

## 2.2

### Industrialization of Powder-Compact Foaming Technique

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There are many different ways to manufacture cellular materials [1]. One of the available processes has become increasingly popular in the past few years and is at the stage of industrial implementation now. The method is sometimes loosely called the “powder-metallurgical route”, but the term “powder-compact foaming technique” seems more appropriate.

#### 2.2.1

##### Principles of Foam Production

The technique consists of mixing aluminum or aluminum alloy powders with appropriate foaming agents, which get entrapped by compacting this mix to a dense product called “*foamable precursor material*”. The powder mix can be compacted directly by hot pressing, conform extrusion, or powder rolling. Alternatively the pow-

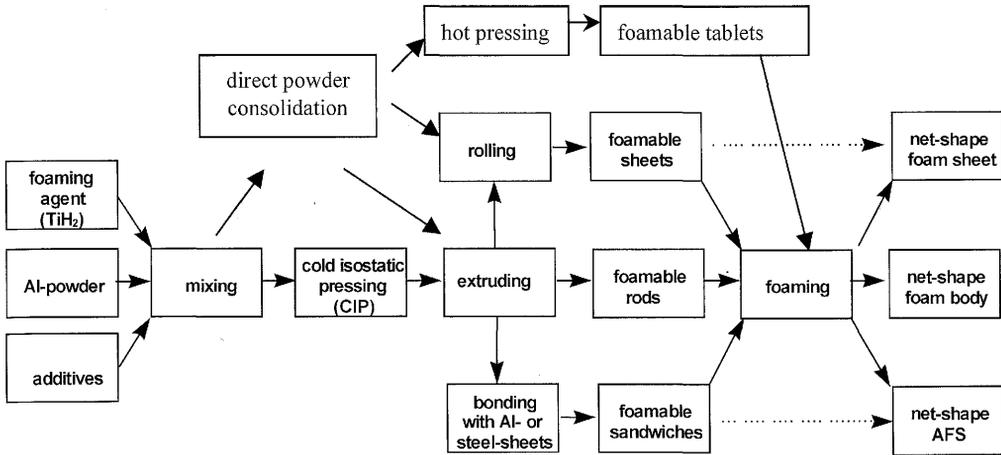


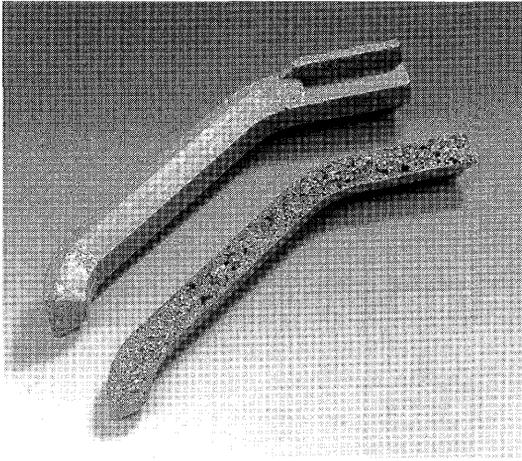
Figure 2.2-1. Foam production by powder-compact foaming technique.

der may be cold compacted for better handling in conventional extrusion or rolling (Fig. 2.2-1). Heating the precursor above its solidus temperature releases the pressure on the foaming agent allowing decomposition and formation of bubbles. After cooling a low-density foam structure of originally closed cells is obtained [2,3].

The method is not restricted to aluminum and its alloys: tin, zinc, lead, gold, and some other metals and alloys can also be foamed by choosing appropriate foaming agents and process parameters (see Section 2.1.2). The most common alloys for foaming, however, are pure aluminum or wrought alloys such as aluminum 2xxx, 6xxx, or 7xxx alloys, e.g. AA 2014, 6060, 6061, 6082, or 7075. Casting alloys such as AlSi7Mg (A356) and AlSi12 are also frequently used because of their low melting point and good foaming properties, although in principle virtually any aluminum alloy can be foamed by carefully adjusting the process parameters.

Quite complex-shaped metal foam parts can be manufactured by expanding the foam inside a mold, thus confining spatial expansion. An example for one such part is shown in Fig. 2.2-2. The part, developed in the framework of a feasibility study, is a novel pantograph horn for an electrical locomotive. This light-weight solution based on aluminum foam replaces traditional cast aluminum parts saving 30 % weight.

A nice feature of the technique is that composite structures consisting of an aluminum foam and bulk metal parts can be made without using adhesives. Examples are foam-filled aluminum sections and sandwich panels with an aluminum-foam core and metallurgically bonded steel, aluminum, or even titanium face sheets. For making such composites the foamable precursor material is first bonded to the solid section or sheet by co-extrusion or roll-cladding, after which the foamable core layer is expanded by heat treatment [4,5] (see also Section 3.3).



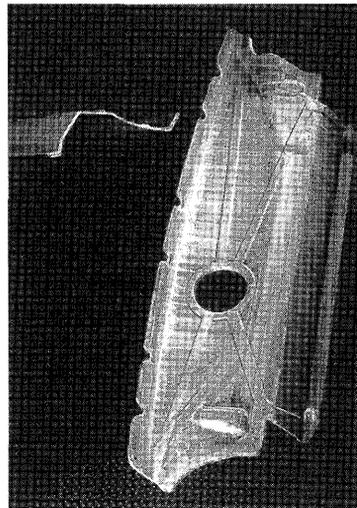
**Figure 2.2-2.** Aluminum foam part (Schunk Sintermetalltechnik, Giessen).

The advantages of the powder-compact route are obvious and are listed in Table 2.2-1. Beside the first two features already mentioned, the flexibility arising from the preparation of the precursor from powders is important. Alloys can be made simply by mixing inexpensive elementary powders. No ceramic additives are needed to stabilize the foam, in contrast to some of the melt-route foaming processes in which up to 15% silicon carbide has to be added [1,6]. However, if required, ceramic powders, metal fibers, or ceramic fibers can be added to the powder blend for special applications, such as for reinforcement or to increase wear resistance. Naturally, there are also some disadvantages that are inherent to the process. Metal powder is more expensive than bulk metal and requires effort for compaction. This rules out applications that require very cheap materials. Moreover, the size of aluminum foam parts that can be manufactured is limited by the size of the baking furnace, and is therefore smaller than for some of the competing melt-foaming processes. The largest sandwich components that have been manufactured using the powder-compact foaming technique are about  $2\text{ m} \times 1\text{ m} \times 1\text{ cm}$  in size (possibly larger in future). At LKR in Ranshofen a part of similar size was produced without face sheets (Fig. 2.2-3). True 3D-volume parts are usually not thicker than 30 cm, a limit which is difficult to shift to higher values. A large aluminum foam column produced at Fraunhofer IFAM was 1 m high and 18 cm in diameter, weighing 13 kg. In contrast, the liquid-metal route allows for making panels 15 m in length [7] and 100 cm thickness [8]. However, as these processes cannot be used for near-net-shape production and only permit very simple geometries, they are appropriate for different fields of application. Continuous foaming of long products is under investigation [9].

The middle column of Table 2.2-1 lists some of the problems that are still encountered when foaming aluminum with the powder-compact melting method but which can, in principle, be solved with further research.

**Table 2.2-1.** Characteristics of powder-compact foaming method: advantages and disadvantages that are inherent are listed together with points that are presently problematic, but can be solved in principle.

<i>Advantage</i>	<i>Problem</i>	<i>Disadvantage</i>
Net-shape foaming possible	Uniformity of pore structure still not satisfactory	Cost of powders
Composites can be manufactured	Process control must be improved	Very large volume parts difficult to make
Parts are covered by metal skin	Permeable (holes)	Coating process requires sealing
Graded porosity can be achieved	Difficult to control	
Flexibility in alloy choice		
No stabilising particles have to be added		
Ceramics and fibers can be added		



**Figure 2.2-3.** Rear wall of an automobile made of aluminum foam (LKR Ranshofen and Daimler-Chrysler AG, see chapter 7.4).

2.2.2

**Practical Aspects of Foam Production**

2.2.2.1 **Powder selection**

The appropriate selection of the raw powders with respect to purity, particle size and distribution, alloying elements, and other powder properties is essential for successful foaming. Commercial air-atomized aluminum powders were shown to

be of sufficient quality. However, powders from different manufacturers led to notable differences in foaming behavior and empirical criteria have been derived to facilitate the selection of powders. The cost of powders and the ability of a manufacturer to provide sufficient quantity with a constant quality are also crucial.

As already pointed out, alloys can be obtained in different ways. The frequently used alloy AlSi7, for example, can be either prepared by atomizing a AlSi7 melt, or by blending pure aluminum powder with 7 wt.-% silicon powder, or, in a third way, by mixing 58 % of standard AlSi12 powders with 42 % aluminum powder.

#### 2.2.2.2 Mixing

The mixing procedure should yield a homogeneous distribution of alloying elements and the foaming agent to ensure that high-quality foams with uniform pore-size distributions are obtained. Powders are mixed in batches of 500 kg at Schunk-Honsel in commercial large-scale tumbling mixers with parameters determined in technological tests. Alternatively, powder mixes can be obtained by aerodynamic mixing. For example, Alulight International GmbH Austria mixes aluminum and titanium hydride in large containers with 50–80 short pulses of pressurized nitrogen gas.

#### 2.2.2.3 Densification

Powder consolidation can be carried out by various techniques. It has to be ensured that the foaming agent is completely embedded in the metal matrix and no residual open porosity remains. One way to obtain foamable precursor material with nearly 100 % theoretical density is the combined use of cold isostatic pressing (CIP) and ram extrusion. CIP is first applied to consolidate the powder mix to billets with a relative density of 70–80 % and a mass of typically 50 kg. These billets are used in the subsequent extrusion step. Although CIPping is not absolutely necessary (powders have been filled into thin-walled aluminum cartouches and inserted into the extrusion machine without prior consolidation) it has additional advantages such as the prevention of powder contamination and powder de-mixing. The CIP billets themselves are not foamable because of their large content of residual porosity, which causes massive hydrogen losses when the material is heated. To obtain foamable material, the billets are preheated to 350 °C and extruded as rods or any other profile. For this a horizontal direct extrusion machine is used (25MN Schunk-Honsel). The extrusion machine is operated in cycles with a new billet inserted after each extrusion step. This way rather high outputs can be achieved.

Foamable material has also been manufactured by rotary continuous extrusion in the so-called *CONFORM* process by Mepura (Ranshofen) [10]. Here a rotating wheel is used to drag the powder into the consolidation chamber from which it is pulled off in radial direction as a compacted wire. Foamable wires of about 8 mm diameter were manufactured from wrought alloys containing titanium hydride.

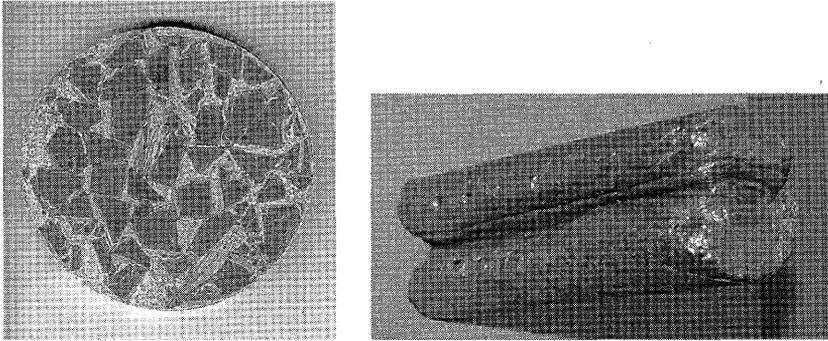
#### 2.2.2.4 Further processing of foamable material

The extruded material can be foamed as it is after consolidation or it can be worked to the required shape. By conventional rolling, foamable sheets with thicknesses down to about 2 mm are produced. Optionally, the foamable raw material can be clad to conventional sheets of metal, of steel or aluminum for example, by attaching two sheets to either side of the foamable precursor before rolling. This way a purely metallic sandwich structure is obtained. By deep drawing, the sheets and the sandwiches may be transformed to 3-D-shaped sheets for special applications. In all cases it is favorable to start from near-net-shape precursors in order to minimize foam flow [11].

#### 2.2.2.5 Foaming

Heat treatment at temperatures above the solidus temperature of the foamable matrix is necessary to produce the foam structure. The gas released by the decomposing foaming agent may form pores in the solid state but only above the solidus are bubbles formed and the matrix expands up to a maximum volume, that is to a minimum density. The density and density distribution of the growing foam can be controlled by several parameters. The foaming agent content in the precursor material is obviously important, but furnace temperatures and heating rates also have an influence [12]. The mold material, the mold shape, and the type of furnace naturally influence the heating rate and have therefore also to be considered. A careful control of the heating conditions during foaming is essential for obtaining high-quality foams. The difficulty is that the liquid foam is thermodynamically unstable and conditions change constantly during foaming. There are various intermediate stages: at first only the mold is heated directly, whereas the foamable material receives heat only indirectly via heat conduction through the mold. Initially there are merely some point contacts between the piece of foamable material in the mold and the mold walls. However, as the temperature increases, the precursor softens and assumes the contour of the mold thus increasing the transfer of heat. Moreover, heat transfer via radiation gains importance with rising temperatures. The reflectivity of the mold and precursor surfaces may change during the process and add a further variable. Finally, after foaming has started, the thermal conductivity of the precursor rapidly decreases thus reducing heat flow. As soon as the mold has been filled with foam it has to be cooled down below its solidus temperature to stabilize the foam structure. The phenomena during cooling are also quite complex and difficult to describe for reasons similar to those mentioned for the heating phase.

Typical densities of aluminum foams are in the range 0.4–0.8 g/cm<sup>3</sup> including the closed skin around the foam body. The final density of a foamed part can be simply predicted if the volume of the hollow mold and the mass of the inserted precursor material are known. The foaming mold may be loaded with several small pieces or one single piece of precursor. Choosing the latter method (which is preferred by LKR and SAS [13]) one has to take into account that each piece of the expanding precursor material has a dense aluminum oxide layer on its sur-



**Figure 2.2-4.** Left) top of aluminum foam part made by inserting various pieces of foamable material into the mold (dark figures indicate original size of the precursor pieces). Right) foam part made of two pieces of precursor without achieving bonding between the two pieces.

face, which has to be broken up by expansion of the individual foam pieces. Incomplete foaming may cause the foamed pieces to remain separated even after the foaming process (Fig. 2.2-4b). A relative movement of the foam pieces to each other helps to break up the oxide films. Fig. 2.2-4 shows an example of a successful formation of a foamed body from various pieces of the precursor and an example of failure. In the former case the location of the original individual foam pieces can still be identified from the contrast in gray scales between the various regions: darker gray identifies oxide layers of extruded surfaces, brighter gray is the new (expanded) surface. This effect is currently exploited to create foam panels and other foamed parts for making designer objects.

### 2.2.3

#### State of Commercialization

Currently the foaming technique described is still in the stage of industrial implementation. Nevertheless, a number of companies have already made commitments for a future production and are building up facilities [14]. The joint effort of *Schunk Sintermetalltechnik* (Gießen) and *Honsel GmbH&Co KG* (Meschede) is one example. Owing to their collaboration with Karmann the activities are preferentially directed towards foam and foam sandwich parts with a complex 3D geometry (see Section 3.3). *Alulight International GmbH* is another example. It is a joint venture of *SHW* (Germany) and *Eckart Austria*. The company offers aluminum foam panels in sizes up to 625 mm × 625 mm, with thickness of 8–25 mm. *Neuman Alufoam*, another Austrian company, also offers foamable precursor material (extrusions) and foamed parts.

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