OPTIMISED THERMOSET MATRIX SYSTEMS FOR THE MANUFACTURING OF SHEET-METAL-FRP-HYBRID-STRUCTURES BY AN OPTIMISED RESIN TRANSFER MOULDING PROCESS

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Abstract

Lightweight design is an important approach e. g. in the automotive sector to meet current and future demands and regulations, such as the reduction of CO_2 emissions or fuel consumption. In this field of application hybrid systems are a promising approach to significantly reduce the weight of structural or chassis components. The available paper shows basic technological investigations in the field of the manufacturing of hybrid materials and structures by using the RTM-technology. In this process, a resin system is injected into a dry textile preform, which was applied on a sheet metal surface. After a curing cycle the hybrid structures can be removed from the heated mould. This process is usable for the manufacturing of components for the automobile, commercial vehicle or railway industry. The hybrid approach leads to new and more comprehensive requirement profiles of matrix systems. For this application thermoset resin systems were developed and qualified for the RTM-process chain. For this new resin systems an adapted RTM-process was specified. The manufacturing process as well as aspects like the optimisation of process parameters (temperatures, times, and pressures) will be discussed in the paper. Here, influences i. e. on the mechanical and adhesion properties will be identified, analysed and evaluated.

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1. Introduction

For reasons of climate protection it is desirable to reduce vehicle masses. A reduction of the CO_2-emissions of about 8.5 g/km for an automobile can be achieved due to a decrease of the vehicle mass by 100 kg. In this context, especially the development of innovative lightweight concepts becomes important. For automotive lightweight design three main trends are obvious. First, high and ultra-high strength steel or aluminum alloys can be used for a optimised lightweight design in large series. Second, the substitution of materials like steel by materials with better specific mechanical properties like aluminum or fiber reinforced plastics (FRP) is an alternative to develop a large lightweight potential. Materials like carbon (CFRP) or glass fibre reinforced plastics (GFRP) provide excellent specific mechanical properties in comparsion to typical construction materials [1], [2]. A high specific modulus and strength are necessary for loadbearing structures in the automotive, energy or aerospace sector, for example. Because of high material and processing costs FRP-structures are utilised in the automotive sector mainly for luxury class vehicles, prototypes, premium products or race cars. For example, the German automotive manufacturer BMW sets on a full carbon passenger compartment in his i-series. The construction results in an enormous weight reduction but also in very high material and production costs. Third, the combination of different materials can be seen as a major trend for diverse technical applications. For automotive lightweight design especially the combination of steel and aluminum sheets or the combination of FRP and metal sheets are promising approaches. Using an intelligent combination of materials means to improve the mechanical properties, while keeping costs down. Such an optimised hybrid design is disussed in the following chapter.

2. Hybrid Structures: Characteristics, Potentials and Challenges

Hybrid materials consist of a sheet metal basic layer, a locally applied FRP reinforcement layer and an optional sheet metal covering layer [3]. The layered structure offers the possibility to tailor components to their expected loading (Fig. 1). Such tailored structures do not only bear a high potential for lightweight design but also show an optimised use of the expensive FRP materials, which finally leads to cost-optimised lightweight constructions [4]. The sandwich structure of hybrid materials increases the stiffness especially of large, flat components. Amongst others press hardened steels can be used as sheet metal blanks [4]. Due to the FRP reinforcements, the wall thickness of the steel parts can be reduced effectively. Hybrid components can be integrated easily into existing processes of vehicle production, because their metallic surface enables the use of conventional joining technologies like spot welding or clinching. The integration into existing body constructions is also possible. Automotive structures in hybrid design can be found in the current BMW 7-series. Here, several structural parts, e. g. the b-pillars, are made of a sheet metal basic structure with a local FRP reinforcement [5].

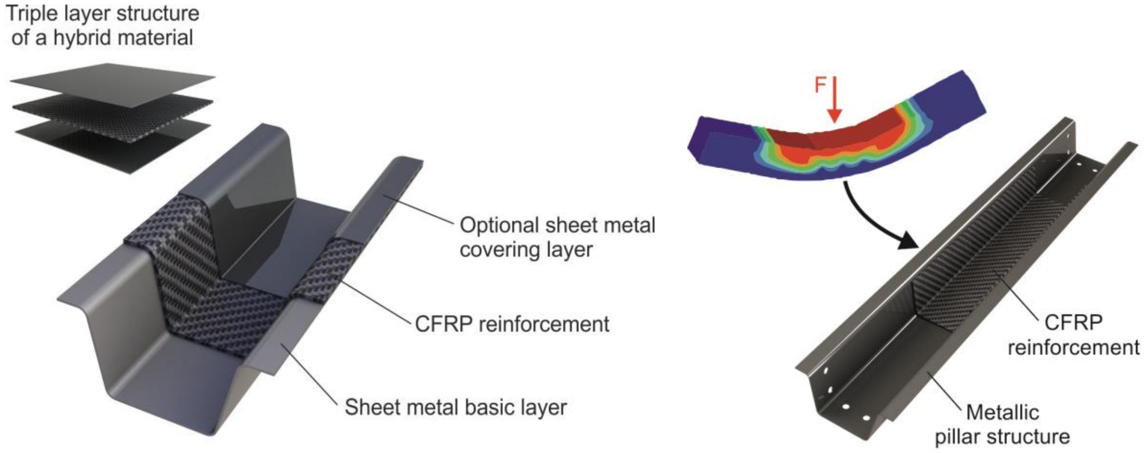

Figure 1. Different layer structures of sheet-metal-FRP-hybrid systems (left) and tailored hybrid pillar structure consisting of sheet metal and local CFRP reinforcement (right).

3. Optimised Resin-Transfer-Moulding-Process for the Manufacturing of Hybrid Structures

In the field of FRP, many different production technologies are available. Hereby, every process has its own specific advantages and disadvantages. The manufacturing technology has a decisive influence on the characteristics of the FRP component [6]. Sheet-metal-FRP hybrid structures can also be realised by different manufacturing technologies. In the automotive sector e. g. the prepreg press technology was intensively investigated over the past years. This process bases on pre-impregnated fibres. The so-called prepregs consist of carbon or glass fibres and an uncured epoxy matrix system. First, the prepregs were stacked and cut corresponding to the geometry of and loads on the final

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component. Afterwards, the laminates are pressed into a formed sheet metal structure in a heated mould. The result is a hybrid component consisting of sheet metal and FRP.

In the series production of automotive structures, use is currently made of several variants of the resin transfer molding (RTM) process [2], [7], [8]. Cycle times of about 8 to 15 minutes can be achieved with this manufacturing technology, depending on the dimensions of the structure. A further reduction of cycle times is possible, e. g. by using new matrix systems or by optimising process parameters and process technology. An adapted RTM process enables the manufacturing of hybrid structures. This so-called intrinsic manufacturing process can be divided into three main steps (Fig. 2). Therby, intrinsic manufacturing means, that the hybrid structure is produced in one single process step [9].

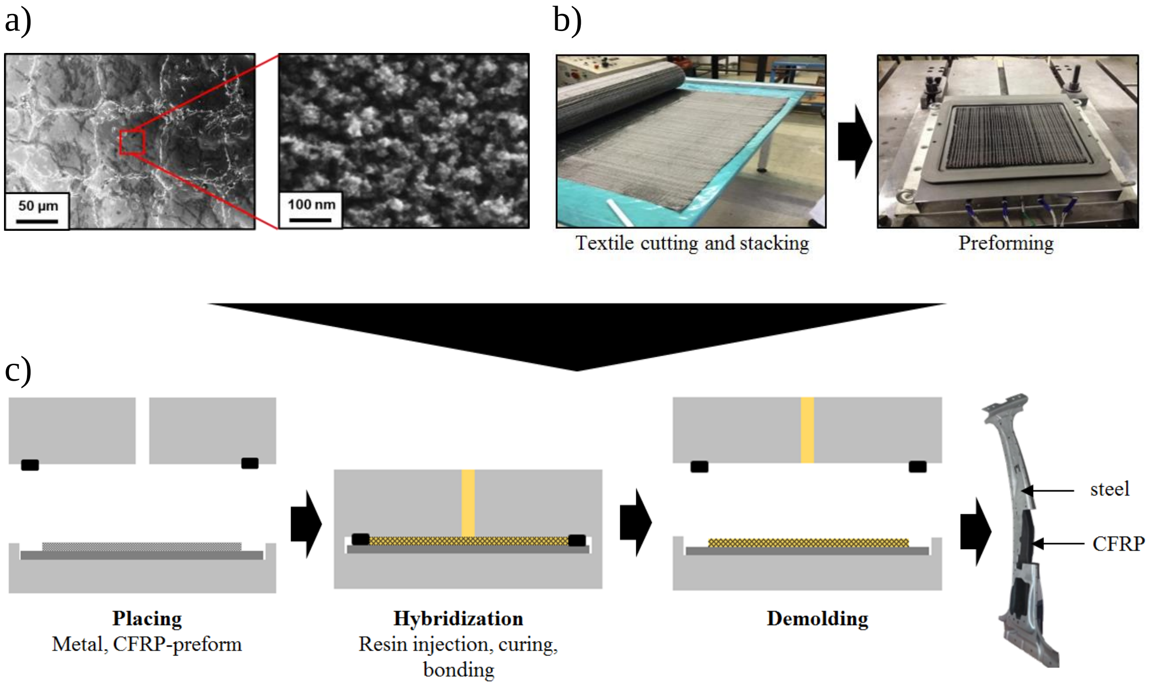

Figure 2. Manufacturing of a hybrid structural automotive component by an optimised RTM-process: a) sheet metal surface structuring, b) fibre handling, c) intrinsic manufacturing.

First, a surface treatment of the sheet metal is realised, i. e. degreasing or laser structuring (Fig. 2 a)). The laser treatment results in a nano-structured surface with undercuts, possible form-lockings and an increased surface area. The different treatment methods were investigated in order to optimise the bond strength between the sheet metal and the epoxy matrix, which is used as an adhesive in this process. Second, the preforming is realised expected to the loads on and geometry of the final component (Fig. 2 b)). In this step dry textiles are cut and stacked. A dry adhesive in powder form is spread on the single layers and activated by heat and pressure in a mould afterwards. Next, the workable preform is placed on a formed sheet metal structure in the RTM-mould. In the following third process steps the intrinsic manufacturing of the hybrid component is realised. The heated mould is closed and evacuated [1]. Hereafter, the epoxy resin is injected into the sealed mould under pressure. The preform is impregnated by the matrix resin and the curing is initiated by an elevated temperature [10]. After the curing cycle the final hybrid component can be removed from the mold. Because of an advanced tooling and sealing technology, a rework of the component is not necessary and it is possible to locally reinforce sheet metal structures (cf. Fig. 1, right).

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The intrinsic RTM-process enables a cost- and time-efficient manufacturing of hybrid structures for automotive structural applications.

4. Optimised Thermoset Matrix Systems for Hybrid Structures

4.1. Requirements for Matrix Systems used in Sheet-Metal-Hybrid-Structures

Multi-material- and hybrid structures create new requirements in the characteristic profiles of matrix systems (Fig. 3). Currently for the manufacturing of pure FRP-components especially the processabilty and other aspects like long processing times are relevant depending on the field of application. As mentioned before, in a sheet-metal-FRP-hybrid structure the matrix resin is used as an adhesive in order to minimise costs, cycle times and process steps. This circumstance requires better joining properties of the resin. Aside, hybrid components are to be used for large-series applications, e. g. in the automotive industry. Here, the curing times of available standard epoxy resins are quite too long, when a series production of 100.000 or even more parts per year is taken into account. This requirement is linked with low viscosities during the injection process. Thus, the infiltration time of the preform can be optimised. In conclusion this aspects lead to a significant reduction of cycle times from about 15 to 30 minutes to under 5 minutes per part in the closed RTM-mould. The last improvement affects the mechanical properties during a crash test.

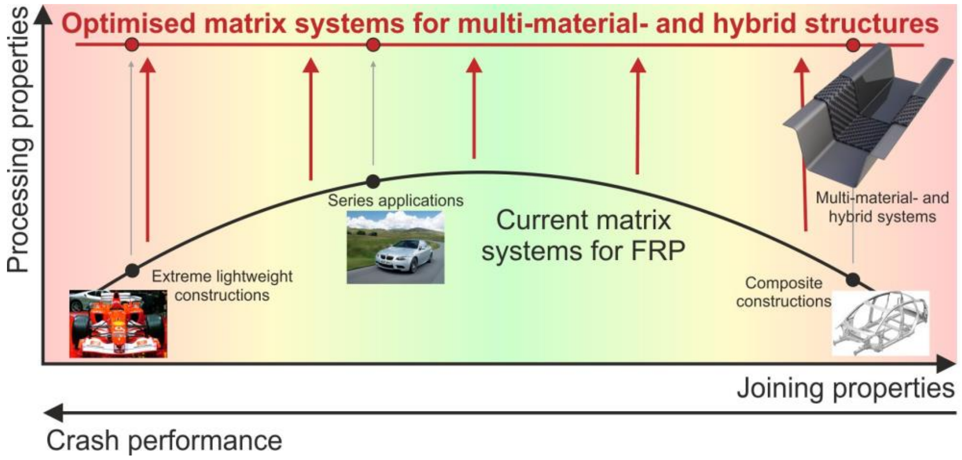

Figure 3. Requirement profiles of optimised matrix systems for multi-material- and hybrid structures.

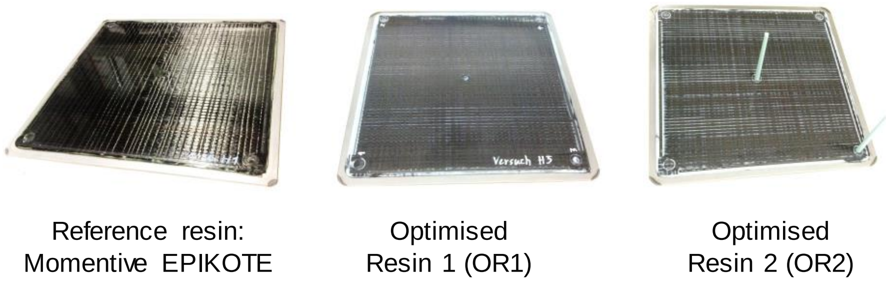
Reference resin: Momentive EPIKOTE
Optimised Resin 1 (OR1)
Optimised Resin 2 (OR2)

Figure 4. Flat test plates made of CFRP with different epoxy resins.

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In the following chapters the investigations on two optimised epoxy resins are discussed. Additionally, a standard epoxy resin was used as a reference. Fig. 4 illustrates flat test plates made of the three resins with a carbon fiber reinforcement. This specimens were used as a basis for the mechanical characterisation. Different standard specimen geometries were cut from the plates.

4.2. Viscosity measurement

The viscosity of the epoxy resin during the infiltration process has a decisive influence on the quality of the manufactured specimens and is necessary for finite element simulations of the mould flow [11]. A lower viscosity enables a better and more uniform infiltration. The result is amongst others a more reproducible fibre volume content and fibre distribution as well as an improved boundary layer between sheet metal blank and FRP. Thereby, a longer available low viscosity enables the manufacturing of larges components with a constant quality. From preliminary investigations two promising optimised epoxy resins could be extracted. These two variants and the reference resin was analysed due to their viscosity characteristics under the influence of relevant process temperatures. The test setup is shown in Fig. 5.

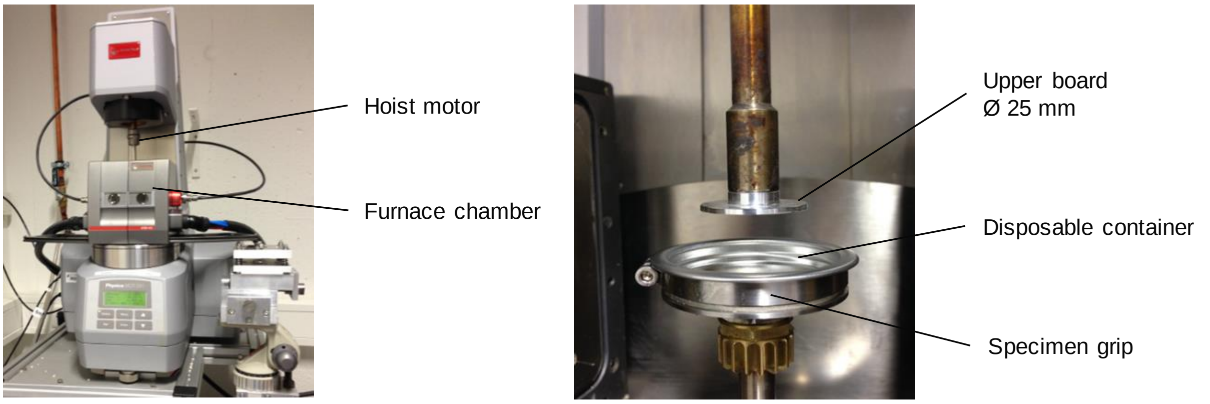

Figure 5..Test setup of the rotational oscillation rheometer.

The following Fig. 6 and 7 show the time-viscosity characteristics of the resins at 80 °C (Fig. 6) and 120 °C (Fig. 7). For both temperatures the optimised resins are characterised by a significant enhancement. After a typical processing time of about 4 to 5 minutes (240 to 300 seconds), the reference resin has a viscosity of about 200 mPa s at a temperature of 80 °C, while the OR1 and the OR2 are in a range from 75 to 100 mPa s. At a temperature of 120 °C the curing time of the resins decreased. For a possible processing time of 50 to 60 seconds the reference resin offers a viscosity of around 200 mPa s. At this time the OR1 is with a viscosity of 14,000 mPa s already in a curing stage. The OR2 shows a similar viscosity behavior to the reference system.

In order to minimise thermal residual stresses in hybrid structures the curing temperature should be choosen as low as possible. At a temperature of 80 °C the optimised epoxy resins show a better performance than the reference resin. A significant reduction of cycle times could be realised with OR1 at 120 °C.

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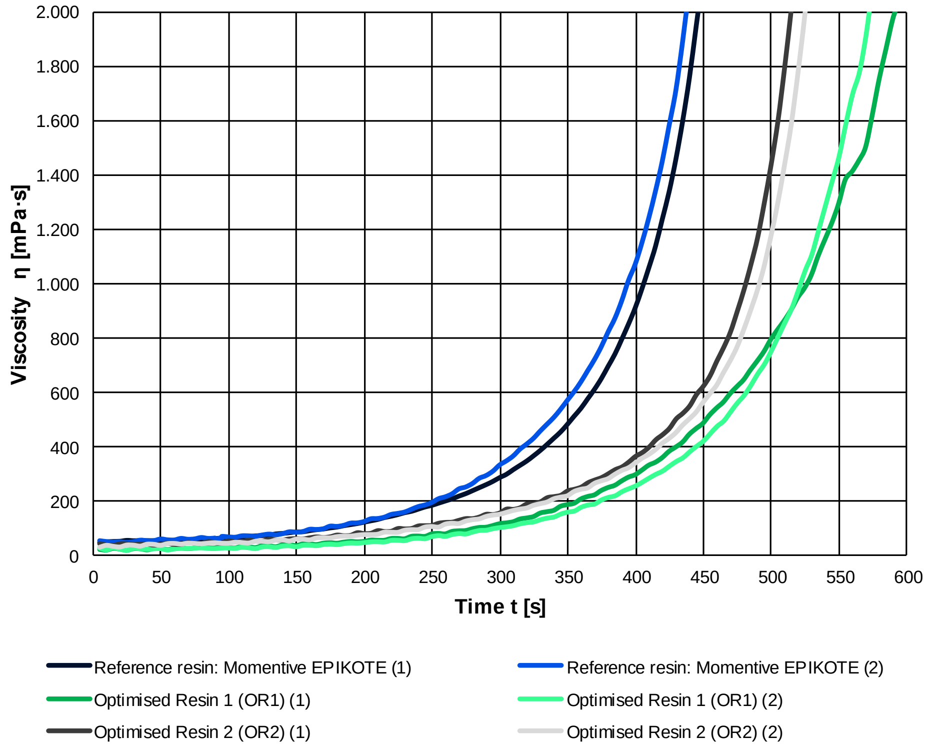

Figure 6. Viscosity measurement of the epoxy resins at 80 °C.

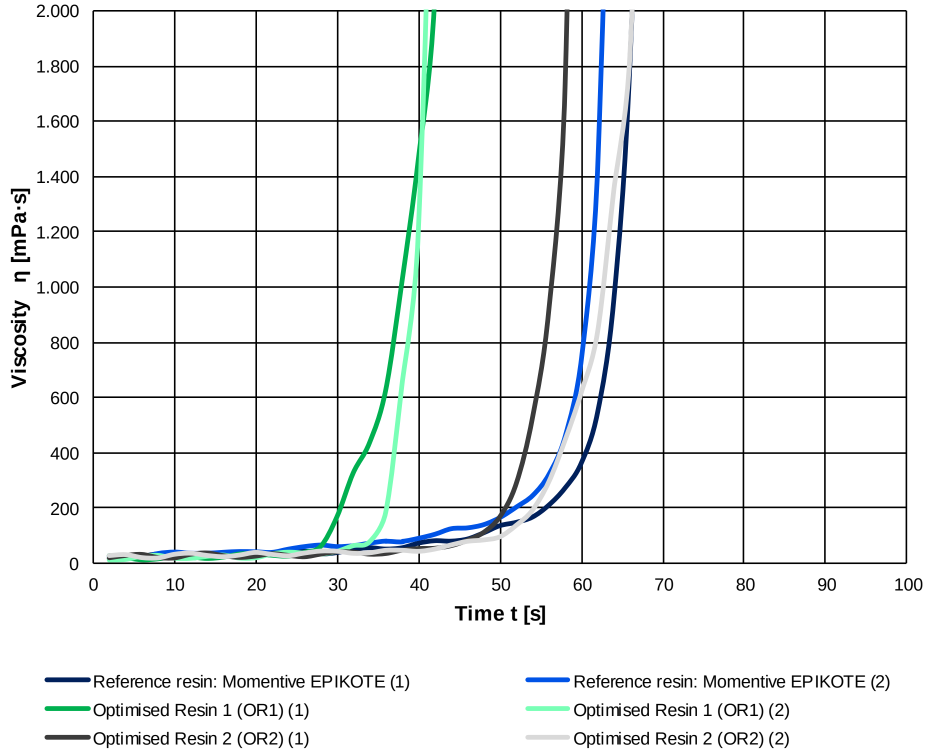

Figure 7. Viscosity measurement of the epoxy resins at 120 °C.

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4.3. Mechanical Properties under quasistatic Loading

The mechanical properties were intended to provide information on the characteristics of the resins in combination with carbon fibers. For this reason several tests, e. g. tensile, bending and lap shear tests, were conducted.

As a reinforcement unidirectional carbon fibers type HPT 320 CO 24 K with an area weight of 335.6 g/m^2 from SGL Kümpers were used. In a first step preforms with three layers and dimensions of 300 x 300 mm were manufactured. Afterwards, the preforms were infiltrated with the different epoxy resins in a varuum assisted RTM-process. From the flat test plates standard specimens for tensile, bending and lap shear tests were cut. For the tensile tests a digital image correlation measurement system was used (GOM ARAMIS) (Fig. 8.).

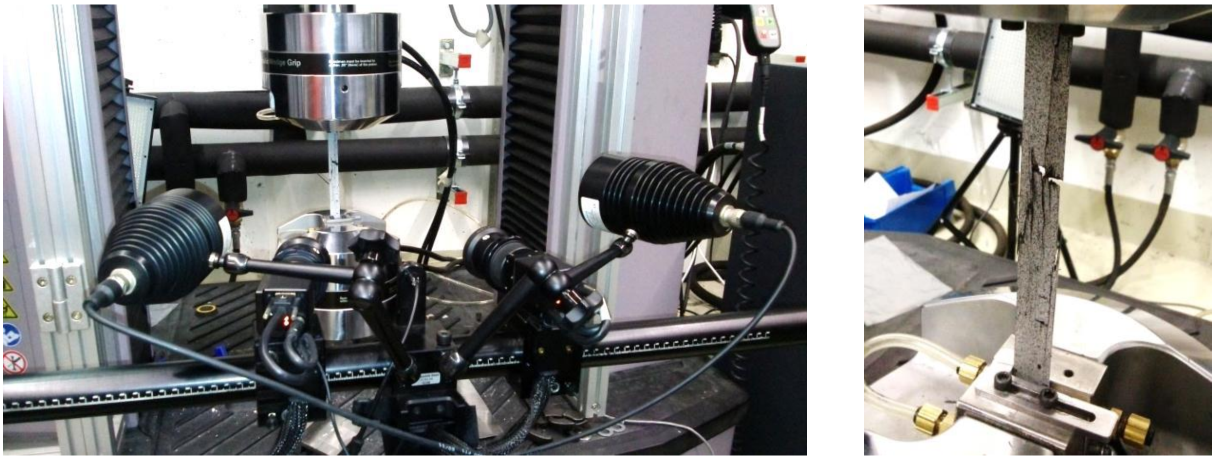

Figure 8. Test setup of tensile tests.

The tensile tests were performed accoding to DIN EN ISO 527-5 [12]. Fig. 9 shows stress-strain-curves for different tensile specimens consisting of carbon fibers with a reference epoxy matrix system from Momentive. The curves are characterised by the known behavior of unidirectional CFRP under tensile loads. At the beginning a linear increase of the stress occurs. The tensile tests ends in a abrupt catastrophic failure in the end. The specimens reaches tensile strengths of around 1,300 MPa and frature strains of about 1.5 %. For the tensile strengths the use of the epoxy resin has no measureable influence because this load case is mainly determined by the fiber reinforcement (Fig. 10). The same study could be made for the fracture strains (Fig. 11).

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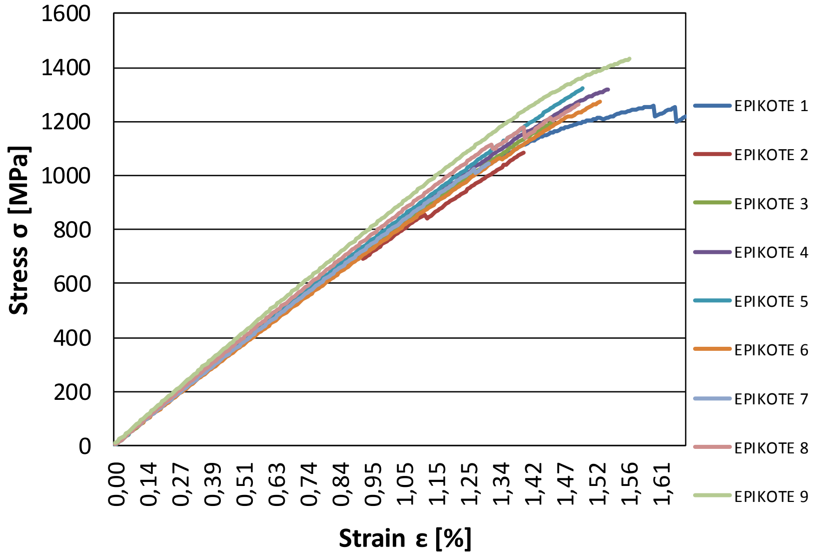

Figure 9. Stress-strain-curves of 0°-tensile tests with epoxy resin Momentive EPIKOTE.

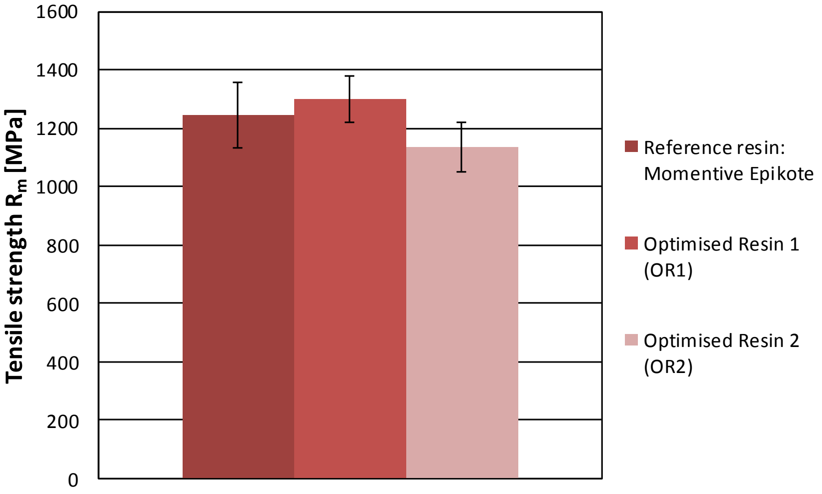

Figure 10. Tensile strength (0° fiber orientation).

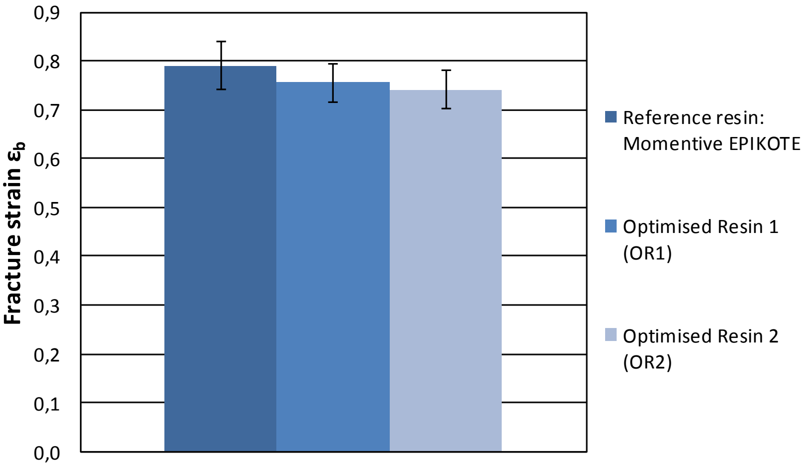

Figure 11. Fracture strain (0° fiber orientation).

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In contrast to a tensile load in 0°-direction, the 90°-direction is mainly characterised by the mechanical properties of the matrix system. The optimised resins showed an increase of the tensile strength from 35 MPa (reference resin) to up to 44 MPa (OR1) (Fig. 12). Aside, the standard deviation decreased in this case. Moreover a significant enhancement of the fracture stains could be detected (Fig. 13). The optimised resin systems reaches a frature strain of 0.34 % (OR1) respectively 0.32 % (OR2), while the reference system Momentive EPIKOTE achieve only a value of 0.21 %.

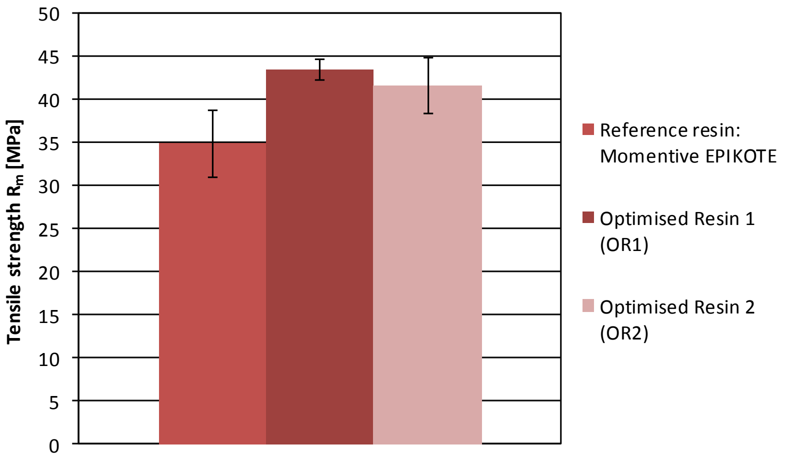

Figure 12. Tensile strength (90° fiber orientation).

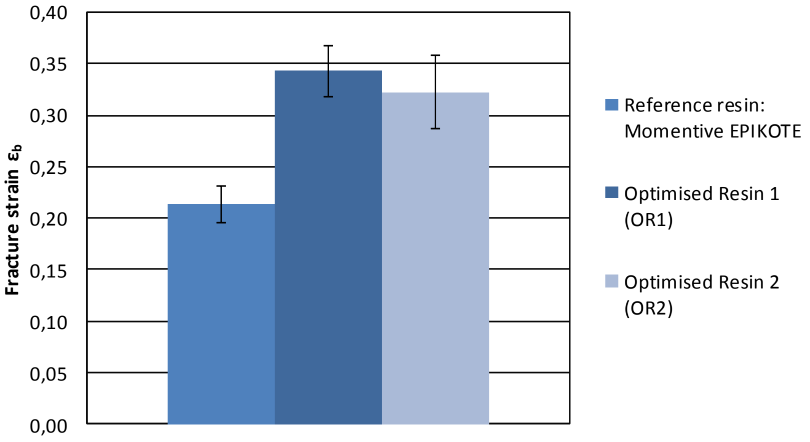

Figure 13. Fracture strain (90° fiber orientation).

After the tensile tests three-point bending tests according to DIN EN ISO 14125 were conducted [13]. Fig. 14 illustrates the results of these tests. The bending strength is on a similar level for the reference resin and OR1. OR2 shows a decrease of the bending strength from 680 MPa to 520 MPa. The flexural modulus of the different resins is on an equal level at around 86,000 MPa.

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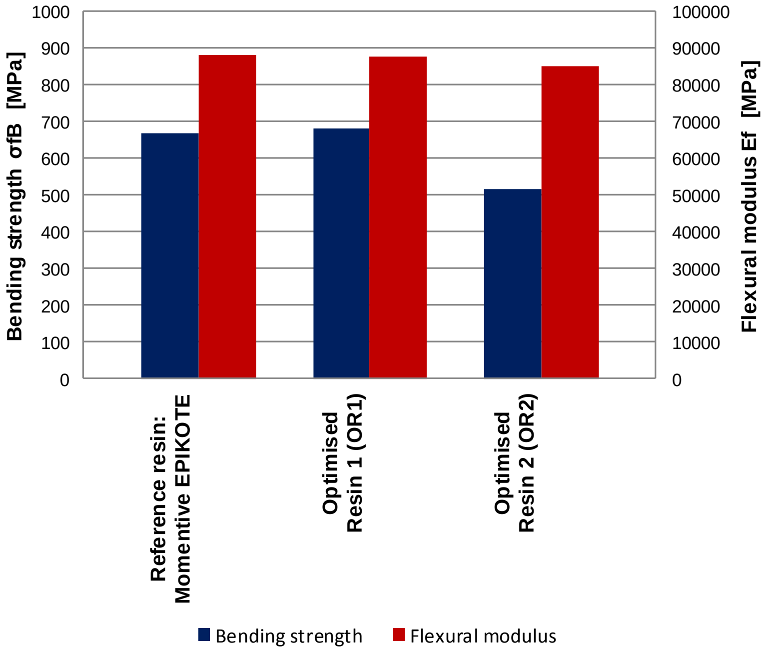

Figure 14. Results of three-point bending tests.

4.4. Adhesive Properties

Besides the viscosity and mechanical characteristics, the adhesive properties of the epoxy resins are of great interest for hybrid materials. Especially because the epoxy resin is used as an adhesive. A strong and durable connection between the sheet metal blank and the CFRP component is a decisive factor for crash- and safety-relavant structures for automotive applications. In order to analyse the adhesive propertie of the investigated matrix systems, lap shear tests according to DIN EN 1465 were performed [14]–[16].

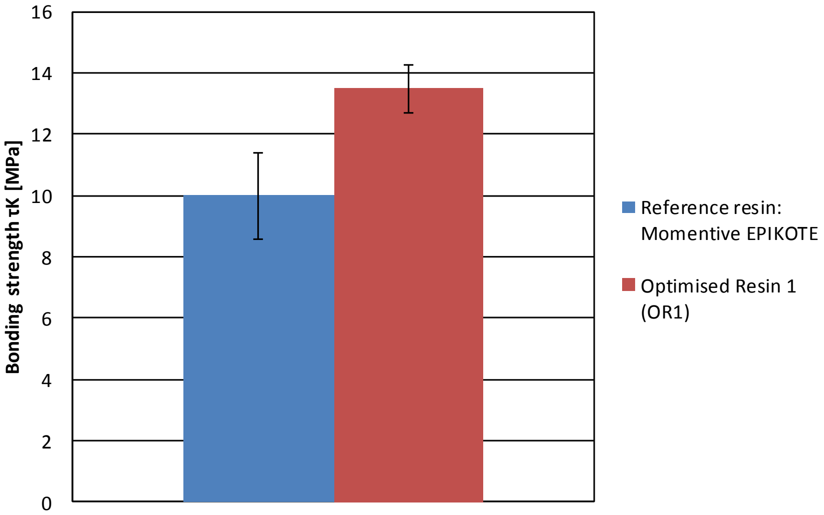

Figure 15. Results from lap shear tests.

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For the tests sheet metal blanks (HC340LA, t = 2 mm) were degreased and placed in the RTM-mould. Afterwards, the preform was inserted and the RTM-process was initiated. Then, lap shear specimens were cut out of the flat test plates. A comparison of the bonding strength of the reference resin and the optimised resin OR1 points out the significant increase. While the reference reaches about 10 MPa, the OR1 achieve a bonding strength of 13.8 MPa. Aside, the OR1 is characterised by a decreased standard deviation. A surface treatment by sandblasting leads to a further improvement of the bonding strength. Lap shear tests showed a value of about 13.5 MPa for the reference system, 19 MPa for OR1 and 17 MPa for OR2.

6. Conclusions

Sheet-metal-CFRP-hybrid structures offer a large weight saving potential for a wide range of applications. In this paper an optimised intrinsic RTM-process was discussed, which enables a large-series manufacturing of hybrid structures. Another aspect of the investigations was the optimisation of the matrix systems with regard to new requirements of hybrid materials. Standard epoxy resins fulfill a large variety of requirements of today’s needs. These needs reflect current applications and processes. A future mass usage of FRP in hybrid structures changes these demands. The optimised epoxy resins are charaterised by an enhanced viscosity course, fracture strain and bonding strength.

Acknowledgments

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