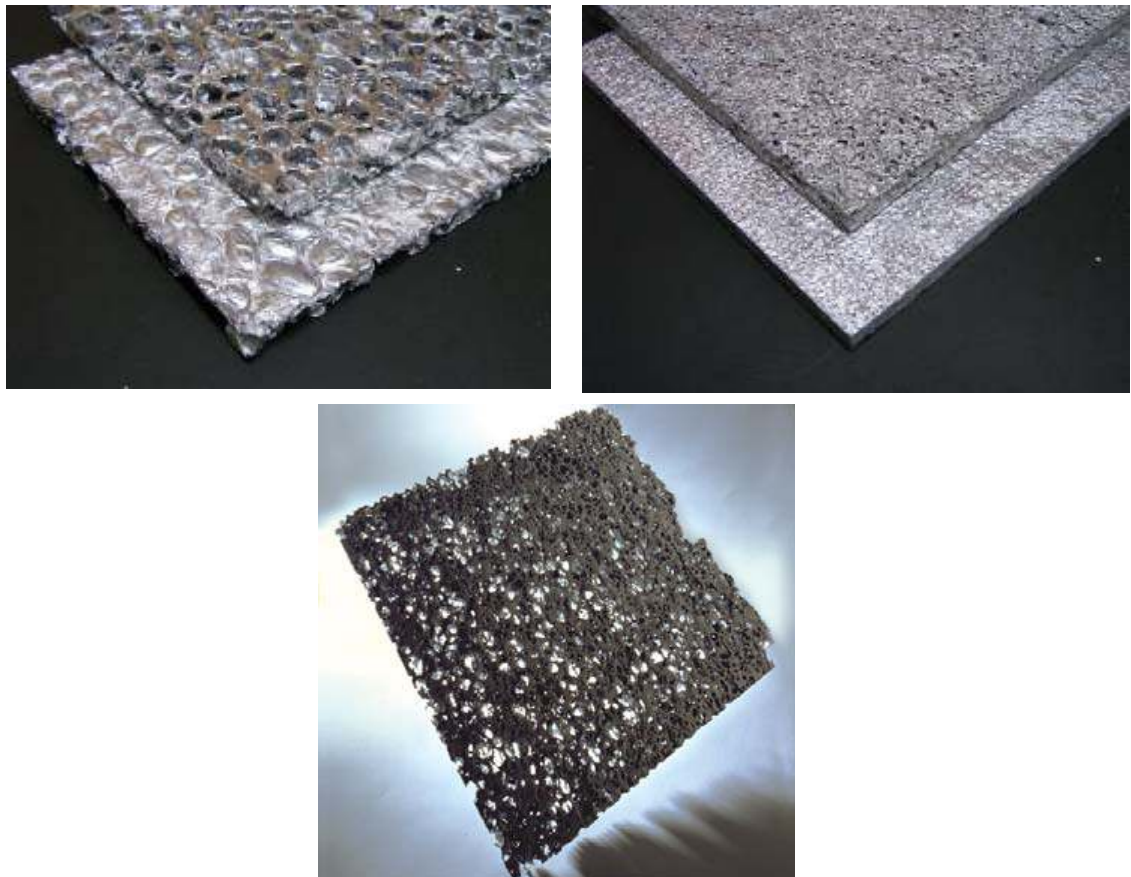


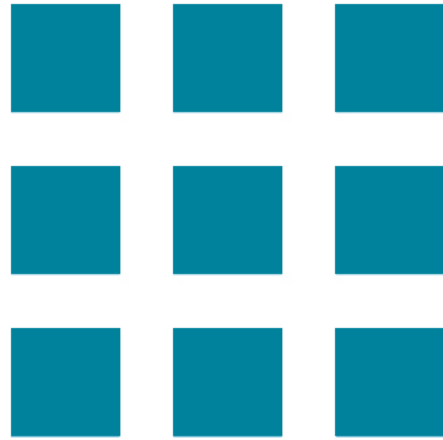
Figure 3.3. Examples of the SAF sheets that can be produced by Cymat

3.2.2 Castings

Figure 3.4 contains examples of 3 dimensional castings. Castings are made according to customer's specifications. Please contact Cymat Technologies Ltd. to enquire about the process method appropriate for your application.



Figure 3.4. 3-D shapes made by Low Pressure Casting



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PRODUCT APPLICATIONS

4 PRODUCT APPLICATIONS

The mechanical properties of SAF make it ideal for many varied applications. These properties include:

- High strength and stiffness to-weight ratio
- Strain rate insensitive (the speed of loading does not affect the strength)
- Notch insensitive (holes do not affect material strength)
- Constant properties over time, temperature and moisture range
- High mechanical energy absorption in all directions
- Not flammable or susceptible to environmental degradation
- Acoustic and thermal insulation properties
- Electromagnetic insulation properties
- Recyclable

SAF panels are an attractive architectural surfacing material are sold under the trade name Alusion™ and can be provided in different surface finishes and cell sizes. For further information on architectural applications please visit the Alusion™ website at www.alusion.com or contact Cymat Technologies Ltd. for technical and design information.

Three application areas have been highlighted in this section to demonstrate how SAF can be utilized in technical applications.

1. Energy absorption for vehicle crashworthiness
2. Energy absorption for blast protection of vehicles and buildings
3. Core for castings for improved stiffness or improved Noise, Vibration and Harshness (NVH) properties

The use of SAF is not limited to the above application areas. Cymat constantly investigates new and innovative uses for its products and welcome feedback and ideas from its customers.

4.1. Energy Absorption in Automotive Applications

Energy absorption is important in all packaging applications. The packaging may protect a computer that is dropped during delivery or a human head in an automobile accident. SAF is an ideal energy absorber and, because it is available in a range of densities from 0.14 to 0.54 g/cc (5%-20%), it can be tailored to a specific application.

4.1.1. Potential Applications for SAF

The potential for use of SAF in crashworthiness applications spans all transport and packaging industries.

Automotive

- Bumper systems
- Side impact protection
- Pedestrian protection – in hoods, cowlings, etc.
- Interior occupant protection

Packaging

- Protection for dangerous, valuable and/or military loads in case of accidents

Rail

- Protection for transported goods

4.1.2. Theory and Calculations

A moving object has kinetic energy (or the energy of motion) associated with it. When that object comes into contact with a large, stationary obstacle (wall, floor, etc.) its kinetic energy must be dissipated as the object comes to a stop. Since all energy is conserved, the kinetic energy must be converted to another form of energy. Ideally, the energy is absorbed by a sacrificial component rather than by the cargo itself.

In order for the contents of a package not to be damaged as it comes to a stop, not only must the energy be absorbed but also the rate of deceleration must be kept low enough not to cause damage. Tables 4.1 and 4.2 give allowable rates of acceleration as well as velocities that can be expected in some typical situations. Damage to an object will be caused by acceleration and its energy determined by its velocity.

Table 4.1. Limiting g-factors*, a¹, for a number of objects (for survivable damage)^b

Object	Limiting g-factor*, a ¹
Human body, sustained acceleration	5-8
Delicate instruments; gyroscopes	15-25
Optical and X-ray equipment	25-40
Computer displays, printers, hard disk drives	40-60
Human head, 36 ms contact time	55-60
Stereos, TV receivers, floppy disk drives	60-85
Household appliances, furniture	85-115
Machine tools, engines, truck and car chassis	115-150

* a¹ = $\frac{\text{acceleration in m/s}^2}{9.81\text{m/s}^2}$

A criterion has been established for the accelerations that are associated with brain injury. This is known as the Head Injury Criteria (HIC). The HIC is an integral of acceleration with respect to time and states that the longer the

acceleration is applied to the head the lower the acceleration must be. The relationship is mathematically stated below.

$$HIC = (t_2 - t_1) \times \left[\frac{\int_{t_2}^{t_1} a(t) dt}{(t_2 - t_1)} \right]^{2.5}$$

For no brain injury $HIC < 1000$

Table 4.2. Impact velocities for a range of conditions^b

Condition	Velocity (m/s)
Freefall from a forklift truck, drop height 0.3 m	2.4
Freefall from a light equipment handler, drop height 0.5 m	3.2
Freefall of carried object or from table, drop height 1 m	4.5
Thrown package, freefall	5.5
Automobile, head impact, roll-over crash in car ^a	6.7
High drag parachute, landing velocity	7
Low drag parachute, landing velocity	13
Automobile, side impact, USA ^a	8.9
Europe ^a	13.8
Automobile, front impact, USA ^a	13.4
Europe ^a	15.6

^a Current legislation

^b Values taken from Metal Foams: A Design Guide (2000), Ashby, et al.

An ideal energy absorbing material has a stress–strain curve with a long, flat plateau region. Any spikes in the stress cause unwanted spikes in deceleration. A plateau in the stress-strain curve tells us that the force is constant with increasing deformation in the material. The energy per unit volume of material that is absorbed is the area under the stress-strain curve, as shown in Figure 4.1.

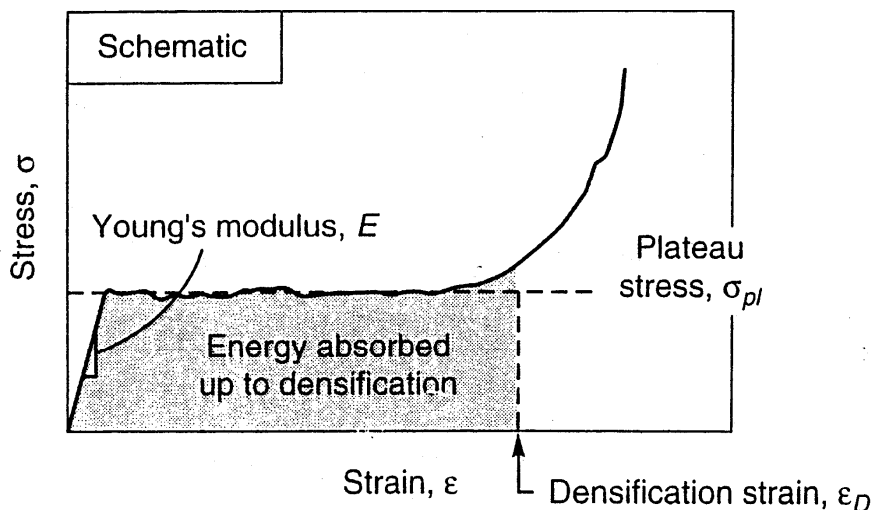


Figure 4.1. Schematic of the stress-strain curve of SAF in compression.

Now we have two conditions that must be met in order for our package to survive an accident unscathed. (1) The total kinetic energy of the moving package must be absorbed by the packaging material, and (2) the force on the package must not cause the deceleration rate to exceed the limiting deceleration.

Force Condition:

The force that can be exerted on the package is given by:

$$\text{Force} = \text{mass} \times \text{allowable deceleration}$$

This force limits the plateau stress of the foam used. The foam exerts a force equal to the plateau stress times the impact contact area, therefore the compressive strength must be less than:

$$(\text{mass} \times \text{allowable deceleration}) / \text{contact area}$$

The compressive strength and densification strain of a foam depend on its density. From the material data charts in Section 5.3 we can select the density of foam to keep the compressive strength under that allowed by the deceleration.

Energy Condition:

The energy absorbed per unit volume of material is the area under the stress-strain curve. The total energy absorbed by the foam must equal the kinetic energy of the moving package.

$$\text{Kinetic Energy} = \frac{1}{2} mv^2$$

Energy Absorbed by Cymat foam

Compressive strength x densification strain x contact area x thickness of foam

Now the thickness of foam required can be determined.

A worked example for the situation of head impact can be found in Appendix A4.

4.1.3. Crashbox

A crashbox is placed between the impact beam and the front rail of the car, as shown in Figure 4.2, to absorb medium speed collision energy and reduce repair costs. Here the crashbox is an aluminum extrusion or welded steel section filled with SAF that will crush along its length to absorb energy. Crashboxes are more widely used in Europe due to insurance industry incentives for their use.

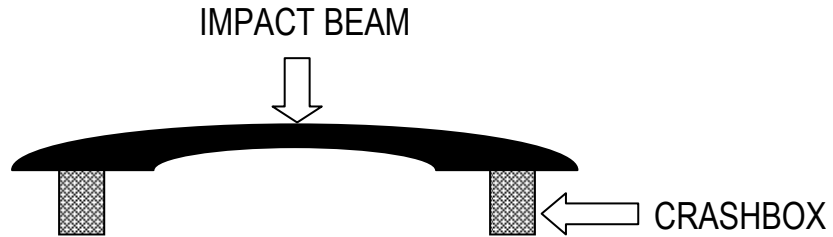


Figure 4.2. Position of the crashbox behind the impact beam (top view).

The photographs in Figure 4.3 show a crushed crashbox and two examples manufactured by different processing routes. The square crashbox had a foam piece press-fit, while the round section has been filled with molten SAF through a casting technique.

(a)



(b)



Figure 4.3. Examples of a) a collapsed crashbox and b) a square and round crashbox.

The advantage of filling a hollow tube with foam is greater than the obvious benefit that the foam will absorb energy. There is also an interaction effect that causes the tube to form more folds down its length causing the total energy absorbed to be greater than the sum of the individual contributions of the foam and tube. Figure 4.4 shows a schematic of the effect.

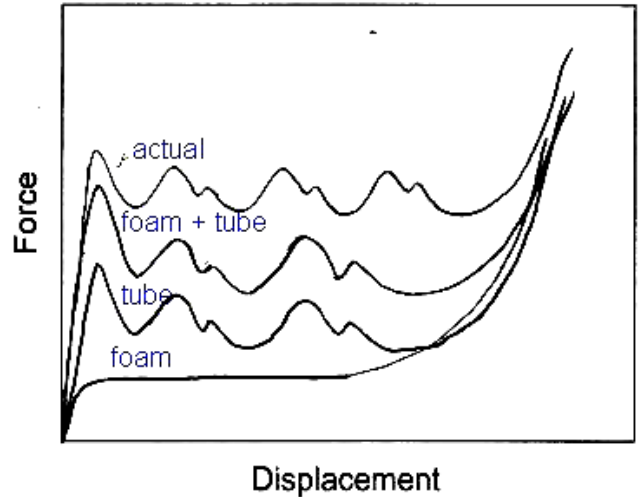


Figure 4.4. The interaction effect between foam and tube in a crashbox.

Figure 4.5 is an example of force-displacement curves for an empty tube and three tubes filled with foams of increasing density.

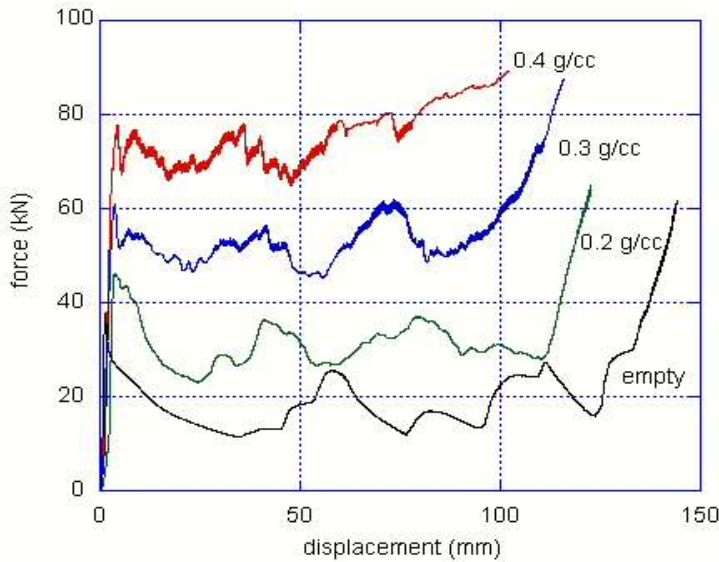


Figure 4.5. Force-displacement curves for square aluminum extrusions filled with varying densities of SAF.

There are design equations that can be used to predict the average collapse force of the crashbox and the energy absorbed. Details can be found in Appendix A4.

4.1.4. Structural Reinforcement

By placing SAF into a thin-walled hollow structure, the bending strength of the structure and the yield strain can be increased. In bending, an empty hollow structure fails by forming a localized plastic hinge on the compressive side. Once the hinge has formed the strength drops off significantly. By filling the section with foam the plastic hinge cannot form and the wall of the section suffers damage over a wider area. As can be clearly seen in Figure 4.6 the strength and yield strain are improved.

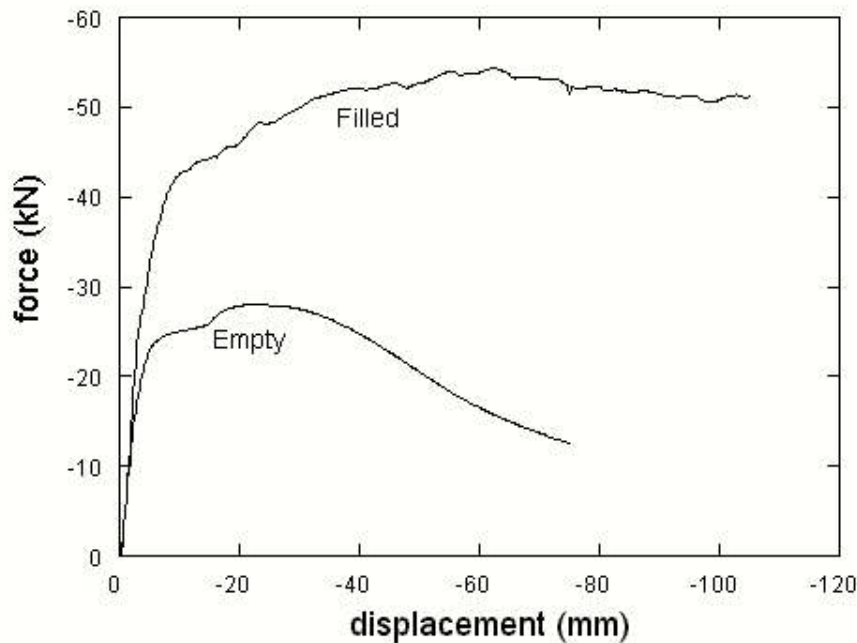


Figure 4.6. Force-displacement curves for a filled and unfilled section under three point bend loading.

4.2. Energy Absorption in Blast Protection

The same properties that make SAF an ideal material for absorbing energy in mechanical crash also make it suitable for protecting against blast and explosion. The subject of blast is a massive one and extremely complex. There are a huge number of situations that may arise. The following will attempt to provide some

simple theoretical background and information to aid in using SAF in blast mitigation applications.

4.2.1. Potential Applications for SAF

The potential applications for SAF in blast mitigation span civilian and military applications.

Petrochemical

- Blast doors
- Enclosures

Government

- Protection of government/embassy buildings and underground parking from explosives

Military

- Protection of personnel and equipment including vehicles and structures

4.2.2. Theory

Explosives create a blast pressure wave approximately triangular in profile. The blast imparts an impulse equal to the integral of the pressure over time or the area under the pressure-time curve (Figure 4.7).

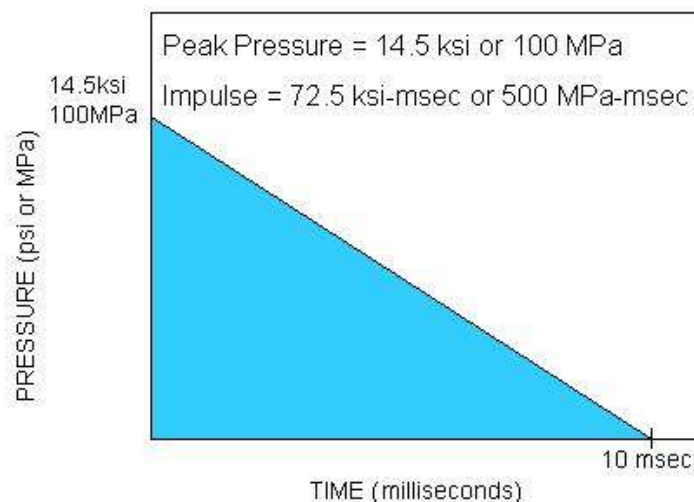


Figure 4.7. Pressure-time curve for a typical explosive blast.

The pressure wave emanates radially as a spherical wave and the peak pressure of the wave decreases as $1/R^2$, where R is the distance from the source. If the explosion occurs in an enclosed space the pressure waves will reflect off surfaces and the incident wave will be reinforced.

The important parameters in blast situations are:

- Type of explosive
- Weight of explosive
- Shape of any obstacles or enclosed spaces

SAF is not capable of absorbing the energy of a blast without a skin of a stiff material on the surface. Depending on the intended application, this skin can be made of a variety of materials including steel, aluminum, fiber composites and ceramics. One of the main benefits of using SAF is that the load transferred through can be controlled.

A simple example is worked through in Appendix A4.

4.3 Casting Cores

The aluminum foundry and die-casting industry typically uses sand cores to make hollow cavities in metal castings and rib structures where stiffening is required. SAF can be used to augment or replace these methods in castings made from zinc, magnesium and aluminum, with the following benefits:

- SAF would not have to be removed after casting (a sand core is usually vibrated out); therefore holes are not necessary in the casting.
- SAF core would reduce the weight of the casting by replacing redundant material
- The SAF core may cost less than the solid aluminum it replaces, depending on the application.
- SAF can collapse in an accident, providing energy absorbing properties to a casting.
- Complex rib structures could be replaced by one simple part incorporating SAF. This will lead to simpler die designs and processing methods.

In addition to being used as a casing core, existing hollow castings of aluminum and steel can be filled with SAF to increase stiffness as well as improve NVH properties by dampening vibrations

Typical applications for SAF cores include hollow parts as such as suspension arms, steering knuckles and engine and transmission brackets as shown in Figures 4.8 and 4.9



Figure 4.8 Examples of SAF Casting Cores



Figure 4.9 SAF filled Engine Bracket

4.1 Worked Examples

4.1.1 Head Injury

The human head is very delicate and requires protection against impact with hard objects during crashes. The following example shows a simple calculation done to estimate the density and volume of foam required to protect a head in a

car traveling at 6.7m/s (24km/hr) at the time of impact with the foam. The average acceleration must be kept below 60g to prevent brain injury. This is meant to be an approximate calculation; testing to determine the exact acceleration-time profile of a headform in contact with foam will give more accurate acceleration numbers for a HIC calculation.

For Human Head:

Average Acceleration without causing damage (Table 4.1) < 60g
Mass = 4.5 kg

The allowable force on the head is:

Mass x acceleration
 $4.5 \text{ kg} \times 60 \times 9.81 \text{ m/s}^2 = 2.6 \text{ kN}$

The contact area of the human head is approximately:
125 mm x 100 mm

The foam that is used must not exert a force greater than 2.6 kN. The maximum compressive strength of the energy absorbing foam is:

Stress = force/area
= $2600 \text{ N} / (125\text{mm} \times 100 \text{ mm})$
= 0.21 MPa

A 5%-6% piece of SAF will absorb the energy and not cause damage (see Section 5.3 compressive strength vs. density plot on page 5-13).

The kinetic energy of the head in a crash is:

K.E. = $\frac{1}{2} mv^2$
= $\frac{1}{2} (4.5\text{kg})(6.7\text{m/s})^2$
= 102 J

How much foam do we need?

All of the kinetic energy of the head must be converted to energy required to deform the SAF.

kinetic energy = foam energy
K.E. = stress x strain x volume of foam

$$102 \text{ J} = (0.21 \text{ MPa})(0.85)(125\text{mm})(100\text{mm})t$$

t = thickness of foam required to absorb the energy of the head

In this case:

t = 46 mm

4.1.2 Crashbox

There are algebraic equations that have been developed to describe and predict the behaviour of foam-filled crashboxes, (see work by Hanssen, Section 9). These give a good approximation of the average forces and energy absorption levels.

The average crush force of the foam filled section is given by:

$$F_{avg} = F_{avg}^0 + \sigma_f A_f + C_1 \sqrt{\sigma_0 \sigma_f} A_0$$

The equation can be split into its three components. The first term represents the crush strength of the tube, the second is the crush strength of the foam, and the third is the interaction of the two parts. From this we can see that the benefit of the whole is greater than the benefit of the sum of the parts.

- F_{avg}^0 average crush force of corresponding non-filled section
- σ_f foam compressive strength
- A_f foam core cross-sectional area
- C_1 dimensionless constant, cross section dependent, see Table 3.3
- σ_0 characteristic stress of the extrusion material taken as $\frac{1}{2}(YS+UTS)$
- A_0 cross sectional area of extrusion

The expression for the crush force of the non-filled section is:

$$F_{avg}^0 = C_0 \varphi^{2/3} \sigma_0 A_0$$

- C_0 cross section dependent constant, see Table 3.3
- φ A_0/A_f : solidity ratio

Table 3.3: Parameters needed to estimate the average crush force.

	Square	Circular
A_f	$(b-2h)^2$	$\pi(d-2h)^2/4$
A_0	$4h(b-h)$	$\pi h(d-h)$
φ	$4h(b-h)/(b-2h)^2$	$4h(d-h)/(d-2h)^2$
C_0	1.3	2.15
C_1	1.4	0.9

Square section side length **b**, wall thickness **h**
 Circular section diameter **d** and wall thickness **h**

The stroke efficiency, S_E , is the maximum stroke length of the absorber, d_{max} , relative to the initial component length, ℓ . The stroke efficiency of a foam-filled section is:

$$S_E = \frac{(F_{avg}^0 + C_1 \sqrt{\sigma_0 \sigma_f A_0}) S_E^F + (\sigma_f A_f) \varepsilon_D}{F_{avg}}$$

where:

$$S_E^F = 0.76(1 - 1.7\bar{\rho}^{0.8})$$

ε_D densification strain of the foam : $\varepsilon_D = 1 - 1.5\bar{\rho}$

$\bar{\rho}$ relative density of the foam (density of the foam/density of solid aluminum)

The absorbed energy is then given by:

Force x displacement

$$F_{avg} \times S_E \times \ell$$

Example

A square aluminum extrusion with outside dimensions 65mm x 65mm, wall thickness of 2mm and length 150mm is filled with SAF with density 0.4 g/cc (14.8%). The compressive strength of the SAF is 6.0 MPa. The YS of the aluminum is 80 MPa and the UTS is 160 MPa. The average strength of the aluminum is $\sigma_0 = \frac{1}{2}(YS + UTS) = 120$ MPa.

A_f	$(b-2h)^2$	3721 mm ²
A_0	$4h(b-h)$	504 mm ²
φ	$4h(b-h) / (b-2h)^2$	0.1354
C_0	1.3	1.3
C_1	1.4	1.4

Average Force	
F_{avg}^0	$1.3 \times 0.1354^{2/3} \times 120 \times 504$ 20.7 kN
$\sigma_f A_f$	6.0×3721 22.3 kN
$C_1 \sqrt{\sigma_0 \sigma_f} A_0$	$1.4 \sqrt{120 \times 6.0} \times 504$ 18.9 kN
F_{avg}	$20.7 + 22.3 + 18.9$ 61.9 kN
Stroke Efficiency	
S_E^F	$0.76(1 - 1.7 \times 0.148^{0.8})$ 0.47
ε_D	$1 - 1.5 \times 0.148$ 0.78
S_E	$\frac{(20.7 + 18.9)0.47 + 22.3(0.78)}{61.9}$ 0.58
Energy	
$F_{avg} \times S_E \times \ell$	$61,900 \times 0.58 \times 0.15$ 5.38 kJ

This crashbox will absorb 5.38 kJ of energy, exert an average force of 61.9 kN and crush to a length of 63mm.

4.1.3 Blast

The complexity and variation of possible blast situations makes it difficult to do simple calculations. In many cases computer simulations are the only way to fully develop a product. Below is a simple example to give a flavor of the benefit of SAF in blast situations.

1 kg of TNT in air produces a pressure pulse of 5MPa (725 psi), and generates an impulse of 600 Ns/m² at a distance 1m from the charge. SAF has been placed against a wall and a steel buffer plate (density = 7900 kg/m³) of thickness 5mm is placed in front of the SAF to deal with the initial impulse.

The impulse imparts a momentum to a unit area of the steel plate.

Impulse = mass x velocity = momentum

$600 \text{ Ns/m}^2 = 7900 \text{ kg/m}^3 \times 5\text{mm} \times 1\text{m} \times 1\text{m} \times \text{velocity}$
velocity of the plate = 15.2 m/s

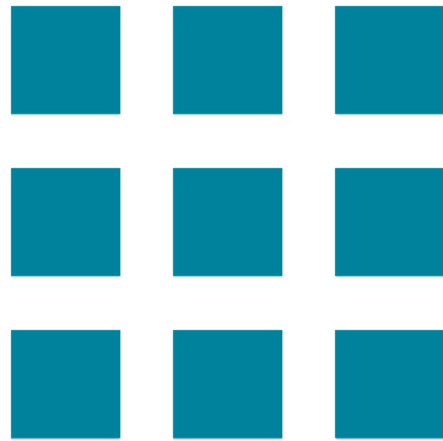
The foam is then used to absorb the kinetic energy of the plate (see previous section on crashworthiness). The structure behind the foam can withstand a stress of 0.3MPa. From Section 5.3 we see that a foam with density 0.15 g/cc will keep the stress under the required level and will absorb 200 kJ/m³ of energy.

By conservation of energy:

Kinetic Energy of the plate = Energy to Deform the Foam

$$\frac{1}{2} mv^2 \text{ (steel sheet)} = 1\text{m} \times 1\text{m} \times \text{SAF thickness} \times 200 \text{ kJ/m}^3$$

SAF thickness = 25mm



CYMAT

MATERIAL INFORMATION AND DATA

5 MATERIAL INFORMATION AND DATA

5.1 Mechanical Behavior of SAF

Stabilized Aluminum Foam (SAF) sheets have a natural directionality. For the remainder of this document the numbering convention shown in Figure 5.1 is followed. The density of foam can be described in two ways. The first is in the conventional units of density such as g/cc, kg/m³, lbs/ft³, etc. The second is to describe the foam by the percent of total volume of the foam that is solid aluminum. For example a foam described to have a density of 10% is 10% solid aluminum and 90% air.

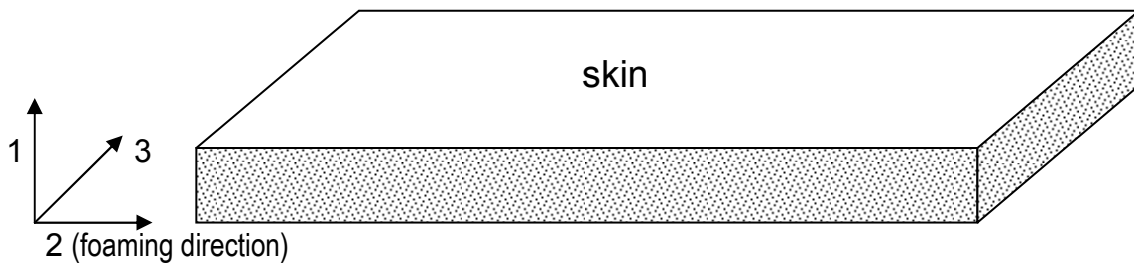


Figure 5.1. Numbering convention of material directions in SAF foam.

5.1.1 Compression

Three representative compressive engineering stress-strain curves for light (5% aluminum, 95% air), medium (10% aluminum), and heavy (15% aluminum) densities of SAF are shown in Figure 5.2. The foams have been compressed in the 1-direction. All three have an initial region of elastic deformation. There is a peak then a drop in stress followed by a region of gentle increase. The sharp increase in the hardening rate at the end of the curve corresponds to densification in the foam. Physically, the deformation of the foam begins in a layer of cells that crush: the material on either side of the crushed zones looks untouched. The crushing sweeps through the foam until all of the cells are consumed by the crushband at which point the foam is said to have densified.

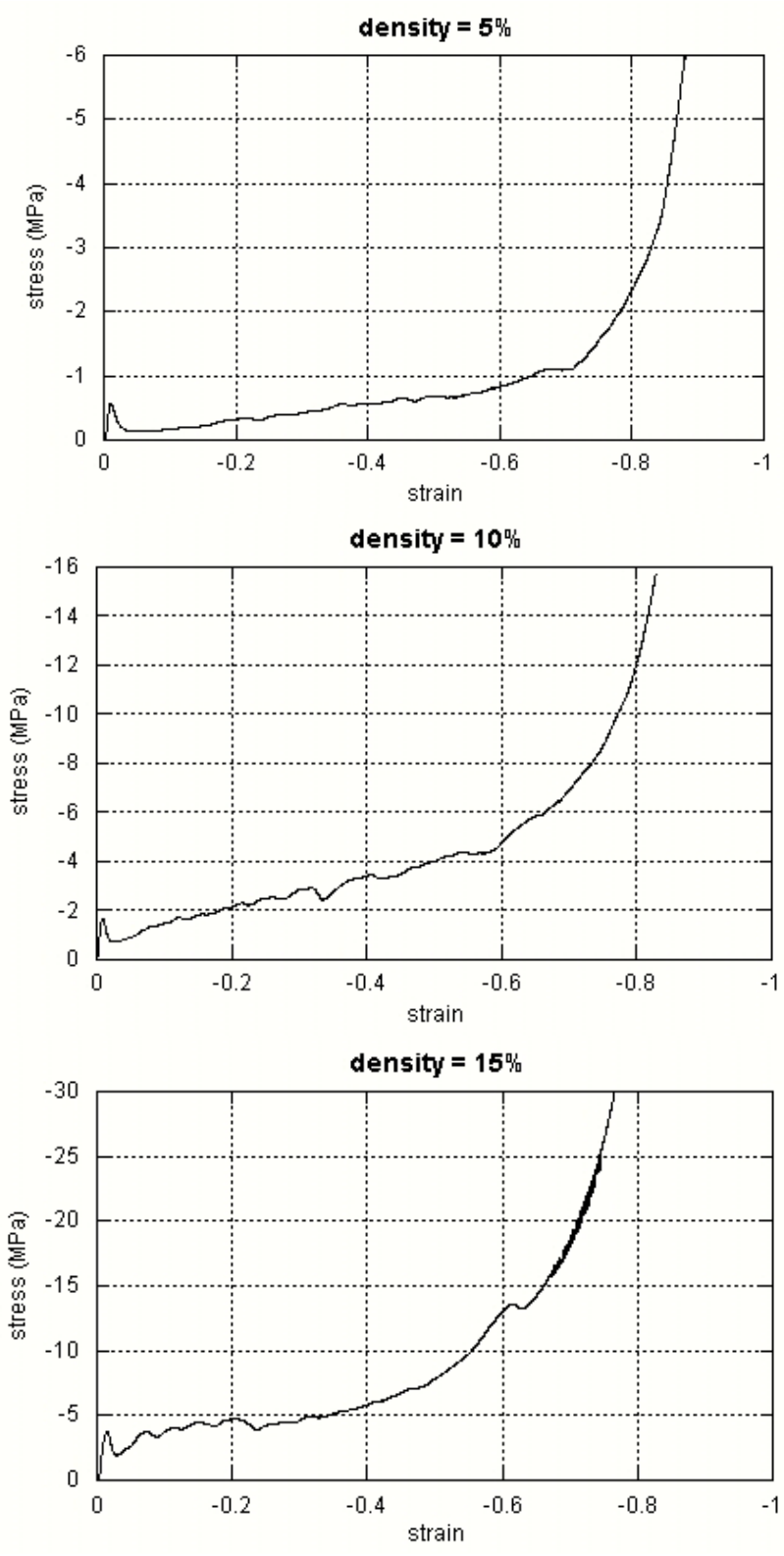


Figure 5.2. The stress-strain curves of SAF in the 1-direction for three densities.

Due to the processing route the foam is somewhat anisotropic. The compressive stress-strain curves for a medium density foam in the three orthotropic directions are shown in Figure 5.3. Note that in the 2 and 3 direction the stress-strain curve is much flatter than in the 1-direction. When compressive strengths are reported the peak stress (Upper Yield Stress) and the minimum stress after yielding (Lower Yield Stress) are reported in the 1 direction but only the average collapse stress is reported in the 2 and 3 direction (Figure 5.4). Although the foam is anisotropic it absorbs large amounts of energy in all directions.

Because of the long stress-strain curve, SAF is ideally suited to applications requiring energy absorption.

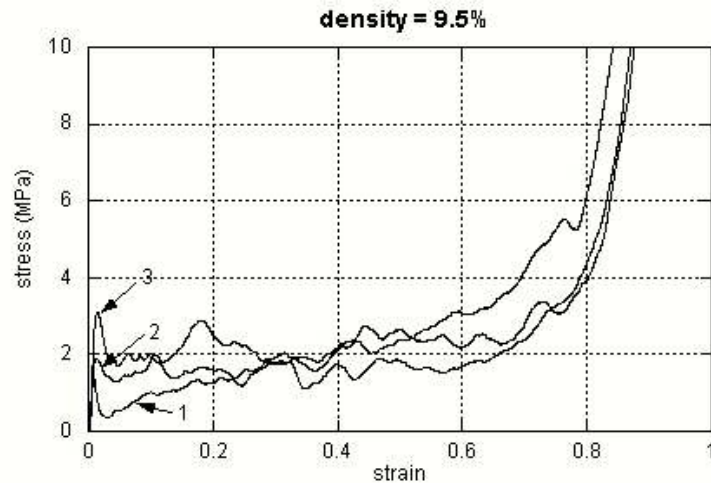


Figure 5.3. Orthotropic properties of SAF foam.

5.1.2 Elastic Modulus

There are two elastic moduli that can be measured for SAF in compression: loading and unloading. Due to very early onset of plastic yielding in foam, the loading modulus appears much lower than the unloading modulus. Both are reported in the data sheets.

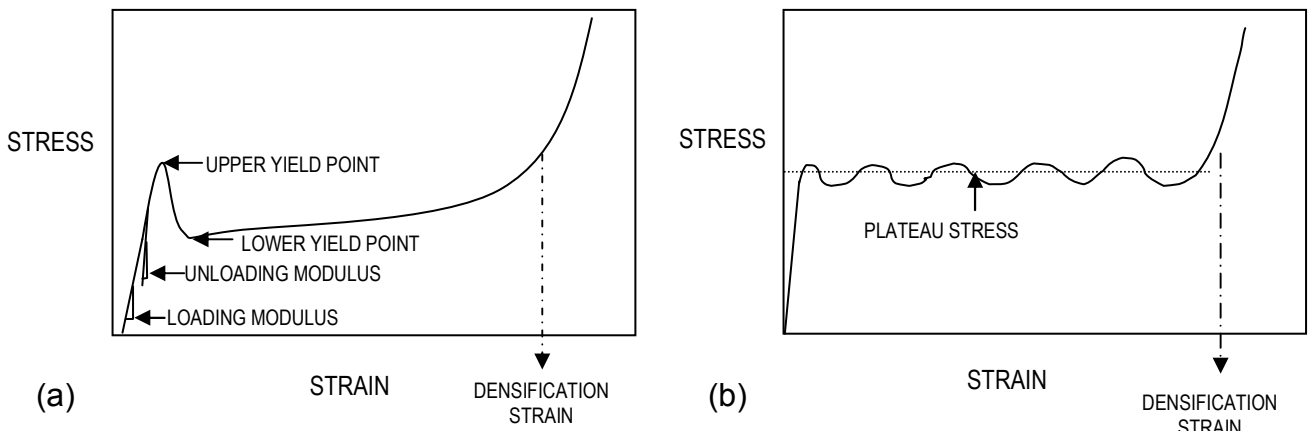


Figure 5.4. Schematic of the compressive stress-strain curves in the a) 1 direction and b) 2 and 3 directions.

5.1.3 Tension

The behavior of SAF in tension is unlike the compressive behavior. In tension, cracks form at relatively low strains. This strain depends on the alloy, the particle content and the density of the foam. At this point the stress drops and complete failure is imminent. The strength in tension tends to be slightly lower than compression. A typical tension curve for 10% SAF is shown in Figure 5.5.

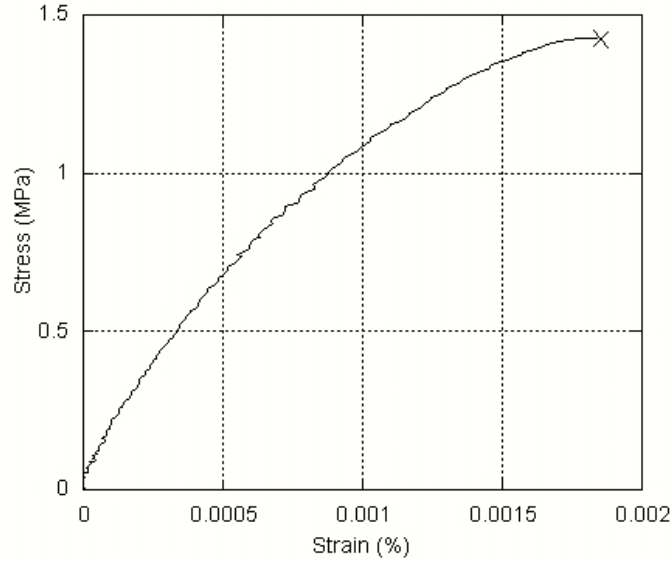


Figure 5.5. A typical stress-strain curve for SAF in tension.

5.1.3. Shear

Shear behavior is comparable to tension. Cracks form along the length of the shear sample at low shear strains, at which point the strength drops off and failure occurs. The strength of SAF in shear is approximately half of the strength in tension and compression. A typical shear stress-shear strain curve for 10% SAF is shown in Figure 5.6.

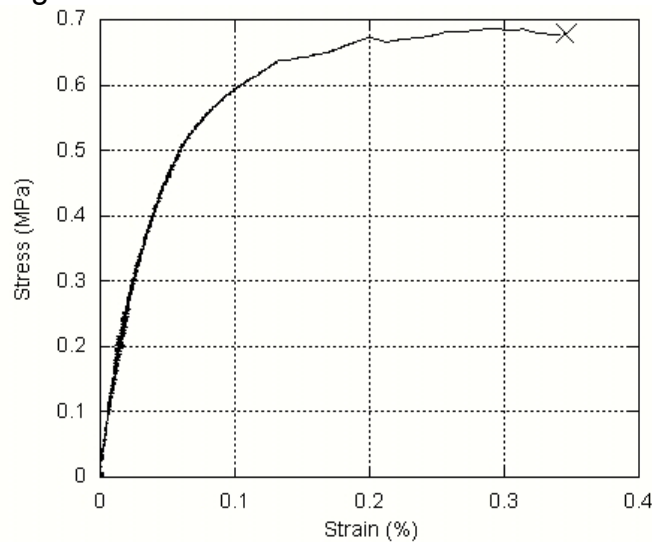


Figure 5.6. A typical stress-strain curve for SAF in shear.

5.2 Testing Procedures

This section gives a brief description of the testing procedures utilized for compiling the following data tables for stabilized aluminum foam. Where possible, reference is given to appropriate ASTM (American Society for Testing and Materials) standards for more detail. Where new standards have been developed specifically for aluminum foam material, details can be found in Appendix A5.

5.2.1 Compression Testing

Compression testing is performed by squeezing a block of foam between two parallel platens, Figure 5.7. For more detailed discussion of the test and data interpretation, refer to Standard Test Method for Compressive Strength of Metal Foams in Appendix A5.

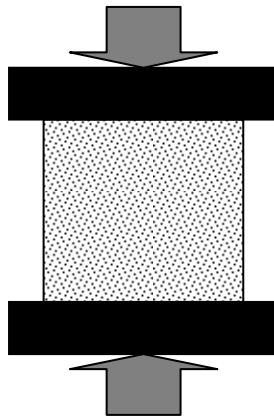


Figure 5.7. Test configuration for the compression test.

A few words of caution:

1. Whenever possible be sure that every dimension of the cuboid specimen measures greater than 10 cells. Some aluminum foams have cell sizes of the order of 10mm-20mm, therefore large specimens are sometimes necessary. Testing on specimens with fewer cells can be done if the application for the material requires SAF of a specific dimension, such as in sandwich panels.
2. The properties of SAF vary with direction. To fully characterize this material compression tests should be done in all three directions. When the loading direction is parallel to the skins (in the 2 and 3 directions), the skins should be left in place during testing if the final application will also use the foam with the skin. Removing the skins for testing will change the measured values.

5.2.2 Tension Testing

As with compression testing, the tensile properties of this material should be tested in the three orthogonal directions. ASTM C-297, designed for testing the core in sandwich panels is the appropriate test for this situation. A schematic for this test set-up is given in Figure 5.8 and the test standard similar to ASTM C-297, modified for metal foams can be found in Appendix A5.2 in “Standard Test Method for Tension Strength of Metal Foams”.

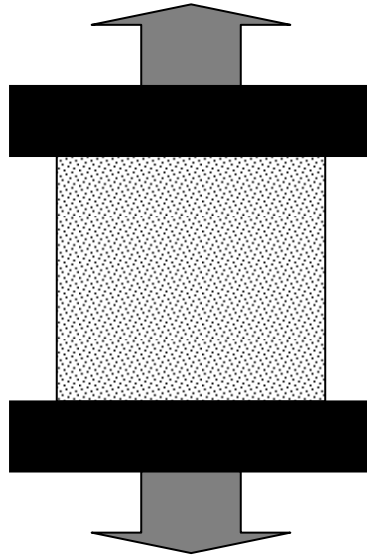


Figure 5.8. Schematic of a tensile test.

5.2.3 Shear Testing

One choice for shear testing metal foams is to use the technique laid out in ASTM C-273: Standard Test Method for Shear Properties in Flatwise Plane of Flat Sandwich Constructions or Sandwich Cores. A slightly modified version “Standard Test Method for Shear Testing of Metal Foams” can be found in Appendix A5.3. ASTM C-273 has been approved by the Department of Defence (US). The line of loading in this test is along a diagonal path from one corner of the specimen to the other (Figure 5.9a)

The test described above requires the length of the shear specimen to be at least 12 times greater than its thickness in order to ensure a state of almost pure shear in the specimen. For thick cores this can lead to unwieldy test specimens. An alternative testing arrangement is shown in Figure 5.9b and involves offsetting the loading line of the test machine so that the plates can be loaded down their center lines. In this way the state of stress is more uniform and shorter specimens can be used. All of the information outside of the test geometry in the previous standard is applicable. Other than the application of the load, the only difference is in the length of specimen required. The specimen length should be five times the thickness to avoid edge effects dominating the results.

Note: It is important that the gripping allows for dilation of the foam specimen during shearing, otherwise normal compressive stresses will be induced.

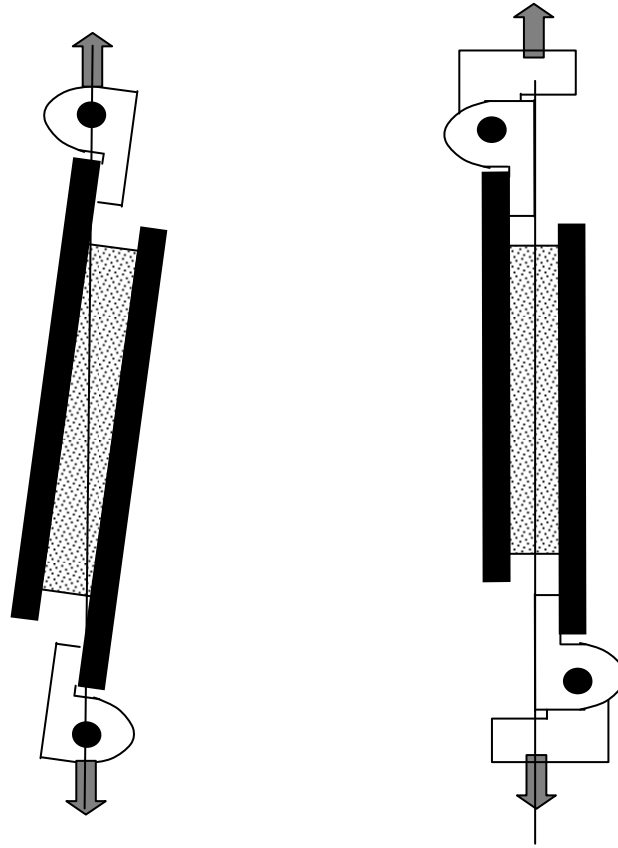
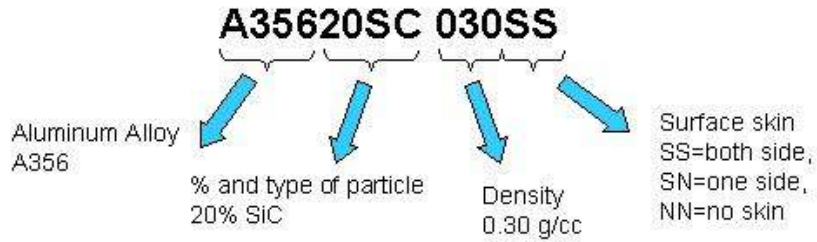


Figure 5.9. The shear set-up a) according to ASTM C 273 and b) with the loading line passing through the center of the specimen.

5.3 Mechanical Data

The following is test data for standard materials produced by Cymat. The materials are named using the following convention.



The terminology used in the data sheets is given in the diagrams in Figure 5.10.

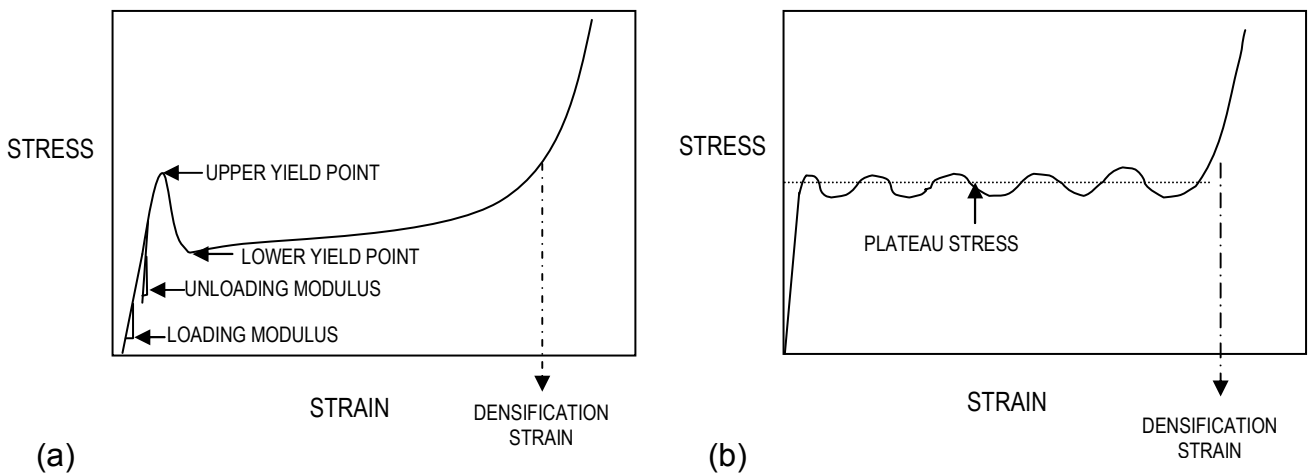


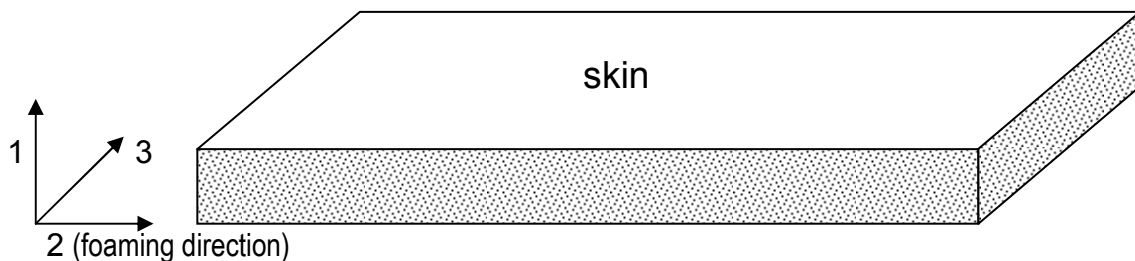
Figure 5.10. Schematic of the compressive stress-strain curves in the a) 1 direction and b) 2 and 3 directions.

A35620SC 020SS

Characteristic	Value	Unit	Characteristic	Value	Unit
Density	200	kg/m ³	Shear Strength	0.5	MPa
Compressive Strength ¹			Shear Modulus	200	MPa
• Upper Yield	1.0	MPa	Shear Failure Strain	0.2	%
• Lower Yield	0.3	MPa	Specific Energy Absorption		
Compressive Strength ²	1.2	MPa	(compression)		
Compressive Strength ³	1.6	MPa	20% strain ¹	0.6	kJ/kg
Compressive Modulus ¹			20% strain ²	0.8	kJ/kg
• Loading**	185	MPa	20% strain ³	1.2	kJ/kg
• Unloading**	230	MPa	50% strain ¹	2.3	kJ/kg
Compressive Modulus ²			50% strain ²	2.5	kJ/kg
• Loading	200	MPa	50% strain ³	3.3	kJ/kg
• Unloading	500	MPa	Volumetric Energy Absorption		
Compressive Modulus ³			(compression)		
• Loading	270	MPa	20% strain ¹	0.11	MJ/m ³
• Unloading	600	MPa	20% strain ²	0.15	MJ/m ³
Densification Strain	80	%	20% strain ³	0.23	MJ/m ³
Tensile Strength ¹	0.7	MPa	50% strain ¹	0.45	MJ/m ³
Tensile Strength ²	0.9	MPa	50% strain ²	0.50	MJ/m ³
Tensile Strength ³	1.5	MPa	50% strain ³	0.67	MJ/m ³
Tensile Modulus ¹	230	MPa	Thermal Conductivity	N/A	W/(m•°C)
Tensile Modulus ²	450	MPa	Operating Temperature	-80 → +300	°C
Tensile Modulus ³	700	MPa	Average Cell Size	7	mm
Elongation to Failure ¹	0.2	%			
Elongation to Failure ^{2,3}	0.2	%			

* Tests done with surface skin in place.

** Due to early onset of plastic deformation in compression there is a large difference between unloading and loading modulus.



Superscripts in the above table refer to direction.

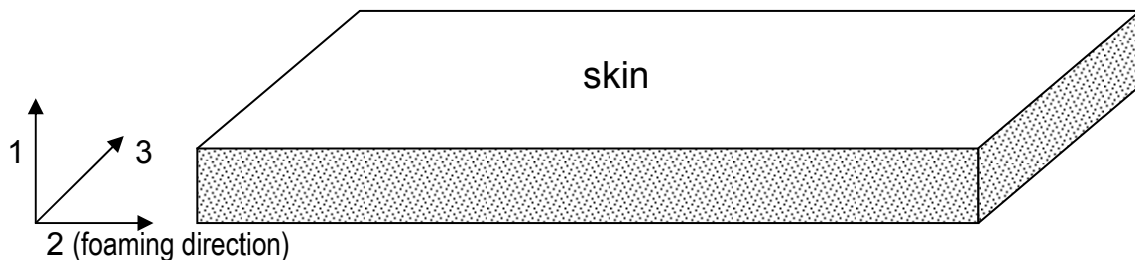
This data represents results from tests performed by Cymat and should be considered representative, although not definitive, of the properties of SAF.

A35620SC 030SS

Characteristic	Value	Unit	Characteristic	Value	Unit
Density	300	kg/m ³	Shear Strength	1.0	MPa
Compressive Strength ¹			Shear Modulus	1000	MPa
• Upper Yield	2.4	MPa	Shear Failure Strain	0.3	%
• Lower Yield	1.1	MPa	Specific Energy Absorption		
Compressive Strength ²	3.0	MPa	(compression)		
Compressive Strength ³	4.0	MPa	20% strain ¹	1.2	kJ/kg
Compressive Modulus ¹			20% strain ²	1.7	kJ/kg
• Loading**	300	MPa	20% strain ³	2.7	kJ/kg
• Unloading**	675	MPa	50% strain ¹	4.7	kJ/kg
Compressive Modulus ²			50% strain ²	5.0	kJ/kg
• Loading	460	MPa	50% strain ³	5.7	kJ/kg
• Unloading	1000	MPa	Volumetric Energy Absorption		
Compressive Modulus ³			(compression)		
• Loading	575	MPa	20% strain ¹	0.3	MJ/m ³
• Unloading	1200	MPa	20% strain ²	0.5	MJ/m ³
Densification Strain	72	%	20% strain ³	0.8	MJ/m ³
Tensile Strength ¹	2.0	MPa	50% strain ¹	1.4	MJ/m ³
Tensile Strength ²	2.5	MPa	50% strain ²	1.5	MJ/m ³
Tensile Strength ³	3.0	MPa	50% strain ³	1.7	MJ/m ³
Tensile Modulus ¹	1000	MPa	Thermal Conductivity	N/A	W/(m•°C)
Tensile Modulus ²	1100	MPa	Operating Temperature	-80 → +300	°C
Tensile Modulus ³	1200	MPa	Average Cell Size	4	mm
Elongation to Failure ¹	0.2	%			
Elongation to Failure ^{2,3}	0.4	%			

* Tests done with surface skin in place.

** Due to early onset of plastic deformation in compression there is a large difference between unloading and loading modulus.



Superscripts in the above table refer to direction.

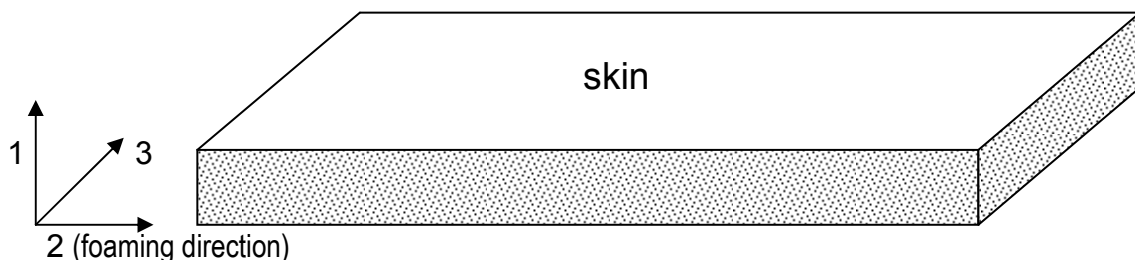
This data represents results from tests performed by Cymat and should be considered representative, although not definitive, of the properties of SAF.

A35620SC 040SS

Characteristic	Value	Unit	Characteristic	Value	Unit
Density	400	kg/m ³	Shear Strength	N/A	MPa
Compressive Strength ¹			Shear Modulus	N/A	MPa
• Upper Yield	4.0	MPa	Shear Failure Strain	N/A	%
• Lower Yield	2.0	MPa	Specific Energy Absorption		
Compressive Strength ²	5.0	MPa	(compression)		
Compressive Strength ³	6.0	MPa	20% strain ¹	1.8	kJ/kg
Compressive Modulus ¹			20% strain ²	2.5	kJ/kg
• Loading**	500	MPa	20% strain ³	2.8	kJ/kg
• Unloading**	1050	MPa	50% strain ¹	6.5	kJ/kg
Compressive Modulus ²			50% strain ²	7.3	kJ/kg
• Loading	700	MPa	50% strain ³	7.8	kJ/kg
• Unloading	1200	MPa	Volumetric Energy Absorption		
Compressive Modulus ³			(compression)		
• Loading	850	MPa	20% strain ¹	0.7	MJ/m ³
• Unloading	1300	MPa	20% strain ²	1.0	MJ/m ³
Densification Strain	68	%	20% strain ³	1.1	MJ/m ³
Tensile Strength ¹	3.2	MPa	50% strain ¹	2.6	MJ/m ³
Tensile Strength ²	3.7	MPa	50% strain ²	2.9	MJ/m ³
Tensile Strength ³	5.0	MPa	50% strain ³	3.1	MJ/m ³
Tensile Modulus ¹	1200	MPa	Thermal Conductivity	N/A	W/(m•°C)
Tensile Modulus ²	1300	MPa	Operating Temperature	-80 → +300	°C
Tensile Modulus ³	1500	MPa	Average Cell Size	3	mm
Elongation to Failure ¹	0.15	%			
Elongation to Failure ^{2,3}	0.2	%			

* Tests done with surface skin in place.

** Due to early onset of plastic deformation in compression there is a large difference between unloading and loading modulus.

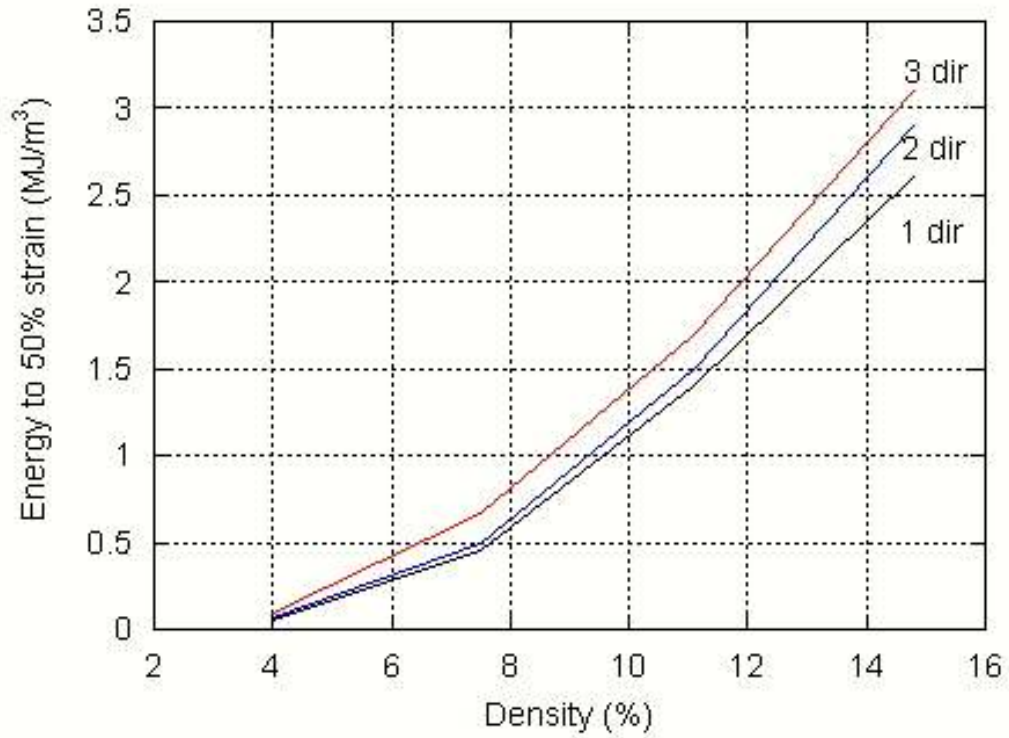


Superscripts in the above table refer to direction.

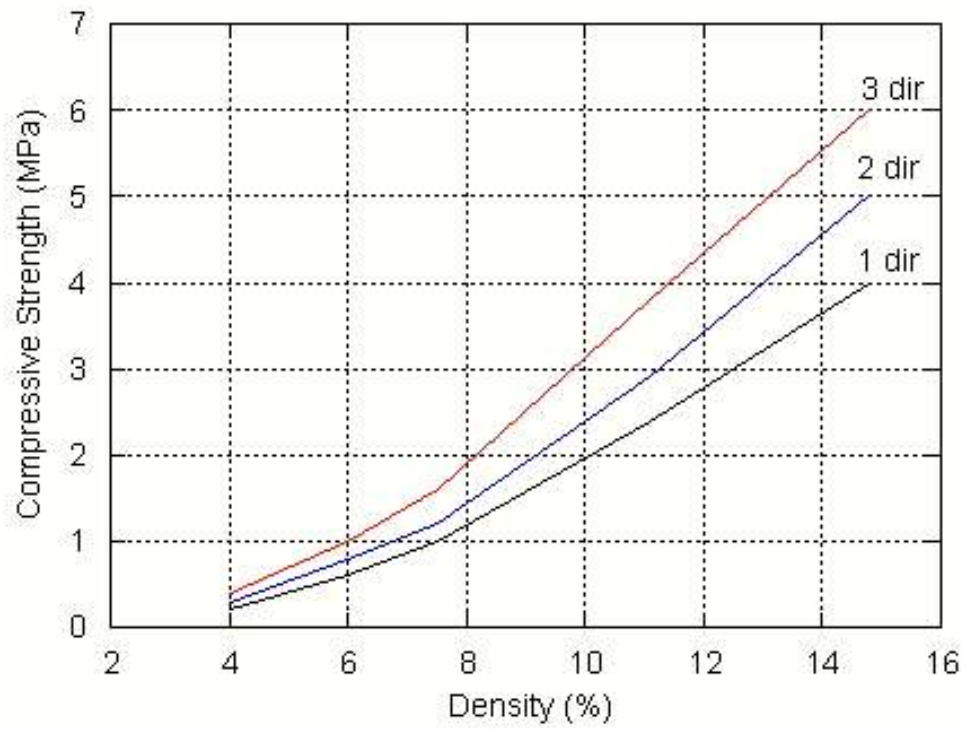
This data represents results from tests performed by Cymat and should be considered representative, although not definitive, of the properties of SAF.

On the following pages are summary plots of a number of mechanical properties of the foam plotted against density.

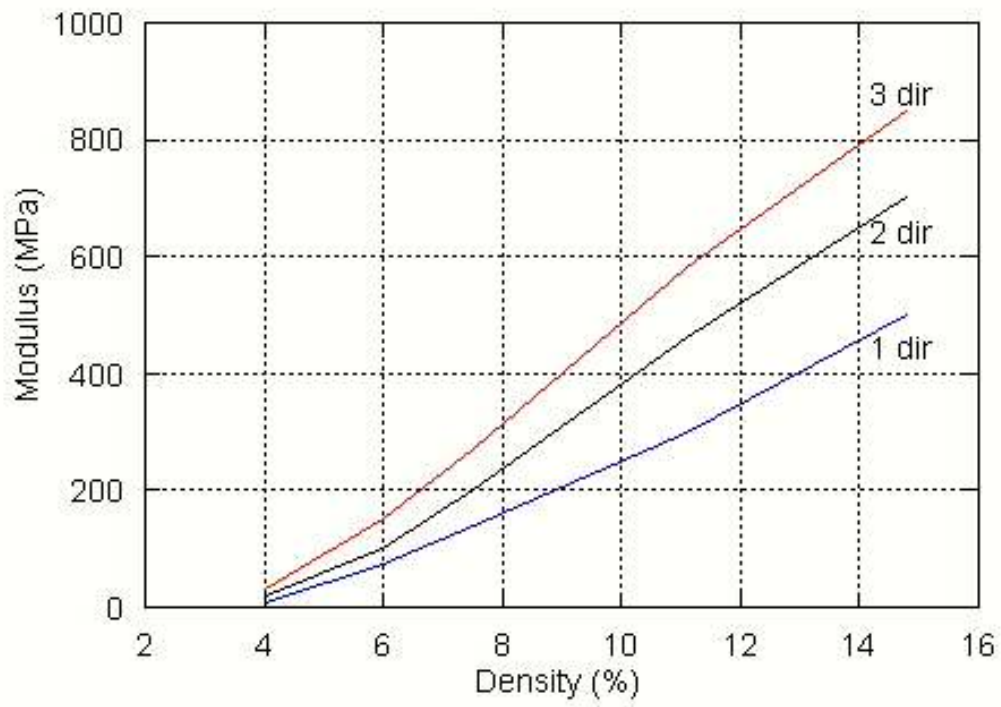
Volumetric Energy Absorption (to 50% strain)



5.3.1.1 Peak Strength (Compression)



Loading Modulus (Compression)



5.4 Acoustic Data

Testing has been done on SAF to determine the acoustic absorption of SAF. Tests were performed on two densities of foam (0.14 g/cc and 0.25 g/cc), with samples that had the surface skin removed and the cellular structure exposed.

The specimens were tested in accordance with the American Society for Testing and Materials designation ASTM C423-99a, "Standard Test Method for Sound Absorption and Sound Absorption Coefficients by the Reverberating Room Method". The tests were conducted using both A and E Mounting as described in ASTM E795-00, "Standard Practices for Mounting Tests Specimens During Absorption Tests".

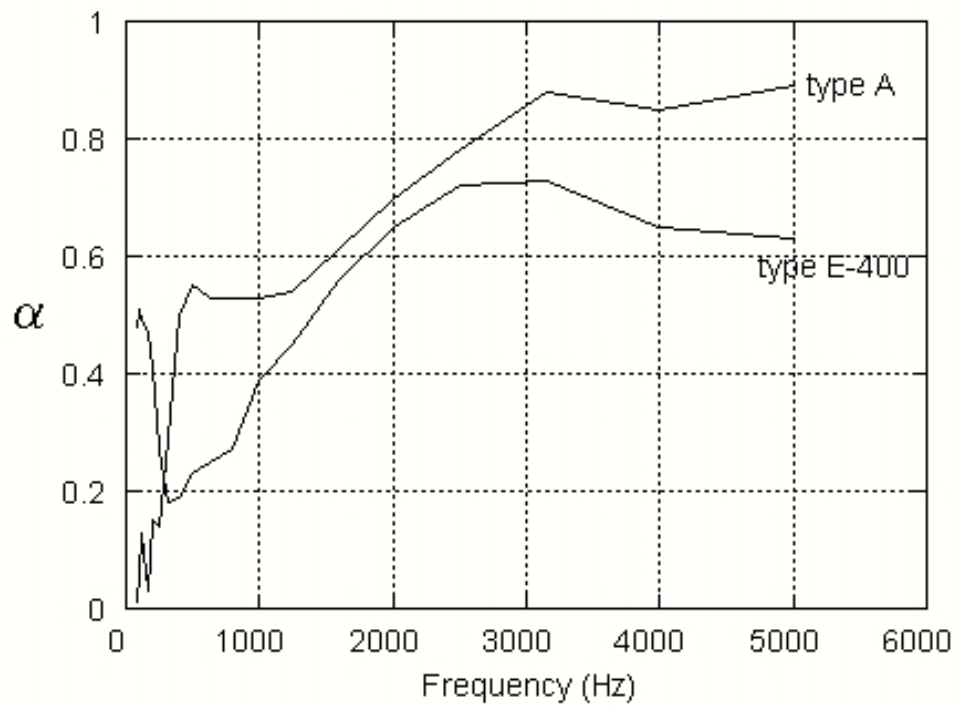
1. Type A – Panels are directly mounted to a surface
2. Type E 400 – Panels are mounted 405 mm from a surface

This test method describes the measurement of sound absorption by analyzing the decay rate of sound in a reverberation room. The difference of the decay with and without the specimen is utilized to determine the sound absorption of the specimen under test.

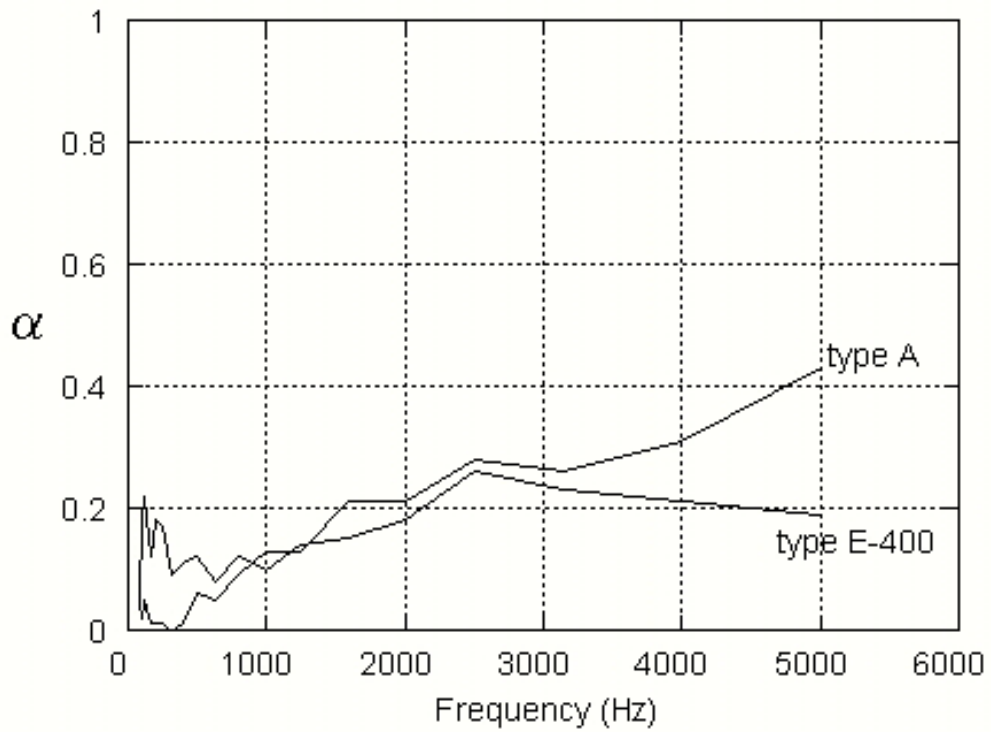
The sound absorption coefficient is ideally defined as the fraction of the randomly incident sound power absorbed by the material. The greater the coefficient, the greater the sound absorption.

The Noise Reduction Coefficient (NRC) is a single number rating obtained by taking the arithmetic average of the absorption coefficients at 250, 500, 1000, and 2000 Hz.

Density = 0.25 g/cc



Density = 0.14 g/cc



5.5 Environmental Testing

SAF has been tested under several environmental test protocols. These protocols specifically apply to architectural applications but can be used to indicate performance in other applications. Specifically, samples of SAF 12.7 mm thick with a density of 0.54 g/cc were submitted for testing as this material is typical of the product used for architectural surfacing, sold under the Alusion™ brand name.;

5.5.1 Impact Resistance

Panels were submitted for testing for impact resistance. The material passed the criteria for the “Ultra-High Impact Resistance” classification according to ASTM E2486.”

5.5.2 Transverse Load

This test, used to simulate performance under wind load conditions was carried out using a full panel supported only at the perimeter with no intermediate support was tested under transverse load conditions as per ASTM E72-05. The panel failed under a uniform load across the surface of 513 kPa. This load is approximately equal to a wind load of 100 kph.

5.5.3 Freeze/Thaw

The material was tested through 50 freeze thaw cycles as per ASTM C67 and ASTM D 3043. The material had an initial average modulus of rupture in flexural loading of 13.1 MPa. After 50 cycles of thermal shock exposure, the breaking strength in flexural loading was evaluated in the same manner, yielding a modulus of rupture of 13.4 MPa.

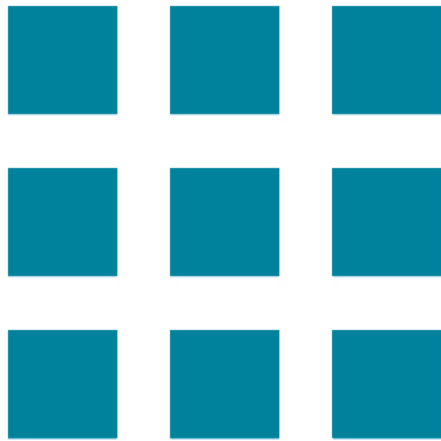
5.5.4 Corrosion

The material was tested through 1000 hours of salt fog spray as per ASTM B117 and D 3043 The material had an average modulus of rupture in flexural loading of 13.1 MPa. After 1000 hours of salt fog exposure, the breaking strength in flexural loading was evaluated in the same manner, yielding a modulus of rupture of 11.6 MPa.

For applications in which SAF will be enclosed with steel such as automotive applications, testing done on steel tubes filled with aluminum foam shows that galvanic corrosion between the foam and steel is not a problem as long as there is a seal against salt spray intrusion.

It is recommended that when SAF is used in a harsh environment that it be sealed and protected to increase its service life. Potential solutions include mechanical sealing or use of polymer adhesives or coatings.

1. Aluminum and Aluminum Alloys, ASM Special Handbook, J.R. Davis, editor, 1993.



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POST PROCESSING

6 POST PROCESSING

6.1 Cutting

SAF is made of aluminum containing a percentage of hard particles; therefore many of the techniques which work well for aluminum do not necessarily work for SAF. If you have a large amount of cutting or milling to do, please follow the advice given here.

6.1.1 Hand Held Circular Saw

- Blades made from steel will not work, use a CARBIDE tipped blade.
- Use a blade with large teeth, not a small tooth blade normally used for metals. We recommend approximately 20 teeth per blade.
- One blade will last for approximately 2000 sq. cm (300 sq. inches) (7.5 m of cutting for a sheet 2.5 cm thick).
- Push the blade through with steady even pressure. Stopping the saw blade will dull it more quickly.
- Lubricants are helpful but will generally stain or mark the foam.
- An industrial grade saw with a worm drive is preferable as it will have the power needed.
- A diamond blade is more expensive but will give a cleaner cut and will last longer.

6.1.2 Bandsaw

- Large carbide teeth
- Bi-metal will work for very short periods of time but cutting SAF will render the blade useless for cutting other materials.
- Using a water based lubricant or a wax stick will double or triple the saw blade life.
- As the blade dulls it will not cut straight.
- For large quantities use a band saw with high power at high speeds.
- For small amount a standard metal bandsaw will suffice.

6.1.3 Water Jet Cutting

The following conditions are recommended for water jet cutting

- Flow pressure of 50,000 psi
- 0.0013" orifice
- Garnet particle
- Be aware that the jet does flare approximately 0.004" for every inch of depth.

6.1.4 Milling

- Use carbide cutting tools
- Standard cutting rotation speeds
- Travel speed is faster than aluminum

6.2 Joining

6.2.1 Gluing

Architectural Panels

- For gluing architectural panels to walls, adhesives made for gluing wood paneling to walls work well. If the panels are being attached to a non-vertical surface, mechanical fasteners are also necessary.

Sandwich Panels

- Adhesives can be used to attach skins to the surface of SAF.
- Film adhesives, such as those supplied by Sarna Xiro AG, and Redux® offer the advantage of ease of use.
- Generally epoxy adhesives can be used in most situations where an adhesive is necessary.

6.2.2 Mechanical Fasteners

The following mechanical fasteners are appropriate for use with SAF:

- Wood screws with large heads, preferably used with a washer.
- Rivets can be used to attach metal skins on the foam surface and for attaching SAF to metal walls or metal studs.
- Through threaded plugs can be used to screw the foam to walls.

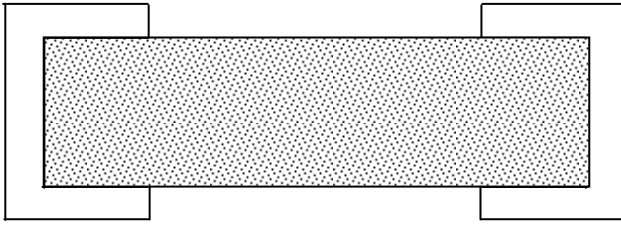
6.2.3 Welding

Welding can be used on SAF with density greater than 15% but not on lower densities. Welding SAF does require some unique techniques.

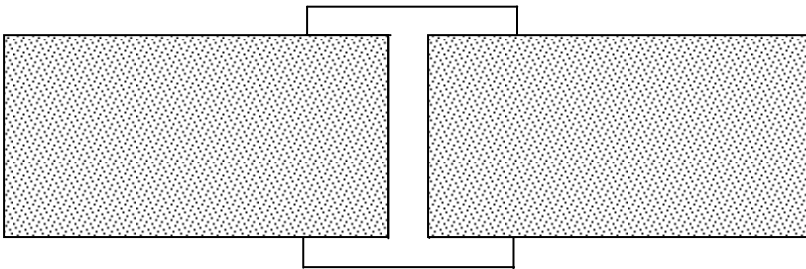
6.2.4 Brackets

Brackets can simplify attaching two sheets of SAF together as shown in Figure 6.1; or, depending on the application, they can be used to attach SAF to a wall or cover a seam. The following are standard bracket shapes and suggested uses.

C-channel



H-channel



T-channel and strips

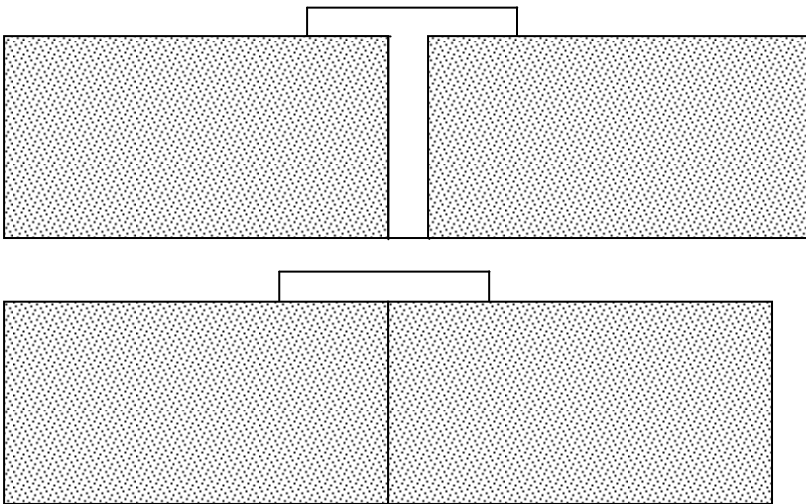


Figure 6.1. Use of brackets for connecting two sheets of SAF.

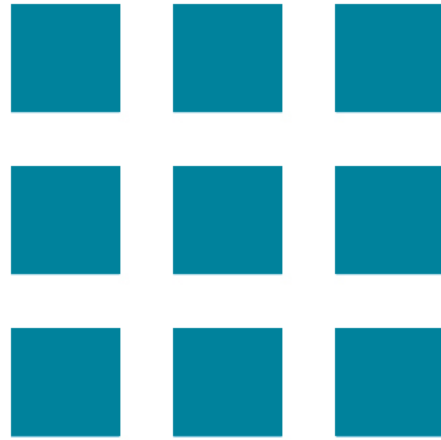
6.3 Heat Treating

The heat treatment schedule for the base aluminum alloy can be used for SAF.

6.4 Coating

SAF can be:

- Powder coated
- Coated in polymers such as a clear coat protector or lacquer
- Over-moulded with plastics to make a hybrid structure
- Painted



CYMAT

FINITE ELEMENT MODELING

7 FINITE ELEMENT MODELING

There are two approaches that can be taken in order to model systems incorporating SAF: 1) using material models which exist in commercial Finite Element (FE) packages such as LS DYNA, PAMCRASH and ABAQUS or 2) implementing a user defined material model developed specifically for aluminum foams. The choice of methods depends on the problem in question. Both will be considered here along with the sort of problems where each is applicable.

For further information and guidance on how to use these models please contact Cymat.

7.1. Existing Material Models

It is not the intention of this section to go into great detail on individual material models. These can be found in the reference books for the FEA software. Our intention is only to give an idea of what the appropriate models are and their advantages and drawbacks.

Several material models from commercial software have been used to predict the behaviour of aluminum foam in structures. One type of model has been developed for honeycomb-like materials to incorporate the anisotropic character of the material. The yield criteria for these models are a set of six criteria where each stress component of the stress tensor has a corresponding yield value associated with it. These models can also typically be used for isotropic materials. In LS-DYNA the material models are numbers 26 and 126. In both models the effects of loading in one direction have no effect on the other two orthogonal directions.

Model 75 in LS DYNA and the crushable foam model of ABAQUS are similar. These models have an elliptical yield surface defined in effective stress-hydrostatic stress space. This recognizes that unlike solid materials, foams can deform under hydrostatic stress. These models both assume that uniaxial loading in any principal direction causes insignificant deformations in the other directions.

It has been found that these models work to an acceptable level as long as the loading conditions are not very complicated and the foam is part of a structure where it plays a secondary role. Model 75 seems to capture the foam behaviour more accurately but does not include any anisotropy capability.

7.2. User Defined Models

For more complicated problems it may be advisable to use one of the material models recently developed for aluminum foam. The most widely used is the Deshpande-Fleck model for metal foams. Like the foam models discussed above, the yield surface depends on the effective stress and the hydrostatic stress. Unlike the above models the plastic Poisson's is not assumed to be zero and the load conditions in the principal directions are inter-dependent.

Details of the Deshpande-Fleck model can be found in the recommended reading list in Section 9. A general overview is given here.

The yield surface is given by:

$$\left(\frac{1}{1 + \left(\frac{\alpha}{3}\right)^2} \right) (\sigma_e^2 + \alpha^2 p^2) - Y = 0$$

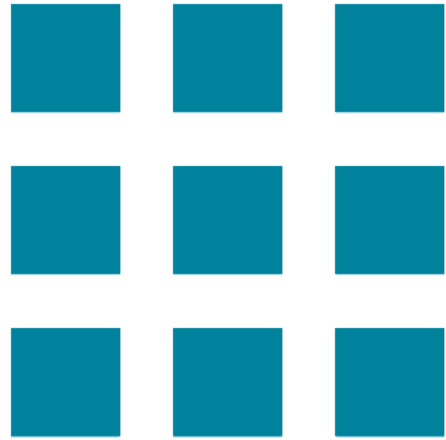
where α is a measure of the ellipticity of the yield surface. α is related to the plastic Poisson's ratio by:

$$\alpha = \frac{9(1 - 2\nu_p)}{2(1 + \nu_p)}$$

and the hardening of the material is described by:

$$Y = Y^0 + H(\epsilon_{pl})$$

The Deshpande-Fleck model has been incorporated into ABAQUS EXPLICIT and will be available in version 6.2. It is currently being implemented into LS-DYNA. For other FE software this model could be programmed as a user defined material model by a highly experienced user. One of the advantages of this model is that it requires only one uni-axial compression or hydrostatic test to calibrate it.



CYMAT

HEALTH AND SAFETY

8 HEALTH AND SAFETY

1. PRODUCT AND COMPANY IDENTIFICATION

PRODUCT NAME: Cymat Corporation – Stabilized Aluminum Foam (SAF)

PRODUCT NUMBER:

SUPPLIER: 0803301

Cymat Corporation

6320-2 Danville Road

Mississauga, ON L5T 2L7

Canada

Business tel: 905-696-9900

Fax: 905-696-9300

SYNONYMS: Metallic Foam, Aluminum Foam

APPEARANCE AND ODOUR: Grey to silver solid; odourless

USES: sandwich panels, energy management, structural enhancement

2. COMPOSITION/ INFORMATION ON INGREDIENTS

EU DIRECTIVE

NAME	CAS #	LD ₅₀	LC ₅₀	Symbol	R phases	CONC.
<u>Matrix</u> (80-90% of total volume)						
Aluminum	7429-90-5	Unknown	Unknown	None	None	>89%
Silicon	7440-21-3	Unknown	Unknown	None	None	8-13%
Iron	7439-89-6	30g/kg(oral-rat)	Unknown	None	None	0-1.0%
Copper	7440-50-8	Unknown	Unknown	None	None	0-1.0%
Manganese	7439-96-5	9000 mg/kg (oral-rat)	Unknown	None	None	0-0.5%
Magnesium	7439-95-4	Unknown	Unknown	None	None	0.1-0.8%
Titanium	7440-32-6	Unknown	Unknown	None	None	0-0.2%
Zinc	7440-66-6	Unknown	Unknown	None	None	0-1.0%

Reinforcement Phase (10-20% of total volume)

Silicon carbide	409-21-2	Unknown	Unknown	None	None	100%
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3. HAZARDS IDENTIFICATION

Not hazardous

4. FIRST AID MEASURES

In case of dust exposure:

Inhalation: In case of discomfort, remove to a ventilated area. If discomfort persists, consult a physician.

Skin contact: In case of burns with hot metal, rinse with plenty of cold water. If burn is severe, consult a physician, contact emergency services.

Eye contact: Flush eyes thoroughly with water, taking care to rinse under eyelids. If irritation persists, continue flushing for 15 minutes, rinsing from time to time under eyelids. If discomfort continues, consult a physician.

Ingestion: Not applicable

5. FIRE OR EXPLOSION HAZARD

EXTINGUISHING MEDIA: Not a fire hazard unless in particle form. Suspensions of aluminum dust in air may pose a severe explosion hazard. A potential for explosion exists for a mixture of fine and coarse particles if at least 15% to 20% of the material is finer than 44 microns (325 mesh). Buffing and polishing generate finer material than grinding, sawing and cutting. In case of aluminum fires, use a class D dry-powder extinguisher. Do not use water or halogenated extinguishing media. Molten aluminum may explode on contact with water.

HAZARDOUS COMBUSTION PRODUCTS: Not applicable

6. ACCIDENTAL RELEASE MEASURES

Recycle. Aluminum in the form of particles may be reactive and its hazardous characteristics should be determined prior to disposal.

7. HANDLING AND STORAGE

HANDLING PRECAUTIONS: Because of the risk of explosion, aluminum foam and foam scrap should be thoroughly dried prior to remelting. Use standard techniques to check metal temperature before handling. Hot aluminum does not present any color change to act as a warning. Exercise great caution, since the metal may be hot. For more information on the handling and storage of aluminum, consult the following documents published by the Aluminum Association, 900 Nineteenth St., N.W., Washington D.C., 20006:

- Guidelines for Handling Molten aluminum
- Recommendation for Storage and Handling of Aluminum Powders and Paste
- Guidelines for Handling Aluminum Fires Generated during various Aluminum Fabricating Operations

STORAGE CONDITIONS: Not applicable

8. EXPOSURE CONTROLS / PERSONAL PROTECTION

Special ventilation should be used to convey finely divided metallic dust generated by grinding, sawing etc. in order to eliminate explosion hazards. Maintain dust concentration in ventilation ducts below the lower explosive limit of 40 g/m^3 (0.04 oz/ft^3). See "National Fire Protection Association Codes":

- Code 65 "Processing and Finishing of Aluminum"
- Code 651 "Standard for the Manufacture of Aluminum and Magnesium Powder"
- Code 77 "Static Electricity".

Use an approved respirator designed for the hazard, where concentrations exceed exposure limits.

The use of both primary and secondary protective equipment is necessary when handling molten metal. Refer to "Aluminum Association" guidelines.

EXPOSURE LIMITS:

(ACGIH = American Conference of Governmental Industrial Hygienists; TLV = Threshold Limit Value; OSHA = Occupational Safety and Health Administration [USA]; PEL = Permissible Exposure Limit; TWA = Time-Weighted Average; STEL = Short Term Exposure Limit; Ceiling = Ceiling value)

	ACGIH (TLV)		OSHA (PEL)	
	TWA	STEL	TWA	Ceiling
Aluminum(total dust)	10 mg/m ³	None	15 mg/m ³	None
-Fume, powder, resp. dust	5 mg/m ³	None	5 mg/m ³	None
Silicon (total dust)	10 mg/m ³	None	15 mg/m ³	None
-Resp. dust	None	None	5 mg/m ³	None
Iron oxide (fume)	5 mg/m ³	None	10 mg/m ³	None
(dust)	None	None	10 mg/m ³	None
Copper (fume)	0.2 mg/m ³	None	0.1 mg/m ³	None
(dust)	1.0 mg/m ³	None	1.0 mg/m ³	None
Magnesium oxide (fumes)	10 mg/m ³	None	10 mg/m ³	None
-Resp. dust	None	None	5 mg/m ³	None
Titanium	None	None	None	None
Silicon carbide – total dust	10 mg/m ³	None	15 mg/m ³	None
-Resp dust	None	None	5 mg/m ³	None

9. PHYSICAL AND CHEMICAL PROPERTIES

pH: Not applicable
boiling point: Not applicable
melting point: 480-660 °C
vapour pressure: Not applicable
vapour density (air=1): Not applicable
evaporation rate: Not applicable.
relative density (water=1): 0.081-0.54
water solubility: Not applicable

odour threshold: Not applicable

flashpoint: Not applicable
autoignition temperature: Not applicable
lower flammable limit: Not applicable
higher flammable limit: Not applicable
explosive properties: Not applicable
NFPA fire code: 0
oxidizing properties: Not applicable
partition coefficient (n-octanol/water): Not applicable

10. STABILITY AND REACTIVITY

STABLE (yes/no): Yes

CONDITIONS AND MATERIAL TO AVOID: Molten aluminum may explode on contact with water. In the form of particles, may explode when mixed with halogenated acids, halogenated solvents, bromates, iodates or ammonium nitrate. Aluminum particles, on contact with copper, lead, or iron oxides, can react vigorously with release of heat if there is a source of ignition or intense heat.

HAZARDOUS DECOMPOSITION PRODUCTS: In the form of particles, aluminum reacts with water, strong basic solutions, strong acidic solutions, halogenated acids (eg. hydrofluoric acid), producing flammable hydrogen gas.

11. TOXICOLOGICAL INFORMATION

ROUTES OF EXPOSURE:

inhalation: Yes

ingestion: No

eye contact: No

skin contact: No

skin absorption: No

ACUTE EFFECTS:

Inhalation: Solid aluminum does not present an inhalation hazard. Aluminum and silicon dusts generated during use are considered nuisance particulates.

Skin contact: Skin contact with hot metal can cause burns. Open surface of foam can be abrasive.

Eye contact: Aluminum dust can irritate the eyes (mechanical abrasion).

Ingestion: Not applicable.

CHRONIC EFFECTS:

Medical conditions aggravated by exposure to the product: Not determined

Carcinogenicity / Mutagenicity / Reproductive toxicity: None of the ingredients present at concentrations equal to or greater than 0.1% are listed as a carcinogen or potential carcinogen by IARC, NTP or OSHA. (IARC=International Agency for Research on Cancer; NTP=National Toxicology Program [USA]; OSHA=Occupational Safety and Health Administration [USA])

SUPPLEMENTARY INFORMATION:

Aluminum fumes generated during welding or melting present low health risks. Welding or plasma are cutting of aluminum alloys can generate ozone, nitric oxides and ultraviolet radiation. Ozone overexposure may result in mucous membrane irritation or pulmonary discomfort. UV radiation can cause skin erythema and welders flash.

12. ECOLOGICAL INFORMATION

Aluminum and its alloys under solid form, such as ingots or manufactured items, do not present any hazard for the environment because metals are not biologically available. Aluminum can be recycled.

13. DISPOSAL CONSIDERATIONS

Recycle. Aluminum in the form of particles may be reactive and its hazardous characteristics should be determined prior to disposal. Dispose of waste in accordance with federal, provincial, or local regulations.

14. TRANSPORT INFORMATION

TDGR: Not regulated **CFR 49:** Not regulated **IMO:** Not regulated **ICAO:** Not regulated
IATA: Not regulated

(TDGR=Transport of Dangerous Goods Regs. [Canada]; CFR 49=Code of Federal Regs. [USA]; IMO=International Maritime Organization; ICAO=International Civil Aviation Organization; IATA=International Air Transport Association

15. REGULATORY INFORMATION

WHMIS CLASSIFICATION (Canada): Not controlled

EUROPEAN UNION CLASSIFICATION: Not classified

Warning symbol: None

Warning word: None

Risk phrases: None

Safety phrases: None

USA REGULATIONS:

This product contains trace amounts of lead (<0.01%), a concentration that does not meet the disclosure requirements of the "Hazard Communication Standard" (HCS) of the United States or the Canadian "Workplace Hazardous Material Information System" (WHMIS). Any process resulting in exposure to more than 0.5 mg/m³ of metal dust per day may result in a daily dose of lead of over 0.5 µg/day, the dose above which the "California Safe Drinking Water and Toxic Enforcement Act" of 1986 requires notification. Refer to the appropriate regulation notification wording guidelines. This is not considered dangerous for health according to current toxicology studies.

8.1 Section 313 Supplier Notification

This product contains no chemicals in concentrations subject to the reporting requirements of Section 313 of the Emergency Planning and Community Right-To-Know Act of 1986 (Title III of SARA) and of 40 CFR 372.

16. OTHER INFORMATION

Suppliers or plants:

Cymat Corp.
6320-2 Danville Road
Mississauga, Ontario
Canada
L5T 2L7

Telephone: 905-696-9900
Fax: 905-696-9300

Abbreviations:

WHMIS = Working hazardous material information system, CAS# = Chemical Abstracts Service Registry Number

LD₅₀ = Lethal dose 50%, LC₅₀ = Lethal concentration 50%, LCL₀ = lowest published lethal concentration.

Note to the forgoing health and safety information:

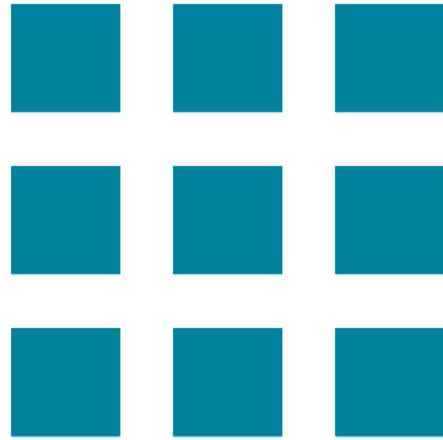
Although the information in the SDS was obtained from sources which we believe to be reliable, it cannot be guaranteed. In addition, this information may be used in a manner beyond our knowledge or control. The information is herefore provided for advice purposes only, without any representation or warranty express or implied.

Prepared by Cymat Corp.
6320-2 Danville Road
Mississauga, Ontario, Canada
L5T 2L7

Date of the previous revision: 2000/02/29

Reason for modification: Revision after three (3) years, according to WHMIS (Canada)

Reference: MSDS for F3S.zzS prepared by Alcan Toxicology Service.



CYMAT

ADDITIONAL READING

9 ADDITIONAL READING

M.F. Ashby, A. Evans, N.A. Fleck, L.J. Gibson, J.W. Hutchinson, H.N.G. Wadley:

Metal Foams - A design guide. Butterworth-Heinemann (2000), ISBN 0-7506-7219-6

J. Banhart, H. Eifert (Editors):

Metal Foams.

Proceedings of Fraunhofer USA Metal Foam Symposium, Stanton Delaware (USA), 7.-8. October 1997, MIT-Verlag, Bremen (1998), ISBN 3-9805748-5-7

J. Banhart, M.F. Ashby, N.A. Fleck (Editors):

Metal Foams and Porous Metal Structures.

Proceedings of the International Conference (MetFoam'99), Bremen (Germany), 14-16 June 1999, MIT-Verlag, Bremen (1999), ISBN 3-9805748-7-3

J. Banhart, M.F. Ashby, N.A. Fleck (Editors):

Cellular Metals and Metal Foaming Technology.

Proceedings of the 2nd International Conference (MetFoam2001), Bremen (Germany), 18-20 June 2001, MIT-Verlag, Bremen (2001), ISBN 3-935538-11-1

J. Banhart (Editor):

Metallschäume. [mostly in German]

Konferenzband zum Symposium Metallschäume, Bremen, 7.-8.3.1997, MIT-Verlag, Bremen (1997), ISBN 3-9805748-0-6

L. Gibson, M. Ashby:

Cellular Solids - Structure and Properties.

Cambridge University Press (1997), ISBN 0-521-49560-1

A.G. Hanssen:

Structural crashworthiness of aluminium foam-based components.

Thesis, University of Trondheim, June 2000.

ISBN 82-7984-102-4

W. Seeliger:

Entwicklung und Programmierung eines Materialmodells für elastoplastische Metallschäume [in German]

Thesis, University of Bremen, MIT-Verlag, Bremen (2000), ISBN 3-935538-10-3.

Massachusetts Institute of Technology:

Impact and Crashworthiness Laboratory, T. Wierzbicki, Reports 1-60.

For a more comprehensive list of journal articles written in the area of metal foams please visit www.metalfoam.net.