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Large-Scale Production of High-Performance Fiber-Metal-Laminates by Prepreg-Press-Technology

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Abstract**—**Lightweight construction became more and more important over the last decades in several applications, e.g. in the automotive or aircraft sector. This is the result of economic and ecological constraints on the one hand and increasing safety and comfort requirements on the other hand. In the field of lightweight design, different approaches are used due to specific requirements towards the technical systems. The use of endless carbon fiber reinforced plastics (CFRP) offers the largest weight saving potential of sometimes more than 50% compared to conventional metal-constructions. However, there are very limited industrial applications because of the cost-intensive manufacturing of the fibers and production technologies. Other disadvantages of pure CFRP-structures affect the quality control or the damage resistance. One approach to meet these challenges is hybrid materials. This means CFRP and sheet metal are combined on a material level. Therefore, new opportunities for innovative process routes are realizable. Hybrid lightweight design results in lower costs due to an optimized material utilization and the possibility to integrate the structures in already existing production processes of automobile manufacturers. In recent and current research, the advantages of two-layered hybrid materials have been pointed out, i.e. the possibility to realize structures with tailored mechanical properties or to divide the curing cycle of the epoxy resin into two steps. Current research work at the Chair for Automotive Lightweight Design (LiA) at the Paderborn University focusses on production processes for fiber-metal-laminates. The aim of this work is the development and qualification of a large-scale production process for high-performance fiber-metal-laminates (FML) for industrial applications in the automotive or aircraft sector. Therefore, the prepreg-press-technology is used, in which pre-impregnated carbon fibers and sheet metals are formed and cured in a closed, heated mold. The investigations focus e.g. on the realization of short process chains and cycle times, on the reduction of time-consuming manual process steps, and the reduction of material costs. This paper gives an overview over the considerable steps of the production process in the beginning. Afterwards experimental results are discussed. This part concentrates on the influence of different process parameters on the mechanical properties, the laminate quality and the identification of process limits. Concluding the advantages of this technology compared to conventional FML-production-processes and other lightweight design approaches are carried out.

Keywords**—**Composite material, Fiber metal laminate, Lightweight construction, Prepreg press technology, Large-series production.

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I. Introduction

LIGHTWEIGHT design is an important contribution to reduce CO_2 emissions and fuel consumption as well as to improve safety and performance of vehicles [1], [2]. Using lightweight technologies, the realization of components with a lower mass and with stable or even better characteristics is possible. In the automotive sector a decrease of the vehicles mass of 100 kg leads to a reduction of CO_2 emissions of about 8.5 g/km and a reduction of fuel consumption of 0.25 l/100 km [3]. However, for many automobiles an increasing weight could be recorded over the last decades. This is a result of improved safety and comfort requirements and was about 100 kg per decade. In current automobile generations, this trend could be reversed.

Currently, three main trends in automotive lightweight construction are obvious: The use of high-strength metal alloys, substituting metals by composites, and the combination of materials. The use of CFRP includes the highest lightweight potential. In terms of a large-series applications main drawbacks are the high material and processing costs [4]. A solution for these challenges could be components realized in multi-material-design. Especially the extensive combination of sheet metal with local CFRP reinforcements is a promising approach, e. g. for b-pillars, sills or other frame structures [5].

II. Sheet Metal-FRP-Hybrid-Structures

A. Overview

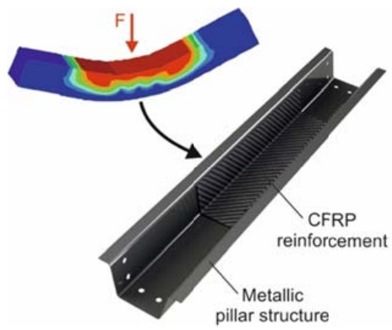

Fig. 1 Tailored hybrid pillar structure consisting of sheet metal and local CFRP reinforcement

Hybrid materials typically consist of a sheet metal basic layer, a locally applied FRP reinforcement layer and an optional sheet metal covering layer. The layered structure offers the possibility to tailor components to their expected loading (Fig. 1). Due to the FRP structure, the wall thickness of the sheet metal structure can be reduced effectively. Thus, hybrid components offer a large weight saving potential. Besides, an optimised lightweight design can be realized, because the cost-intensive CFRP is only used in highly loaded areas. Other advantages of hybrid structures are an easy integration into existing processes of vehicle production or into existing body constructions [6].

B. Manufacturing Process

The manufacturing of automotive hybrid structures can be realized e.g. by the prepreg press technology or an intrinsic resin transfer molding process. Using pre-impregnated semi-finished fiber products offers the possibility to outsource the time consuming injection and infiltration process of the textile. Therefore, the prepreg technology include a high potential to significantly reduce cycle times in comparison to conventional FRP-processes and enables a large-series manufacturing of hybrid structural automotive components.

The prepreg press technology can be divided into four steps (Fig. 2). The input for this process is continuously produced prepregs, that are shipped on coils, and formed sheet metal structures. In the first step, the prepregs are stacked corresponding to the expected loads in the final component. After a compaction of the layer structure in a calender, the prepreg stack is cut to the geometry of the final component, e.g. by an ultrasound cutter. In the second step, a robot with a special gripper system handles the uncured tacky prepreg. Together with a formed sheet metal structure, the prepreg is inserted into a heated mold in step three. The laminate is pressed on the metallic surface by a hydraulic press device with a pressure of about 0.1 to 0.5 N/mm^2. At a temperature of 140 to 180 °C, the prepreg is pre-cured for a time of 90 to 120 seconds depending on the laminate thickness. Afterwards, the final hybrid structure can be removed from the mold and stacked. 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.

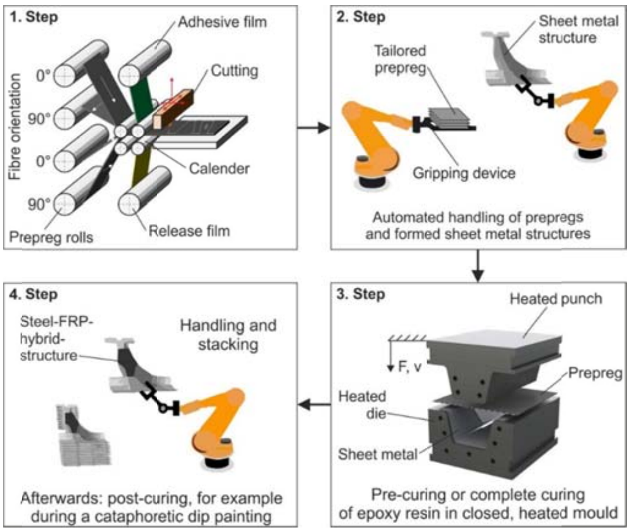

Fig. 2 Process steps for the manufacturing of hybrid automotive structural parts, for example a b-pillar, by prepreg press technology

Another approach is combined forming of sheet metal and CFRP. Here, an uncured CFRP prepreg is applied locally to a sheet metal blank and then both components are formed 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 [7].

C. Mechanical and Adhesive Properties

The process parameters have a great influence on the mechanical properties and the quality of the manufactured structures. Aside, the process parameters also influence the cycle times and thus the cost of the process. Several investigations on this topic have been accomplished and published, i.e. in [6], [8], [9].

The samples for the investigations consisted of sheet metal and CFRP. For the metal component a S235JR with a thickness of t = 2 mm was used. The prepregs were standard semi-finished products from SGL. The epoxy resin from SGL (Type E201) embeds carbon fibers in a symmetric 9 layer scrim $(90/02/90/0)_S$. The prepregs were manufactured by prepreg press technology. For the bonding with epoxy resin as an adhesive, the prepreg was directly pressed on the metallic surface.

The manufacturing process was divided into several steps. First, prepregs, sheet metal and release film were cut and layered. Second, the press process was realized. For this step different defined parameters were used. The test plates were post-cured in a furnace for 30 minutes at a temperature of 180 °C, which simulates the cataphoretic painting process. Next, three-point bending samples were cut from the test plates and tested with a three-point bending setup.

During the experimental investigations, different combinations of temperature, pressure and time for the consolidation process were used. The aim was to identify a suitable process window to minimize the cycle times of the prepreg press process.

In Fig. 3, the results of three-point bending tests for different process parameters are illustrated. As a consolidation pressure 0.3 MPa was used. It can be seen that the values for the maximum bending stress achieve a plateau of about 750 MPa for pre-curing times above 60 seconds and temperatures above 160 °C. The values decrease at temperatures higher than about 190 °C.

Summarizing, optimal process parameters for the prepreg press process were found: the temperature for low cycle times should be about 180 °C, the pressure should be between 0.3 and 0.4 MPa and the time should be above 90 seconds. These values depend on influence factors such as the layer thickness, the materials or the textile semi-finished component.

For the hybrid three-point bending samples, a characteristic failure behavior could be found (Fig. 4). The sheet metal plastically deforms under influence of the test force, while the CFRP component fails by delamination and fiber breakage. For a force transmission not from the metal side but from the side of the CFRP, the failure is characterized even by delamination and fiber breakage – in this case, as a result of compression forces in the CFRP structure.

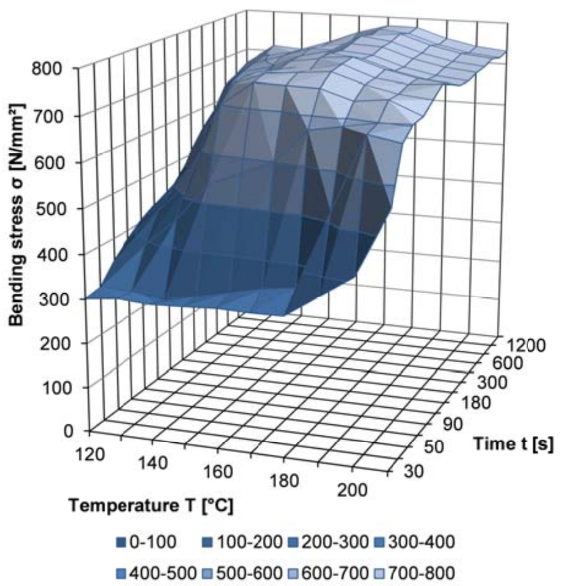

Fig. 3 Results of three-point bending tests for different process parameters [10]

Fig. 4 Failure behaviour of hybrid three-point bending samples (force transmission from the side of the sheet metal)

The performance of a multi-material or hybrid structures is strongly influence by a permanent and solid bonding. For the combination of sheet metal blanks and CFRP different bonding technologies are available. Especially the adhesive bonding is an interesting option because of large overlap area between the single components. In order to characterize the bonding properties and to compare them with those of adhesive-bonded joints, shear-tensile specimens (Fig. 5) were analyzed according to DIN EN 1465 [11]. For the investigations, the same materials as described in Chapter II *C* were used. 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).

In Fig. 6, the maximum forces and the tensile energy absorptions of shear tensile specimens are shown. On the one hand, the epoxy matrix resin was used as an adhesive. The specimens were pre-cured at temperatures from 140 to 180 °C. As a reference an impact-resistance modified structural epoxy adhesive was used (Dow Betamate 1620) [12]. The maximum forces for the different pre-curing temperatures are on a similar level at about 7.5 kN. The use of a structural adhesive leads to slightly higher forces of about 8.2 kN. The tensile energy absorption reveals that the failure behavior of the epoxy resin as an adhesive is quite brittle. This results in low values for the energy absorption of around 2.5 J, while the impact resistant modified Dow Betamate 1620 reaches 3.7 J. Summarizing the bonding performance of the Dow Betamate is above the level of the epoxy resin. This is not surprising because the adhesive war optimized for this application. On the other side it can be noted, that the use of the epoxy resin offers an optimized bonding solution for hybrid structures, when costs and mechanical properties are taken into account.

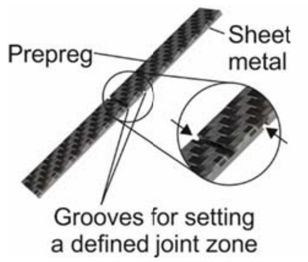

Fig. 5 Specimen geometry for shear tensile tests according to DIN EN 1465 [11]

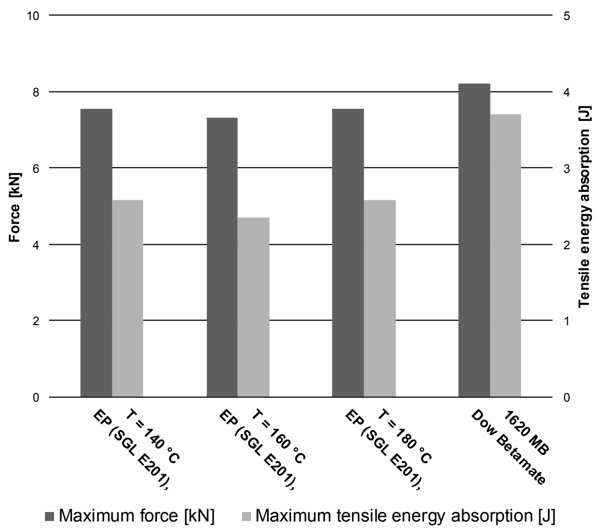

Fig. 6 Comparison of maximum force and tensile energy absorption of different bonding technologies for hybrid structures

III. High-Performance FML

A. Overview

In comparison to sheet-metal-FRP-hybrid structures FML consists of several thin sheet metal and FRP layers (Fig. 7). Well-known examples for industrially used FMLs are GLARE, ARALL or CARALL. Corresponding to their indication glass, carbon or aramid fibers are used in combination with e. g. an epoxy resin as a reinforcement structure for aluminum [13], [14].

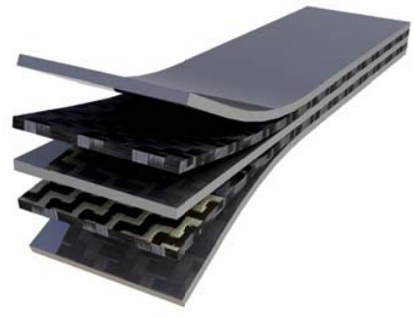

Fig. 7 Schematic layout of a FML consisting of three sheet metal and two FRP layers

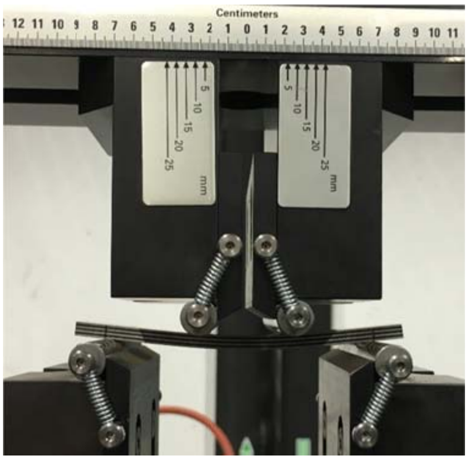

Fig. 8 Four-point bending test of a FML specimen

FMLs feature several advantages against pure sheet metal or FRP structures. They are characterized by a high specific stiffness and strength. FMLs offer a good burn ratio as well as an advantageous damage tolerance, fatigue and crack propagation behavior [14]. Just like for sheet-metal-FRP-hybrid systems, an integration into existing structures or assemblies is possible in most cases by using conventional bonding processes. Nowadays, main disadvantages of FMLs can be found in high material and processing costs. Aside, the available production technologies are not appropriate for the manufacturing of pillar structures, which are of enormous relevance in the automotive industry and other industrial sectors.

B. New Manufacturing Process

The starting points of the development of a new large-scale production process for FMLs were the mentioned disadvantages. The approach to address these disadvantages was the utilization of the prepreg press technology (Fig. 2), where a prepreg reinforcement is directly formed into a sheet metal structure or where a combined forming operation of prepreg and sheet metal is initiated [9], [15]. For an effective production of fibre-metal-laminate-structures with short cycle times less than 5 minutes prepregs and sheet metal plates were stacked. Afterwards, the laminates were pressed and cured using optimized process parameters. Further investigations will focus on a combined forming of the laminates.

As a first step, flat test panels were manufactured using the new approach. The metal components consisted of a deep-drawing steel (type: DC01) in the first case and of a stainless steel (type: 1.4301) in the second case. The thickness of the sheet metal blanks was t = 0.5 mm in both cases. For the CFRP reinforcement, again SGL prepregs with an epoxy matrix resin (cf. chapter II.) were used. The expoy resin was used as an adhesive. The layer structure of the FML was symmetric with the following stacking sequence: metal / CFRP (0/90/0)° / metal / CFRP (0/90/0)° / metal / CFRP (0/90/0)° / metal.

For the manufacturing of the test plates sheet metal blanks and CFRP Prepregs were cut, degreased and stacked. After these steps, the plates were pressed and cured with optimized, defined parameter sets. The test plates were post-cured in an air circulated furnace for 30 minutes at a temperature of 180 °C. This step simulated a cataphoretic dip painting process, which is generally used for structural automotive parts. Next, three and four-point bending (Fig. 8) as well as tensile samples were cut from the test plates and tested with appropriate test setups. The geometries of the specimens and the test parameters were selected referring to DIN EN ISO 14125, DIN EN ISO 527-1, -4 and -5 as well as DIN EN 2562 [16]–[19].

C. Properties and Performance

In order to realize a general qualification for the prepreg press technology to produce FMLs in high qualities within short cycle times, basic investigations were conducted. As mentioned before essential mechanical tests and the analysis of microsections were completed in a first step.

Typical stress-strain-curves are shown in Fig. 9. These tests were conducted at a universal testing machine at the laboratory of the LiA at the Paderborn University. The specimens were manufactured with two different sets of process parameters for the pre-curing in the closed mold: T_1 = 150 °C and t_1 = 300 s respectively T_2 = 180 °C and t_2 = 90 s. The subsequent post-curing was realized at T = 180 °C for 30 minutes. The different curves are characterized by a knee in the beginning. Therefor the failure of 90°-plies might be responsible. The further shape of the curves shows a linear progression until the fraction of the 0°-plies. From this point, the composite is mainly characterized by the sheet metal components, which is not illustrated in the diagram.

The summary of the tensile tests is presented in Fig. 10. It can be observed that a higher pre-curing temperature results in a slightly reduced tensile strength, while the fracture strain is not visibly affected. The standard deviation is small for the different process parameters, which can be seen as an indicator for a robust and reproducible process.

The performed three-point bending tests show the same tendency, but the fracture strain is affected by higher pre-curing temperatures (Fig. 11). Aside, the standard deviation is larger than before. However, with the four-point bending tests (Fig. 12) the tendency could be pointed out as well, but the standard deviation especially for the pre-curing temperature of

T = 150 C° is quite smaller (Fig. 13).

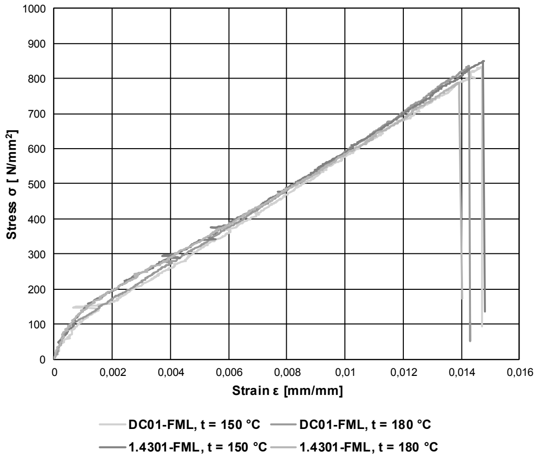

Fig. 9 Stress-strain-curves from tensile tests of different FMLs

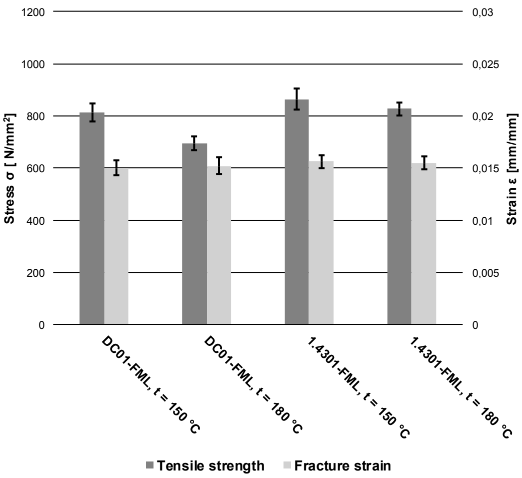

Fig. 10 Results from tensile tests of different FMLs

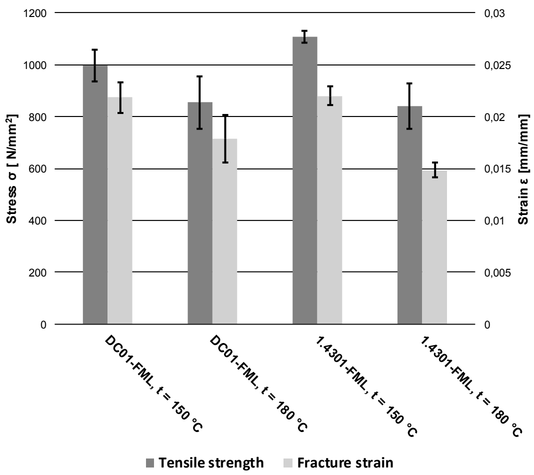

Fig. 11 Results from three-point bending tests of different FMLs (calculations of stress and strain according to DIN EN ISO 14125)

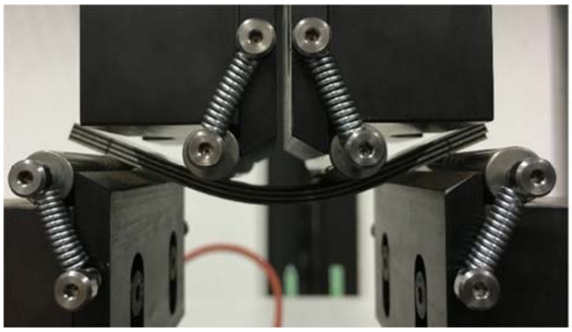

Fig. 12 Four-point bending test of a FML specimen

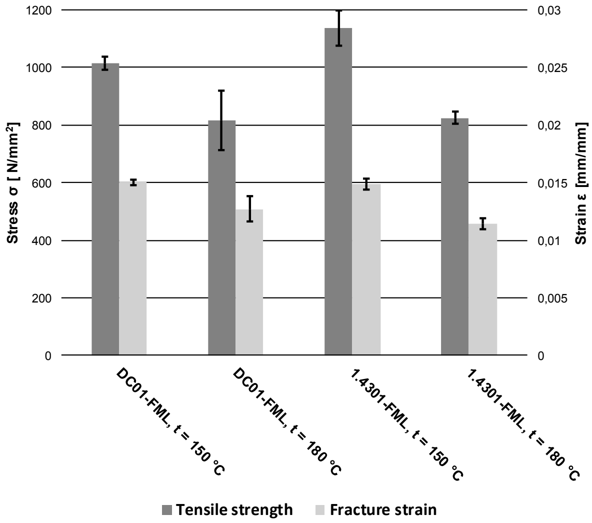

Fig. 13 Results from four-point bending tests of different FMLs (calculations of stress and strain according to DIN EN ISO 14125)

In order to analyze the laminate quality several microsections were generated. For the used sheet metal blanks and the different process parameters, the results are shown in Figs. 14 and 15. The micrographs are characterized by a good laminate quality with nearly no pores or other imperfections. The thickness of the single plies (0/90/0°) is even and the boundary between the plies is well pronounced.

(a) (b)

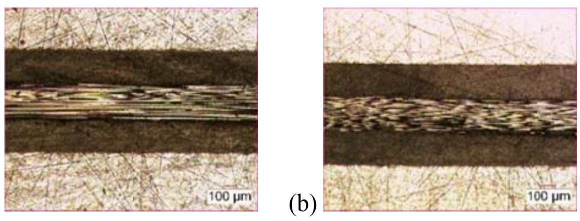

Fig. 14 Microsections of the middle plies of the DC01-CFRP-FML manufactured with the following pre-curing parameters: (a) 150 °C, 300 s and (b) 180 °C, 90 s

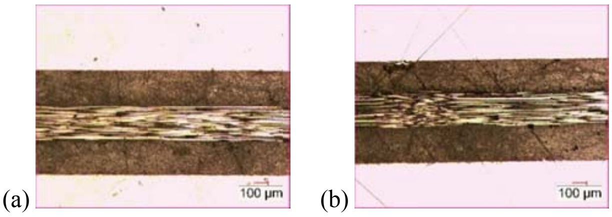

Fig. 15 Microsections of the middle plies of the 1.4301-CFRP-FML manufactured with the following pre-curing parameters: (a) 150 °C, 300 s and (b) 180 °C, 90 s

IV. Conclusion

Hybrid systems consisting of sheet metal blanks and fiber reinforced plastics offer a major potential for lightweight design in different industrial sectors, i. e. the automotive or aircraft industry. A new approach in this field is the extension of the area of applications of FML. Currently, main applications of FML can be found in straight or slightly curved components for the aircraft industry.

The manufacturing of FMLs by prepreg press technology enables the production of complex pillar structures, which are used in a wide range of industrial applications. Aside, this technology allows a significant reduction of cycle times from sometimes several hours to under 5 minutes.

The available paper shows basic investigations of the manufacturing of FMLs by this technology. Therefore, plane hybrid test plates were manufactured with different process parameters. From these plates standard test specimens were cut out. The results from the conducted tensile, three- and four-point bending tests demonstrated the potentials of this innovative approach. The process enables a manufacturing of materials with a good and reproducible mechanical performance and a high quality within cycle times of less than 5 minutes.

References

[1] J. C. González Palencia, T. Furubayashi, and T. Nakata, "Energy use and CO2 emissions reduction potential in passenger car fleet using zero emission vehicles and lightweight materials," *Energy*, vol. 48, no. 1, pp. 548–565, Dec. 2012.

[2] G. Kopp, E. Beeh, R. Schöll, A. Kobilke, P. Straßburger, and M. Kriescher, "New Lightweight Structures for Advanced Automotive Vehicles - Safe and Modular," *Procedia - Soc. Behav. Sci.*, vol. 48, pp. 350–362, 2012.

[3] M. Goede, "Karosserieleichtbau als Baustein einer CO2-Reduzierungsstrategie," 2007.

[4] A. Horoschenkoff, "Statt Stahl und Aluminium," *Kunststoffe*, no. 5, pp. 50–54, 2010.

[5] S. Grasser, "Composite-Metall-Hybridstrukturen unter Berücksichtigung großserientauglicher Fertigungsprozesse," presented at the Symposium Material Innovativ, Ansbach, 2009.

[6] C. Lauter, T. Krooß, and T. Tröster, "Manufacturing of Hybrid Structures by Prepreg Press Technology," presented at the 19th International Conference on Composite Materials, Montreal, 2013.

[7] W. Homberg, J. Dau, and U. Damerow, "Combined Forming of Steel Blanks with Local CFRP Reinforcement," presented at the 10th International Conference on Technology of Plasticity, 2011.

[8] C. Lauter, M. Sarrazin, and T. Tröster, "Joining technologies for hybrid materials consisting of sheet metal and carbon fibre reinforced plastics," presented at the 1st International Conference of the International Journal of Structural Integrity, Porto, 2012.

[9] C. Lauter, J. Niewel, and T. Tröster, "Quasistatic and crash tests of steel-CFRP hybrid pillar structures for automotive applications," *Int. J. Automot. Compos.*, vol. 1, no. 1, pp. 52–66, 2014.

[10] C. Lauter, Z. Wang, I. Koke, and T. Tröster, "Influences of process parameters on the mechanical properties of hybrid sheet metal-FRP-composites manufactured by prepreg press technology," presented at the 20th International Conference on Composite Materials, Kopenhagen, 2015.

[11] "DIN EN 1465: Klebstoffe. Bestimmung der Zugscherfestigkeit von Überlappungsklebungen," 2008.

[12] "Betamate 1620. Crashstabiler Strukturklebstoff. Technisches Datenblatt," 2006.

[13] N. Asnafi, G. Langstedt, C. H. Andersson, N. Östergren, and T. Hakansson, "A new lightweight metal-composite-metal panel for applications in the automotive and other industries," *Thin-Walled Struct.*, vol. 36, pp. 289–310, 2000.

[14] T. Sinmazçelik, E. Avcu, M. Ö. Bora, and O. Çoban, "A review: Fibre metal laminates, background, bonding types and applied test methods," *Mater. Des.*, vol. 32, no. 7, pp. 3671–3685, Aug. 2011.

[15] H. C. Schmidt, U. Damerow, C. Lauter, B. Gorny, F. Hankeln, W. Homberg, T. Tröster, H. J. Maier, and R. Mahnken, "Manufacturing processes for combined forming of multi-material structures consisting of sheet metal and local CFRP reinforcements," *Key Eng. Mater.*, vol. 504–506, pp. 295–300, 2012.

[16] "DIN EN ISO 527-1: Kunststoffe. Bestimmung der Zugeigenschaften. Teil 1: Allgemeine Grundsätze," 1996.

[17] "DIN EN ISO 527-4: Kunststoffe. Bestimmung der Zugeigenschaften. Teil 4: Prüfbedingungen für isotrop und anisotrop faserverstärkte Kunststoffverbundwerkstoffe," 1997.

[18] "DIN EN ISO 527-5: Kunststoffe. Bestimmung der Zugeigenschaften. Teil 5: Prüfbedingungen für unidirektional faserverstärkte Kunststoffverbundwerkstoffe," 1997.

[19] "DIN EN 2562: Luft- und Raumfahrt. Kohlenstoffaserverstärkte Kunststoffe. Unidirektionale Laminate. Biegeprüfung parallel zur Faserrichtung," 1997.