MULTI-MATERIAL SYSTEMS FOR TAILORED AUTOMOTIVE STRUCTURAL COMPONENTS

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1 Introduction

Protecting passengers and their comfort, reducing vehicle weight, and minimizing production costs are important aspects in developing new automobile components and structures. These apply in particular to developing crash-relevant structures. In addition, to meet future regulations in climate protection, the automotive industry must develop innovative and integral approaches for lightweight construction.
Currently, three main trends in automotive lightweight construction are obvious: Lightweight design can imply high-strength metal alloys, substituting metals with composites, and the combination of different hybrid materials.
Using high-strength metal alloys offers the opportunity to reduce wall thickness of structures. However, once a critical minimum thickness is reached, designers can expect stability problems. Thus, the potential of high-strength materials for light weight construction is limited.
Second, substituting conventional construction materials with carbon fibre reinforced plastics (CFRP) allows considerable weight savings [1], [2]. This substitution is restricted to high-priced vehicles because of long cycle times and high material costs.
Hence, structural components realised in multi-material design are an interesting alternative. In this context a combination of sheet metal blanks from steel with a local CFRP reinforcement is investigated. This design should allow manufacturers to produce safety-relevant vehicle components, such as b-pillars, at lower costs compared to a mere CFRP design [3].
The local CFRP reinforcement in sheet metal structures offers a high weight-saving potential because the reinforcing patch can be applied only in highly loaded areas while the reinforcing properties can be adjusted to special load cases [4]. Locally applying the CFRP can reduce the wall thickness of the steel parts. Furthermore, the material costs can be effectively reduced when compared to mere CFRP parts. An adequate component could be realised by separately forming the sheet metal component, manufacturing the CFRP reinforcement, and bonding with an adhesive. This combination results in comparatively long process chains as well as long cycle times because of the curing time of adhesives of about 30 minutes.
An alternative process is the prepreg press technology where an uncured CFRP prepreg is directly formed into sheet metal structure. No limitations regarding the material type occur for the metallic component so presshardable steels are also usable. In this case the epoxy resin of the prepreg becomes an adhesive. After the forming process the tool is kept close about three to five minutes where a pre-curing could occur. The final curing of the CFRP reinforcement could take place, for example in a downstream, cataphoretic painting process.
A further approach is the combined forming of semi-finished components made of a sheet metal blank and CFRP prepreg during one process step. Thus, an uncured CFRP prepreg is applied locally to a sheet metal blank and then both components are deformed until reaching the desired geometry. The curing process can occur analogously to the prepreg press technology. This approach should allow a further significant reduction of process steps and cycle time.
Before an industrial application of these approaches can be realized, basic research work regarding results and a suitable process design for prepreg pressing as well as a combined forming are necessary. Especially the highly diverse material properties of the semi-finished components require an adequate process design. Accordingly, the aim of

the technological research work is developing suitable process strategies and tool concepts so that components with good performance can be produced in a short and robust process chain at minimal costs.

2 Prepreg-Press-Technology

2.1 Process Run and Parameters

Prepregs are pre-impregnated, semi-finished fibre products that are produced continuously on special machines and shipped on coils. After realization of a layer structure according to the expected loads and cutting, the prepregs and the sheet metals are joined in a separate forming process. To activate the process, a robot places formed sheet metals into the mould. Then the tailored prepreg is put automatically into the mould and pressed by a heated punch onto the sheet metal (Fig. 1.).

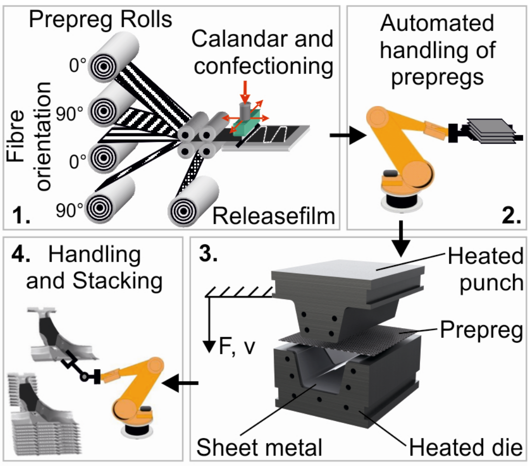
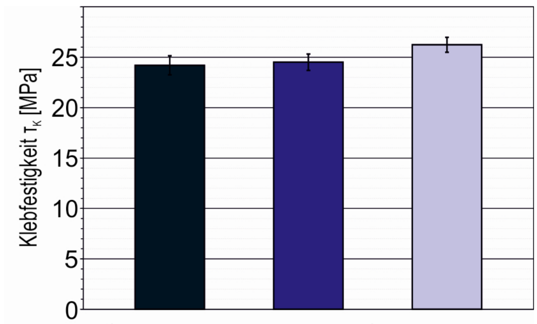


Fig. 1. Process steps for prepreg-pressing to produce hybrid automotive structural parts, for example a b-pillar.

Under the influence of elevated tool temperature (180 °C) and pressure (0,2 to 0,5 N/mm²), the prepreg is pre-cured in the closed mould. This step can occur within short cycle times of about 120 seconds by using optimized process parameters. The final curing of the epoxy resin occurs in a downstream cataphoretic painting process that is simulated by a furnace heating of 30 minutes at 180 °C. Using the matrix resin as an adhesive to bond the sheet metal and the CFRP makes an additional joining process superfluous.

2.2 Bonding of CFRP and Sheet Metal

Bonding between the CFRP and sheet metal is a decisive factor for the functioning and strength of hybrid materials. In order to characterize the bonding properties and to compare them with those of adhesive-bonded joints, shear-tensile samples were investigated according to DIN 1465.
To find an optimum of the conflict between economical aims and strength of the joint, time and temperature for consolidation during the prepreg-press process was varied according to the reaction-velocity temperature rule (Arrhenius equation). Temperature was varied between 120 °C and 200 °C, while the highest strength was reached at a temperature of 180 °C at a curing time of 210 seconds. The prepreg-pressed samples were compared with adhesive-bonded samples and the influence of different types of surface treatment was investigated (Fig. 2.).



Bonded with:	Epoxy resin (SGL, Type E201)		Betamate 1620
Temp.:	180 °C		180 °C
Time:	210 s (EP resin)		210 s (EP) 1800 s (1620)
Surface:	Oiled	Defatted	Defatted
Strength:	24,2 MPa	24,5 MPa	26,2 MPa

Fig. 2. Comparison of joint strength of prepreg-pressed samples with adhesive-bonded samples.

For the adhesive-bonded samples an impact-resistance, modified structural epoxy adhesive was used (Dow Betamate 1620). In all samples, the orientation of the fibres closest to the boundary layer was vertical to loading direction (90°). Notice that no significant differences in strength occur between the prepreg-pressed samples and the adhesive-bonded samples. While for the pressed samples failure occurred in between the boundary layer and the second fibre layer of the CFRP, the adhesive-bonded samples failed through delamination of the first fibre layer. The joint area itself remained undamaged.

The fibre orientation of this layer has the greatest influence on the properties of the joint (Fig. 3.). Samples with fibres vertical to the direction of loading (90°) had the highest strength. The elastic matrix material dominated the mechanical properties close to the boundary layer. The fibres only bear a small part of the load. Thus, the laminate can absorb local tension peaks like a bond line. Samples with fibres parallel to loading, in the contacted layer, failed with 75 % of the load applied.

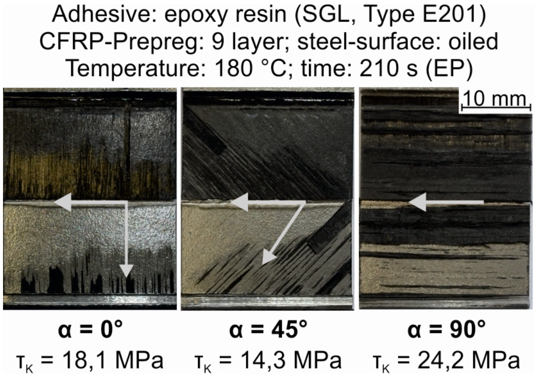


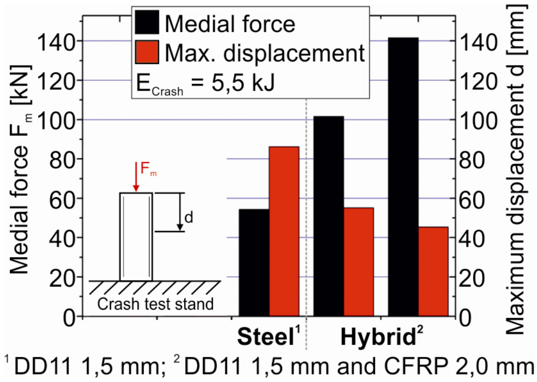
Fig. 3. Influence of fibre orientation of the contacted layer on the bond strength.

The inhomogeneous structure of CFRP is reflected in the properties of the joint. Special properties of such materials need to be considered in the design of multi-material systems in order to achieve the intended properties of the compound.

2.3 Crash Tests of Hybrid Structures

Applications for hybrid structures manufactured by prepreg-pressing are crash-relevant automotive structural components. To analyse the behaviour of hybrid materials under crash loads, different tests have been accomplished. For a fundamental qualification double-Z-profiles made of 2 mm DD11 steel and 9 layer CFRP reinforcement have been manufactured. These profiles were tested on a carriage crash tests stand under compression forces comparable to an automotive crash box.

As a first result, hybrid materials offer a significant weight saving potential. The medial forces and the maximal displacement of deformation of hybrids are on average 120 kN and 50 mm for an application of energy of 5,5 kJ. Steel structures achieve about 80 kN and 55 mm (Fig. 4.).



[1] DD11 1,5 mm; [2] DD11 1,5 mm and CFRP 2,0 mm

Fig. 4. Medial forces and maximal displacement of double-Z-profile samples under crash loads.

Next steps are to expand the number of crash tests. This means to vary steel-materials, prepreg layers, and other forces, for example three point bending.

3 Combined Forming Process

3.1 Process Run and Used Semi-Finished Component Design

A further approach to manufacturing automobile structure components in multi material design is a combined forming of sheet metal blanks and CFRP prepregs. There the material behaviour of the metallic component and the CFRP prepreg differs extremely and must be considered during the forming process. For example, major deformation mechanisms of the CFRP prepreg are draping, interlaminar layer slip as well as transversal flow and resin percolation inside the prepreg [5].

Appropriate tests examined the behaviour of the components during the forming process. In addition, the process and interaction between the components of the semi-finished material were characterised.

The semi-finished component used for first experiments consisted of a sheet metal blank (DC04, s_0 = 1 mm) and a non-cured CFRP prepreg as shown in Fig. 5. Here, the CFRP prepreg is made of 9 layers with 230 g/m² weight of fibre per unit area and 39 % content of epoxy resin. To ensure comparability the same CFRP prepreg as for separately manufactured and adhesively bonded components is used. The single layers of the CFRP prepreg are arranged to the U-shaped profile axis by 0° and 90° fibre orientation so the CFRP prepreg has an orthotropic design, as shown in Fig. 5.

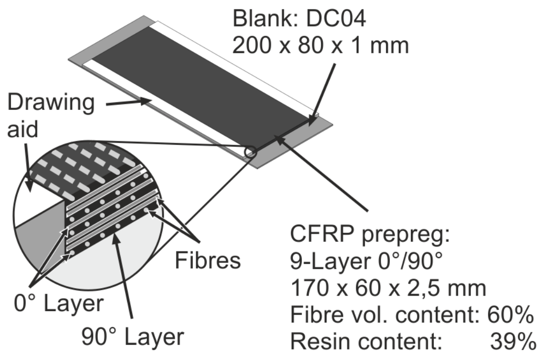


Fig. 5. Setup of the semi-finished component consisting of sheet metal blank and CFRP prepreg.

The first step combines forming the CFRP prepreg and the sheet metal blank. To achieve an unhindered process, course drawing aids with the identical height as the CFRP prepreg are placed beside the CFRP prepreg in the drawing direction. The drawing aids allow constant gaps between the tool components, preventing too high pressure on the CFRP prepreg and excessive transversal flow as a consequence.

In a next step the forming process is initiated. Therefore, the punch force as well as the blank holder force is set and the semi-finished component is formed by the punch into the die. After the forming phase the part remains inside the tool analogous to the prepreg press technology at specially adjusted pressures and tool temperatures for a pre-curing process (Fig. 1.). The final curing of the CFRP component can be also accomplished afterwards, as described above.

For a detailed analysis of the forming process and an evaluation of the achieved quality of the reinforced component, specimens were cut in the centre and examined by optical methods, for example microscopy. Thus, typical failures could be identified (Fig. 6.):

- High local variation of wall thickness (X_{DR}, X_{PR}) of the CFRP, especially in the range of radii, and
- Large extrusion of the CFRP component in the edge region (Δl).

In addition, this method allows a detailed examination of the fibre orientation in the forming direction along the cutting line. Thus, a qualitative statement about the interlaminar layer slip can be taken. Stretched fibres indicate a ‘good’ sliding of the layers, while wrinkled fibres point to no or only low sliding of the layers. Pores and blowholes in the drawing die radius region, as shown in Fig. 6, are probably the result of a low surface pressure during the curing process.

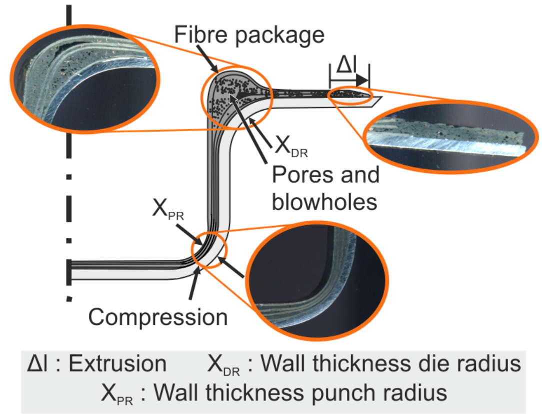


Fig. 6. Characteristics for the evaluation of the forming quality.

3.2 Course of Cold and Warm Forming Processes

An important process parameter is the tool temperature. The combined forming process uses two major strategies. The first strategy is a cold die process. In this process, the semi-finished component is formed until the desired punch force and blank holder force are reached. When the forming process is finished, the punch and blank holder forces are reduced and the tool temperature is set on $T_{Tool} = 200°$ C for a pre-curing. When the necessary temperature for curing is reached, the formed component remains for 4 minutes in the tool while the punch and blank holder forces are kept up. The whole process takes about 24 minutes as seen in Fig. 7, which is almost the same period needed for curing the adhesive when components are manufactured separately and adhered in a further process step.

By using this strategy manufacturers can achieve good results considering the quality characteristics as described above. When choosing favourable process parameters the fibres are stretched in the feed direction and they have no wrinkles. Consequently, a good interlaminar layer slip can be expected. The extrusion of the CFRP prepreg in the flange is $\Delta l = 3$ mm. The wall thickness in the punch radius where high pressure on the CFRP prepreg prevails is reduced by $\Delta X_{PR} = 0{,}7$ mm, and the increase of the wall thickness in the die radius (where less pressure appears) is only $\Delta X_{DR} = 0{,}7$ mm. These effects occur primarily in the

CFRP component while the change of the sheet metal blank thickness is almost negligible. The analyses have shown that a low pore formation in the CFRP component appears that can be traced to the drawing aids. Thus, major extrusions during the forming process can be avoided, but reducing pore formation requires further investigations concerning the optimal height of the drawing aids.

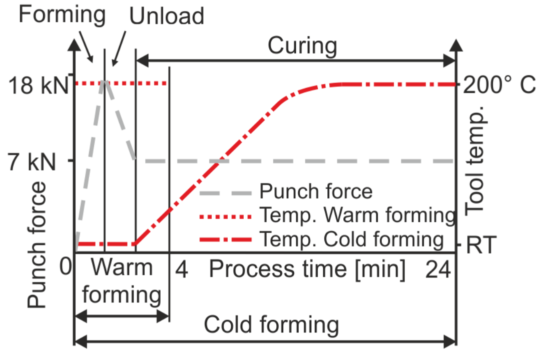


Fig. 7. Process diagram of cold and warm forming.

The second investigated strategy is the forming at elevated temperatures. Therefore, the tool is already heated up to $T_{Tool} = 200° C$ for the forming. Accordingly, time-consuming periods of heating up and cooling down can be avoided and cycle times of less than 4 minutes are possible.
Similar to the cold forming process, the semi-finished component is placed in the tool and is formed. The semi-finished component reaches the temperature from the tool within a few seconds, which reduces the viscosity of the resin inside of the CFRP prepreg. Consequently, the CFRP prepreg shows an extremely different behaviour during the forming process when compared to the cold forming. That results in an increasing CFRP prepreg extrusion at the flange (Δl at 266 % larger) and more variations in wall thickness in the punch radius region (ΔX_{PR} at 29 % more compressed) as well as in the die radius region (ΔX_{DR} at 79 % higher). Furthermore, pore formation can be observed in the die radius, too.
The combined forming shows good results related to forming sheet metal blanks while the forming results of the CFRP prepreg vary extremely. Thus, the appearances of failure modes in a warm forming process (Fig. 6.) are more intensive than in cold forming processes and depend on the pressure distribution on the CFRP prepreg. In this context, the challenge for the combined forming process is to analyse and optimise the forming behaviour of the used materials. Further research work on the tool design is necessary for applying different, locally-defined surface pressures during curing by passively or actively adjustable tool segments.

3.3 Transversal Fibre Flow during Bending Operations

As previously described the forming temperature strongly influences the results of the forming process. At elevated temperature, characteristics as shown in Fig. 6 are more pronounced than in cold forming process. That is presumably the result of reducing the matrix viscosity by increasing the forming temperature that further causes the transversal fibre flow. Transversal fibre flow is one of the secondary forming mechanisms in addition to resin percolation [5], but regarding the contact pressure between the prepreg and the tool elements, this forming mechanism becomes more important. First investigations concerning the transversal fibre flow behaviour of CFRP prepregs are made by compression tests to analyse the stress strain behaviour (Fig. 8.). Strain effects in fibre direction are almost negligible, thus lateral expansion of the CFRP specimen occurs mainly by transversal fibre flow.

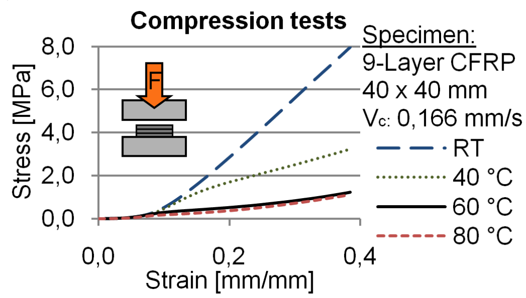


Fig. 8. Stress strain diagram from compression tests.

One can observe a progressive course of the compression stress by analysing the compression stress strain behaviour at room temperature (RT). Compared to that at elevated temperature first, a progressive course with a digressive transition to a slightly progressive course occurs. Probably this effect is the result of the layer arrangement and fibre redistribution, while compression that is significantly influenced by the matrix viscosity. First fibre redistribution occurs in doubled layers (2, 3 and 7, 8). Then, with decreasing layer thickness, the compression stress increases and results in fibre redistribution in further layers. In principle these effects are also seen even if the test temperature is rising but with the difference that compression stress is significantly lower. So, rising temperature leads to decreasing compression stress and thus causes higher transversal fibre flow (Fig. 8.).

Hence, the knowledge of pressure distribution on the CFRP prepreg is necessary for the process design and forming strategies. To influence the transversal fibre flow, further investigations concerning the compression behaviour and the pressure distribution on the CFRP prepreg during a forming process will be performed.

4 Approaches for Mass Production

Substantial demands to implement hybrid structures into automotive applications are adequate approaches for mass production. The prepreg-press and the combined forming processes are able to solve this demand by using automation tools like robots or assembly lines (Fig. 9. a)).

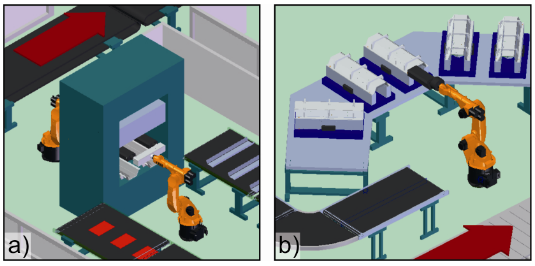


Fig. 9. Automated prepreg-press process a) with a single press device and a double mould and b) with multiple, flexible press devices.

In this case a robot inserts formed sheet metal into a heated mould. The same robot inserts a tailored prepreg. For the integrated forming, the robot handles an advanced, semi-finished part. The forming and curing are realized as described in chapters 2 and 3. This procedure is able to manufacture automotive structures, for example b-pillars or rocker panels, within cycle times of less than 5 minutes. Using multiple tools or multiple, flexible press devices allow a further reduction of cycle times (Fig. 9. b)).

5 Conclusions

Multi-material systems consisting of sheet metal and fibre reinforced plastics offer a major potential for lightweight design in the automotive industry. Two different approaches to manufacturing these structures have been presented: the prepreg-press-technology and the combined forming. Both concepts allow a significant reduction of process steps as well as process times.

By using prepreg-press-technology CFRP prepregs are formed into steel structures. The bonding is realised by the use of the epoxy resin as an adhesive, which offers a high joint strength. Further, it has been shown that the structures offer a high crash performance.

Another approach is the combined forming of CFRP prepreg and sheet metal blank. It has been shown that the forming temperature influences the forming results considerably. Notice that lower temperatures lead to positive effects concerning wall thickness distribution and reduced transversal fibre flow.

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References

[1] D. Lutz “Chassis lightweight design exemplified on a suspension strut – State of the art and potential”. *Proceedings of 11. Aachen Colloquium Automobile and Engine Technology*, Aachen, pp. 437-455, 2002.

[2] A. Horoschenkoff “Statt Stahl und Aluminium”. *Kunststoffe*, No. 5, pp. 50-54, 2010.

[3] S. Grasser “Composite-Metall-Hybridstrukturen unter Berücksichtigung großserientauglicher Fertigungsprozesse”. *Proceedings of Symposium Material Innovativ*, Ansbach, 2009.

[4] M. Maciej “Faserverbundkunststoffe: Von der Kleinserienfertigung von Sichtbauteilen zur Großserienproduktion von Strukturteilen”. *Proceedings of InnoMateria – Interdisziplinäre Kongressmesse für innovative Werkstoffe*, Köln, 2011.

[5] S. P. McEntee and C. M. O’Bradaigh “Large deformation finite element modelling of single-curvature composite sheet forming with tool contact”. *Composites*, Part A26A, pp. 207-213, 1998.