IMPLEMENTATION OF A DESIGN GUIDELINE FOR ALUMINUM FOAM SANDWICH BASED ON INDUSTRIAL DEMANDS

Hommel, Patrick;
Roth, Daniel;
Binz, Hansgeorg;
Kreimeyer, Matthias

University of Stuttgart

ABSTRACT

Aluminum foam sandwich (AFS) is an innovative material for lightweight structures, consisting of an aluminum foam core surrounded by two face sheets of aluminum. The advantages of AFS are a low density combined with a high bending stiffness, good energy absorption properties, and high recyclability, meaning it can be used for many different applications. However, the number of realized series applications with AFS is low caused by a lack of design knowledge, as shown in various studies. In order to address this lack of design knowledge, a design guideline is to be developed. This paper focuses on the development of such a design guideline based on requirements and demands from the industry and presents a structure. In addition, the individual contents of the design guideline are explained in more detail in order to clarify how designers can be supported in the future when designing products with AFS, so that the full potential of this material can be realized. Finally, a survey in an industrial context evaluates the extent to which this design guideline is a useful form of support, in order to check whether its application can improve the design process with AFS.

Keywords: Aluminum foam sandwich, Design guideline, Design for X (DfX), Lightweight design, Design methods

Contact:
Hommel, Patrick
University of Stuttgart
Germany
patrick.hommel@iktd.uni-stuttgart.de

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1 INTRODUCTION

The increased consumption of products and the rise in production have made the use of sustainable product development indispensable. Weight reduction and lightweight design strategies in general offer cross-industry solutions for the major ecological challenges of our time and are essential for safe and sustainable mobility (Friedrich, 2017). Especially for moving components, a mass reduction as a result of a lightweight design can not only reduce the amount of required material, and thus the material costs, but can also have further positive effects such as reduced moving masses and thus lower operating costs (Krause et al., 2018).
In times of rising material costs, a design must be as efficient as possible and combine several advantages. In this context, the aluminum foam sandwich (AFS) represents an innovative material combination for lightweight structures that has gained particular importance in recent years thanks to its ever-increasing quality (Banhart et al., 2019). As can be seen in Figure 1, AFS typically consists of a core of aluminum foam that holds apart two face sheets, also made of aluminum. The powder metallurgy manufacturing process, which creates the foam by heating the raw material, creates a metallic bond between the face sheets and the foam core (Seeliger, 2011). Due to this characteristic manufacturing process, no adhesive is necessary, which means AFS has a high recyclability.

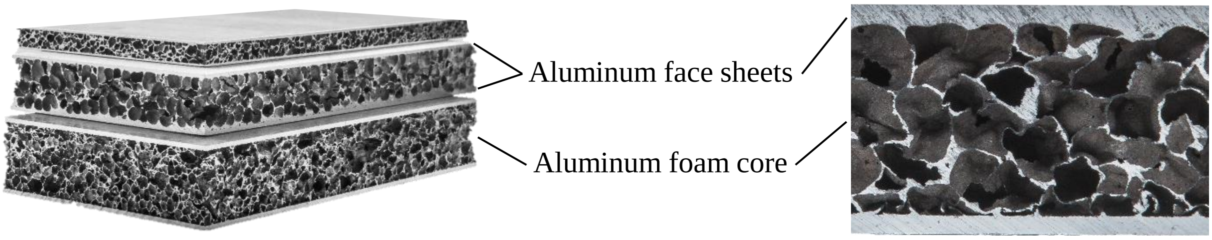

Figure 1. Aluminum foam sandwich

Thanks to the other advantages of AFS, such as low density, high specific bending stiffness, and good damping properties, this material can be used for a wide range of different applications (Banhart et al., 2019; Drossel et al., 2018; Hommel et al., 2021a). These particularly include crash-relevant components (Banhart et al., 2019), where the high energy absorption capacity of AFS is advantageous, as well as moving components in machine tools (Hohlfeld et al., 2018) and in general transport vehicles (Viehweger and Sviridov, 2015).

2 PROBLEM CLARIFICATION AND RESEARCH OBJECTIVE

Although AFS has many advantages for several applications, practical use is rare and the number of realized series applications is far below the application possibilities of the material (Banhart et al., 2019; Florek et al., 2014). A survey (Hommel et al., 2020) has identified several obstacles preventing its use that are responsible for this divergence. The needs for designing products with aluminum foam sandwiches from an industrial perspective were investigated. The most commonly cited obstacles in the survey were excessive costs and a lack of design knowledge. The quality of aluminum foam has been increasing in recent years, so costs have already decreased slightly (Banhart et al., 2019). These costs will continue to decrease as more material is produced and used, but this in turn requires improved design knowledge and greater awareness. For example, there is a lack of methodological support, including a lack of reference applications and advice indicating the potential uses and associated advantages to designers. So far, designers do not know where the material can be used appropriately. This lack of design knowledge can be remedied with the help of a design guideline (Hommel et al., 2021b). Given that this kind of methodological support does not yet exist for AFS, it is time that a design guideline is developed. Therefore, the research question of this paper is:
What should a guideline to support designing products with AFS look like?

3 STRUCTURE OF THIS PAPER

The previous sections of this paper set out the scope of the research. In the following section, the basics for the development of the design guideline are described, which corresponds to the first

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descriptive study according to Blessing and Chakrabarti (2009). This involves gathering the necessary content, the appropriate delivery method, and the key support requirements. This is followed by the prescriptive study. In Section 5, the design guideline is developed based on the previously acquired knowledge – initially as a fundamental document-based version. Due to various advantages of a digital method, the implementation of the design guideline in the form of a digital prototype is addressed in Section 6 and its planned usage is explained. To evaluate the support potential, a survey was conducted and the results are presented in Section 7. Finally, the findings are summarized and discussed in Section 8 and an outlook on further necessary steps in the research is given.

4 DEVELOPMENT OF THE DESIGN GUIDELINE FOR ALUMINUM FOAM SANDWICH

Lightweight design in product development in general requires the designers to have very extensive specialized knowledge (Krause et al., 2018). In the case of sandwich materials, such as aluminum foam sandwich, an especially high level of know-how is required in the design process (Reuter, 2021). As discussed in Section 2, from an industrial perspective, a lack of design knowledge is a major reason for an inhibited use of AFS. It has been shown that required information is not yet available in a condensed form and, in some cases, has not even been sufficiently researched, which leads to obstacles or exclusions in the use of the material. In the course of writing this paper, this was also confirmed in discussions with design engineers and from the perspective of sales representatives of AFS manufacturers.

The necessary and desired information for designing products with AFS has already been identified in a previous study by Hommel et al. (2021b), and the different types of support have been discussed. Based on requests from potential users in the industry, an extended design guideline in the form of a manual is considered to be a suitable tool to provide methodical support for the design and manufacture of components made from AFS, allowing quick access to the necessary content. This guideline is also intended to be made available as an internet-based platform in the future to enable a broader application. The content identified as being necessary includes, for example, indications and recommendations on restrictions concerning the manufacturing process, characteristic material properties, reference applications, guidelines for designing, analytical calculation rules, simulation suggestions, applicable machining processes, and suitable joining techniques. (Hommel et al., 2021b)

Once the necessary content for the support had been identified, the requirements and framework conditions for the design guideline were first clarified, so that the design support could be developed in a targeted manner. For this purpose, the criteria according to Keller and Binz (2009) have to be met, namely revisability, practical relevance & competitiveness, scientific soundness, comprehensibility, usefulness, problem specificity, structure & compatibility, and flexibility. In order to simplify the designers' daily work with AFS, the support should also meet the specific requirements from Hommel et al. (2021b), most of which are listed below:

- Guideline should be person-independent and mobile (location-independent) with easy access
- Guideline should be easy to use by presenting the content in a compact and structured way
- Content should be complete
- Content should be presented in a comprehensible way
- Content should be useful when designing products with AFS

Furthermore, it is essential to define the structure of the guideline and determine a uniform layout (which will be explained in more detail in Section 5), in order to be able to prepare and compile the relevant content. Different sources of reference are defined for this purpose. Some content is provided directly by aluminum foam sandwich manufacturers or is published in scientific papers or even in reference works (for example Hipke et al., 2007; Gomeringer et al., 2022). Other content has to be prepared independently, for example by manufacturing sample components in one's own workshop or with the help of partners, in order to obtain relevant findings and parameters. For the purpose of illustrating the contents, in particular the design rules, the guidelines “Honeycomb Sandwich Design Technology” by Hexcel (2000) and “Konstruktionsrichtlinie Blech” (Design guideline for sheet metal) by Trumpf (2011), which originate from similar material areas, are used as a reference.

The developed knowledge will initially be collected in document form to serve as a guide or manual, which can be used as a training document. In the next section, the fundamental design support for AFS is presented, and the developed content is explained using excerpts.

5 DESIGN GUIDELINE FOR ALUMINUM FOAM SANDWICH

The developed design guideline for aluminum foam sandwich is intended to assist designers through the lightweight product development process. In order to meet the requirements and achieve the required aims, the content must be adequately prepared and presented in a consistent layout. Sample pages of the document-based design guideline can be seen in Figure 2.

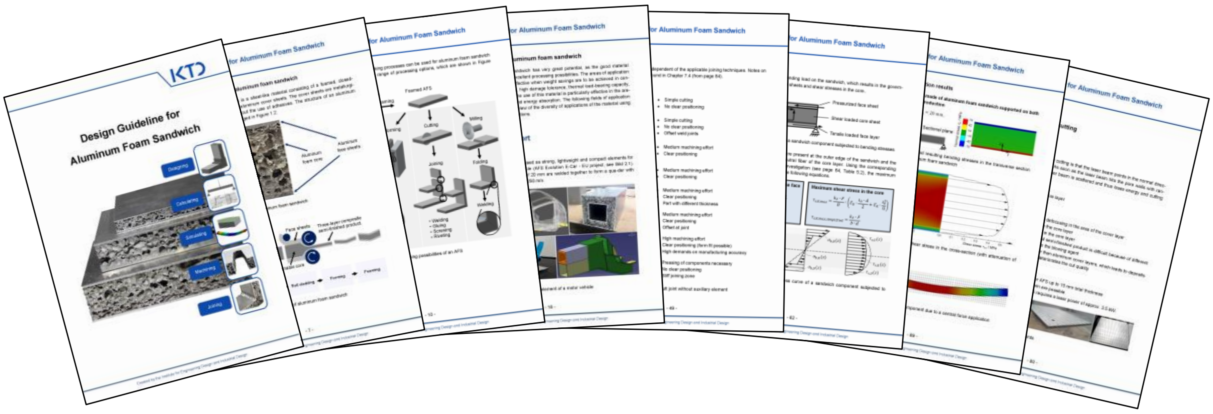

Figure 2. Illustration of example pages of the document-based design guideline

The design guideline can be **divided into four main topics**: *material properties*, *design recommendations*, *calculation approaches*, and *machining processes*. The first topic provides **information** about the production process and the resulting manufacturing restrictions, material-specific properties, material characteristics, and possible geometries and different types of AFS. In addition, reference applications (see Figure 3) are used to illustrate the wide range of applications and potential uses, with advantages and disadvantages. Furthermore, food for thought for new applications can be given, so that designers can be inspired by best-practice examples.

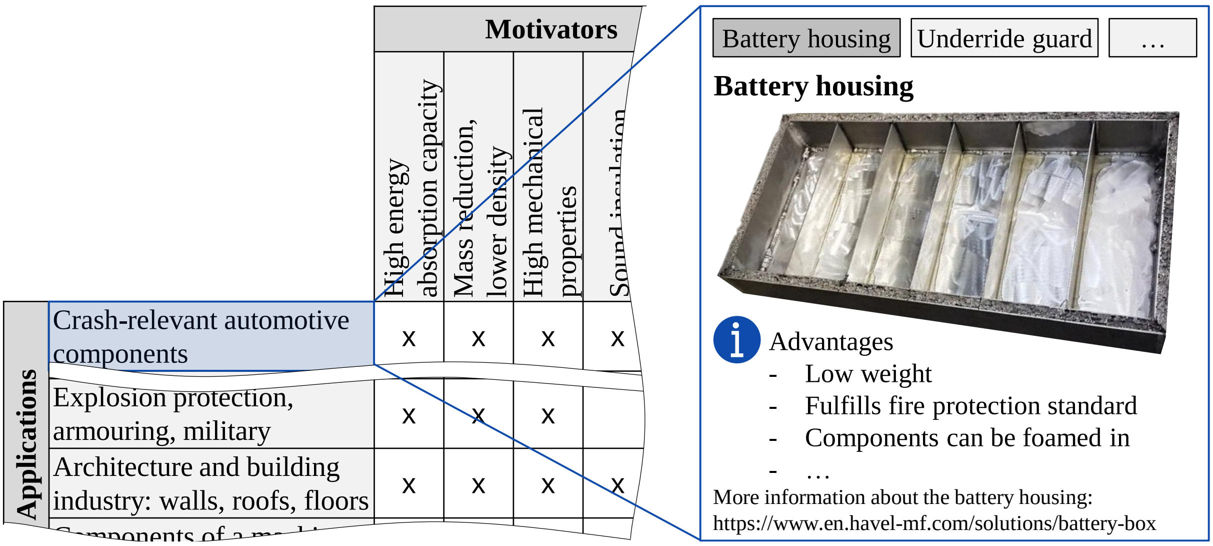

Figure 3. Excerpt from the reference applications

The second part of the guideline sets out **principles and recommendations for designing** products with aluminum foam sandwich. In addition to the general, basic design rules, design principles, and design guidelines – which can be found for example in Degischer and Lüftl (2009), Ehrlenspiel and Meerkamm (2017), Klein and Gänsicke (2019), or Pahl et al. (2007), some further design rules are necessary due to the particular sandwich structure of AFS. These include, for example, the force transmission points, the edge closures, the shaping possibilities of the foam components, the necessary preparation work for different types of connections, and suitable types of joints. In addition to the principles for lightweight design using AFS, design guidelines that are suitable for machining are also visualized using good and bad examples, which is illustrated in Table 1. A procedure for selecting a suitable joining method is also provided to support designers during the concept phase.

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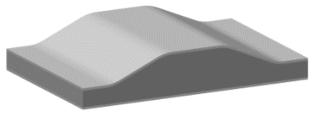
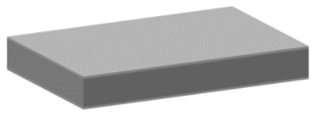
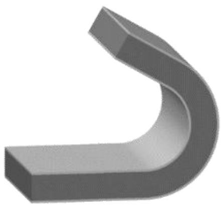
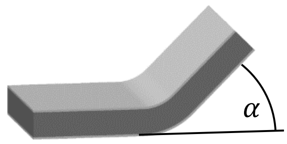
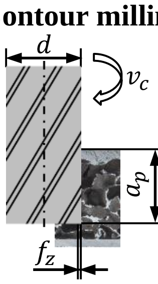
Table 1. Principles for the production-ready design of AFS

	Unsuitable for manufacturing/machining	Suitable for manufacturing/machining
Ensure constant component thickness		
Avoid foaming of U-shaped cross-sections; use a V-shape instead		 Recommendation: $0° \leq \alpha \leq 45°$ Acceptable: $\alpha_{max} = 60°$
Respect maximum possible bending angle		 Recommendation : $0° \leq \alpha \leq 45°$ Acceptable : $\alpha_{max} = 60°$

The section on **calculation approaches** contains both analytical calculation rules and simulation recommendations. The most common load cases of sandwich components are summarized in order to support the preliminary design of structures made of aluminum foam sandwich. Based on the analytical calculation approaches, a supplementary digital calculation tool was also developed to calculate the maximum stresses and the deflection of a beam or a plate.
In order to be able to carry out more complex calculations with the use of computer-aided simulations, the finite element method will be used. The design guideline is intended to convey the most important principles in a compact format by providing information and empirical values for conducting the simulations to simplify the model setup.
The last part of the design guideline sets out potential **machining processes** and provides practical recommendations, empirical values, and the technological limits of machining techniques for AFS. In particular, process-specific recommendations are provided for processes in the cutting and joining groups with reference to proven process parameters, as can be seen in Table 2. An overview of various joining techniques with comparative criteria is also provided to assist designers in selecting a suitable joining process. Independently conducted pull-out tests, for example, resulted in maximum pull-out forces of (detachable) fasteners.

Table 2. Extract from a table of recommended machining parameters for contour milling with a solid carbide end mill



Contour milling with a solid carbide end mill	Roughing			Finishing		
Cutter diameter d in mm	4	12	20	4	12	20
Cutting speed v_c in m/min	320 … 350 … 380			750 … 800 … 850		
Feed per cutting edge f_z in mm	0.02	0.07	0.12	0.024	0.079	0.126
Cutting depth a_p	corresponds approximately to the cutter diameter					

The focus of this paper lies on supporting the design with AFS. However, both the structure and the identified content can also be transferred to other new materials. The guideline for AFS can therefore also help improving the work with other materials in the future.

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6 PROTOTYPE OF THE INTERNET-BASED PLATFORM FOR DESIGNING PRODUCTS WITH ALUMINUM FOAM SANDWICH

Using the structure described in Section 5 and the outlined framework of the design guideline, all of the required contents can be displayed appropriately. Initially, the guideline was planned to be implemented as a purely document-based guide or manual. But following discussions with design engineers and the results of a survey (see more on this in Chapter 7), it was concluded that a digital-based implementation might be more suitable. The advantage of an internet-based implementation is that it enables worldwide access to knowledge, as access can be independent of time and place. A digital application also opens up other possibilities, such as using three-dimensional components as reference applications, which can be viewed as rotatable models. Programs and automatic procedures can also be integrated more easily using a platform. For example, a strategy for selecting a material or a joining process could be realized by using filter options (e.g., by asking about objectives such as process duration and costs via a drop-down menu) and direct inputs to arrive at the best solution, which is then displayed on the computer.

At the moment, the implementation of the internet-based platform is still in progress. When using the platform in the future, users will have to log in at the start. This is so that different user rights can be assigned. After launching the platform or logging in, the start page shown schematically in Figure 4 is displayed. The clear structure should enable users to navigate quickly through the platform. Below the header with the title, there are a few shortcuts, and below them, the main content is displayed in tiles. Users can either navigate using the tiles and click directly on the content or open the content tree, which can be expanded using the top left menu bar. All of the chapters are listed there, so users can navigate manually. The content is structured both in the content tree and in the tiles according to the product development process to ensure user-friendly operation. The individual areas contain links to enable users to switch from one topic to a related topic area and view the relevant information directly. Alternatively, users can also use the search function (to the right of the start page button) and search for a specific term, which displays all of the pages containing that term. Users can log out and switch user accounts by pressing the button in the top right.

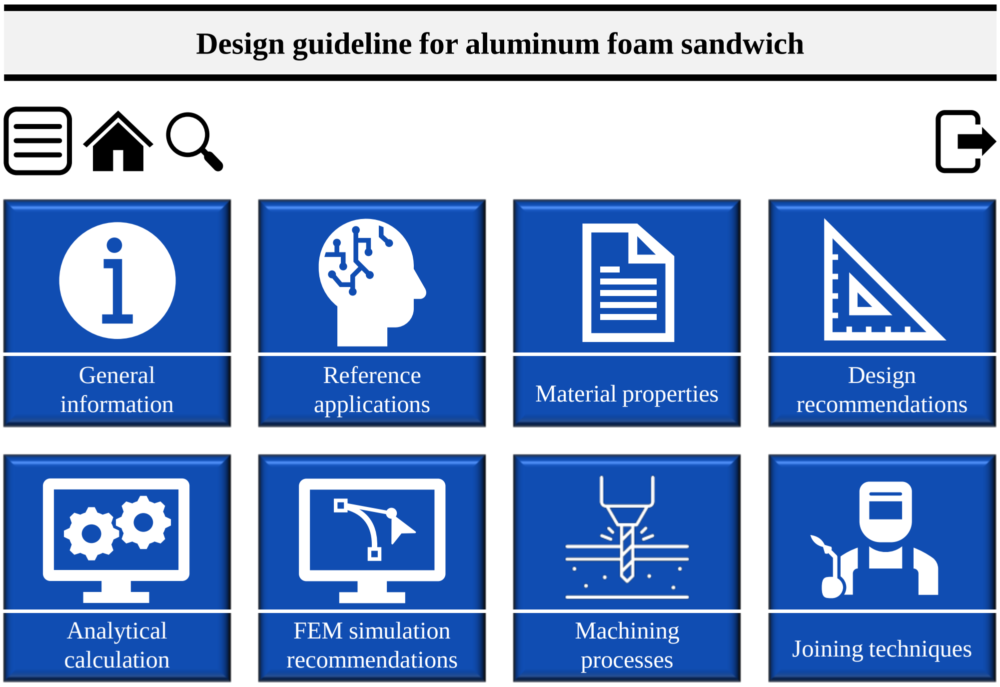

Figure 4. Illustration of the internet-based platform for designing products with aluminum foam sandwich

7 EVALUATION OF SUPPORT POTENTIAL OF AFS DESIGN GUIDELINE

Having developed the concept of the design guideline, prepared the content, and built a prototype for an internet-based platform, this section focuses on the evaluation of the results. Even though the contents and the manner of providing these contents were constantly checked and confirmed in the

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course of various discussions with designers and manufacturers, a final survey was conducted with potential users to provide further insights and evaluate the support holistically by examining the requirements listed in Section 4. The survey was carried out in an industrial context. In order to validate and optimize the questionnaire, first a pretest was conducted with three people, and the actual survey was subsequently conducted in October 2022.

AFS and the challenges of using it were explained at the start of the survey, so that each participant had the same background knowledge. The survey consisted of 31 questions (single-choice, multiple-choice, and free-text) and was divided into the following areas: activities and prior experience with AFS, assessment of the basic concept and content of the design guideline, review of the implementation of individual topics, and a final evaluation of the added value of the support. Due to rounding numbers up or down, the sum of the individual values in the following charts may differ from 100 percent.

The survey target audience consisted mainly of engineers, most of whom have a background in research and development, or work in design departments or project management. 61 people responded, with an even distribution of work experience and company size. The participants' positions in the company ranged from employees without management responsibility all the way up to managing director level. Only four persons were not at all familiar with the material prior to the survey. All other participants had at least heard of it (56%) or were also familiar with the features of AFS (38%). The vast majority (71%) had not yet had direct contact with the material, while some had already used it in their designs (26%) – three people of them (5%) even had experienced AFS in machining in addition to design.

The most important results of the survey that concern the design guideline will now be explained. First, the participants were asked whether the contents (see descriptions in Section 5) were complete from their point of view. Figure 5 shows that 82% considered the contents to be complete (43% “Yes”, 39% “Rather yes”). 8% said they thought some content was missing. They were asked to elaborate on this in a further free-text question and explain what content they considered missing. It was established that some of this content was actually already included, but was not clear to users. However, recycling recommendations and information about carbon dioxide consumption were indeed missing and will be included in the future.

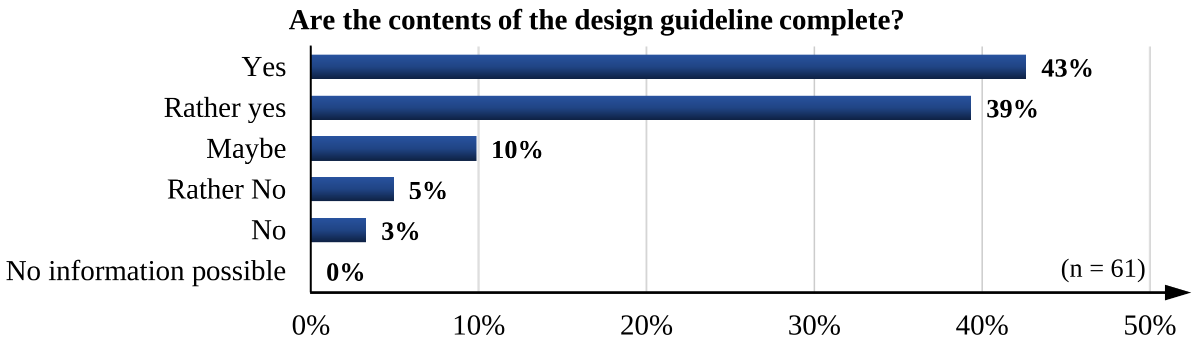

Figure 5. Completeness of the contents of the design guideline

The next question addressed the suitability of the form described for providing knowledge. Here, a total of 91% said that the form is suitable (70%) or rather suitable (21%), while 8% answered the question with “Maybe” (see Figure 6). None of the participants stated that such a form of knowledge provision is unsuitable.

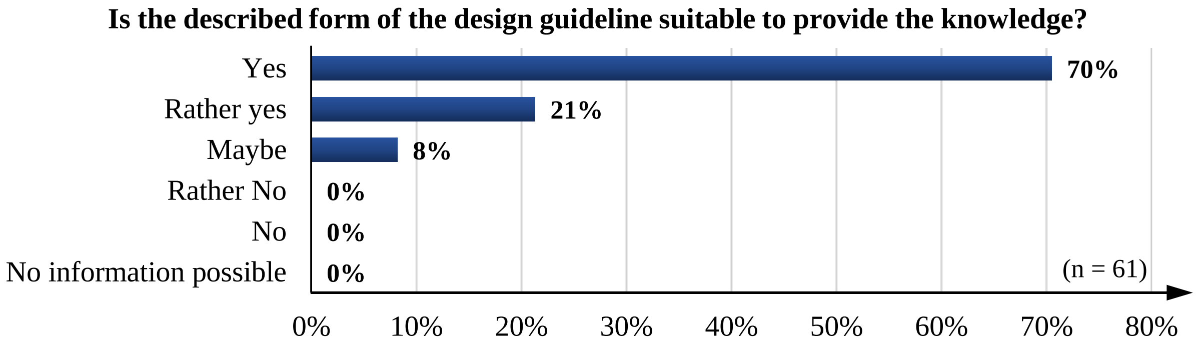

Figure 6. Suitability of the form of the design guideline for providing the knowledge

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The next questions concerned the realization of the individual contents. The reference applications, design guidelines, overview of joining techniques, and tables of machining parameters (all mentioned in Section 5) were examined as examples. In each case, the participants were asked whether the respective content was helpful for support and whether the visualization of this content was suitable. As can be seen in Figure 7, all four pieces of content mentioned were rated as very helpful. Apart from a few individual responses, the majority answered the question about whether the content was helpful with "Yes" (62% to 87%) or "Rather yes" (11% to 21%).

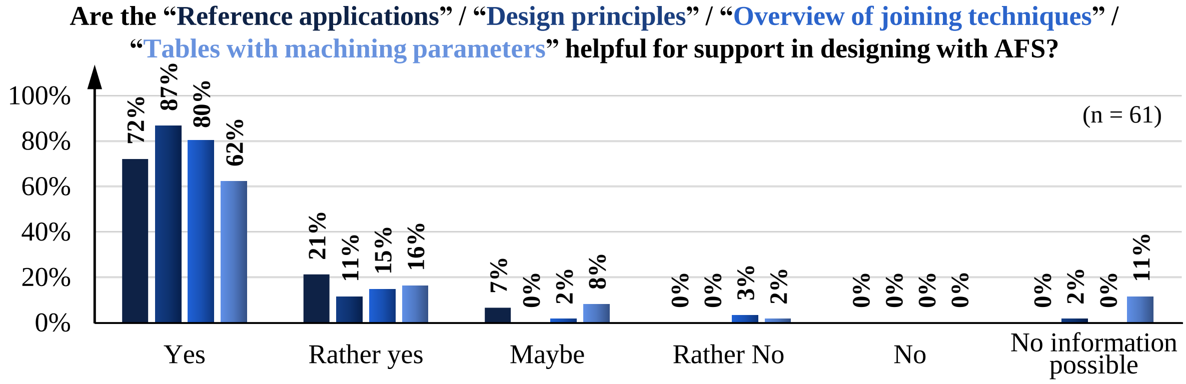

Figure 7. Review of the helpful support of individual contents

The results were similar for questions concerning the suitability of the visualization format, which assessed whether the contents were viewed as being presented in a comprehensible manner. All of the four described pieces of content were rated very positively (more than 85% for "Yes" or "Rather yes"). The results were especially positive for visual implementation of the design principles, which 100% of participants rated as suitable or rather suitable. Participants were also asked to provide suggestions for improvement in free-text questions, which produced some good ideas and reaffirmed some of the plans.
The reference applications were generally rated positively, but participants also expressed a desire to obtain as much information about the applications as possible (number of units, wall thicknesses, implementation of joining techniques). They also thought classification of the applications, e.g., according to the type of load (impact, constant, etc.) would be helpful. In terms of joining techniques, the participants reported wanting a selection method that enabled a suitable joining technique to be selected quickly and easily. Economic aspects were also very important to the respondents. Cost comparisons are included where possible, but are often difficult to assess.
At the end of the survey, the guideline was evaluated again as a whole, after individual contents and the concept had previously been successfully evaluated. In terms of the question about whether the design guideline (regardless of whether it is internet-based or not) is a suitable form of support for designing products with AFS, 74% answered with "Yes", 21% answered with "Rather yes", and 5% answered with "Maybe" (see Figure 8, left). A clear majority thus considered this form of design support to be of added value. Following on from this, 66% stated that they believe an internet-based variant would be of greater benefit, while 30% think that both the digital solution and the document-based version are equally suitable, as can be seen in Figure 8 on the right.

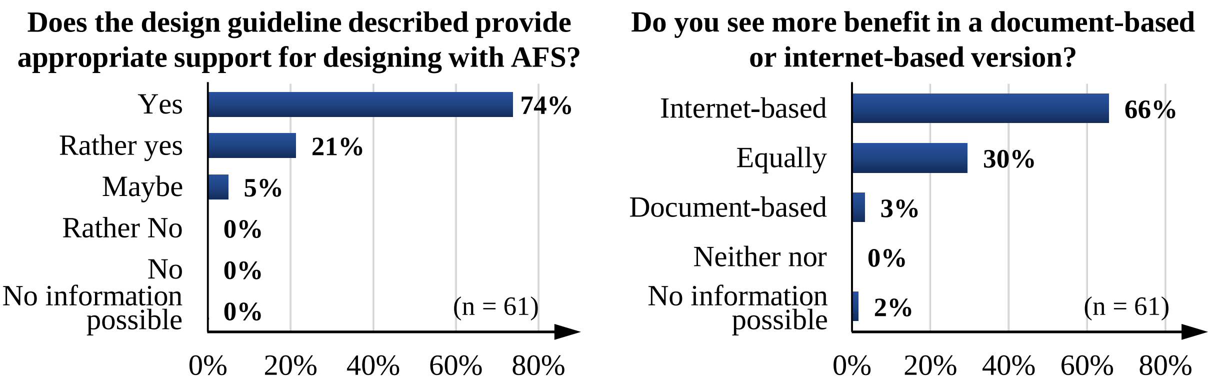

Figure 8. Support potential of the design guideline (left) and comparison between document-based and internet-based implementation (right)

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Finally, the participants were asked whether they would use the design guideline if they had to design a product using AFS. As can be seen in Figure 9, a total of 95% answered in the affirmative (79% "Yes", 16% "Rather yes"), while 5% were undecided or did not answer the question. None of the respondents indicated that the design guideline would not be used.

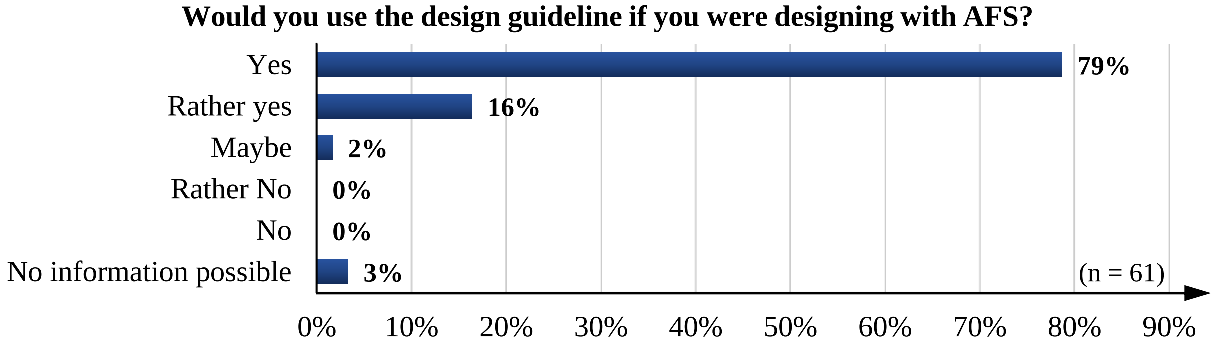

Figure 9. Future use of the design guideline when designing with AFS

8 CONCLUSION AND OUTLOOK

The reduction of information and knowledge deficits regarding the use of appropriate materials, design for X, and appropriate machining processes is essential in order to continue the advancement of lightweight designs (Schmidt and Puri, 2001). The objective of this paper was to address one of the existing obstacles preventing the use of AFS, namely the lack of design knowledge. In order to provide designers with as much knowledge as possible at the right time, the aim of the paper was to create a form of support for designing products with AFS. In doing so, a design guideline was developed initially in the form of a manual. The development of this guideline was explained and the outcome of the guideline was presented. In addition, insights into the structure and form of the individual contents were provided, for example by using excerpts from the design guideline to clearly illustrate the reference applications, guidelines for designing, and suitable joining processes. The implementation as an internet-based platform was also demonstrated and the future application of this was explained.

Finally, a survey about the design guideline supporting the design of products using aluminum foam sandwich was conducted to verify the additional benefits of the design guideline and to investigate whether it meets the industry's needs. In this support evaluation, it was confirmed that the content of the guideline is sufficient and broad enough to provide adequate support. The form of implementation was also evaluated positively, with a clear desire for a digital variant. In particular, problem specification (method addresses problem), practical relevance (novelty and improving the state of the art), and comprehensibility (comprehensible and applicable) could be successfully verified at this stage. The problem formulated at the beginning – the lack of design knowledge and the lack of a suitable knowledge database for designing products with AFS – can be solved by providing knowledge within the context of the developed design guideline.

In the future, the internet-based platform has to be developed further and the contents prepared properly. Some content, such as a suitable selection method for material use, is currently still in progress and needs to be finalized and evaluated before it can be implemented in the digital design guideline. There is also a need to follow up on the survey comments, for example, that more support is also required for the economic evaluation of AFS as well as for the selection of appropriate joining techniques. Another area where research is still lagging behind is the support for simulations, e.g., with the help of validated material cards.

At the current stage of processing the design guideline, it has already been possible to examine most of the basic support requirements presented. After completing all the necessary work for the design guideline, its application now has to be holistically evaluated by conducting various studies. Applying the design guideline in different projects should help to assess its usefulness and evaluate the completeness of the contents. This will be done on the one hand with surveys but also, for example, with the help of comparisons of designs created with and without the guideline.

In the future, with increasing use of AFS, more characteristic values and further knowledge will be created, which in turn will be incorporated into the adaptable guideline. A learning effect in the use of the guideline can therefore be expected.

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