On the development of an intrinsic hybrid composite

R Kießling¹, J Ihlemann¹, M Riemer², W.-G Drossel³, I Scharf³, T Lampke³, S Sharafiev⁴, M Pouya⁴ and M.F.-X Wagner⁴

¹ Professorship of Solid Mechanics, Faculty of Mechanical Engineering, Technische Universität Chemnitz, D-09126 Chemnitz, Germany
² Fraunhofer Institute for Machine Tools and Forming Technology, D-09126 Chemnitz, Germany
³ Professorship of Materials and Surface Engineering, Institute of Materials Science and Engineering, Technische Universität Chemnitz, D-09125 Chemnitz, Germany
⁴ Chair of Materials Science, Institute of Materials Science and Engineering, Technische Universität Chemnitz, D-09125 Chemnitz, Germany

Abstract. Hybrid parts, which combine low weight with high strength, are moving into the focus of the automotive industry, due to their high potential for usage in the field of crash-relevant structures. In this contribution, the development of an intrinsic hybrid composite is presented, with a focus on the manufacturing process, complex simulations of the material behaviour and material testing. The hybrid composite is made up of a continuous fibre-reinforced plastic (FRP), in which a metallic insert is integrated. The mechanical behaviour of the individual components is characterised. For material modelling, an approach is pointed out that enables modelling at large strains by directly connected rheological elements. The connection between the FRP and the metallic insert is realised by a combination of form fit and adhesive bonds. On the one hand, adhesive bonds are generated within a sol gel process. On the other hand, local form elements of the metallic insert are pressed into the FRP. We show how these form elements are generated during the macroscopic forming process. In addition, the applied sol gel process is explained. Finally, we consider design concepts for a specimen type for high strain testing of the resulting interfaces.

1. Introduction

Hybrid composites are made of different classes of materials to combine the advantageous properties of the single components (see, e.g. [1, 2]). Due to the complex and expensive manufacturing process as well as difficulties in material testing and simulation, the application of these composites, e.g. in the field of crash relevant structures, is currently not considered in commercial production (see [3]). This contribution outlines the development of an intrinsic hybrid composite that can be manufactured robustly and reproducibly. The corresponding manufacturing process, based on the emergence of the compound and the simultaneous generation of the component geometry in a combined forming process, is devised. Furthermore, the material testing of the interfaces and the material modelling of the components of the hybrid composite at large strains are presented.
2. Materials of the components and the related material models
The investigated hybrid composite consists of a continuous fibre reinforced plastic (FRP) with an integrated metallic layer as shown in figure 1. The FRP is a unidirectional carbon fibre sheet composed of a PA 6 Ultramid B40 (BASF) matrix and Toray’s T700S (50-K) carbon fibres. AA 1005 is employed for the metallic insert.

![Macro and mesostructure of the investigated hybrid composite.](image)

Finite element simulations are performed to estimate and optimise the crash behaviour of a structural part made of the hybrid composite. To simulate the corresponding mechanical behaviour of the deployed components at large strains, precise viscoplastic material models are required. The formulation and implementation of such a model requires a profound knowledge in the field of nonlinear continuum mechanics. Ihlemann [5] developed a general approach that enables material modelling at large strains based on the direct connection of rheological elements. Within this concept, rheological elements, representing elastic, viscous and plastic material behaviour, are combined in series and parallel connections. To deduce the required material model, only relations demanding the stress power equivalence of the rheological connections have to be evaluated. A numerical procedure by Kießling et al. [6] implements directly these connection relations. Consequently, a complex material model can be generated by the composition of a rheological model and the selection of provided rheological elements. Furthermore, it can be employed in commercial finite element codes by user subroutines, like UMAT for Abaqus. Therefore, this straight-forward and flexible approach of material modelling at large strains is deployed to develop the viscoplastic material models of the components of the intrinsic hybrid composite studied here.

The mechanical behaviour of the aluminium alloy is covered by the rheological model shown in figure 2(a). As demonstrated by Kießling et al. [6], the evaluation of the associated connection relations shows accordance with the material model presented by Shutov and Kreißig [4], which is able to simulate the viscoplastic behaviour of this material type. The rheological model, which is applied for the matrix material of the FRP, is given in figure 2(b). Furthermore, an extension of this rheological model, which covers anisotropic effects, is introduced. The resulting homogenised material model can be utilised for the FRP. Consequently, the mechanical behaviour of the applied components can be estimated as shown by the simulated stress-strain curves in figure 3 and utilised in finite element simulations of the intrinsic hybrid composite.

3. Connection between the fibre-reinforced plastics and the metallic insert

1.1. Form fit by local form elements
One aim of this project is to identify basic mechanisms to establish a form fit between the laminate layers following the intrinsic concept. A general approach is to utilise in-plane deformations to trigger out-of-plane reactions of the geometric structure.
One promising effect, generating out-of-plane deformations, is local buckling [7]. To generate the required local compression stress, in-plane bending is utilised. By loading a curved beam, tensile forces can be converted into a bending moment. Figure 4(a) shows the basic geometric element with the width w, the length l and the eccentricity e of the applied load.

The applied force F generates the bending moment and thereby areas of the local compression state (cf. figure 4(b)). When the load exceeds a critical value, the structure suddenly starts to buckle and an out-of-plane deformation is realised (see figure 4(c)). The value of the critical load strongly depends on geometric ratios. Our investigations show that a large value of the parameter w favours the out-of-plane deformation. The length l has no significant influence on the critical load. In contrast, an increased eccentricity e leads to a reduced critical load. Taking the results of the numerical parameter studies into account, a specimen with an array of 4 form fit elements was designed (figure 5(a)). The linear buckling analysis of the specimen shows the out-of-plane deformation of the form fit elements under tensile load (figure 5(b)).

In a next step, physical specimens were manufactured by laser cutting and tensile tests were performed. Figure 6 illustrates a force-displacement curve from a representative specimen. From 0 to 3 mm traverse displacement, the elastic deformation of the specimen is observed. At the first peak of the curve, the critical buckling load is reached and the out-of-plane deformation occurs. This is combined with a significant reduction of the applied force. Beyond an extension of 10 mm, the applied force F continues to rise until fracture. The force which is achieved right before the failure of the form fit element is even slightly higher than the critical buckling load. This is an important relation aiming at a series combination of several elements.
1.2. Sol-gel process generating adhesive bonds

The generation of an appropriate interface is one key requirement for the material compatibility of the heterogeneous materials system of metal insert and fibre-reinforced polymer matrix composite. This enables a better adhesion between fibre-reinforced polymer and the metal substrate. Furthermore, the adapted interface decouples the corrosion potentials. Carbon fibre reinforced polymers are considered as particularly critical. Sol-Gel coatings provide an advantage as corrosion barrier. They form dense layers and provide good adhesion. The application of sol-gel layers prevents contact corrosion between the noble fibre-reinforced polymer (redox potential of + 0.74 V) and the less noble aluminium substrate (redox potential of - 1.67 V). It is challenging to develop a formulation for a sol-gel coating on aluminium before the forming process: The ductility of the coating has to be sufficient for this subsequent process.

Another function of the sol-gel coating is the optimisation of cohesive interactions between heterogeneous partners in the hybrid component to achieve the best possible connection. Therefore the coating is modified to their chemical surface composition to produce stronger interactions from the selected PA 6 matrix. For example, the properties of the sol-gel layer are modified by using hybrid sole [8], a mixture of chemically different silicates, for their production. This allows changing the wetting behaviour of the interface with the selected chemical composition. Furthermore, it is possible to determine the voltage profile in the layer with strains during the forming process by using structurally different organic silicates, so-called ORMOSILS. The wettability of the fully crosslinked surface of the sol-gel coating can be improved in a further step to achieve maximum intermolecular interactions to the polyamide. For example, alkylated silicates are used to modify the surface in the desired manner [9]. So the sol-gel layer gets a very oleophilic character. This is promoting the connectivity to thermoplastic polymers and adds a maximum material connection of both joining partners in the hybrid composite.
4. Mechanical characterisation of the interface
The interfacial properties of an intrinsic hybrid strongly affect the total composite strength. It is necessary to find a general approach for characterisation of the mechanical properties of hybrid structures with different interface concepts, and to understand the relevant strength and damage mechanisms in their interfaces, both under quasi-static and dynamic loading conditions. Typically, mechanical testing of composite structures is performed by conventional shear tests and/or tensile tests normal to the interface. However, information from such tests is often limited to critical forces (or nominal stresses) for complete failure. In order to characterise the microstructural developments and damage processes of metal-plastic interfaces in greater detail, experiments need to be interrupted (preferably at different, well-defined time increments). In our recent experiments, we use the digital image correlation (DIC) method for measurements of local strain distributions. This technique allows mapping of surface strains and provides considerably more information in terms of local strain/stress peaks and damage initiation compared to conventional mechanical testing. Such strain mapping methods are also useful for careful design of stopped experiments, which yield partially damaged samples that can then be further analysed, for instance with optical or electron microscopy.

Figure 7. AA/PA 6 composite in a shear test: (a) DIC image representing the strain distribution, (b) FEM simulation showing the von Mises stress distribution for two different specimen geometries.

The deformation and damage mechanisms and hybrid response differ at quasi-static and dynamic conditions. The conventional specimen geometries for static shear tests cannot be used for dynamic tests. A hybrid composite exhibits local stiffness changes at the interface, and this effect leads to impedance jumps and thus to undesirable wave reflections during dynamic deformation; reflected elastic waves distort the measured pulse signals. Therefore, one key goal of this project is to develop new sample geometries that allow for a careful control of stresses and strains at hybrid interfaces during dynamic loading. In figure 7, we present first examples of our experimental and numerical research on such improved sample geometries. Figure 7(a) shows DIC data (the color code is related to the maximum principal strain) obtained during a quasi-static test of an AA/PA 6 composite sample. Damage and crack initiation in the interface is associated with large displacements, and the DIC algorithm interprets these data as locally strongly increased strains. Clearly, this method can be used to optimise experimental procedures for stopped tests. Moreover, the strain data can also be used to validate finite element simulations of similar experiments. Figure 7(b) shows two examples (also quasi-static) of sample geometries using the finite element method to search for samples that provide more homogeneous stress distributions in the interface: the conventional sample geometry is associated with an inhomogeneous distribution of von Mises stresses, whereas a sample with adapted cross sections of the AA and PA 6 parts clearly shows a much more homogeneous distribution. Current and future work is focused on using similar methods to experimentally and numerically study stresses and strains during dynamic deformation, and to analyse the resulting interface damage.
5. Concluding remarks
In summary, the experimental and numerical findings presented in this short paper represent the current state of the ongoing development of an intrinsic hybrid composite. Clearly, our project requires the combined expertise of the research centres of production engineering, materials engineering and applied mechanics. Current work is focused on combining the individual results in order to actually manufacture a demonstrator of the investigated hybrid composite.

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6. References

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