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ADVANCED MANUFACTURING TECHNOLOGIES FOR AUTOMOTIVE STRUCTURES IN MULTI-MATERIAL DESIGN CONSISTING OF HIGH-STRENGTH STEELS AND CFRP

Meike Frantz, Christian Lauter, and Thomas Tröster

University of Paderborn, Chair for Automotive Lightweight Design

ABSTRACT

This paper will show basic technological investigations in the field of prepreg-press-technology to manufacture multi-material or hybrid structures for automotive applications. After giving an overview of the process, research results regarding process and forming parameters as well as process control and cycle times will be discussed. Additional results for crash tests, e. g. of double-Z-profiles, demonstrate the crashworthiness of this new class of materials. Finally, detailed concepts for high-volume processing of structural automotive components with multi-material systems will be discussed. With expected cycle times of 2 to 5 minutes the developed approaches for manufacturing local reinforced structures are possibilities to solve the challenges of high-volume manufacturing in the field of CFRP.

Index Terms - Multi-material system, Hybrid material, Sheet metal, Carbon fibre reinforced plastic (CFRP), Automotive lightweight construction, Prepreg-press-technology, Manufacturing of CFRP components.

1. INTRODUCTION

Due to economical and ecological constraints the development of lightweight concepts becomes extremely important. These apply in particular to developing crash-relevant structures. In addition, the automotive industry must develop innovative and integral approaches for lightweight construction to meet future regulations in climate protection. Currently, there are three main trends in automotive lightweight construction: The use of high-strength metal alloys, substituting metals by composites, and the combination of hybrid materials.

By using high-strength metal alloys the wall thickness of structures can be reduced. However, once a critical minimum thickness is reached designers can expect stability problems. Thus, the potential of high-strength materials for lightweight construction is limited.

The second approach: substituting conventional construction materials by carbon fibre reinforced plastics (CFRP) allows considerable weight savings [1, 2], but 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 [3]. In this context, the manufacturing of components consisting of sheet metal blanks made of steel with a local CFRP reinforcement is being investigated. This combination should allow manufacturers to produce safety-relevant vehicle components, such as b-pillars, at lower costs compared to components made of mere CFRP [4].

Furthermore, this component design offers a high weight-saving potential as the reinforcing patch can only be applied in highly loaded areas while the reinforcing properties can be adjusted to special load cases [5]. Thus, a reduction of the wall thickness of the steel parts can be realised and material costs can be effectively reduced 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 [6]. 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 a sheet metal structure [7]. There are no limitations regarding the material type for the metallic component, meaning that press-hardable 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 for about three to five minutes where a pre-curing could occur. The final curing of the CFRP reinforcement could, for example, take place in a downstream, cataphoretic painting process [8].

Before an industrial application of these approaches can be realised basic research work regarding results and a suitable process design for prepreg-pressing 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 to develop suitable process strategies and tool concepts so that components with good performance characteristics can be produced in a short and robust process chain at minimal costs.

2. PREPREG-PRESS-TECHNOLOGY

2.1. Process run

The process of prepreg-press-technology can be divided into four main parts (figure 1). First, prepregs (pre-impregnated, semi-finished fibre products) are produced continuously on special machines and shipped on coils. The layer structure is realised according to the expected loads in the component, for example a b-pillar. The laminate is cut corresponding to the later structure geometry.

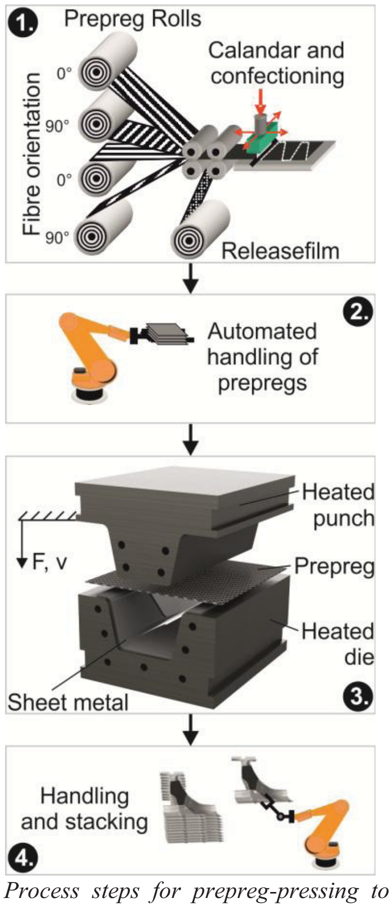

Figure 1: Process steps for prepreg-pressing to produce hybrid automotive structural parts, for example a b-pillar

Second, a robot handles the prepregs. After inserting an already formed steel structure into a heated steel tool the prepreg is applied to the steel structure by automated handling. Then the tailored prepreg is pressed onto the sheet metal by a heated punch. As the epoxy resin functions as an adhesive the joining of sheet metal and CFRP is realised in this third step, too. After a pre-curing of about 90 to 120 seconds, depending on the thickness of the prepreg, the hybrid component is removed by a robot and stacked. The post-curing of the components is realised during a downstream cataphoretic painting process.

2.2. Process parameters

The closed mould of the prepreg-press-technology can be identified as a bottleneck. A high cycle time reduces the qualification of prepreg-pressing for a large volume production. Adequate process parameters correlate directly with the cycle time of the press process. Thus, process parameters should allow low cycle times and good mechanical properties at the same time. The influence of different parameters is discussed below.

To investigate the process parameters epoxy-resin prepregs with 9 layers were used. The layer structure of the bidirectional carbon fibre scrim was (90/0/0/90/0/90/0/0/90°). As matrix resin a SGL type E201 was employed. For the steel component a DD11 and a 22MnB5 alloy, respectively, was utilised. In a first step, test plates (sheet metal material: DD11) and hat sections (sheet metal material: 22MnB5), respectively, were manufactured by prepreg-pressing. After a press process using a pre-curing time tprc, a consolidation pressure and temperature, the plates were post-cured in a furnace heating of 180 °C and tpoc = 30 minutes. In a next step three-point-bending samples were cut from the test plates and hat sections, respectively, and analysed with a testing machine. Using the matrix resin as an adhesive to bond the sheet metal and the CFRP makes an additional joining process superfluous.

Figure 2 shows the results of hybrid three-point-bending samples cut out of test plates. In the force-displacement diagram four curves for different process parameters are plotted. The consolidation temperature was not varied in this case. Varied parameters were the consolidation time (t_{prc} = 60 and 90 seconds) and the consolidation pressure (p = 0.1 and 0.6 MPa). For the curves a characteristic run can be identified. After a first rising the run flattens slightly. At the maximum force the main breakage occurs. Afterwards, single layers break step by step. In the end the fibre component fails completely and only the steel component absorbs the working forces.

Aside from these characteristics, the influence of different process parameters can be seen. In this case only four different combinations of consolidation pressure und pre-curing time were stated. A pressure of p = 0.1 MPa leads, for example, to a higher fibre volume ratio compared to p = 0.6 MPa. A higher fibre volume is directly linked to better mechanical properties, for example force and displacement. Another point is the allocation of fibres in the composite. This is especially important for bidirectional scrim because aspects like the fibre flow during the press process might be problematical.

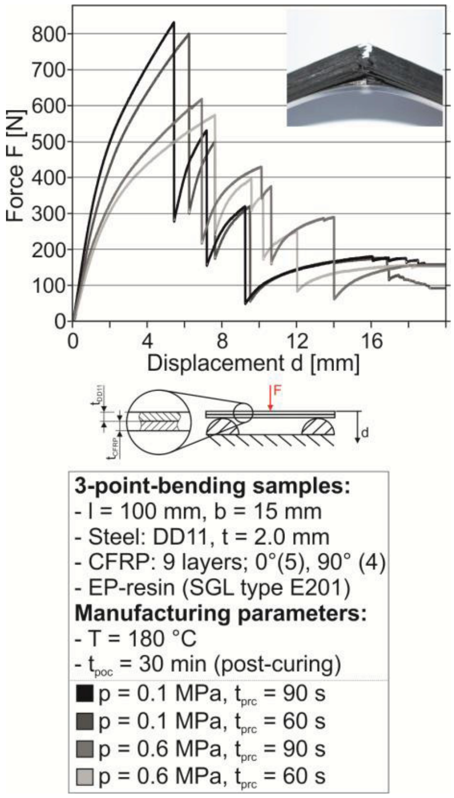

Figure 2: Force-displacement diagram for hybrid three-point-bending samples

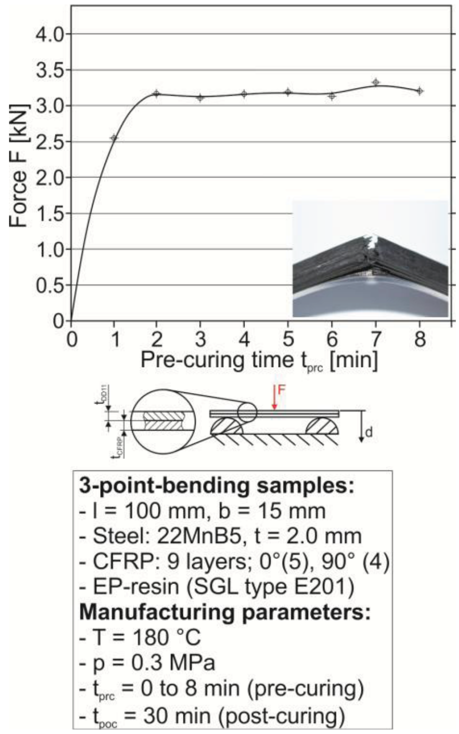

Figure 3: Force-pre-curing-time diagram for hybrid three-point-bending samples

To realise short cycle times the pre-curing time is the most important process parameter. Several hat sections, as seen in figure 1 (downright, No. 3.), were manufactured with a consolidation pressure of p = 0.3 MPa and a temperature of T = 180 °C by prepreg-pressing. The pre-curing time t_{prc} differed from 0 to 8 minutes. The hat sections were post-cured for t_{poc} = 30 minutes at T = 180 °C. Afterwards, three-point-bending samples were cut out of these hat sections. The results of the tests are illustrated in a force-pre-curing-time diagram (figure 3). The maximum forces for the bending samples reach a steady level for at least about t_{prc} = 60 seconds. A higher pre-curing time does not lead to higher maximum forces. The maximum forces vary between 3000 N and 3300 N. The failure of the CFRP is analogous to the samples described before. Thus, a minimum pre-curing time of 90 to 120 seconds is realistic for a prepreg-thickness of 2 mm and the use of standard epoxy resins. Due to variances in the tool temperature a safety factor should be taken into account.

2.3. 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 characterise 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 solution of the conflict between economical aims and the 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). The 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 (figure 2).

For the adhesive-bonded samples an impact-resistant, 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 due to 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. 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.

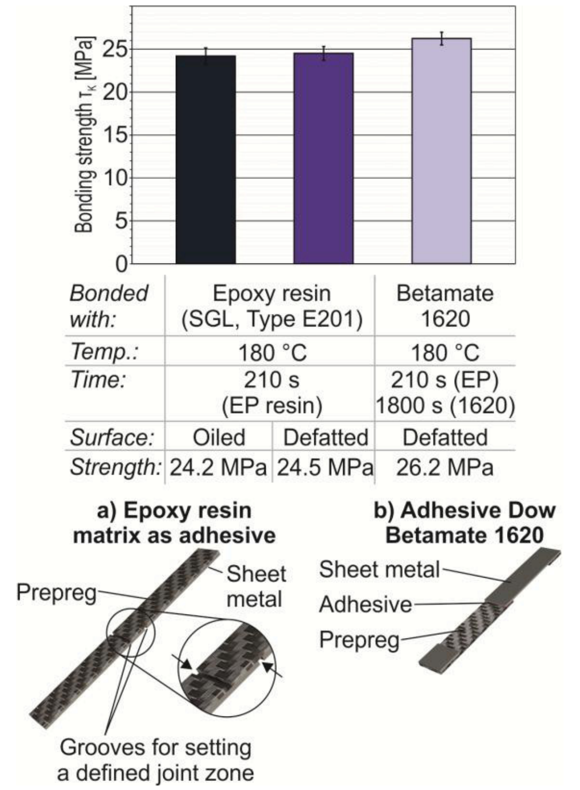

Figure 4: Comparison of joint strength of prepreg-pressed samples with adhesive-bonded samples

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.

3. CRASH TESTS

Applications for hybrid structures manufactured by prepreg-press-technology are, for example, crash-relevant automotive structural components. To analyse the behaviour of hybrid materials under crash loads different tests have been accomplished. After explaining the carriage crash test facility and the test specifications results for crash tests with pressure load and, afterwards, with three-point-bending load are shown.

3.1. Crash test facility

The crash tests were performed on a carriage crash test facility (figure 5). The impact carriage is accelerated by a hydraulic drive system and guided on special rails. Different component jigs can be attached to a span, for example for tests with pressure or bending loads. The mass of the impact carriage can be varied between 50 and 500 kg. A maximum speed of 25 m/s can be reached. An optical measurement system with a frequency of up to 100 kHz gauges deformation and strain.

For the crash tests two different sample geometries were manufactured. The crash tests with pressure load were performed with a 320 mm long double-Z-profile. For the three-point-bending tests a 1000 mm long profile was used. In both cases the cross section had a width of w = 100 mm and a height of h = 100 mm without bonding flanges. The sheet metal was a DD11 with a wall thickness of 1.5 and 2 mm. For both geometries a 300 mm long CFRP reinforcement was pressed centred into the sheet metal. The same layer structure as for the bending samples was used to investigate the process parameters. The epoxy resin from SGL (Type E201) embeds carbon fibres in a 9 layer bidirectional scrim (90/0/0/90/0/90/0/0/90°). The steel components were bonded in the flange area by a Betamate 1620 adhesive. The thickness of the bonding was 0.3 mm.

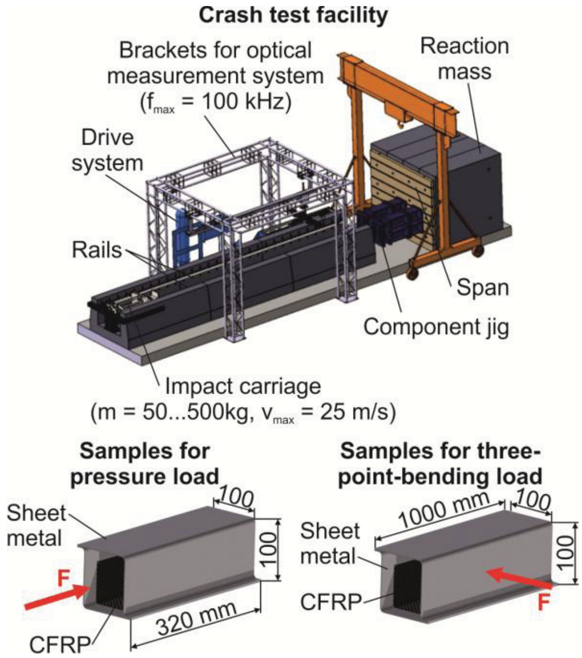

Figure 5: Crash test facility (left), samples for crash tests with pressure load (upper right) and with three-point bending load (lower right)

The samples were manufactured with a pre-curing time of t_{prc} = 120 seconds (crash tests with pressure load) and t_{prc} = 120 and 300 seconds (crash tests with bending load), respectively. The post-curing time was t_{poc} = 30 minutes. As a temperature for both curing processes T = 180 °C was used. The consolidation pressure exceeded p = 0.3 MPa.

3.2. Crash tests with pressure load

The crash tests with pressure load were realised with the 320 mm long double-Z-profiles. The load case is comparable to an automobile crash box. Four different configurations were tested (figure 6): 1 mere steel

(t_{DD11} = 1.5 mm), 2 hybrid (t_{DD11} = 1.5 mm; t_{CFRP} = 2.0 mm), 3 mere steel (t_{DD11} = 2.0 mm), and 4 hybrid (t_{DD11} = 2.0 mm; t_{CFRP} = 2.0 mm). For the combinations 1 and 2 the impact energy exceeded E_{Crash} = 5.8 kJ with an impact velocity of v_{Crash} = 9.6 m/s. The combinations 3 and 4 were tested with E_{Crash} = 8.0 kJ and v_{Crash} = 11.5 m/s.

The medial forces and the maximal displacement of deformation of mere steel structures and hybrid solutions can be seen in the column diagram in figure 6. As a first result, hybrid materials offer a significant weight saving potential. In a next step, the number of crash tests could be expanded. This means, for example, to vary steel materials or prepreg layers.

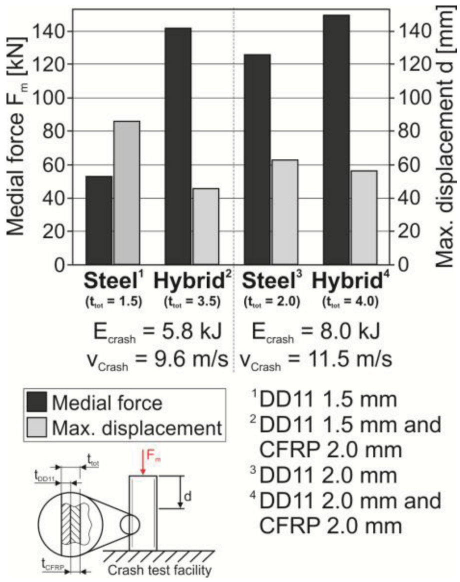

Figure 6: Medial forces and maximal displacement of double-Z-profile samples under pressure crash load

3.3. Crash tests with three-point-bending load

The crash tests with three-point-bending load were realised with the 1000 mm long double-Z-profiles. This load case is important for pillar structures, for example a b-pillar. The tests were performed with two different hybrid structures. On the one hand, the thickness of the DD11 steel exceeded t_{DD11} = 1.5 mm; on the other hand, the thickness was t_{DD11} = 2.0 mm. In both cases a CFRP patch with a thickness of t_{CFRP} = 2.0 mm was employed. Two different pre-curing times were investigated: t_{prc} = 120 seconds and t_{prc} = 300 seconds. Thus, there are four combinations. The impact energy exceeded E_{Crash} = 1075 J and the impact velocity v_{Crash} = 4.5 m/s.

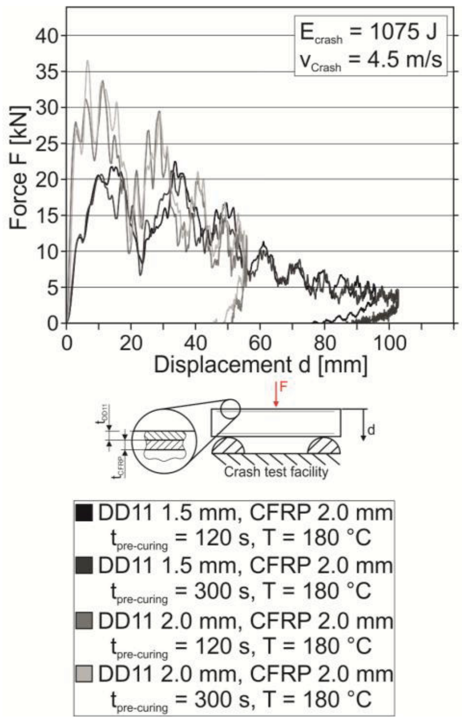

Figure 7: Force-displacement diagram of double-Z-profiles under three-point bending crash load

The results of the crash tests are shown in figure 7. It can be seen that the influence of the variation of the pre-curing time is slight. The maximum forces for the samples averaged 22 kN and 34 kN, respectively. The maximum displacement was about 103 mm or 57 mm. As a result it can be stated that a pre-curing time of 120 seconds is sufficient for the used layer structure. Next steps could be geared to expand the number of crash tests. This means, for example, to vary steel materials or prepreg layers and to investigate mere steel structures as a reference.

4. APPROACHES FOR MASS PRODUCTION

Substantial demands to implement hybrid structures into automotive applications are adequate approaches for mass production [9, 10]. The prepreg-press-technology is able to meet these demands by using automation tools like robots or assembly lines (figure 8 a). In this case, a robot inserts formed sheet metal into a heated mould. The same robot inserts a tailored prepreg. The forming and curing steps are realised as described above. 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 (figure 8 b).

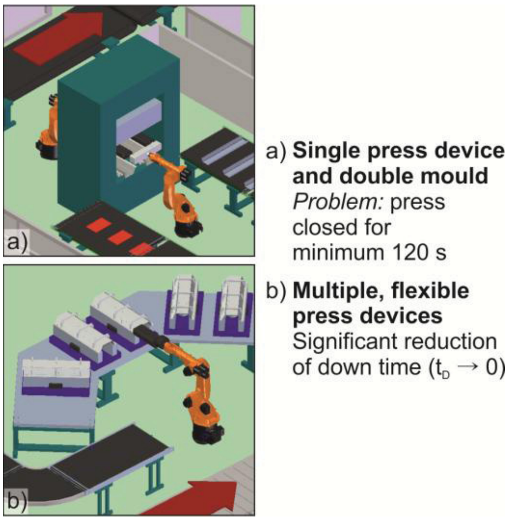

Figure 8: Automated prepreg-press process a) with a single press device and a double mould and b) with multiple, flexible press devices

5. CONCLUSIONS

Multi-material systems consisting of sheet metal and fibre-reinforced plastics offer a major potential for lightweight design in the automotive industry. The prepreg-press-technology allows a significant reduction of process steps as well as process time.

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 good crash performance.

6. ACKNOWLEDGEMENT

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