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**ABSTRACT**

The design and the requirements within the constructive development of technical systems cause a connection of different material properties and the combination of different production processes to novel and innovative material systems. Therefore, materials are specifically positioned according to their mechanical properties in the technical system, and manufactured to meet a manageable manufacturing strategy to the component or semi-finished product. By using this fusion of technology, high-performance components fulfill the claims for high economic and technical performance in complex assembly structures of today's (and tomorrow's) technical systems. They are flexible, compact and meet the current requirements for efficiency and safety. Due to the achievable synergy effects, multi-material assemblies are increasingly applied, especially in automotive lightweight design.

In this context, the present paper deals with the development of innovative Hybrid Sandwich Composites (HSC), made of Carbon Fiber Reinforced Plastics (CFRP) arranged with new isotropic Aluminum Foam (AF) structures. The novel HSC form the basis for novel weight-optimized, as well as cost-effective, applications and lead to high a bending stiffness and high strength of structures, that also show excellent damping properties at high damage tolerances. The flexural modulus and the flexural strength were increased by a variation and optimization of the CFRP/AF-interfaces.

**KEYWORDS:** lightweight design, sandwich, hybrid, composites, aluminum foam, carbon fiber reinforced plastics

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**INTRODUCTION**

Increasing environmental and economic demands in mechanical engineering require specific material combinations and adjusted manufacturing processes. Due to the achievable synergy effects, especially in automotive lightweight design, multi-material assemblies are increasingly applied [1]. A high demand of the bending stiffness and the damage tolerance of a component, as well as an efficient and suitable mass production, can be met reliably by the very good mechanical properties and the known production methods with the individual materials. With regard to their high tensile strength, Carbon Fiber Reinforced Plastics (CFRP) are predestined for the use as a extrinsically tension element. In contrast, metallic materials have good compressive strengths and build an inherent interface for the integration of HSC into metal material systems. The combination of both materials (Figure 1) imposes high demands on the material system and the reproducibility of the material interface and the manufacturing process.



Figure 1. Closed-Pore Aluminum Foam Structure (left), Continuous Carbon Fiber Reinforced Plastic Sheet (right)

### STRUCTURE OF THE HYBRID SANDWICH COMPOSITES (HSC)

In view of the examinations to determine the most important mechanical characteristic values, the geometric structure of the sandwich composite is outlined with regard to DIN 53239. The preliminary tests, represented by the short-bending test in accordance with DIN EN 2377, and the testing of samples in accordance with DIN 53293, require a comparable profile in all variants. Due to the investigations of the HSC, a specimen geometry of (a) 128.5 mm x (b) 63.5 mm was defined for preliminary investigations. In addition a symmetrical layer structure was elected. Thereby, a core made of Closed-Pore Aluminum (c) was reinforced with unidirectional thermoplastic CFRP top layers ( $t_1$ ,  $t_2$ ).

The manufacturing of the HSC in a hot press method can implement high internal stresses on the material, due to the material's different expansion coefficients. To prevent this undesirable effect and to compensate defects or large irregularities on the surface of the joining partners, an intermediate layer is provided as a buffer zone between top layers and core material. This thin additional layer flattens the high gradients of the two Young's moduli between the outer CFRP-layers and the core [2]. The intermediate layer consists of thin a combination between thermoplastic glass fiber reinforced Prepregs (PA6 GF60) and multiple slides of polyamide foil (Figure 2).

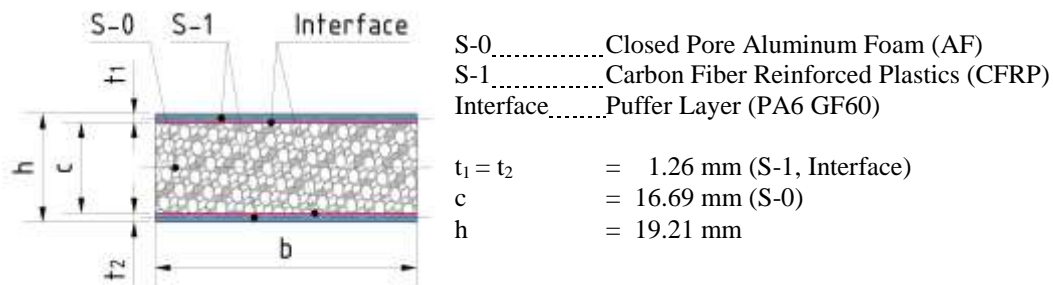
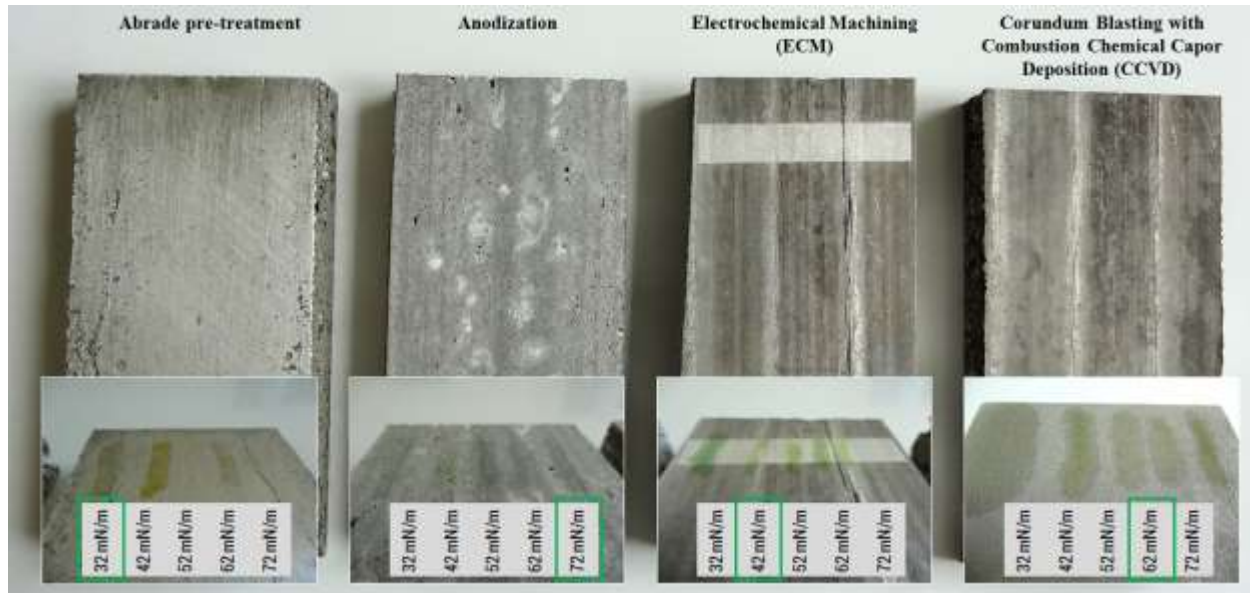


Figure 2. Structure of the Hybrid Sandwich Composite according to DIN 53239

### PRE-TREATMENT PROCEDURES

The main requirement to realize HSC-structures with the achievement of high stiffness and strength properties is an optimized interface design with a perfect adhesion between top layers and core material [2]. To achieve this aim, different pre-treatment procedures were applied on the interfaces for preliminary investigations (Figure 3).



*Figure 3. Overview of pre-treatment procedures*

### **Abrade pre-treatment**

The most commonly used method of surface preparation is abrade pretreatment. In comparison to other conventional processes, it is very cost effective and requires minimal effort. In addition, the use of an automatic process allows highly reproducible results. Depending on the selection of the abrasive and of the corresponding type of application, surfaces can be created with various roughness, whereby the required surface roughness depends on the selected material combination. Matched to the sensitive surface of the aluminum foam and justified by the partially very thin skin on the surface, roughnesses ( $R_z$ ) of between 5 and 10 micrometers are fine abrasives according to DIN 69100, compared with the 100 grit for a mean surface roughness. Figure 3 shows the measurement of surface tension by the use of a specific test ink.

As a result, almost no damage to the thin surface, and the outer pores of the aluminum foam were caused by abrasive pretreatment. The surface tension is about 32 mN / m, and moreover, by mechanical embracing a positive bonding between the joining partners is expected. With constant tool-side parameters and under reproducible conditions, this method of treatment can be integrated very well within a process chain in mass production. It can be reduced to the region of the joining zone and requires a very small time window for the application. In addition, no particular constraints as a protective environment or additional storage times are to observe.

### **Anodization**

The electrochemical surface conversion by an anodic oxidation characterizes the anodizing of aluminum components. Through an electrically conductive liquid (electrolyte), the exchange of metal ions between different metals is effected in an electroplating system, whereby the anode is attacked and oxidized.

After degreasing, basic and acidic pickling, the specimens are dipped into an aqueous solution of sulfuric acid. During the treatment, the aluminum structure is connected as an anode. By applying a DC voltage with high current density, the natural oxide film is amplified and can be adjusted to a desired level. After several downstream cleaning baths, the component has a surface that is suitable for their mechanical roughness particularly for the adhesive interface bond. Figure 3 shows the measurement of the material's surface tension by the use of a test ink. The anodized specimen exhibits a significant increase of the surface tension to 72 mN / m, what can be explained by the changing potential of the material, but also with the altered oxide surface. The thickness of the oxide layer should be in a range between 0.05 mm to 0.1 mm.

### Corundum Blasting with Combustion of Chemical Capor Deposition (CCVD)

The corundum blasting is a commonly used mechanical process for structuring or activating a surface and to remove undesired surface coatings. The easy control of processing parameters allows the reliable production of reproducible roughnesses. In the current study, a white corundum Specification F100 was processed at the blasting unit. Table 1 lists the parameters for the corundum blasting, which were determined iteratively for the test specimens. A deviation from the determined parameters causes an inferior result. By increasing the pressure of the compressed air or the reduction of the jet distance, the skin of the aluminum foam gets partially destroyed. This would lead to a local penetration of the polymer matrix into the uncovered pores.

*Table 1. Corundum Blasting Process Parameters*

Parameters	Value
Pressure of compressed air	5 bar
Jet angle of incidence	45°
Beam distance	100 mm
Jet duration	20 s

For another preparation variant, the mechanically, by corundum blasting, roughened surfaces of the aluminum foam cores were flame coated, to improve adhesion by activating the surface by organic contaminants. This flame coating process adds a silane coupling agent on the material's surface (Figure 4) [5].



*Figure 4. Combustion of Chemical Capor Deposition (CCVD)*

During the flame coating process, the purple appearing field of the burning flame should be kept on the surface. This creates the requested precipitation of the adhesive, which can be clearly seen, even during the application. The duration of treatment depends on the materials to be processed and was determined through previous tests. Since a short time, highly active surfaces can be produced by the silicoater process. The specimens should be processed quickly afterwards, to avoid a degradation of the agent. Figure 3 shows the surface tension of the corundum blasted and flames coated samples.

### Electrochemical Machining (ECM) [4]

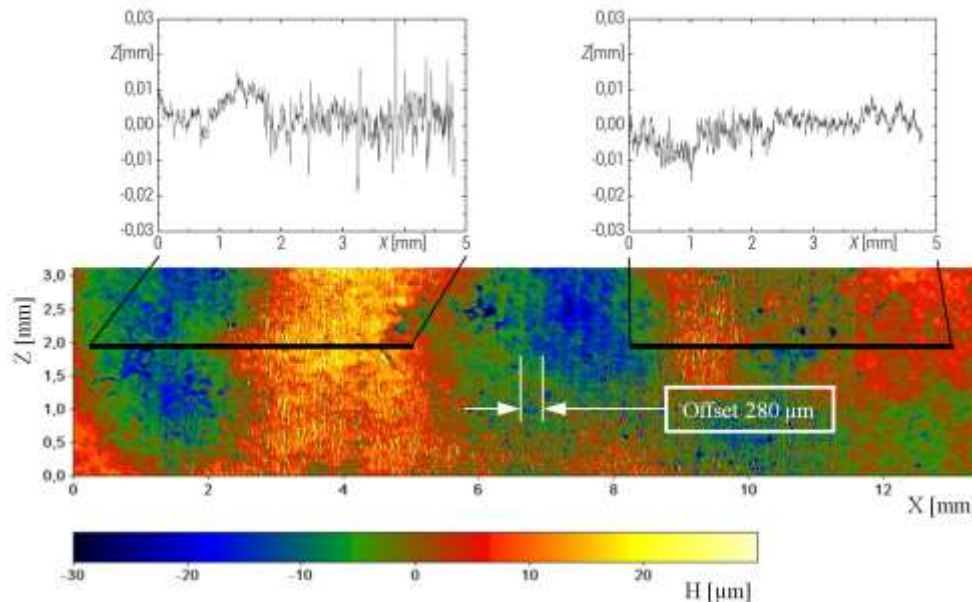
An effective method for the microstructuring of metallic surfaces is the electrochemical erosion with a closed electrolytic free jet. The process, follows the principle of anodic oxidation in the electrochemical machining (ECM - Electro-Chemical Machining). It is performed in an electrolyte via a locally applied voltage jet, wherein the surface is dissolved selectively and free of forces by an electrochemically process without mechanical contact between the tool (cathode) and component (anode). In opposite to other known methods for the structuring of surfaces, it is obtained by a contactless scanning of the surface by a nozzle, that is able to recognize unevenness and to take them into account accordingly. The destruction of the thin skin at the surface of the aluminum foams can therefore be

practically precluded. For the determination of the electrolyte and the required processing speed, several test cycles are performed. The crucial aspects include the amount of material, the manufacturing accuracy and the duration of processing. Alas, the expected processing time is unattractive for large-scale production. The specified parameters for the electrochemical machining are summarized in Table 2.

**Table 2. ECM Process Parameters**

Parameters	Value
Jet diameter	100 $\mu\text{m}$
Electrolyte type	$\text{NaNO}_3$
Electrolyte flowrate	10 ml/min
Machining speed	900 $\mu\text{m/s}$
Line offset	280 $\mu\text{m}$
Operating distance	100 $\mu\text{m}$
Machining time	5,77 h

For the preliminary investigations, the specimen were machined on both sides on the entire surface. Figure 3 shows a sample of the first successful test cycles, wherein a surface tension of 42 mN / m was measured. During the preparations, the surfaces are examined by micro-CAD projection. The result of this process-integrated scan is a high-resolution imaging of surface structures with a measurable surface roughness and its distribution over the entire component. The documentation for each sample and the color visualization are shown in Figure 5.

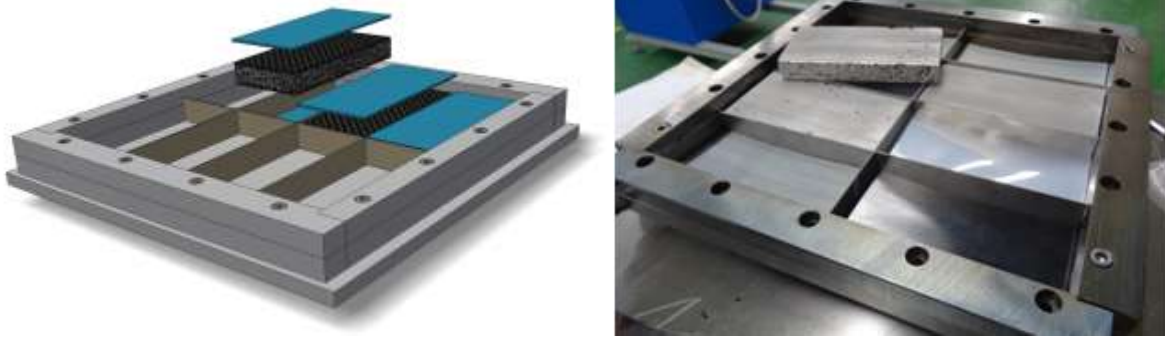


**Figure 5. Color visualization of an aluminum foam surface skin**

## MANUFACTURING PROCESS

The manufacturing of the HSC-specimens is a hybrid thermal pressing technology. To avoid a delamination in the interface between the core and the top layers in downstreamed process steps (e.g. cutting) [3], a Near-Net-Shape thermal pressing tool was designed, which realized the subsequent specimen geometry (Figure 6).



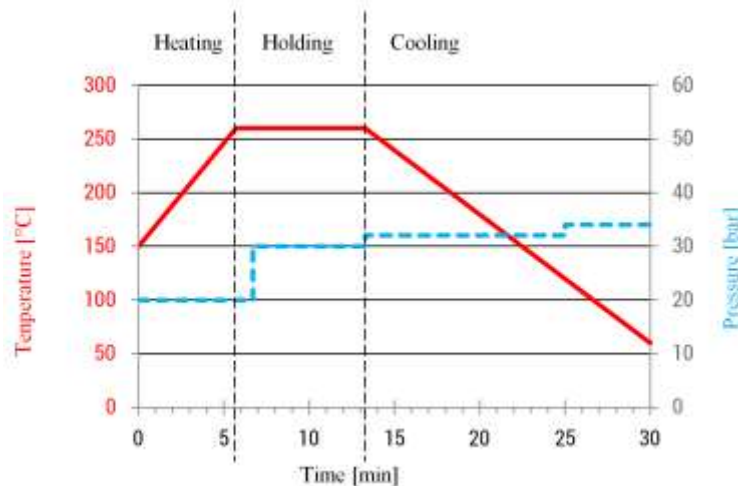


**Figure 6. Near-Net-Shape Thermal Pressing Tool (concept, prototype)**

Justified by the formation of internal stresses in the preparation of core composites, in addition to the integration of the buffer layers, a special temperature/ pressure-profile was dictated [6]. It is divided into three phases: heating, holding and cooling. The first phase starts at a mold temperature of 150° C and 20 bar pressure. Due to the low temperature, the plasticized thermoplastic matrix of the outer layers is comparatively high viscous. In addition to the relatively low compression, no fibers are displaced in the mold.

In the second phase shortly after reaching the maximum preset temperature of the base plates from 260°C, the initial pressure of 20 bar is raised to 30 bar. Under this pressure, the viscous matrix begins to fully impregnate the the inherent reinforcing fibers. With the beginning of the cooling phase, the pressure gets slightly raised in several steps to counteract the effect of residual stresses, that would cause delaminations.

The described profile in the temperature/ pressure-time curve was developed in extensive studies for the production of hybrid laminates and composite sheets. It is schematically shown in Figure 7.



**Figure 7. Temperature-/pressure profile of HSC processing**

## BENDING TEST, RESULTS

During the bending tests, the specimens, prepared as a core composite, indicate the typical failure pattern, according to DIN 53290. The failure of the core is followed by a delamination of the outer layers. For all samples, the complete component network remains intact especially between the cover layers and the core. A emergency operation mode is ensured. In comparison to non-reinforced aluminum foams, HSC cause a significant increase in the flexural modulus, observed in consideration of the strong variations in the distribution of the density. That is recognizable by the specific flexural modulus, in wich the flexural modulus refers to the density of the individual samples. The increase of the specific bending stiffness can primarily be assigned to the influence of the outer layers (Figure 8).

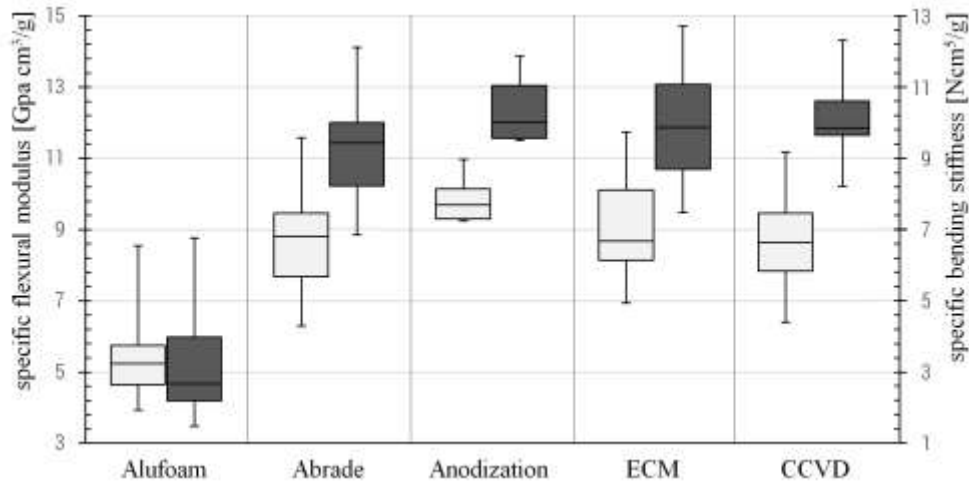


Figure 8. Specific flexural modulus and specific bending stiffness

## CONCLUSION - POTENTIAL FOR APPLICATION IN PASSENGER VEHICLES

Motivated by the homogeneous properties of aluminum foam structures, the sandwich construction offers the main advantages of continuous semi finished parts. In reference to the characteristics of a shear wall support, the main burden of tensile and compressive forces of bending loads are assigned to the outer layers, whereby shear loads are transfer to the internal core structure. Thus, the the different layers can be specifically designed to meet the demands in an integrated design. The principle of sandwich construction allows a reduction of the mass of about 59%. With a dedicated manufacturing process, regarding to the subsequent part geometry, the outstanding characteristics of Hybrid Sandwich Composites (HSC) can be fully exploited by the influence of the interface design.

## ACKNOWLEDGEMENTS

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