IOP Conf. Series: Materials Science and Engineering **118** (2016) 012042 doi:10.1088/1757-899X/118/1/012042

Process combinations for the manufacturing of metal-plastic hybrid parts

W-G Drossel, C Lies[1], A Albert, R Haase, R Müller and P Scholz
Fraunhofer Institute for Machine Tools and Forming Technology IWU, Chemnitz, Germany
[1] Corresponding author

Abstract. The usage of innovative lightweight materials and processing technologies gains importance in manifold industrial scopes. Especially for moving parts and mobility products the weight is decisively. The aerospace and automotive industries use light and high-strength materials to reduce weight and energy consumption and thereby improve the performance of their products. Composites with reinforced plastics are of particular importance. They offer a low density in combination with high specific stiffness and strength. A pure material substitution through reinforced plastics is still not economical. The approach of using hybrid metal-plastic structures with the principle of "using the right material at the right place" is a promising solution for the economical realization of lightweight structures with a high achievement potential. The article shows four innovative manufacturing possibilities for the realization of metal-plastic-hybrid parts.

1. Introduction

In the automotive industry, there is a longstanding effort to find lightweight construction solutions that on the one hand ensure that car body components have the necessary stability, but on the other hand allow the parts to be produced at low cost. Along with lightweight materials such as aluminium, magnesium and high strength steels, nowadays multi-material design and hybrid components made of plastics and metals can help achieve these objectives. As a result, it is not only possible to further reduce weight [1], but also to implement more complex structures, which for instance can be achieved by injection moulding. Beside the integration of additional functions, the implementation of functional elements for joining or assembly purposes becomes feasible by means of plastic injection moulding. However, the metal guarantees the strength of the component and assembly to the car body by well-established processes. It is essential that the production technology applies these composite structures made of plastics and metal. As a rule, the metal components are made first in separate processes. Afterwards they are joined with the plastic component in the injection moulding process. To guarantee reliable adhesion between metal and plastics, the metal components must also be coated with a bonding agent. The resulting process chains are extensive, labour-intensive and costly. In the following four innovative manufacturing possibilities are presented for the realization of metal-plastic hybrid parts.

2. State of the art

2.1. Metal/plastic hybrid components

Metal-plastic hybrid components applied in the car industry can generally be classified into two classes according to the underlying metal component: sheet based (Figure 1) and tube based (Figure 2) parts.

Figure 1. Audi TT front end carrier [2]

Figure 2. Mercedes B class front end carrier [3]

In sheet based parts, one or several – mainly deep drawn – metal component(s) are combined with an injection moulding component. This approach is for instance applied to front end carriers. In tube based metal-plastic hybrid components, a hollow profile made by hydroforming is used as the metal carrier component, which is com-pounded with an injection moulding component. These parts are employed as cockpit cross members. In the state of the art, the tube or sheet parts are produced separately from the plastic parts. The injection moulding process is applied to form the plastic parts and join the components only. The current process chains are accordingly long. As a consequence, new approaches have to be investigated to shorten these process chains.

2.2. Components based on hybrid materials

Within mobility applications, most structures are assemblies of shell-like components. Conventional solutions e.g. for a car body are based on monolithic sheet metal and forming and joining technologies which are able to provide large outputs and high productivity at the same time. Following the demand for lightweight solutions and improved performance, a replacement of the pure metal sheets by hybrid laminates is intended. Aiming at high bending inertia for structural applications, the typical metal-plastic-metal composition arises. Steel and aluminium are the common options for the cover sheets, while the core layer can consist of different plastics, including optional fibre reinforcement. Different hybrid laminates are available on the market as pre-materials. The thickness of the metal skins is commonly within the range of 0.2–0.25 mm. The core layer usually exceeds that value by a factor of 2–5 and is within the range of 0.4–1.0 mm. Materials with thicker cores are also available on the market, but of less importance to forming caused by the decrease in formability.

In parallel, the requirement for high efficiency of the manufacturing processes re-mains. Accordingly, the initial approach was to use hybrid laminates as pre-material for well-established sheet forming technologies. The increased laminate thickness on the one hand allows improved mechanical properties, but on the other hand appears as an obstacle to conventional forming technologies (Figure 3).

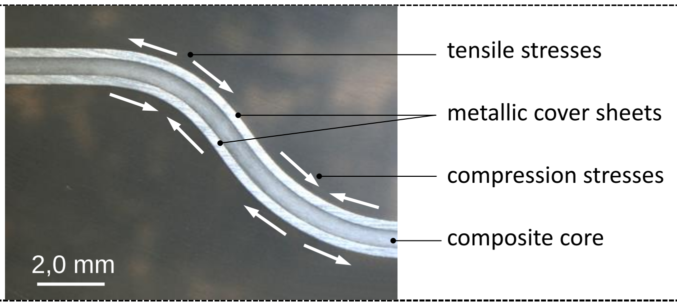

Figure 3. Layer composition and stress state in a deep-drawn laminate component.

New failure modes came up such as delamination of the layers due to excessive shear tension and wrinkling of the metallic cover sheets into the less compression resistant core material. As a consequence, the forming limit was significantly decreased for bending and deep drawing processes compared to monolithic blanks. To overcome these limitations, alternative process routes have to be developed. By temperature-supported forming, the fixed bond can be released and allows a shear deformation between the single layers. Another option is to form the single components first and to establish the layer bond subsequently. The solidification of the core material needs to be completed before ejecting the component from the tool. The use of this approach enables to increase the forming limit and the manufacturing of composite parts which are free from forming induced defects.

2.3. Lightweight structures with aluminium foam core

Aluminium foam combines low density with high stability; it shows a good mass/stiffness ratio, and due to its cellular structure it has high energy absorption and damping capacities. Because of this diversity of properties, aluminium foam offers excellent possibilities for the production of statically and dynamically stable lightweight construction [4].

Usually, semi-finished aluminium foam products such as sandwiches and foamed profiles are produced, which can be easily assembled to large assemblies. Today, foaming procedures and manufacturing of semi-finished products such as sandwiches are well mastered. Many prototypes and also serial assemblies show the trend towards an intensive use of aluminium foam as a material for lightweight construction, either the pure material or in composites [5].

Basically, two ways of producing aluminium foam/steel sandwiches are used:

- Direct application of foam and thus bonding of the cover sheets;
- Gluing of the pre-fabricated foam core with the cover sheets.

The sandwich fabrication by direct foam application is realized in several process steps (Figure. 4):

- Production of a mixture of the metal base powder (e.g. Al) and a foaming agent (e.g. TiH2);
- Compacting the powder mixture, e.g. by the process steps of axial pressing and extrusion moulding;
- Positioning and fixing the sandwich cover sheets in the foaming mould;
- depositing the foamable pre-material, and sealing the border areas;
- Foaming of the charged pre-material in the foaming mould at the melting temperature of the aluminium alloy, and subsequent cooling.

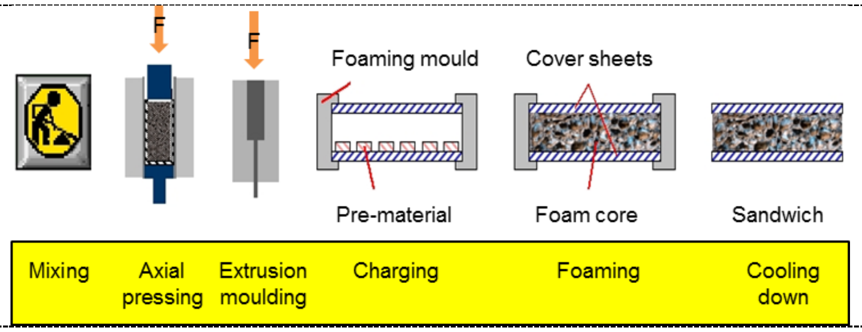

Figure 4. Fabrication of aluminium foam/steel sandwiches by the melting powder metallurgical procedure.

3. New processes for the in-situ manufacturing of metal-plastic-hybrid parts

3.1. Process combination of deep drawing and injection moulding

Within the framework of the Federal Cluster of Excellence MERGE, in cooperation between the Fraunhofer IWU and the TU Chemnitz, a hybrid process was developed, combining the technologies of deep drawing, injection moulding and forming by means of the molten plastic. This combination of technologies allows in-situ manufacturing of sheet-based metal/plastic hybrid components in one die using only one hybrid process. The designed manufacturing process consists of two stages (see Figure 5). In the first step, the sheet to be formed is fed into the die and deep drawn mechanically. After deep drawing, the plastic is injected. This is used to manufacture the plastic component and furthermore for media-based forming of the metal component. The test part consists of a cup with interior ribbing and undercut, shown in Figure 6).

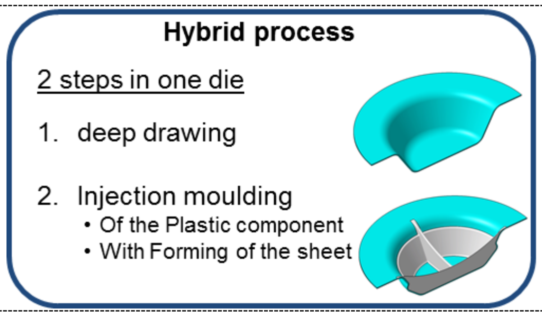

Figure 5. basic principle of the combined deep drawing and injection moulding process

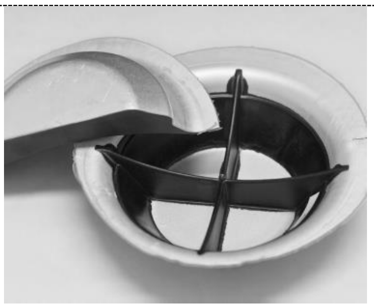

Figure 6. manufactured demonstrator part

To realize deep drawing, the die was designed for utilization on a deep drawing press. A bolt-on unit was used for the injection moulding procedure (see Figure 7). The adhesion was not only achieved by the form fit that was generated by the manufactured undercut, but also by using a chemical bonding agent previously deposited on the blank surface.

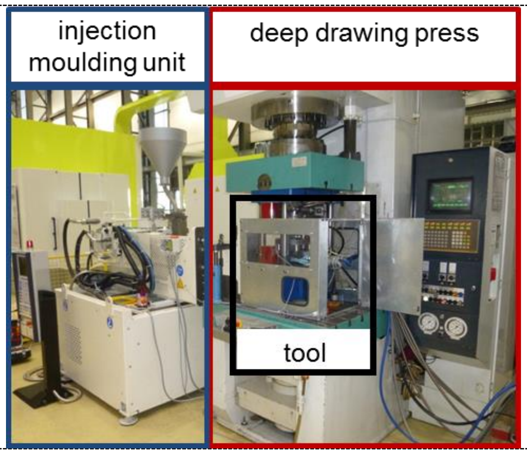

Figure 7. deep drawing and injection moulding: experimental setup

Process parameter	Value
Tool temperature	80 °C
Melt temperature	265 °C
Plastic	Durethan BKV 60
Metal	DC04, with and without bonding agent

Figure 8. process parameters

3.2. Process combination of hydroforming and injection moulding

The second method is focused on the combination of tube-based hydroforming and injection moulding (see Figure 6). This technology entails a tube that is formed by an inside-operating medium (here: nitrogen), which generates secondary design elements. With the necessary cavities on the outer side, plastic components are applied via injection moulding. The compressed medium inside the tube ensures the necessary counter–pressure, which avoids the collapse of the tube.

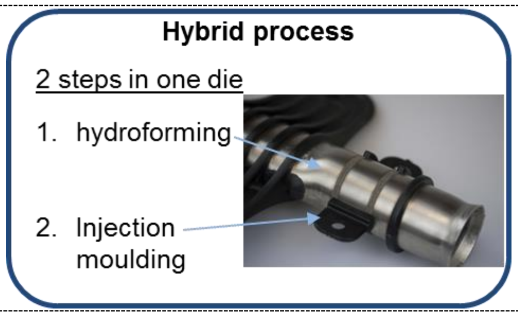

Figure 9. basic principle of the combined hydroforming and injection moulding process

Figure 10. manufactured demonstrator parts

A focal point is to evaluate the bonding strength (tensile, shear, torsional) between the metal tube and the plastic component. For this purpose, different tool inserts were realized for applying plastic elements with varying parameters. To ensure the bonding strength, mostly chemical bonding agents are used such as Vesta-melt®X1333. However, they are very cost intensive. The aim is to substitute these chemical bonding agents by surface structuring of the metal tubes. The surface structuring methods blasting (several grain sizes), knurling and laser structuring were investigated. For comparison with the preferential state of the art solution, a chemical bonding agent (Vestamelt®X1333) and tubes without any treatment were also examined. The following factors were considered in the experiments:

- Tube material: aluminium EN AW 6060; stainless steel (grade 1.4301)
- Tube temperature: room temperature, 80 °C, 140 °C, 200 °C, 250 °C
- Surface treatment: without, Vestamelt®X1333, corundum blasting, laser
- structuring, knurling

PA6 with 60 % fibre glass reinforcement (Lanxess Durethan® DP BKV 60 H2.0 EF) was used as the plastic material.

In terms of surface treatment, maximum shear strength was achieved at 19.7 N/mm², and thus the best composite bonding was achieved by using the chemical bonding agent Vestamelt®X1333. In case of the laser structured parts, the joint failed only slightly earlier at 18.1 N/mm². Even in case of the knurled tubes, it was possible to achieve good maximum shear strength values of 6.1 N/mm². In contrast, the tubes without coating showed shear strength values below 1 N/mm², and the sandblasted tubes values below 2 N/mm², scarcely providing any potential for good shear strength of the compound as a whole. An influence of the tube material on the shear strength could only be found in the laser structured and knurled test parts. In the case of the laser structured tubes, maximal shear strength of the adhesion is approx. 18.1 N/mm² (steel tubes) and approx. 12.3 N/mm² (aluminium tubes). The reason for these results is the different failure behaviour of the joint as well as the different laser structuring. During laser structuring, the surface of the tubes is melted and the molten material swirled. In the case of the steel/plastic composite components, only the joint breaks. In the case of the aluminium/ plastic joints, the failure is partially represented by the fracture of the filigree aluminium structures. Tempering of tubes does not significantly affect the bonding strength relating to shear strength.

Tensile strength of the bond between the hydroformed metal tube and the injection moulded plastic component could only be realized with the chemical bonding agent or by laser structuring of the surface. The best bonding strength with the use of Ves-tamelt®X1333 could be realized with a tube at room temperature. By using the laser structured tube, the metal components have to be heated up for better tensile strength. The bonding strength with the laser structured steel tubes with a tube tem-perature of 250 °C is nearly the same bonding strength compared to using Vesta-melt®X1333 with tubes at room temperature. Like the shear strength, also the tensile strength of the parts with laser treated aluminium tubes is lower than using Vesta-melt®X1333 treated tubes. Figures 11 and 12 shows the realized bonding strength values determined for components hydroformed in combination with injection moulding (metal tube and injected PA6/GF, test speed 2 mm/min, 3 repetitions of every test).

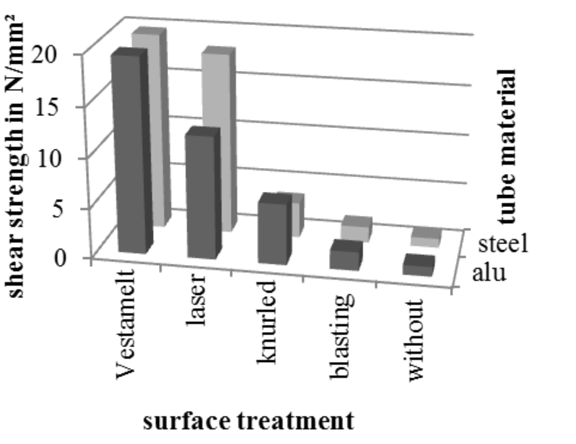

Figure 11. *shear strength*

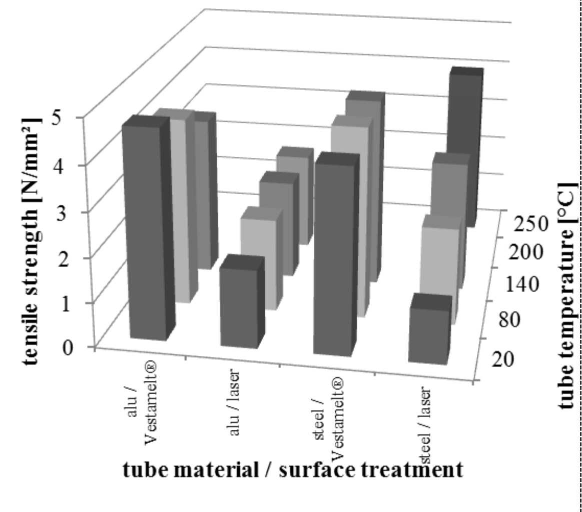

Figure 12. *tensile strength*

In the previous investigations, the authors immediately achieved outstanding shear strength and tensile strength values that are commensurable with those of the chemical bonding agent. These results were obtained by laser structuring without any additional optimizations in the first test loop. Depending on the requirements to be fulfilled by the corresponding part, a knurling treatment may be sufficient as a standalone solution. However, when using knurled tubes, the joint created cannot withstand tensile nor shear stresses. In contrast, laser structured parts can be subjected to tension without any global form fit.

4. Production technologies for hybrid laminates

Aiming for an increased formability and to create high-volume production compatible technologies, different process routes (Figure 13) were benchmarked.

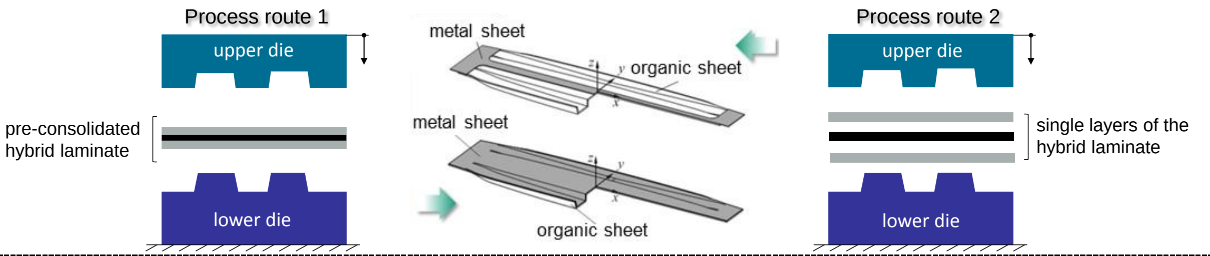

Figure 13. Process routes for the manufacturing of hybrid laminates, left: forming of pre-consolidated hybrid laminates, right: consolidation during forming process

Pre-consolidated hybrid laminates are used in forming process route 1 providing the following characteristics:

+ hybrid joint is already established
+ no bonding process needs to be considered
+ processing quite similar to monolithic material
- significantly lower forming limit
- forming induced defects possible

The hybridization of the single components during the forming operation as shown in process route 2 does provide the following properties:

+ sliding of layers during forming is possible
+ increased forming limit
+ prevention of forming induced defects
- bonding needs to be considered as an integrated / subsequent step
- higher cycle time due to tempering of part and tool

Within the DFG-AiF Cluster ‘Process chains for complex parts made of hybrid laminates’, an actively heated and cooled forming die (Figure 14) was developed with the aim to realize short cycle times. To investigate the feasible cycle times the hybrid part was equipped with thermocouples and heated up in the forming tool to 230 °C (melting temperature polymeric core material) to ensure a complete consolidation. Afterwards the forming tool was cooled down until the ejection temperature of the hybrid part from 180 °C. The heating and cooling took 3.5 min and 2.5 min respectively. The thermal behaviour concerning the heating phase is illustrated in Figure 15).

IOP Conf. Series: Materials Science and Engineering **118** (2016) 012042 doi:10.1088/1757-899X/118/1/012042

Figure 14. *Lower die with stacked laminate and temperature sensors*

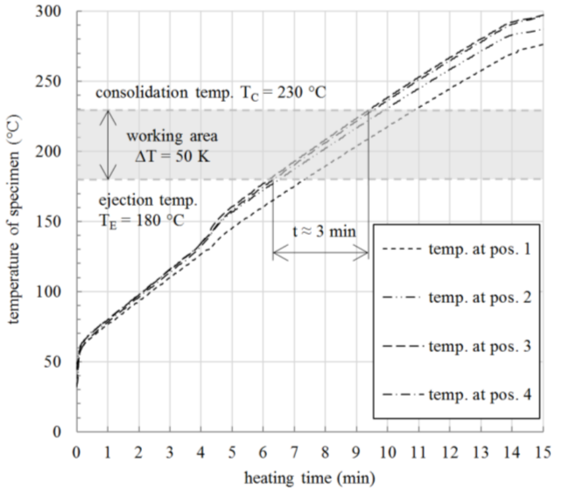

Figure 15. *Temperature behaviour of tool and clamped laminate in heating phase*

At a heating rate of 0.25 K/s and a cooling rate of 0.33 K/s, an overall cycle time be-low 6.5 min could be achieved. For potential mass production the cycle time has to be reduced further. For example lower cycle times could be achieved by reducing the tempered mass in combination with an adaption of the design of the temperature conditioning devices. The correlation between the critical cooling rate and thus induced residual stresses is one major focus for future research activities.

5. New production technology for hybrid-lightweight-structures with aluminium foam core

One focus of the Federal Cluster of Excellence MERGE is the development of light-weight sandwich composites made of metal foam and fibre-reinforced plastics (FRP). Metal foams are highly suitable for lightweight structures. The combination of metal foam with sheet metal covers as sandwich structures is already used in manifold applications [6].

In order to enhance the level of lightweight construction in metal sandwich structures, the substitution of metal cover sheets with fibre-plastic composites provides an effective approach. By adapting the thickness of core and FRP layers in combination with high performance fibres to the applied load, it is possible to realize specific structural properties with a customized design [7]. The permanent bonding of the sandwich components is realized in a pressing process. Therefore, the sandwich components need to be preheated. To increase the energy efficiency, a technology will be developed using the process heat of the foaming instead of additional preheating. For achieving a high functional density, an injection moulding process can be used to implement thermoplastic elements, e.g. stiffening rips or mounting interfaces, into these sandwich structures based on metal foam cores. One key aspect is the bonding of both components. To find an optimal combination, many experiments have been carried out to investigate the influence of various parameters, e.g. the modification of the metal foam surface and thermoplastics or the use of adhesive agents. To compare different surfaces and surface treatments, tensile tests were executed as part of this investigation. For the tensile tests sample plates of 170 mm x 170 mm were foamed. As an additional step, some of them were pre-treated by the SACO-process (Figure 17). It is a sandblasting process with a chemically modified blasting material to create a certain roughness to increase the bonding surface and additionally coat the surface [8].

As an alternative to additional surface treatment with sand blasting, a structure was implemented on further samples to increase the surface area. Different structures are feasible. The first tested structure is displayed in Figure 16. The structure of the foaming tool is very well reproduced by the foaming process. It is a lattice structure with a distance of approx. 1 mm between 2 peeks and the peaks have a height of approx. 230 µm. Afterwards the samples were compression moulded with the cover plates – polyamide 6 with glass fibre reinforcement. Out of these combinations smaller samples of 50 mm x 50 mm were cut by waterjet. The samples were glued onto adapters for the tensile testing machine. Then the samples were tested with an extension rate of 0.5 mm/min at room temperature based on DIN 53292: "testing of sandwiches; tensile test perpendicular to the faces".

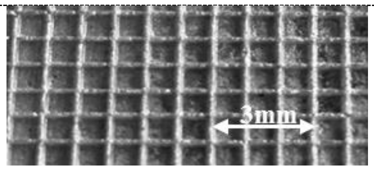

Figure 16. *Foam with structured aluminium skin,*

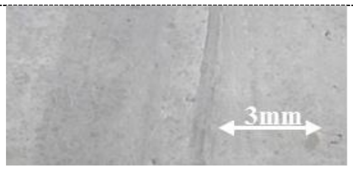

Figure 17. *SACO-treated foam*

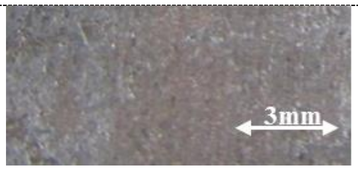

Figure 18. *untreated foam*

The test results show that the SACO-treated samples sustain a very good average test force of 10.8 kN. A couple of samples failed in the foam core, which was due to a significantly lower density compared to the other samples. These values were left out of the calculation of the average force.

Looking at the valid samples, the failure occurred not in the sample itself, but the glued test adapters detached. Therefore the mechanical strength of the samples themselves should clearly exceed the joint strength. More experiments with a better adhesive have to be executed to derive a more accurate bonding strength of the samples. Nevertheless the aim is to have a bonding strength higher than the tensile strength of the foam core. For densities up to 1 g/cm³ this was already achieved. For most of the applications, lower foam densities are used. The structured samples break at an average force of 0.9 kN. The untreated samples (Figure 18) reach an average force of 2.6 kN, Figure 19.

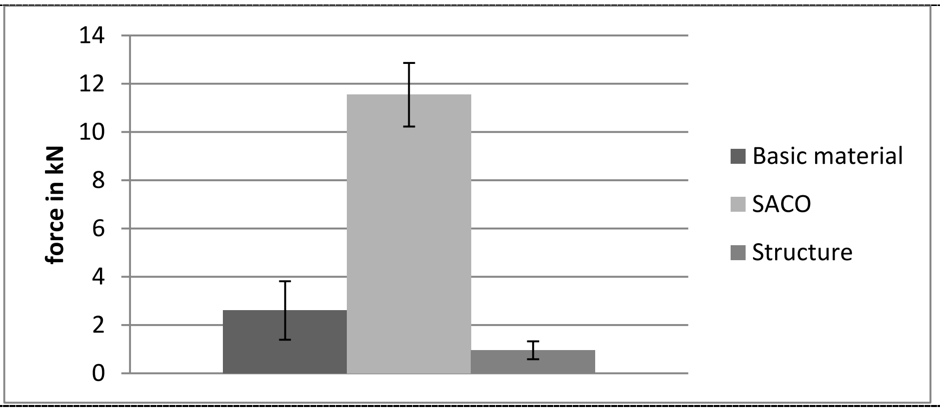

Figure 19. Average of the maximum resulting forces of the tensile tests

In comparison, the SACO-processed samples reach the highest values, but for a series production of this kind of sandwich parts a route without additional steps such as sandblasting was clearly preferred. Despite of the increase of the surface area to 140 %, the maximum force of the structured samples reached lower forces in comparison to the basic aluminium foam. One reason for the poorer results of the structured samples could be the entrapped air in the "pockets" between the ridges which prevent good bonding of the components. This assumption will be reviewed by microscopy in the next step. To provide better bonding, finer structures should be tested, taking into account the achievable reproducibility of such structures in the foaming process. Furthermore an additional layer of matrix material e.g. granulate is suggested to secure that no ambient air gets entrapped.

6. Summary and outlook

Until now, the manufacturing of metal-plastic hybrid components has still been very labour and cost intensive due to the separate production of metal and plastic components. For this reason, integrated processes are developed to enable the production of affordable hybrid components.

In the Federal Cluster of Excellence »Merge – Technologies for multifunctional lightweight structures« the focus lies on process combinations for manufacturing of sheet metal based and tube based hybrid components. The developed concept for the production of sheet metal-based hybrid components is a combination of deep drawing and injection moulding. Furthermore, the melt is used for media-based forming. For the production of tube-based hybrid components, the combination of hydroforming and injection moulding is following a similar approach.

The adhesion between the two components is very important in order to use the high potential for such a lightweight construction. In industry, the bond strength is mostly realized by a chemical bonding agent. The aim of the current work is the replacement of chemical bonding agents by surface structuring of the metal component. Especially the structuring by laser showed enormous potential in preliminary investigations.

Within the DFG–AiF Cluster 'Process chains for complex parts made of hybrid laminates' tempered forming strategies for single or even readily joined laminate com-pounds are elaborated. A suitable design of the interface between metallic and polymeric component dominates the research activities in this field. The production of the composite and the simultaneously occurring forming is determined as a complex hybrid process. To meet the demands of mass production, the different process routes are compared and evaluated in terms of forming limits as well as regarding the possible output quantity. For profound understanding and systematic improvement of the layer adhesion, the adhesive mechanisms are considered at different levels of scale and targeted through customized semi-finished properties and process parameters.

In addition using conventional materials, further research priorities are the development and efficient production of composites of aluminium foam and FRP layers with a high degree of lightweight construction with high functional integration.

Acknowledgments
The presented results were elaborated within the Federal Cluster of Excellence EXC 1075 "Merge Technologies for Multifunctional Lightweight Structures" and DFG-AiF Cluster 'Process chains for complex parts made of hybrid laminates'. The projects are supported by the German Research Foundation (DFG) and German Federation of Industrial Research Associations (AiF) respectively. Financial support is gratefully acknowledged.

Literature

[1] Abibe A B, Amancio-Filho S, dos Santos J, Hage Jr E: 2013 *Materials and Design 46* Mechanical and failure behavior of hybrid polymer-metal staked joints, pp. 338–347

[2] LANXESS Deutschland GmbH 06.08.2007 *Anwendungsbeispiel: Das erste Frontend in Aluminium-Hybrid-Technik mit Durethan® BKV 30* Business Unit SCP TI 2006-047 DE

[3] http://www.plasticsnews.com/article/20131015/NEWS/131019961, status 20.05.2014

[4] Neugebauer R, Lies C, Hohlfeld J, Hipke T 2007 *Production Engineering Volume 1* Adhesion in sandwiches with aluminium foam core pp 271-278.

[5] Hipke T, Lange G, Poss R *2007 Taschenbuch für Aluminiumschäume. 1st edn.* Aluminium-Verlag Marketing & Kommunikation GmbH pp 24–25

[6] Nestler D, Jung H, Trautmann M, Wielage B, Wagner G, Drossel W-G, Drebenstedt C, Hipke T 2015 *Materials Science Forum Volumes 825–826* New sandwich structures consisting of aluminium foam and thermoplastic hybrid laminate top layers pp 797–805

[7] Drebenstedt C, Lies C 2014 *Ingenieurspiegel 3* Herstellung und Einsatzpotenzial hybrider Leichtbaustrukturen mit Aluminiumschaumkern. pp 60–61

[8] Habenicht G 1973 *Kleben 6th edition*, Springer, Berlin Heidelberg New York