

Title

Alternative Starting Materials for the Production of Aluminium Foam by the Powder Metallurgical Process

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Abstract

In the past it has already been proven that aluminium foam is a construction material appropriate for numerous applications. Especially in domains such as machine tool manufacture and vehicle construction the combination of lightweight construction and vibration damping is of great importance and aluminium foam can unfold its full potential.

The widespread use of aluminium foam is still hampered by the high production costs resulting from the costly production process and from expensive starting materials. The present work focuses on studies on alternative, cheaper starting materials.

The results of current investigations follow the idea aluminium chips may be successfully used as base material instead of atomised powders, without negatively influencing the macroscopic foam structure. It could also be proven that good foaming rates can be achieved with calcium carbonate as foaming agent for aluminium.

That means that already in the near future series production of aluminium foams by the powder metallurgical process (PM process) based on recycling materials such as aluminium chips will become possible. Since sorted aluminium chips cost less than 1 €/kg, and calcium carbonate costs only a fraction of titanium hydride, a distinct cost reduction for aluminium foam, and the lowering of the inhibition threshold for its application should be possible.

Further studies are required to examine the static and dynamic properties of the foams and to compare them with the properties of conventional aluminium foams.

Keywords

Aluminium foam, powder metallurgical process, aluminium chips, titanium hydride, calcium carbonate

1. Introduction

Aluminium foam belongs to the group of cellular metals and got great application potential especially in the fields of lightweight construction, vibration damping and crash absorption. With respect to other materials, aluminium foam has some particular qualities, such as low density and high energy absorption capacity.

Especially in the domain of machine tool manufacture the combination of these two properties is of special interest. The stringent requirement to reduce the primary processing and non-productive times and to continuously improve the workpiece quality require further technological and material developments. A possible approach could be the combination of lightweight structures and material lightweight construction using steel coated aluminium foam sandwiches instead of massive steel components. Due to distinctly higher moments of inertia, such material composites finally result in flexural strengths many times higher than those of steel sheets with equal mass. Prototype applications as well as already existing series applications underline the advantages of this approach [1-3].

At present, the high production costs are disadvantageous for the application of aluminium foam – and in this context the materials used are a non-negligible cost factor. In order to be able to realize a widespread market introduction of the material aluminium foam, significant cost reduction is necessary. Current R&D projects of leading research facilities and companies focus on this topic.

Approaches for a significant cost reduction consist in the improvement of the manufacturing techniques and technologies, and in the use of cheap starting materials. The results presented here refer to studies with respect to the use of cheap alternative starting materials and foaming agents.

2. Production of aluminium foam by the powder metallurgical process

The production of aluminium foam by the PM process is carried out in several steps. Roughly, these steps are the following: Mixing of the starting materials (metal and foaming agent powders), compacting, e.g. by extrusion, and heat treatment (foaming) [2].

As starting materials for the aluminium foam production atomised aluminium powder and titanium hydride powder is used. For customary aluminium alloys and purchase quantities of a few tons, the costs are at present about 8 €/kg. The costs of the foaming agent are a multiple of those of the metallic basic alloy. In Germany one kilogram of TiH_2 costs about 400 € at present. Even if the foaming agent proportion is only 0.8 percent by weight in the foamable aluminium, the foaming agent adds up to about 3 €/kg in the powder mixture. These prices lead to a market price of almost 15 €/kg for the precursor material.

In order to successfully attain a cost reduction for the material aluminium foam several approaches exist based upon the use of alternative metallic materials such as chips, the reduction of the foaming agent proportion and the substitution of the expensive foaming agent TiH_2 .

3. Studies on the use of aluminium chips

The substitution of the expensive atomised aluminium powder by cheaper starting materials (e.g. chips) is a good starting point for drastically lowering the material cost proportion of the aluminium foam. That's why studies of the Fraunhofer IWU focused on this subject. Sorted milling chips were ground in a "Chip-Breaker" developed for this purpose. The technologies that were used at that time exclusively on the laboratory scale only proved the general feasibility. No industrial solution could be developed until now.

The "Chip-Breaker" is based upon the basic principle of a cross flow shredder and was developed together with the project partner Anlagenbau Umwelt + Technik Chemnitz GmbH. In an inerted atmosphere, two cen-

trally driven and speed controlled steel chains are turning in a container as flexible beating elements. They are breaking any existing structure and transform the initial material into granulate material or powder, respectively. In this case the fracturing effect is based upon three different principles:

- friction of the particles among each other,
- impact energy of the chain links and
- friction of the particles at the container wall.

A final automatic sieving and dust removal procedure ensures the required defined grain size distribution.

In a series of experiments the parameters influencing the degree of fracturing the chips has been examined. The experiments were designed and carried out according to the methods of DoE ⁽¹⁾. A rotatable central composite and non-orthogonal design for three variables (20 experimental points, $\alpha = 1.682$, single execution) [4] has been used. As variables the quantity of chips, the fracturing time, and the chain frequency were determined. As target parameter the D_{50} value ⁽²⁾ of the fractionated chip mixtures (response parameter) was chosen.

The chip fractions produced in the context of the experimental programme were analysed and evaluated by means of a sieve system. The evaluation resulted in the following reduced and transformed model equation, for which an adequacy of 95 % for the experimental space was determined:

$$D_{50} \approx 4.78 - 0.03 \cdot M - 0.02 \cdot Z - 0.12 \cdot F + 0.002 \cdot M^2 + 0.001 \cdot F^2 - 0.001 \cdot M \cdot F. \quad (1)$$

The produced fractionated chips can be processed like the aluminium powders, i.e. they can be mixed with the foaming agent and subsequently be densified.

Foaming experiments with the foamable semifinished aluminium product made of the chip material have been done. In a reproducible manner, volume increases by a factor of greater than three were found. This corresponds to an aluminium foam density of about 0.7 g/cm^3 , as it is also typical for aluminium foams on powder basis. The two microsections of aluminium foams based on chips and powder (**fig. 1**) do not show significant differences in the structure. This indicates that chips evidently are a good substitution material for powder in the aluminium foam production by the PM process.



a) Chip basis

b) Powder basis

Fig. 1: Aluminium foams made of different initial materials.

⁽¹⁾ ... Design of Experiments

⁽²⁾ ... Average grain size

4. Studies on the use of an alternative foaming agent

The substitution of the high-priced foaming agent TiH_2 is another approach for lowering the aluminium foam costs. From the melt-metallurgical foam production it is known that CaCO_3 is well appropriate as gas-releasing foaming agent. With respect to the standard foaming agent TiH_2 , these foams have better processing properties. The process can be easier controlled because the resulting pore structure in the molten state is significantly more stable. Additionally, a distinct reduction of the melting agent costs is possible [5-7].

The goal of the experiments presented below was to check the appropriateness of CaCO_3 as foaming agent for the powder metallurgical foam production. For this purpose the foaming agents calcium carbonate (CaCO_3) and titanium hydride (TiH_2) were mixed in different ratios with aluminium powder (AlMg1Si0.5). The experiments were based upon a unified rotatable central composite design for two variables. In this way the quantified influences of the foaming agent onto the foaming process could be determined with high confidence level. The examined response parameters were the mean foaming rate (volume increase in the foaming process) and the ratio of the mean pore diameter to the mean foaming rate.

TiH_2 ($D_{50} = 54 \mu\text{m}$), CaF_2 coated CaCO_3 ($D_{50} = 3 \mu\text{m}$), and uncoated CaCO_3 ($D_{50} = 40 \mu\text{m}$) were used as foaming agent powders. As base alloy AlMg1Si0.5 ($< 160 \mu\text{m}$) has been used.

The influence of the type of foaming agents and their mixing ratios, respectively, on the maximum volume expansion (foaming rate) was also used in the context of a design of experiments. A rotatable central composite and non-orthogonal design for three variables (13 experimental points, $\alpha = 1,414$, single execution) [4] was used. For the experimental design the foaming agents TiH_2 and CaF_2 coated CaCO_3 were used. For comparison samples with uncoated CaCO_3 have been produced as well, but they haven't been part of the design of experiments.

The production of the foamable samples was carried out by the powder metallurgical foaming process. In order to determine the foaming rate pieces of each billet were cut out and foamed to the maximum volume.

Light-microscopy examinations of the foamable aluminium samples showed that the titanium hydride particles were evenly distributed in the precursor material. The coated CaCO_3 has mostly been found in agglomerated, lamellar shape (**fig. 2**). This indicates that the powder mixing process did not proceed optimally. In contrast, the samples with uncoated CaCO_3 didn't show any agglomerates and textures.

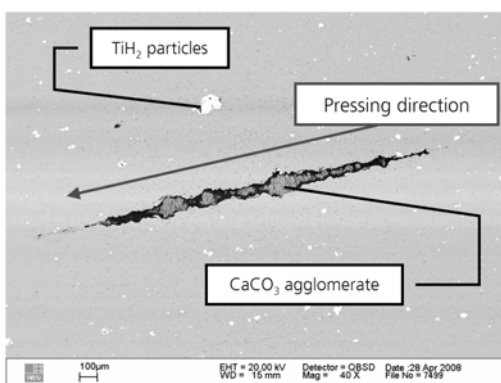


Fig. 2: Foaming agent inclusions in the foamable aluminium, SEM photograph.

By the use of uncoated CaCO_3 (foaming rate 4.4) similarly high foaming rates compared to TiH_2 (foaming rate 4.1) have been attained. Only the coated CaCO_3 seems not appropriate as foaming agent (foaming rate 2.5). Probably the CaF_2 coating impeded the release of a sufficiently high gas amount.

With a combination of the foaming agents, a significant increase of the foaming rate has been reached. Additionally, the use of CaCO_3 led to a significant stabilisation of the foam structure during the foaming process. Gergely [7] already described this effect for foam production by the FOAMCARP process.

Again, the results were evaluated according to the methods of the design of experiments. With an adequacy of 95 % the following reduced and transformed model equation applies:

$$\overline{\text{FR}} \approx 2.55 + 0.99 \cdot C_{\text{CaCO}_3} + 5.13 \cdot C_{\text{TiH}_2} . \quad (2)$$

In Fig. 3 the determined model has been illustrated. According to the model an average foaming rate of nine is expected for 1.7 weight percent CaCO_3 and 0.9 weight percent TiH_2 . It also becomes clear that already low amounts of 0.1 weight percent TiH_2 in combination with CaCO_3 are sufficient to set foaming rates of greater than four.

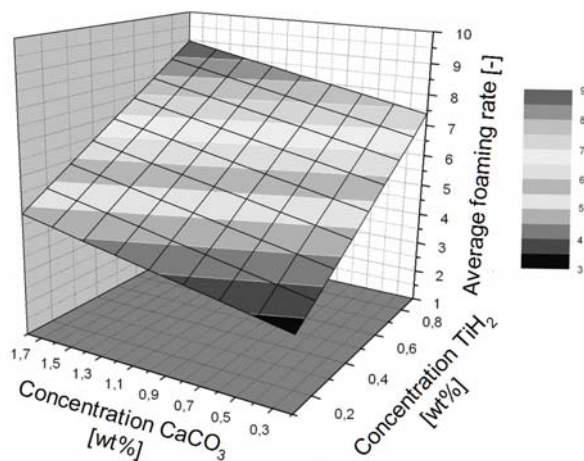
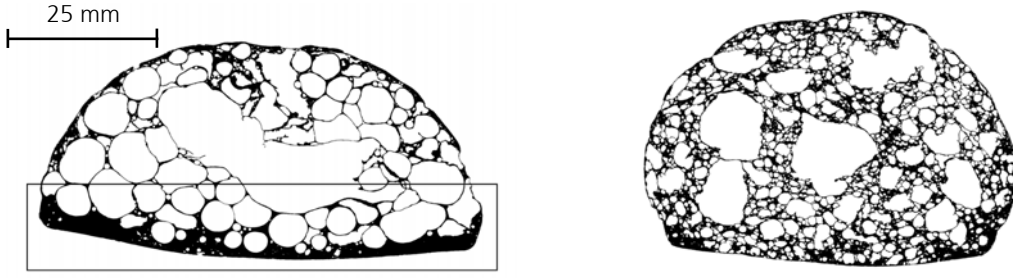


Fig. 3: Model of the estimated mean foaming rates.

For comparison of the pore structures foamed samples were analysed by image analysis to determine the mean pore diameters. Besides the already proven increase of the maximum foaming rates, the combination of CaCO_3 with TiH_2 also leads to significantly finer pore structure at the foaming maximum and also to a decreased drainage in the sample (**fig. 4**). The pore structure of the CaCO_3 -foamed samples was partially disturbed by individual large pores. The source of which could be traced back to the CaCO_3 agglomerates found in the precursor material.



a) Significant drainage (1 weight percent TiH_2) b) Low drainage (1 weight percent CaCO_3)

Fig. 4: Drainage behaviour and pore aggregation in dependence of the used foaming agent.

The evaluation of the designed experiment for the response parameter $\bar{d}_p / \overline{\text{FR}}$ resulted in the following adequate, reduced and transformed regression polynomial (adequacy 95 %):

$$\bar{d}_p / \overline{\text{FR}} \approx 0.55 - 0.22 \cdot C_{\text{CaCO}_3} - 0.42 \cdot C_{\text{TiH}_2} + 0.22 \cdot C_{\text{CaCO}_3} \cdot C_{\text{TiH}_2} \quad (3)$$

By means of the model (**fig. 5**) it can be deduced that the ratio of the mean pore sizes to the obtained foaming rate becomes significantly smaller with increasing CaCO_3 . If, at the same time, the model of the attainable foaming rates (**fig. 3**) is taken into account, it becomes evident that in spite of increasing foaming rates the model value significantly decreases with increasing CaCO_3 addition. Hence one can deduce that the increased foaming rate is not the result of larger pores but of a significantly higher number of pores. That is possible because of the already described stabilisation of the melt by the CaCO_3 and also by the great number of added very fine foaming agent particles serving as growth nuclei for the pores.

The use of CaCO_3 in combination with TiH_2 or as unique foaming agent, respectively, leads to a significant increase in the foam stability during the heat treatment process. This behaviour has been analysed in further experiments based on samples exclusively made for this experimental series by a PM process. It has been recognised that the use of CaCO_3 delays the foaming start compared to samples containing TiH_2 . Higher decomposition temperatures of the carbonate will probably be the reason for this effect.

Against the description above the maximum foaming rate for samples have been higher than those of the previously described experimental (TiH_2 - foaming rate 3.7; CaCO_3 foaming rate 5.7). This increase can very likely be explained by the modified geometry of the precursor material ($20 \times 5 \text{ mm}^2$). The surface volume ratio of the flat material used is significantly more favourable with respect to the heat treatment than the previously used round material (diameter 22 mm). The faster heating of the precursor material caused significant increases of the foaming rates.

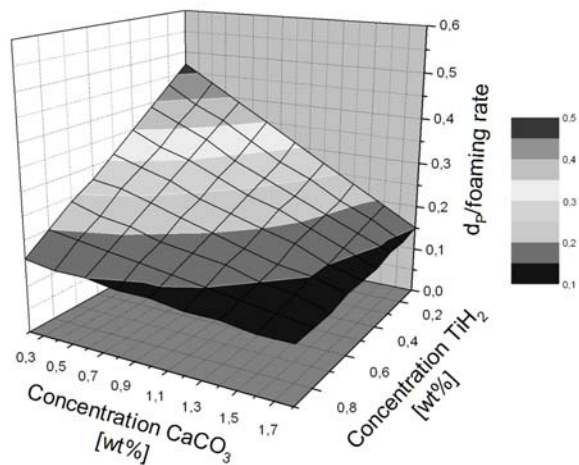


Fig 5: Model for the response parameter $\bar{d}_p / \overline{FR}$.

Comparing the volume changes in dependence of the time it is obvious that calcium carbonate leads to a significant stabilisation of the foam structure during the foaming process (**fig. 6**). The foam body remained 3 times longer at more than 80 % of the maximum foaming rate than in case of TiH_2 foamed aluminium. The foam collapse after the foaming maximum has been distinctly retarded and much slower. While the TiH_2 -foamed aluminium almost came back to the initial density after 15 min, the $CaCO_3$ -foamed aluminium was still about 60 % of the maximally attainable foaming rate after 30 min.

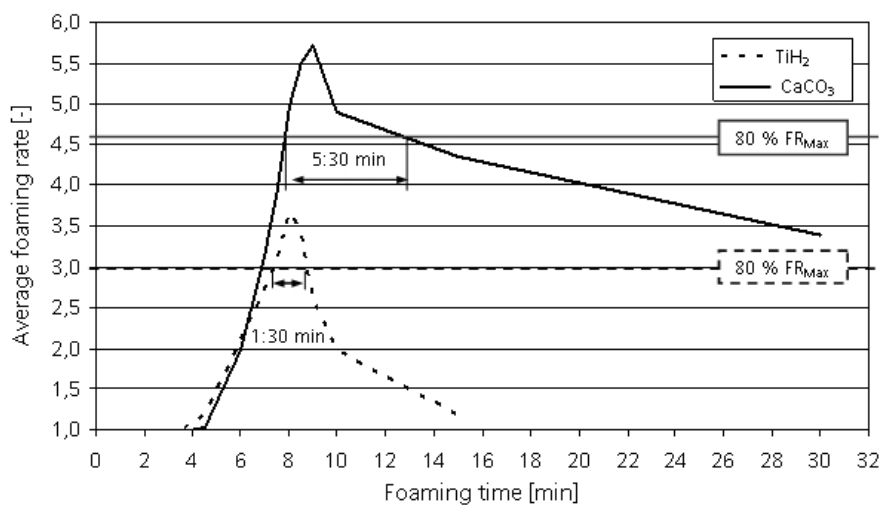


Fig6: Comparison of the determined foaming rates in dependence of the foaming time.

5. List of symbols

α	...	Star point distance	C	...	Content [weight percent]
D_{50}	...	Mean particle diameter [mm]	\bar{d}_p	...	Mean pore diameter
F	...	Frequency/rotational frequency [Hz]	FR	...	Foaming rate
M	...	Mass [kg]	Z	...	Time [min]

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