

DERIVATION OF MOTIVATORS FOR THE USE OF ALUMINUM FOAM SANDWICH AND ADVANTAGEOUS APPLICATIONS

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ABSTRACT

Aluminum foam sandwich (AFS) is an innovative material combination for designing lighter products and has many advantages such as a high bending stiffness at a low density and good energy absorption properties. Although the material is ready for series production, the number of industrial applications is low because of the high costs of the material, a lack of design knowledge and missing reference applications. This paper focuses on the aspect of missing reference applications and how to improve this situation in order to give designers an idea of where the material could be used profitably and to provide the basis for a selection method. Therefore, a systematic literature review is carried out to identify profitable applications with their respective advantages. As a main result, a set of motivators for the use of aluminum foam sandwich is developed, which will support the designer in evaluating the potential use of aluminum foam sandwich.

Keywords: Aluminum foam sandwich, Lightweight design, Design for X (DfX), Decision making

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1 INTRODUCTION AND MOTIVATION

The challenge of making products and structures lighter opens up a wide range of applications for sandwich materials. In particular, aluminum foam sandwich (AFS), which is shown in Figure 1, is an innovative material combination for the use of constructions in lightweight design (Banhart et al., 2017; Binz et al., 2018; Sviridov, 2011). The top layers of AFS are typically made of aluminum alloy sheets, although other materials such as stainless steel may also be used (Baumeister, 1999). The core of the sandwich consists of a porous foam structure made of aluminum. Among the large number of possible manufacturing processes (Banhart, 2018), the powder metallurgical route has become well-established for AFS with aluminum face sheets, because it is well suited for industrial applications (Orovčík et al., 2016). This manufacturing process creates a metallic bond between the face sheets and the foam core, which requires no adhesives and has a high recycling quality (Seeliger, 2011). Due to other advantages, such as a high bending stiffness at a low density and good energy absorption properties, the aluminum foam sandwich has a wide range of possible applications (Banhart et al., 2017; Sviridov, 2011).



Figure 1. Aluminum foam sandwich

2 PROBLEM AND GOAL

Although there are many advantages of aluminum foam sandwich and the material is ready for series production (Seeliger, 2011), the number of industrial applications is below the potential of the material (Banhart et al., 2017). The reasons for the obstacles to the use of AFS were investigated in a survey within the industrial environment (Hommel et al., 2020). The main reasons for the non-use were high costs, a lack of design knowledge and missing reference applications. While the price will decrease with increasing use of the material, the lack of design knowledge as well as the lack of reference applications suggests a need for more research. There are already different approaches to how a design support could be realized in order to make design knowledge available, for example by providing design guidelines.

In this paper the main focus is on the aspect of missing reference applications and how they can be compiled. The current situation indicates that designers do not know where the material can be used profitably. According to Seeliger (2004), an optimal utilization of the material characteristics is very important for a successful AFS application. An application should combine different advantages of the material in order to ensure a significant technical and economic benefit for the user.

In conclusion, a support for the usage of the material is needed, which means that a selection method for identifying the targeted use of AFS has to be developed in the future. Therefore, past applications are relevant as well as an analysis of the respective application criteria. A systematic literature review will help to answer the main questions about where AFS has been used or could be used and which advantages result from this. Thus, the aim of this paper is to provide an overview of the applications and to develop a set of criteria for the application, which is the basis for a future selection method. The research question is: *What are the motivators for using aluminum foam sandwich and which applications do they enable?*

3 STRUCTURE OF THIS PAPER

In the former sections, the research is clarified (RC), which is the first step of the Design Research Methodology (DRM) according to Blessing and Chakrabarti (2009). The DRM provides the methodological framework for this paper. Within the next two sections the detailed first descriptive study (DS I) is conducted. Section 4 shows current and past projects of a large German manufacturer of aluminum foam sandwich to give a brief insight into the state of the art. Moreover, the motivation for the usage of AFS and the advantages compared to materials that have been substituted in these described projects are explained. In Section 5, the motivation for the use of AFS is elaborated with a systematic literature review. The results of the two analyses are then combined in Section 6 as an initial prescriptive

study (PS). As a result, a support in the form of an overview table with different motivators for use and assigned possible reference applications is worked out. In Section 7 the findings are summarized and critically discussed. The paper concludes with an outlook on further activities.

4 CURRENT APPLICATIONS IN INDUSTRY - AN INSIGHT INTO THE STATE OF ART

Before the detailed literature research was conducted, previously known applications from the industry were examined first. To get an impression of the various advantages of the material, exemplary projects of a manufacturer for aluminum foam sandwich were analyzed. Table 1 lists various applications with corresponding reasons for using aluminum foam sandwich instead of another material.

Table 1. Various applications with respective reasons for using aluminum foam sandwich

Applications	Motivators for the usage of AFS	Substituted material
Step of a train	Mass reduction to reduce energy costs	Solid aluminum
Part of a moving machine table	Mass reduction for improved acceleration, damping effect for more even movement	Casting
Base plate for manually exchangeable testing device	Mass reduction in favor of better handling and no lifting gear (crane)	Solid aluminum
Partition wall of a compressor unit	Sound insulation and easier installation	Steel sheet
Back wall of a monitor / industrial touch panel	Mass reduction, better heat dissipation, integration of functions through electromagnetic shielding and thus reduction of manufacturing costs	Solid aluminum
Protective housing of a gear unit	Energy absorption and protection in case of control failure	-
Multiple transport packaging for explosives	Energy absorption, explosion protection, heat resistance, cost reduction (previously single packaging of other materials necessary for safety reasons)	Various (Single packaging)

Mass reduction is often cited as a reason to achieve further positive effects. Havel metal foam GmbH (2019) advertises that in addition to mass reduction, at least one other advantage (e.g. energy absorption, easier processing, fire resistance) should be considered in order to generate new cost-effective solutions. This is confirmed by other examples such as bumpers or crash elements in the automotive sector, which enable not only mass reduction but also have high energy absorption and the ability to dampen engine vibrations. The lightweight and protective material may also be used as mobile noise barriers or to separate unattended luggage at the airport (Havel metal foam GmbH, 2020).

While this section gave an insight into current applications and prototypes in the industry, the next two sections provide a detailed analysis of the literature of the last decades and collect the applications cited there to provide an overview of the most common motivators for the use of aluminum foam sandwich.

5 MOTIVATION FOR USING ALUMINUM FOAM SANDWICH - A LITERATURE PERSPECTIVE

In order to identify the motivators for the use of aluminum foam sandwich from a literature or research perspective, a systematic literature review was planned and conducted. In this section the general procedure is explained and the references found are classified according to their relevance. The following steps were carried out:

1. Definition of the search operations and synonyms for applications of aluminum foam sandwich
2. Execution of the actual research using electronic databases and the previously defined search strategies
3. Review of the sources found and an initial selection
4. Detailed analysis of the selected relevant papers

The results of the analysis of the papers are presented in Section 6.

At the beginning of the literature review the search criteria were defined. The aim was to find different applications of AFS and to identify the respective reasons for its use. As the applications of aluminum foam sandwich and aluminum foam are sometimes not clearly distinguishable in the literature and the applications often resemble each other, both terms were searched for. Then, the found applications have to be verified for their transferability to AFS. When searching for “aluminum foam” also terms with “aluminum foam sandwich” are found at the same time and therefore also terms like “sandwich with

aluminum foam” were found. So only “aluminum foam” was used as search operation. In addition, the term was searched for both in American English (aluminum) and British English (aluminium). For the central search logic, a combination of terms about material and terms about applications was chosen. Synonyms for the application were for example “use”, “usage” or “example”. The terms used were examined in an initial search and found to be suitable, while other terms led to a low number of hits. The terms were searched in both, English and German and in singular and plural form.

Four electronic literature databases were used for the search: *Science Direct*, *Web of Science*, *ProQuest* and *DOMA Machinery and Plants*. The search itself was conducted in October and November 2020.

An unfiltered search with the above-mentioned search logic resulted in a large number of hits (see Figure 2, left), therefore the use of special filters was necessary to reduce the number to an analyzable size. While aluminum foam has been around for several decades (Seeliger, 2011), the development of AFS has been rapid since the mid-1990s and the material has then been brought to technical readiness (Baumeister et al., 1994). Therefore papers published between 1990 and the present (2020) were taken into account. Preferably conference and journal contributions were searched for. If necessary, further filters were set individually for the databases, e.g. topics or categories, to obtain the technical, engineering design and material science context. With these filters set, there were 612 papers remaining. The filtered articles were then screened by analyzing the title, keywords and abstract to see if there are any hints for applications of the material. All papers dealing with different applications of the material were considered potentially relevant, hoping to find more detailed information about the exact reasons and motivations in the main part. Throughout this preselection the number of papers could be further reduced. Papers that were not publicly available were not taken into consideration.

After this procedure there were 228 papers left, which were then examined in more detail and the complete contents were reviewed. Finally, 65 papers could be classified as relevant in terms of applications with assigned reasons. Papers with advantages and reasons for use but without the associated applications mentioned were not considered as relevant for this work. The number of papers was spread over the four databases, with a total of three papers appearing double in two databases (Web of Science and ProQuest). The exact number of papers for the individual steps is shown in Figure 2.

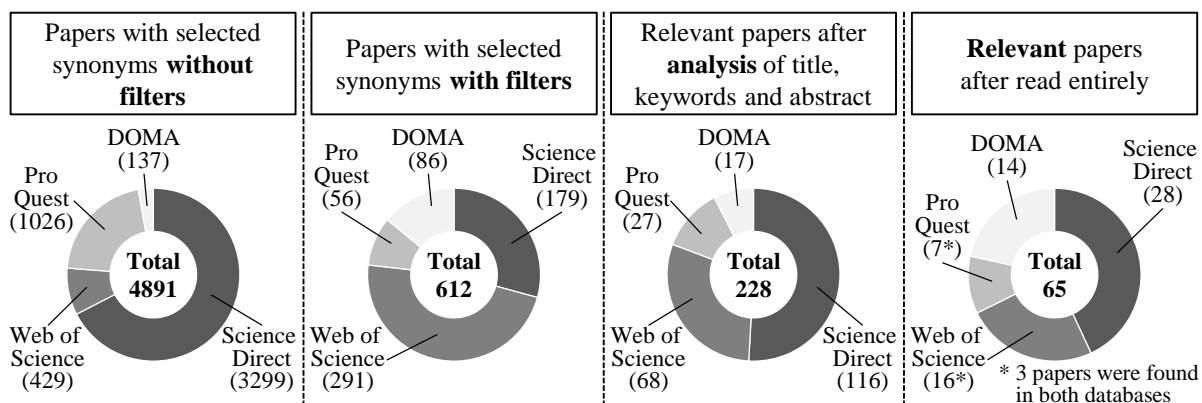


Figure 2. Number of papers related to applications of aluminum foam and aluminum foam sandwich with respective reasons for use

The relevant 65 papers were then analyzed according to their applications and motivation. The results are presented in the next section.

6 SET OF MOTIVATORS FOR USING ALUMINUM FOAM SANDWICH AND POSSIBLE APPLICATIONS RESULTING FROM IT

The aim of this section is to list the motivators found for the respective applications and to make a conclusion on the most frequently mentioned aspects. Therefore, the first part will identify the motivators according to the references and in the second part, the corresponding applications are assigned. As explained in Section 5, this paper will only deal with those references that have also related the benefits to a specific application. General statements about the advantages of the material without allocated applications are not considered in this article. A total of 15 different motivators for various applications were identified from the 65 relevant papers. An allocation of the motivators to the references is shown in Table 2. Because three papers were found twice, 62 sources are listed in Table 2.

Table 2. Set of motivators for using aluminum foam sandwich

	Motivators (Reasons for use)														
	High energy absorption capacity	Mass reduction, lower density	High mechanical properties	Sound insulation	Better heat transfer	Vibration damping	Non-inflammability, fire/heat resistance	Lower thermal conductivity	Radiation protection	Recyclability	Corrosion resistance	Reduction of costs, fewer individual parts	Tune vibration frequency	Appealing optical design	Integration of function (e.g. integrated cooling)
Aggogeri et al., 2017		x	x			x									
Ahmad and Thambiratnam, 2009	x														
Baiocco et al., 2017					x										
Banhart and Seeliger, 2008		x			x										
Banhart et al., 1998	x	x	x	x		x		x							
Banhart, 1999				x	x										
Banhart, 2001		x	x												
Banhart, 2003	x		x												
Baroutaji et al., 2015	x														
Bauer et al., 2013	x			x		x									
Baumeister et al., 1995	x														
Baumeister et al., 2007	x	x	x	x		x			x						
Baumeister et al., 2014	x	x	x					x							
Binz et al., 2018		x													
Boomsma et al., 2003					x										
Bornstein and Ackland, 2013	x														
Borosova et al., 2015				x											
Chen et al., 2014									x						
Claar et al., 2000	x		x	x		x	x	x							
Crupi et al., 2011	x	x	x												
Djamaluddin et al., 2016	x														
Epasto et al., 2020	x														
Fernandez-Morales et al., 2014					x										
Gama et al., 2001	x														
García-Moreno, 2016	x	x	x	x		x	x			x	x			x	
Hackert et al., 2017		x													
Hipke et al., 2014	x	x	x	x		x	x		x						x
Höfler et al., 2006		x	x	x								x			
Hohlfeld et al., 2015		x													
Huisseune et al., 2014		x			x										
Khateeb et al., 2004					x										
Klan et al., 2007	x		x	x											
Knuth, 2015		x		x		x	x			x					
LaJeunesse, 2015	x														
Lantz et al., 2016	x	x													
Li et al., 2017a	x														
Li et al., 2017b	x	x	x												
Maine and Ashby, 2002	x	x		x	x		x								
Navacerrada et al., 2013				x			x	x		x	x				
Noh et al., 2006					x										
Odabae et al., 2013					x										
Qi et al., 2014	x	x													
Reglero et al., 2010	x														
Reglero et al., 2011	x	x	x												
Rodríguez-Méndez et al., 2019	x				x	x			x						
Rossi et al., 2017			x				x								
Sampath et al., 2017	x	x													
Schamphelire et al., 2013		x			x										
Schmerler et al., 2017		x													
Schultz and Schindler, 2000												x			
Schwingel et al., 2007		x	x												
Seeliger, 1999		x		x				x							
Seeliger, 2004		x													
Setiawan and Salim, 2017	x														
Simon, 2015	x	x													
Smith et al., 2012	x	x	x			x							x		
Smith, 2015	x														
Tanaka et al., 2011	x	x													
Vicario et al., 2016		x													
Wang et al., 2020	x	x	x												
Wellnitz, 2011	x	x													
Zhang et al., 2011	x		x												
Frequency of mentioned motivators	35	32	19	14	12	10	7	6	3	3	2	2	2	1	1

The frequency of the reasons for using aluminum foam sandwich are summarized in the bottom line of Table 2 and could indicate for which advantages the use of the material is suitable. The most cited motivators are high energy absorption capacity (35 hits), mass reduction/lower density (32 hits), high mechanical properties (19 hits) and the potential for sound insulation (14 hits). The frequent occurrence of high energy absorption capacity (35 hits out of 62 references) is remarkable. This trend is also shown by the fact that a lot of references have been published in the last few years. This indicates that the use of AFS for example in crash applications is becoming increasingly important and more future-oriented.

At a first glance the heat specific motivators are notable, since in some applications good heat transfer is cited as the reason for use, while in other applications low thermal conductivity is important. This seems to depend significantly on the application and on the density of the foam. Furthermore, this property must also be seen in relation to a reference material.

With the motivators of Table 2 the advantages, which result from the material usage, were derived consistently. This overview and the following conclusions will help to identify suitable applications in the future. At this point it should also be mentioned that the derived motivator-set does not claim to be complete, as there are certain restrictions to the holistic nature of the literature review. However, due to the systematic approach, a good quantity is reached and the most important aspects are included.

In the second part of the study, the applications with the underlying motivators are presented. Table 3 shows the allocation of applications and motivators and provides information about which applications are mentioned most frequently in the relevant literature (left column) and which applications combine most motivators (right column). For a better understanding, individual applications have been grouped together. For example, crash-relevant vehicle components include a crash box as well as a foam-filled bumper or the B-pillar. Based on the examined references, the allocation was then carried out and the identified motivators were combined as a union for the respective type of application.

Table 3. Applications of aluminum foam sandwich with the respective motivators based on references

	Number of references in which the application is discussed	Motivators (Reasons for use)													Frequency of motivators per application		
		High energy absorption capacity	Mass reduction, lower density	High mechanical properties	Sound insulation	Better heat transfer	Vibration damping	Non-inflammability, fire/heat resistance	Lower thermal conductivity	Radiation protection	Recyclability	Corrosion resistance	Reduction of costs, fewer individual parts	Tune vibration frequency		Appealing optical design	Integration of function (e.g. integrated cooling)
Crash-relevant automotive components, crash absorbers	19	x	x	x	x		x										5
Transportation: train, truck, ship, metro	17	x	x	x	x		x	x	x				x				8
Heat exchanger	10		x				x										2
Explosion protection, armouring, military	9	x	x	x				x									4
Architecture and building industry: walls, roofs, floors	7	x	x	x	x			x	x	x	x			x	x		11
Components of a machine tool	7	x	x	x	x		x		x					x			7
Aerospace industry: spacecraft, airplane, rocket	6	x	x	x			x						x	x			6
Housing for radiation protection	3									x							1
Battery box of an electric vehicle	2	x	x	x					x								4
Cookware	1						x										1

The frequency with which the applications were mentioned correlates with the importance of the respective application for the use of AFS. Therefore, the greatest potential can be seen in crash-relevant structures in the automotive sector (19 relevant references) as well as in various other transportation vehicles (17 relevant references). Furthermore, applications as heat exchanger and in explosion protection and in the architectural field are often mentioned. Because some literature had several applications, the amount is now greater than the number of references. This distribution of the applications is also intended to fill the gap of missing reference applications shown in previous studies (Hipke and Wunderlich, 2000; Hommel et al., 2020).

As already discussed in Sections 2 and 4, this investigation has now shown that many applications address several advantages at the same time. Especially in the architecture and building industry (11 motivators) as well as in transportation (8 motivators), a large number of occurring advantages is obvious. The combination of the advantages is necessary to justify the costs of the material and thus to increase the application potential.

7 CONCLUSION AND OUTLOOK

The aim of this paper was to develop a set of motivators for the use of AFS and to determine existing applications and the reasons for their use. For this purpose, the authors first analyzed some industrial applications to get a preliminary impression. Then a comprehensive systematic literature review was conducted, which resulted in a large number of applications as well as the corresponding reasons for the use of aluminum foam sandwich. Thereby 15 different motivators for the use of AFS could be identified. The described applications could be allocated to different industries and have various reasons for the use of AFS. Frequently occurring motivators were energy absorption, mass reduction but also mechanical properties as well as absorbing properties. Moreover, it could be determined that the AFS usage in these applications has several advantages at the same time (see Table 2). Thus, this investigation confirmed the assumption that several advantages should be combined when using AFS to justify the price of the material. For mass reasons alone, the use of AFS is rarely profitable. The frequency of the applications mentioned is in accordance with the experience of the authors. It is therefore understandable that especially applications in crash-relevant structures as well as general applications in transport vehicles are promising, which is shown by the large number of references of these applications. Possibly because more costs are allowed here.

However, it must also be noted that there are limitations in the search procedure, e.g. the databases may not find all existing publications. Furthermore, companies often do not publish their applications. Major books such as Ashby et al. (2000) and Hipke et al. (2007) were not selected using the databases, but they already contain the applications shown in the examined papers. Although no claim to completeness can be made, a very large quantity was considered in this investigation and the motivators and applications are valid.

Future investigations will have to extend the set of motivators for the use of aluminum foam sandwich and also evaluate it. In order to support the designer in the material selection and to assist a larger use of aluminum foam sandwich, the reference applications will be visualized and described clearly.

Whereas in this study the applications of AFS have been investigated, a future work may explore the motivators and applications of sandwich panels in general. By comparing the two, it will be possible to check which sandwich areas can currently be served by AFS parts and which cannot. Based on this, the questions of why some areas have not been used so far and whether these could be of interest in the future could be answered and areas where research work is still necessary could also be identified. As described in the introduction, the selection of suitable applications for AFS is a great challenge. Therefore, a selection method has to be developed in order to indicate the parts of an application in which the use of the material is profitable and to support the designer when evaluating the potential of AFS in possible applications using the presented motivator-set.

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