Concept development and implementation of new hybrid compounds

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Abstract

Increasing vehicle mass due to the integration of driver assistance systems and the requirement to improve fuel efficiency force car manufacturers into innovations. This primarily means the substitution of steel by lighter materials (such as aluminum, fibre-reinforced polymer (FRP) or mixed materials as metal-FRP-hybrid materials).
In this paper, various approaches are developed, to optimize aluminum-FRP-hybrid materials. A focal point is in the combination of materials with different coefficients of thermal expansion at high temperatures. Nevertheless interaction of different material properties can improve the performance of components and reduce the weight of a vehicle with similar or even increasing safety.

1. **Introduction**

In the present day and also in the future, vehicle development is strongly influenced by environmental awareness. Similarly, increasing passenger safety is paramount. New material technologies and manufacturing processes provide innovative design approaches. In particular, research in the field of the mixed-material-hybrid design possibilities arises to combine the development objectives of lightweight and safety. In this paper, the joining of metal and FRP and the different thermal expansions of these materials are in focus. So the use of impact protection system (IPS) geometry is possible for different vehicles. Depending on the level of energy intake, the increase on IPS varies.
Previous investigations showed the great potential of IPS with fibre reinforcement. [1] On account of the complex failure mechanism in the joint between the different materials, a higher strength and energy absorption than conventional designs were detected. The challenge for the concepts studied was to avoid the delamination of the FRP compound during cataphoretic painting (caused by the different thermal expansions of the materials) and the delamination during the crash test. An important requirement for cost reduction is a quick assembly during production in order to avoid additional process steps.

The interplay of different material properties can improve the performance of components and reduce the weight of a vehicle with constant or even increasing safety. To avoid additional process steps and to enable rapid implementation in series production, the focus of the joining technology is in bonding of the components made by different materials.

The demand for new lightweight materials in automobile construction is very large and growing steadily. The competitor is trying to integrate FRP in its processes. However, the high production costs are still a disqualifying criterion for the use of such materials. The use of metal-FRP-hybrid materials, with minimal change in the manufacturing process, has the advantage of cost and weight saving. The use of IPS geometry with adjusted reinforcing can be using in different classes of vehicles. In this way, the weight and energy consumption of IPS may be one optimal composite.

2. Materials and different joining technologies

Bonding is one of the joining methods, which connect different materials. The connection of two materials is possible in different ways. In addition, the following concepts were considered:

- Mechanical joining
- Hybrid joining
- Adhesive bonding
- Material engagement with laser welding

2.1 Mechanical joining

The concept of „mechanical joining" can be divided into the customary types of connection such as punch riveting, blind rivets, clinching and screws. The form closure or strength closure connection has a high static strength [2]. Moreover, this offers reasonable readiness for duty in view of the future serial production and the process times linked with it. The $\Delta\alpha$ problems during cataphoretic painting can be handled through the application of a mechanical connection.

Nevertheless, the connection realised in this way would show no huge improvement in comparison to the aluminum IPS in relation to strength or energy absorption in a crash. The joint would be reduced by drillings or openings. Additional notch stresses in these locations would lead to a lower loading capacity. Inhomogeneous strength application and tension distribution in the joint and the local destruction of glass fibres would be also posted joining. In summary, it can be said that a purely mechanical connection is not to be recommended in this case of a dynamic (impact) loading [2].

2.2 Hybrid joining

The second concept considered, "Hybrid joining", is a combination of a form or strength connection and an adhesive bond. With this developed joining process, a bolt is turned in the component at a very high speed. Based on the high local temperatures generated, the bolt and the aluminum lead to a "welded joint". The dynamic loading capacity in the joint becomes higher in comparison to the mechanical connections mentioned in chapter 2.1 [3]. In addition, the adhesive bond raises the strength or energy absorption. Peel strain, arising by reason of a large deformation, is decisive for the failure of an adhesive connection [4]. The bolts reduce the peel stress and extend the area of the static stress capacity of the connection. Disadvantageously, the openings, introduced for the application of a mechanical load, create consequent interruptions of the glass fibres in the patch. The glass fibres could be led around the openings by an additional amount of work and with special devices, as shown in Figure 1. This would lead to a certain reduction of the loading capacity, because the fibres follow a change of course in certain areas.

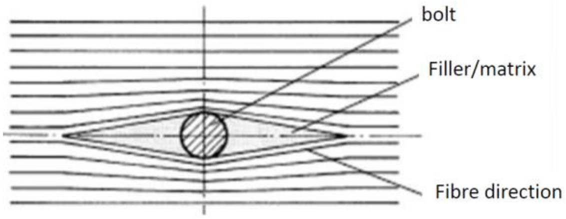

Figure 1: Opening with glass fibres [2, P530]

2.3 Adhesive bonding

Currently, the production of car bodies is being influenced increasingly by the application of adhesion. Equally high stiffness can be reached by the application of this joining-procedure with lower component weight. So, the biggest advantage is the adhesive bond with the materials. By the adhesion of the complete surface of the fibreglass patch with the aluminum IPS a high energy absorption capacity under mechanical loading can be delivered. This is allowed by the homogeneous tension distribution in the adhesive layer.

2.4 Material engagement with laser welding

The application of a firmly bonded connection by laser welding assumes the use of a thermoplastic matrix. The application temperature and duration of cataphoretic painting show another limitation for the thermoplastic used. For this use case, plastics such as PET, PA 6, PA 66 etc. can no longer be considered [5]. The matrix material may not change this property. The glass crossing temperature Tg is a measure of this criterion [2]. This may reach a value higher the 200 °C, if the joining of the FRP-patch with the aluminum beam has to be manufactured before cataphoretic painting. From this restriction the exclusive application of high-capacity plastics is necessary. The use of thermoplastics offers, above all with regard to the mechanical load, some advantages in comparison to thermosetting plastic. Nevertheless, the prices of these polymers with high temperature resistance are excessively high [6].

The laser welding process based on two steps. The first step is the "laser micro-structuralisation“. Strictly speaking, a surface treatment of the aluminum IPS by a laser takes place here. With the "laser micro-structuralisation“, the surface takes on a defined roughness and undercut [7]. Figure 2 shows the surface with defined roughness and undercut.

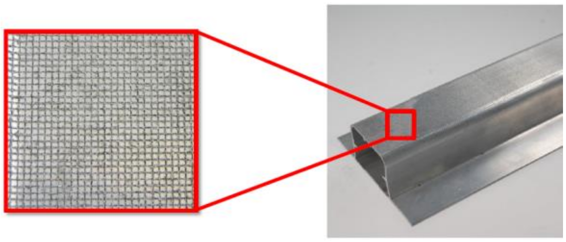

Figure 2: IPS after laser micro-structuralisation

The second step is the local warming of the joint. This can be done by inductive warming, which is caused by induced fields in the aluminum. Thereby, the plastic becomes more elastic and is able to run with pressure in the defined undercut. In the cooling process, the hard plastic clings to the metal surface and realizes cohesion of the joint.

The Laser welding process is not optimised for thin-walled aluminum beam like the aluminum IPS with a closed crossection yet. Therefore, the needed heating and pressure to fix the FRP-patch on the aluminum beam was realised by a heating press. As shown in Figure 3 the thickness of the profile must have a defined value for the force of the heating press.

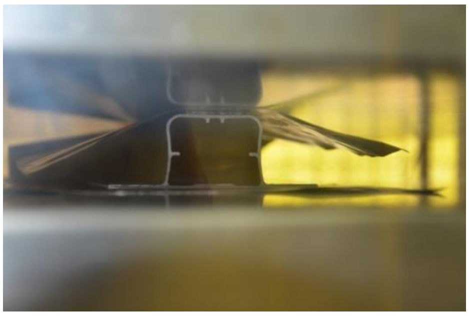

Figure 3: heating press with aluminum/thermoplastic IPS

3. Optimisation of the thermal expansion coefficient

Caused by the $\Delta\alpha$ problem the connection of two materials has the main disadvantage that two different behaviour patterns arise through temperature changes. For example, the aluminum and the matrix of FRP-patches behave isotropically. However, the complete component with the fibre reinforcements shows anisotropic behaviour [8]. This quality of the component is caused by the fibres as well as their arrangement (orientation). In Table 1, the problems of the different coefficients of expansion α are shown.

MATERIAL	**α in 10^{-6} K^{-1}**
ALUMINUM	23-24
STEEL	11-17
EPOXYRESIN	60-70
GLASFIBRE	5

Table 1: expansion coefficient of different materials [7, 13]

Caused by the three extremely different expansion coefficients it becomes clear that the connection between aluminum, epoxy resin and fibreglass is certainly complicated. The expansion coefficient of the FRP (epoxy resin and fibreglass) can be adapted by the fibre orientation. Therefore to get similar coefficients of expansion in FRP and aluminum the fibre orientation has to be changed.

The optimal fibre orientation can be calculated with two different formulae (1) and (2) or (3) and (4) per expansion direction [8].

$$\alpha_{11} = \alpha_{11,F} \frac{\alpha_M - \alpha_{11,F}}{\left[\frac{\varphi}{1-\varphi} * \frac{E_{11,F}}{E_M} + 1\right]} \quad (1)$$

$$\alpha_{11} = \frac{\varphi * E_F * \alpha_{11,F} + (1-\varphi) * E_M * \alpha_M}{\varphi * E_F + (1-\varphi) * E_M} \quad (2)$$

$$\boldsymbol{\alpha_{22} = \alpha_M - \left(\alpha_M - \alpha_{22,F}\right) * \left[\frac{2*(\vartheta_M^3 + \vartheta_M^2 - \vartheta_M - 1) * 1{,}1 * \varphi}{1{,}1 * \varphi * (2\vartheta_M^3 + \vartheta_M - 1) - (1 + \vartheta_M)}\right] - \frac{\vartheta_M + \frac{E_{22,F}}{E_M}}{\frac{E_{22,F}}{E_M} + \frac{1 - 1{,}1*\varphi}{1{,}1*\varphi}}} \quad (3)$$

$$\alpha_{22} = \varphi * \alpha_{22,F} + (1-\varphi) * \alpha_M + \varphi * \alpha_{22,F} * \vartheta_F + (1-\varphi) * \alpha_M * \vartheta_M - (\varphi * \vartheta_F + (1-\varphi) * \vartheta_M)\alpha_{11} \quad (4)$$

The thermal coefficient of expansion (α) with index 11 represents the expansion in the direction parallel to the fibre and with index 22 in the direction crosswise to the fibre direction. The other dimensions are a fibre volume ratio (ϕ), Young´s modulus (E), Poisson´s number (v) and the indices F and M refer to fibre and matrix.

With typical values of the other parameters there arises the result of α_{11} = 7.4e^{-6} K^{-1} and α_{22} = 35.6e^{-6} K^{-1} or α_{22} = 44.9e^{-6} K^{-1}. The difference in the expansion crosswise to the fibre direction gets with the calculated Young´s modulus. A comparison of the result to the expansion for aluminum α_{Alu} = 23-24 K^{-1}once again demonstrates the problems of the different expansions.

With the transformation matrix T based on (5) and (6) and the calculated coefficient of expansion in and crosswise to the fibre direction, it is possible to calculate the optimum angle for an expansion equivalent to that of aluminum [8].

$$(\boldsymbol{\alpha})_{\boldsymbol{\theta}} = [\boldsymbol{T}]^{\boldsymbol{T}} * (\boldsymbol{\alpha})_{\boldsymbol{ortho}} \quad \boldsymbol{or} \quad (\boldsymbol{\alpha})_{(\boldsymbol{x},\boldsymbol{y})} = [\boldsymbol{T}]^{\boldsymbol{T}} * (\boldsymbol{\alpha})_{(\boldsymbol{1},\boldsymbol{2})} \quad (5)$$

$$\begin{pmatrix} \alpha_{xx} \\ \alpha_{yy} \\ \alpha_{xy} \end{pmatrix}_{\theta} = \begin{bmatrix} cos^2\theta & sin^2\theta & 2\sin\theta\cos\theta \\ sin^2\theta & cos^2\theta & -2\sin\theta\cos\theta \\ -\sin\theta\cos\theta & \sin\theta\cos\theta & cos^2\theta - sin^2\theta \end{bmatrix}^T * \begin{pmatrix} \alpha_{11} \\ \alpha_{22} \\ \alpha_0 \end{pmatrix}_{ortho} \quad (6)$$

The calculations indicate the requirement for an angle of θ_{11} = 49 ° and θ_{22} = 131 ° or θ_{11} = 41° and θ_{22} = 139°. This result is charted in Figure 4 and Figure 5.
Figure 4 and Figure 5 show how the coefficient of expansion of the composite behaves in comparison to aluminum or steel according to the angle direction of the fibres. Therefore an improvement of the $\Delta\alpha$ problems would be reached by the arrangement of the fibres in a fibre direction of 45 °.

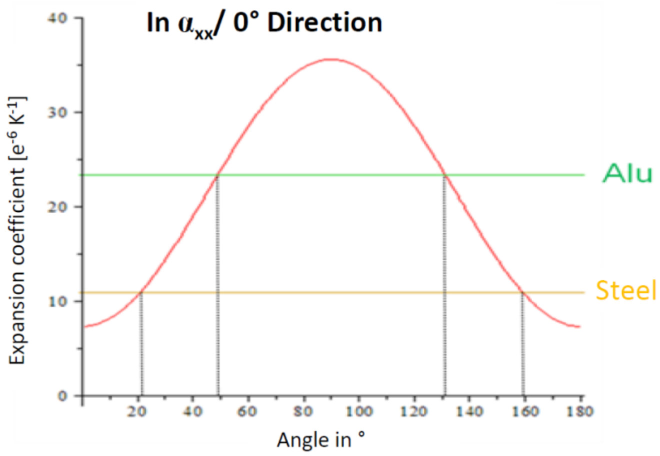

Figure 4: Expansion coefficient in the fibre direction as a function of fibre orientation [8]

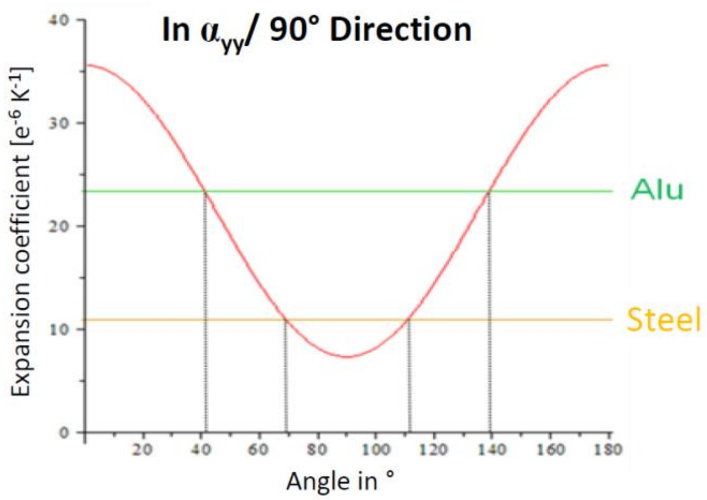

Figure 5: Expansion coefficient transverse to the fibre direction as a function of fibre orientation [8]

Another possibility to adapt the coefficients of expansion is to change the fibre volume content. Through the variation of fibre volume content in and crosswise to the fibre direction, the expansion can be adjusted. This is shown in Figure 6.

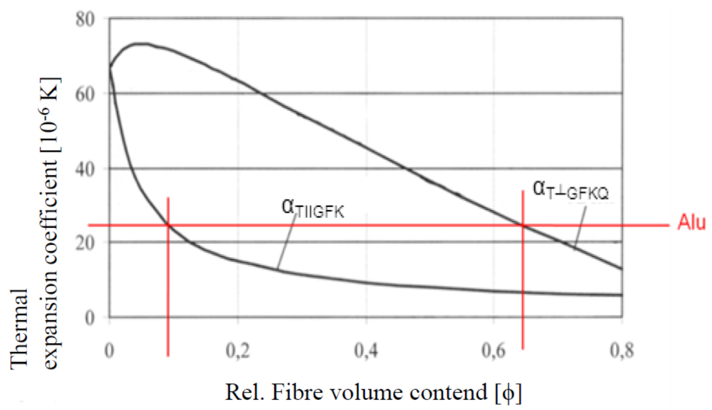

Figure 6: Expansion coefficient as a function of fibre volume and the fibre direction [9]

The lower curve refers to the fibres in fibre direction, the upper curve crosswise to the fibre direction. The content of approx. 8% in the fibre direction and about 65% crosswise to the fibre direction provides a similar coefficient of expansion to that of aluminum. 8% of fibre content is not sufficient for a strengthening of the composite. The fibres content is too low and therefore this possibility is not beneficial for a safety component.

4. Results and Discussion

In this paper, an E-Glas fibre reinforced epoxy resin was bonded on the aluminum IPS with an adhesive layer. After curing, the hybrid IPS was reheated for 30 minutes at 200 °C in an oven, which was simulated cataphoretic painting. In addition, the concept was optimised to the rate of thermal expansion of aluminum. It was necessary to choose the fibre directions of the first 3 layers so that the thermal induced shear stress between the aluminum and the FRP was as low as possible. The variety of the layers was based on the calculations in chapter 3. The first layers for reducing the shear stress during cataphoretic painting have the following for fibre orientation: 45°, 90°, and -45°.

In the first test of the simulated cataphoretic painting, there was no delamination between the patch and aluminum detectable. However, first delaminations of the components occurred after 30 minutes during the cooling process at different points of the patch. Because of this 30 minutes time delay the performance, as well as the thermal induced changes of the adhesive needs further investigation.

In comparison to the results of previous studies, the results are an improvement relating to cataphoretic painting of aluminum-thermosetting IPS. For the next steps of this development, the adhesive as well as the bonding area have to be matched. The shear stress between the FRP-patch and the aluminum IPS have to keep low and the adhesive have to resisted against the temperature during cataphoretic painting and the cooling process. In the calculations, the strength values are estimated, so for exact calculation measured strength values of the materials are needed.

Nevertheless as presented in Figure 7 the excellent energy absorption in the 3-point- bending test with FRP-light-metal hybrid beam demonstrates the great potential of this development with a low weight increase.

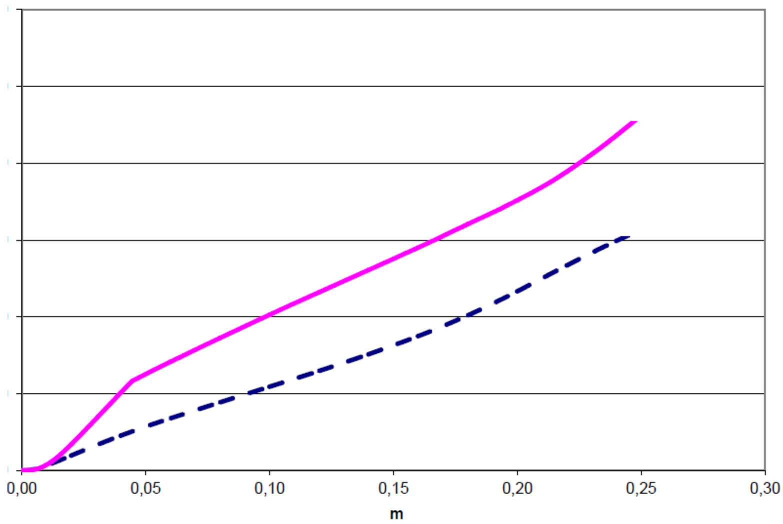

Figure 7: Energy absorption-deflection graphs measured in a 3 point bending test - without FRP Patch (dashed line) with FRP Patch (Solid line): 10% more weight caused and approx. 50% energy absorption.

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