

# Metal Foams—from Fundamental Research to Applications

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**Abstract.** Aluminium foam can be manufactured applying a variety of methods including direct foaming of aluminium alloy melts and advanced metal powder processing. Complex-shaped foam components and 3D-shaped sandwich panels consisting of foam cores and aluminium face sheets can be produced. A short review of the most promising techniques is given. The application potential of these materials is discussed for various fields, namely light-weight construction, crash energy absorption and thermal or sound insulation. Various case studies are presented—a lifting arm for a lorry, a crash box for a car, an impact energy absorber for a tram, a motor bracket for a car and a transverse beam for a machine. Such studies allow us to assess in which application fields aluminium forms perform well and in which direction future development should be directed.

**Keywords:** *Aluminium foam, light-weight construction, energy absorption*

## 1 Introduction

Solid metallic foams—especially the ones based on light-weight metals—are known to have many interesting combinations of different properties such as high stiffness in conjunction with very low specific weight or high compression strengths combined with good energy absorption characteristics. For this reason, the interest in these materials is still increasing. The development of metal foams is described in review articles and conference proceedings [1–5]. A dedicated web-page offers up-to-date information [6]. The present paper will be restricted to closed-cell *aluminium alloy foams* which have a good potential for market introduction. We shall first review different manufacturing routes, address the importance of fundamental research and then discuss applications.

**Table 1** Basic foaming routes for metal foams and current manufacturers for aluminium-based foams (Names given in brackets are registered trademarks.)

Direct foaming	Melt alloy make alloy foamable create gas bubbles collect foam solidify foam	Indirect foaming	Prepare foamable precursor remelt precursor create foam solidify foam
Manufacturers (products)	Cymat, Canada ( <i>SAF</i> ) Foamtech, Korea ( <i>Lasom</i> ) Hütte Kleinreichenbach (HKB), Austria ( <i>Metcomb</i> ) Shinko-Wire, Japan ( <i>Alporas</i> ) (Distributor: Gleich, Germany)	Manufacturers (products)	alm, Germany ( <i>AFS</i> ) Alulight, Austria ( <i>alulight</i> ) Gleich-IWE, Germany  Schunk, Germany

## 2 Manufacturing Methods

There are two main strategies for making aluminium foams (Table 1). Direct foaming methods start from a molten metal containing uniformly dispersed non-metallic particles into which gas is injected to create a foam. Alternatively, titanium hydride can be added to the melt, after which decomposition leads to the same effect.

Indirect foaming methods start from solid precursors which consist of an aluminium matrix containing uniformly dispersed blowing agent particles, mostly titanium or zirconium hydride. Upon melting this precursor expands and forms a foam.

### 2.1 Direct foaming of melts by gas injection

Foaming aluminium or aluminium alloys by gas injection is already in the state of commercial exploitation [7]. Silicon carbide, aluminium oxide or other ceramic particles have to be admixed to make the alloy foamable. The volume fraction of the reinforcing particles typically ranges from 10 to 20%, and the mean particle size from 5 to 20  $\mu\text{m}$ . Gas injection (usually air) is done through specially designed injectors, some of which have been described to rotate or vibrate. The resultant foam accumulates on top of the liquid from where it can be pulled off, for example, with a conveyor belt, and is then allowed to cool and solidify.

The foamed material is either used in the state it comes out of the casting machine, having a closed outer surface, or is cut into the required shape after foaming. Advantages of this foaming process include the large volume of foam which can be produced and the low densities which can be achieved. Cymat, Canada, produces its foam—called ‘*Stabilized Aluminium Foam (SAF)*’—in this way.

Quite recently the melt foaming route has been revolutionised by scientists working at the Light-metals Competence Centre (LKR) and the metallurgical plant in Kleinreichenbach (HKB), both in Austria [8]. The key point is a new concept of gas injection which leads to foams with an excellent uniformity of cell sizes. Moreover, by casting the foam into moulds, complex-shaped foamed parts with a closed outer skin can be generated. Commercial exploitation of this type of aluminium foam—called ‘*Metcomb*’—is on the way.

## 2.2 Foaming of precursors

Foamable precursor materials can be produced in various ways:

- by mixing aluminium powder and titanium hydride and compacting this mix, example, by hot pressing, extrusion or powder rolling to a dense precursor [9]. If alloy foams are required, powdered metals have to be added to the mix accordingly (*'Foam-in-Al'* or *'Alu-light' process*),
- by pre-compacting powder mixtures to billets, heating these billets to the semi-solid state and thixocasting them to shaped precursor parts [10],
- by adding blowing agent to an aluminium alloy melt after which the melt is solidified. This can be done in a die-casting machine [11] or in an ordinary crucible in which case, however, the blowing agent powders have to be pre-treated to prevent them from premature decomposition [12] (*'Formgrip'* process).
- by processing a liquid aluminium spray and allowing for deposition in the presence of a blowing agent.

In all cases a foamable precursor is obtained which can be foamed by (re-)melting. Foam making based on one of the indirect foaming methods (first in the list) is now in the stage of a small-scale commercial exploitation by the companies Schunk (Gießen, Germany), Applied Light-weight Materials, *alm* (Saarbrücken, Germany), Innovativer Werkstoffeinsatz, *iwe*, (Stralsund, Germany) and the Austrian company Alulight (Ranshofen) [6].

## 3 Fundamental Research

The history of metal foams is quite interesting and dates back to the 1940s [13]. A large number of patents were issued in a first surge from the late 1950s to the 1970s and many variants of foaming processes were proposed. Hardly anything was ever published beside the patents by the companies involved in the research. Therefore many details were forgotten and it is difficult to assess today whether all the ideas proposed then actually worked.

A second surge of scientific activities starting in the late 1980s led to the re-establishment of some of the old techniques and the discovery of new ones. At first companies like Alcan, Hydro Aluminium and Shinko Wire carried out in-house research but as the attitude towards publication seems to have changed since the 1970s some publications emerged even from the company laboratories. Fraunhofer-Institute in Bremen entered the field in 1990 after they had re-discovered an old powder-based metal foaming process. From the beginning this institute carried out and published work related to the processing of foams. However, still the work was not fundamental and processing issues were mostly solved more in a trial-and-error manner than by exploring systematically the background of technology which is typical for industry-driven research. In the mid-1990s an American research programme and shortly after a German state-funded research network started considerable fundamental research on metal foams. At that moment the situation was that fundamental research was trying to catch

up with an already existing industrial production technology. Nowadays the number of basic research publications is increasing every year. At present (mid 2005) at least 550 journal publications on metal foams exist [6].

One lively research area is that of *metal foam physics*. The task is to understand how metal foams are stabilised and how stability can be improved. The aim is to make production more reliable and to improve the properties of foamed metals. It was realised that the presence of non-metallic particles in the size range from tens of nanometres to tens of micrometers in the liquid metal is crucial for foam stability. However, the stabilisation mechanism is still under dispute. In analogy to aqueous foam physics the term *high-temperature colloid chemistry* has been coined for this research field [14].

A second important field is the investigation of *structure-property relationships*. Intuitively it seems obvious that a uniform metal foam with smooth cell walls yields the best mechanical properties. However, an actual proof is still lacking. As there is a wealth of macroscopic and morphological parameters describing a metal foam – foam density, cell size distribution, cell size orientation, cell wall curvature, cracks in cell walls – and the microstructure also plays an important role – grain size distribution, impurity level, ageing conditions – an easy and comprehensible representation of the experimental evidence is difficult to find.

Third, *modelling* of metal foam structures is important for being able to interpret the experimental data and to help design engineers to apply the material. Here modelling on various level has been attempted, starting from micro-modelling of foam structures themselves—usually by representing the actual foam by a simplified geometry—and ranging to modelling work of entire components in which the foam is represented by an effective medium.

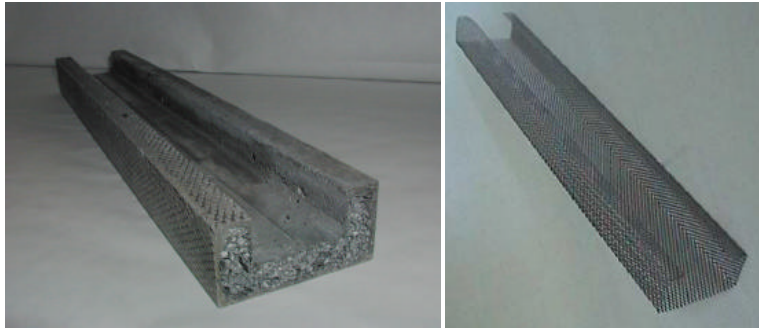
Beside these areas there are other more technological fields of interest such as joining, cutting, or coating of metal foams. Examples for fundamental research can be found in the conference proceedings of all MetFoam conferences [2–4, 15] and the two handbooks available [5, 16].

## 4 Applications

### 4.1 General concepts

Metal foams have properties which make them suitable for automotive industry which has been extremely interested in them since they were first developed. Potential applications also exist in ship building, aerospace industry and civil engineering [1]. The principal functionalities can be distinguished as follows:

- *Light-weight construction*: Aluminium foams can be used to optimise the weight-specific bending stiffness of engineering components. The bending stiffness of flat foam panels is approximately inversely related to foam density. Light-weight construction exploits the quasi-elastic and reversible part of the load-deformation curve.
- *Energy absorption*: Owing to their high porosity, aluminium foams can absorb a large quantity of mechanical energy when they are deformed, while stresses are limited to the



Courtesy of F Simancik

**Fig. 1** Aluminium foam section reinforced with a steel mesh. Right: composite, left: pre-shaped steel mesh.

compression strength of the material. Foams can therefore act as impact energy absorbers which limit accelerations in crash situations. This mode exploits the horizontal regime of irreversible deformation in the load-deformation diagram. As metal foams can have much higher collapse strengths than polymer-based foams—up to 20 MPa—they can find applications in areas not accessible to foams up to date.

- *Acoustic and thermal control:* Aluminium foams can damp vibrations and absorb sound under certain conditions. Moreover, their thermal conductivity is low while they can withstand elevated temperatures. These properties are not outstanding—polymer foams, for example, can be much better sound absorbers—but they could be useful in combination with other features of the foam. This application makes use of the internal configuration of a foam, namely the labyrinth of struts and the associated air-filled voids.

A metal foam is more likely to be competitive if, not just one, but two or even more properties are exploited. True *multi-functionality* would, example, imply that a light-weight construction reduces noise and absorbs energy in the case of a crash. In most cases a bare foam is not the optimum solution for a given engineering problem. Stiffness optimisation calls for sandwich panels with dense face sheets rather than for simple foam panels and foam can act very efficiently if filled into dense metallic sections or hollow cast parts which are reinforced by the foam filling. Alternatively, metal foams can be reinforced with a steel mesh to improve their resistance against tensile loading. This could be a competition for sandwich panels in certain situations [17]. Figure 1 shows an example of such a composite.

We shall discuss four different concepts of aluminium foam composites and corresponding applications.

#### 4.2 Light-weight construction with aluminium foam sandwich (AFS) panels

The AFS technology developed in 1994 by Fraunhofer-IFAM in Bremen and Karmann GmbH, a German car builder, is one example for the use of foams in conjunction with dense material [18]: sandwich panels consisting of a foamed metal core and two metal face sheets

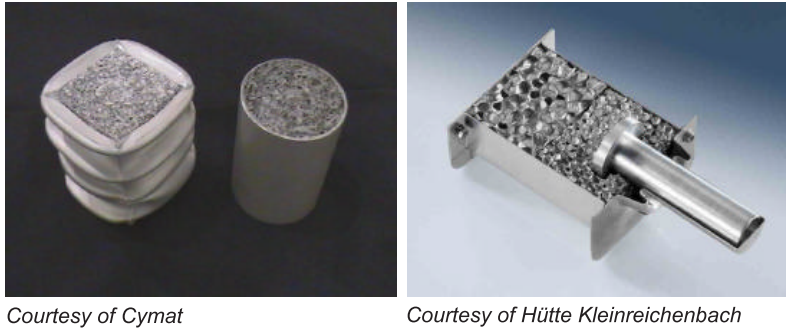
can be obtained by roll-cladding conventional aluminium sheets to a sheet of foamable precursor material manufactured from powders. The resulting composite can be shaped in an optional step, example, by deep drawing. The final heat treatment, in which only the foamable core expands and the face sheets remain dense, then leads to sandwich structures. The ability to make 3D-shaped panels and the high stiffness-to-weight ratio are a clear advantage over competing technologies such as honeycomb structures. In combination with new constructional principles AFS could replace conventional stamped steel parts in a car and lead to significant weight reductions. At the same time AFS could also reduce the number of parts in the car frame, facilitate assembly and therefore reduce costs while improving performance because such sandwich panels act as vibration dampers beside being light. AFS sandwich parts can be joined with aluminium sections by various welding techniques which facilitates their integration into the car body [19].

Recently Applied Light-weight Materials (alm)—a spin-off company of Karmann’s metal foam activities—has constructed a novel lifting arm supporting a repair platform mounted on a small lorry [20] (see Fig. 2). The objective was to increase the vertical elevation range of the platform from 20 m to 25 m while keeping the total weight of the vehicle below 3.5 tonnes. The idea was to keep operational costs low by preventing the lorry from falling into a different weight class above 3.5 tonnes implying higher insurance rates and requiring more skilled drivers. Finite-element calculations showed that a welded structure based on aluminium sections would not be able to support the weight of the platform, while a steel-based structure would be at least 80 kg to heavy. AFS panels could be successfully used to solve the problem. The solution consists of flat AFS panels which were MIG-welded together. The total weight is 105 kg which is acceptable. The vertical force at the turning point of the arm is 65 kN, the torque at the bottom part of the arm 85 kNm. The components were tested quasi-statically and in cyclic tests to up to 80,000 cycles and showed no signs of damage. There is now a small-scale production of parts for the manufacturer of the lifting system, Teupen GmbH Gronau



*Courtesy of alm*

**Fig. 2** Base of a lifting arm made from AFS sandwich panels.



**Fig. 3** (a) Prototypes of crash absorbers based on Al extrusions with a filling of Cymat aluminium foam, and (b) design example based on Metcomb aluminium foams of two different densities.

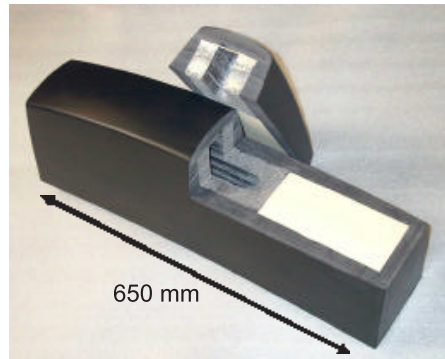
(Germany). AFS is successful in this case because it allows one to increase the lifting height of the system while keeping the weight below a certain threshold defined by legislation.

#### 4.3 Foam-filled tubes and sections

Another example for aluminium foam applications are crash absorbers. As insurance companies are enforcing safety guidelines that protect the passengers in the event of a collision and also minimize damage done to the car and the ensuing repair costs, automakers have been using the idea of a crash box to meet these standards. Such crash boxes are placed between the impact beam and the front rail of the car. They deform to absorb all the energy of a  $15 \text{ km h}^{-1}$  crash, protecting more expensive front end components in addition to the car frame. One choice for the crash box is an empty tube that plastically collapses and in doing so absorbs energy. The failure mode of the tube is to create plastic folds along the length of the tube at regular intervals. By inserting an aluminium foam core made by direct foaming of a melt into the centre of the tube energy absorption could be increased. The outer tube still folds along its length but the number of folds increases; as a result the energy absorbed by the filled tube is greater than the empty tube. Energy is also absorbed by the foam core and the total energy absorbed by the foam filled tube is greater than the sum of the individual energies of the tube and the foam. Figure 3(a) shows a deformed foam-filled tube. Studies done by FIAT and the Norwegian University of Science and Technology show that, along with the improved axial energy absorption, there is also great improvement of energy absorption in off-axis collisions. Cymat had a joint development program with Valeo to design a crash box for implementation in Valeo's front-end module systems. A slightly different design concept is shown in Fig. 3(b) where foams of two different densities are used to fine-tune the deformation curve of the absorber.

#### 4.4 Metal foams as reinforcement of polymer structures

Crash absorbers are also required for rail-based vehicles, example, trams (railcars) [21]. Again, the driver for technological innovation is safety. Trams must have an underride pro-



Courtesy of Hübner, Schunk, Siemens

**Fig. 4** Crash energy absorber for a tram built for the COMBINO vehicle system.

tection which prevents pedestrians hit by the tram to be dragged under the vehicle. This and other consideration sets certain design rules which have to be obeyed. At the same time, effective crash protection for collisions with heavier objects such as, example, cars, is required. As mounting space is very limited the use of aluminium foam can be useful. A collaboration of three companies (the tram manufacturer Siemens, the manufacturer of the crash absorber Hübner, and the metal foam producer Schunk Sintermetalltechnik, all Germany) developed the crash system shown in Fig. 4 for the modular tram concept COMBINO<sup>®</sup> which allows to realise customer-given design requirements with components based on the same chassis. The Al foam core was made by foaming precursors obtained by extruding powder mixtures and embedding the foam into a rubber shell. The crash absorbers are now being produced in quantities of hundreds and are also sold to other tram manufacturers and operators for refurbishment.

#### 4.5 Aluminium foams as cores for castings

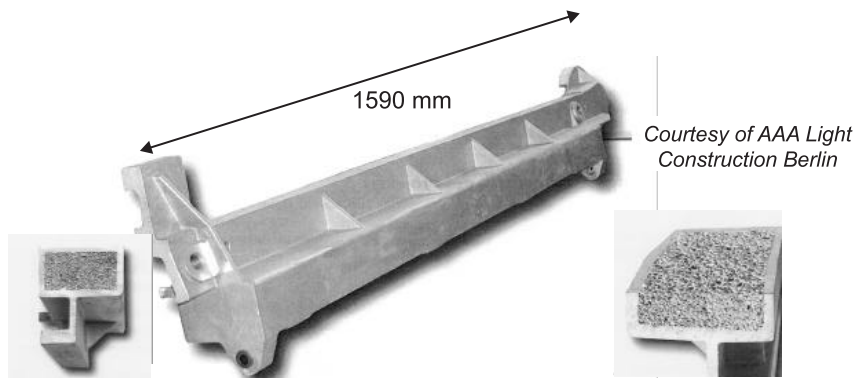
Yet another application makes use of the beneficial properties of Al foam inside a dense aluminium shell both during manufacture and in use after. One starts from a shaped part of aluminium *Metcomb* or *Alulight* foam (indirect or direct foaming). The parts have dense outer skins and can therefore be used as cores in low-pressure die-casting during which composites consisting of a cast outer surface and a light-weight inner core are formed [8, 22, 23]. Such composites have advantageous service properties such as higher stiffness and improved damping compared to the empty hollow parts while their weights are only marginally higher. LKR (Austria) and the German car maker BMW have jointly designed an engine mounting bracket based on such composites (see Fig. 5). The produced parts show no noticeable infiltration of the *Metcomb* core itself by the melt during casting. It can be loaded with the high weight of a car engine and absorbs mechanical vibrations by internal dissipation into thermal energy. Stiffness is enhanced and, as fracture toughness of such composites is high, these parts also increase safety in crash situations.





*Courtesy of LKR*

**Fig. 5** Prototype of a BMW engine mounting bracket manufactured by LKR Ranshofen. From left: empty casting, composite part consisting of foam core and cast shell, and section through composite part.



*Courtesy of AAA Light Construction Berlin*

**Fig. 6** Transverse beam of a machine. Two insets show cross sections in different direction of the beam.

Another example for such applications is given in Fig. 6. Here, an Alporas aluminium foam core was processed to a composite part in which the foam is completely embedded in a dense skin. Sand casting was used for manufacture. The skin is made from a AlZn10Si8Mg alloy, whereas the foam core consists of the typical AlCa1.5Ti1.5 alloy used by Shiko Wire Co. for foaming. The part is designed such that vibration frequencies up to 370 Hz are damped by internal friction and/or interfacial slip between core and skin. Seven hundred machines have been equipped with this composite part up to now. Noise damping levels up to 60% in the frequency range mentioned have been achieved. Costs for the part are only marginally higher than costs for the traditional beam cast with a sand core. Therefore, the future looks bright for this type of application.

## 5 Challenges

Although the development of metallic foams looks back on a long history none of the processes available nowadays and in the past has been brought to a level of sophistication comparable with that of, example, polymeric foams. It is obvious that there are difficulties in finding applications for metallic foams outside niche markets. Deficiencies of the various metal foaming techniques can be found on many levels, namely,

- *Lack of understanding of the basic mechanisms* of metal foaming: Knowledge is still speculative and some points remain unclear. Example, what is the reason for the existence of a critical cell wall thickness?
- *Insufficient ability to make foams of a constant quality* with pre-defined parameters, that is, the lack of control of structure and morphology. Limited stability of emerging metal foams is one reason for these problems,
- *The interrelationship between morphology and structure* on the one hand, and mechanical (or other) *properties* on the other is not sufficiently understood,
- *Physical properties of foams are not good enough*: There seems to be still some potential for an improvement of properties by optimising foaming processes and materials selection,
- *Knowledge of foam properties is insufficient*: further characterisation of properties is necessary,
- *Transfer of research results to construction engineers not sufficient*: Databases and design guidelines for metallic foams have to be created and disseminated,
- *Foams are still too expensive*: Mass production will lead to lower prices but metal foam will never be a really cheap material. Therefore, the selection of applications where the specific properties of foams are fully exploited is indispensable. Because this search cannot be done without a detailed knowledge of the properties of foams and of the limits of foaming processes design engineers will not start such a search: a classical vicious circle.

## 6 Conclusion

A number of new metal foaming technologies have been developed in the past decade which now offer a wide range of different forms of this exciting material. Compared to early developments in the 1950s to 1970s the quality of metal foam has been improved and the possibilities for making composites widened. With some first applications already on the road it seems quite realistic that aluminium foams will find an even wider use very soon in cars, ships, aircrafts or even spacecrafts.

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## References

- [1] Banhart J, Manufacture, characterisation and application of cellular metals and metallic foams, *Prog. Mater. Sci.*, 2001, Vol. 46, 559–632.
- [2] Banhart J, Ashby MF, Fleck NA, Eds., *Metal Foams and Porous Metal Structures*, MIT-Verlag, Bremen, 1999.
- [3] Banhart J, Ashby MF, Fleck NA, Eds., *Cellular Metals and Metal Foaming Technology*, MIT-Verlag, Bremen, 2001.
- [4] Banhart J, Fleck NA, Mortensen A, Eds., *Cellular Metals: Manufacture, Properties, Applications*, MIT-Verlag, Berlin, 2003.
- [5] Degischer HP, Kriszt B, Eds., *Handbook of Cellular Metals*, Wiley-VCH, Weinheim, 2002.
- [6] www.metalfoam.net
- [7] Harte A-M, Nichol S, in Ref. [3], p. 49.
- [8] Leitmeier D, Degischer HP, Flankl HJ, Development of a foaming process for particulate reinforced aluminum melts, *Adv. Eng. Mat.*, 2002, Vol. 4, 735–740.
- [9] Baumgärtner F, Duarte I, Banhart J, Industrialisation of P/M foaming process, *Adv. Eng. Mat.*, 2000, Vol. 2, 168–174.
- [10] Stanzick H, Wichmann M, Weise J, Banhart J, Helfen L, Baumbach T, Process control in aluminium foam production using real-time X-ray radioscopy, *Adv. Eng. Mat.*, 2000, Vol. 4, 814–823.
- [11] Melzer A, Banhart J, Baumeister Weber JM, German Patent 19813176.
- [12] Gergely V, Clyne TW, The FORMGRIP process: Foaming of reinforced metals by gas release in precursors, *Adv. Eng. Mat.*, 2000, Vol. 2, 175–178.
- [13] Banhart J, Weaire D, *Physics Today*, 2002, 55, 37–42.
- [14] Babcsán N, Banhart J, in *Colloidal Particles at Liquid Interfaces*, Binks BP, Horozov TS, Eds., Cambridge University Press (in press).
- [15] Proceedings of Metfoam2005, Kyoto (Japan), 21–23 September 2005 (in preparation).
- [16] Ashby MF, Evans A, Fleck NA, Gibson LJ, Hutchinson JW, Wadley HNG, *Metal foams – a design guide*, Butterworth-Heinemann, Boston, 2000.
- [17] Jerz J, Simancik F, Bortel M, Kubo S, Kovacik J, in Ref. [4], p. 43.
- [18] Baumeister J, Banhart J, Weber M, German Patent 44 26 627.
- [19] Banhart J, Seeliger W, Beichelt C, in Ref. [5], p. 113.
- [20] Seeliger W, in Ref. [4], p. 5.
- [21] Geyer KE, in Ref. [3], p. 31 and Ref. [4], p. 25.
- [22] Heinrich F, Körner C, Blenk M, Singer RF, in Ref. [3], p. 147.
- [23] Brunnbauer M, Körner C, Singer RF, in Ref [4], p. 187.