Concepts for interface engineering and characterization in composite hybrid structures

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Abstract. Multi-material design is a key technology for lightweight design and calls for combining different materials such as steels, light metals and composites like carbon fiber reinforced plastics (CFRP) into load-bearing structures. Due to the minor chemical affinity of such materials and contact corrosion aspects, the design of an appropriate interface is a current challenge. Aiming on highly performant single-stage manufacturing processes, the paper presents investigations on several surface treatment techniques like a laser pretreatment, the use of primers and a sol-gel coating. Beside investigations on the achievable joint strengths, the corresponding joining concepts to facilitate the in-mould assembly of hybrid structures are validated. In this case the intrinsic manufacturing methods of the Resin Transfer Moulding (RTM) and the Automated Fiber Placement (AFP) technology are presented. Furthermore corrosion protection measures for CFRP and aluminum are analyzed via immersion and salt spray tests.

1. Introduction

The use of lightweight structures offers nowadays the possibility to achieve a significant reduction of weight. In this context, a complete substitution of a monolithic material by one another is in general not adequate for the consistent use of the potential of lightweight structures [1, 2]. In contrast, the multi material design approach considers the entire structure and is based on a hybrid material combination. The concept of the hybridization of individual components into an integral structure gains therefore more importance and can basically be realized through two different methods. The utilization of consecutive manufacturing processes (post-mould assembly) such as adhesive bonding or screwing and riveting does not exploit the maximum lightweight potential either [1]. As an alternative concept, the hybridization within a single-stage process is most promising.

However, the utilization of intrinsic hybrids needs to meet essential requirements such as resource-efficient production, characterization and design of load-optimized hybrid components. In this context, suitable methods for the design of the hybrid interfaces are of particular interest. The paper presents different approaches to design and characterize the interface of intrinsic hybrids made out of the following material combinations:

- CFRP with duroplastic matrix and aluminum
- CFRP with duroplastic matrix and steel
- CFRP with thermoplastic matrix and aluminum

The dissimilar material combinations show varying coefficients of thermal expansion and different electrochemical potentials as well as chemically and mechanically strongly differing properties. Thus, adhesion and corrosion aspects need to be taken into account. Apart from the adhesion qualities of the resin, the surface pre-treatment is one of the most important steps to achieve a satisfying joint strength [3][4]. In terms of improving the adhesion on steel, various surface pre-treatment techniques, e.g. etching, anodizing, plasma spraying or blasting, were investigated in the recent years (cf. [5][6]). Several investigations, especially on titanium alloys, revealed that a laser pre-treatment of the metal surface represents a fast, easy and cost-efficient way to enhance the adhesion [7][8][9]. The laser pre-treatment leads to a nanostructured and open-porous surface as well as fine nano cavities, which enable a mechanical interlocking between the metal surface and the resin. This ensures a satisfying bond strength [3].

Sol-Gel coatings provide excellent corrosion protection of aluminum and steel substrates. However, the coatings can additionally be modified to achieve chemical compatibilization in metal-FRP composites [10]. In this way, an interface concept combining corrosion protection and high bond strengths can be utilized.

Further, surface treatments already existing on the market, like anodizing, as well as the utilization of priming processes will be investigated in this paper for their suitability for single stage manufacturing of intrinsic hybrids. The characterization of the interface is conducted based on shear, shear-lap and double cantilever beam (DCB) tests. In addition, different corrosion protection measures are applied accounting to the increased corrosion potential of CFRP and aluminum due to the high electrochemical potential difference between the two counterparts.

2. Surface treatments for hybrid structures

2.1. Sol-Gel process generating adhesive bonds

The concept of the interfacial design through a sol-gel intermediate layer particularly addresses an improved adhesion between the CFRP and the metal. For this purpose, the chemical composition of the sol-gel is adapted towards the selected polymeric matrix (polyamide 6) and the sol is applied onto the metal substrate (aluminum) via dip coating [10]. The properties of the sol-gel are adaptable by using a hybrid sol [11], which is a mixture of different organically modified silicates (ORMOSIL). This allows the change of the wetting behavior of the interface due to the selected chemical composition. The effect of polymerizing the sol into gel is shown in Figure 1.

Furthermore, the silicate layer acts as a dense physical barrier and thereby decouples the corrosion potentials of the metal and the CFRP. Thereby, contact corrosion between the noble CFRP (redox potential of +0.74 V) and less noble aluminum (redox potential of -1.67 V) is avoided. Hence, the challenge is to develop a formulation for a sol-gel coating on aluminum, which resists the forming and joining process and therefore can be applied before the hybridization step.
The wettability of the fully crosslinked sol-gel coating can be further improved by an additional subsequent functionalization step in order to achieve an increased intermolecular interaction towards the polymer. For example, alkylated silicates are used to modify the surface in the desired manner [12]. In this way, the sol-gel layer gets a very oleophilic character promoting the connectivity towards multiple thermoplastic polymers. However, the challenge within the production of a suitable coating system is to achieve a maximum adhesion in combination of the coating and functionalization methods as well as the validation of the mechanical properties.

In order to characterize the mechanical adhesion properties of composites with different coating treatments, simple quasi-static shear tests were carried out. The composite sample geometry corresponds to the standard for the determination of the tensile lap-shear strength of bonded assemblies according to DIN EN 1465. The joining area was set to 25 x 12.5 mm using a force of 79 N during the melting time of 10 s. The shear tests were performed at a velocity of 1 mm/min on a Zwick universal tensile testing machine with a maximal nominal force of 20 kN.

Figure 2 summarizes the experimental results of the shear tests; the shear strength data are given for three different surface conditions. The untreated sol-gel coating can be taken as a reference. These results show that, on average, an increased shear strength occurs in the composite sample with an ORMOSIL coating treated with Trimethylchloro silane (Me3-Si-), whereas the shear strength of ORMOSIL treated with Octadecyltrimethoxy silane (n-C18-Si-) is hardly changed compared to the reference sample. Highest joint strengths are observed for ORMOSIL treated with Aminopropyltrimethoxy silane (NH2-Si-). We note, that the shear strength data are considerably more scattered compared to the reference material. The interactions of the alkylated surfaces are based on van der Waals interactions. However, the surface of the octadecyl substituted sol-gel is less polar than the methyl substituted one. Thus, the interaction of the octadecyl towards the polar polyamide is less attractive and accordingly the joint strength is lower. The Amino functionalized surface interacts by hydrogen bonding with the polyamide. Thus stronger bonds are formed and a higher shear strength is achieved.
2.2. Laser induced surface nano structuring for hybrid structures

Beside the presented approach of improving adhesion through chemical bonding via a sol-gel coating process, a fast and efficient laser surface pre-treatment is used to improve the adhesion properties of hybrid structures based on a micro-alloyed steel (1.0548) as well as an aluminum alloy (EN AW-6082, 3.2315) and CFRP. As the laser-induced generated oxide layer cannot completely guarantee protection against (contact) corrosion, an additional glass fleece is utilized as an interfacial layer between the metal and the CFRP component. The intrinsic manufacturing of the hybrid structures is realized by using a modified Vacuum Assisted Resin Transfer Molding (VARTM) process. The matrix material used is a fast curing epoxy resin system (EPIKOTE 05475/ EPIKURE 5443, Momentive). Therefore, the manufacturing of a complex hybrid structural part is feasible in around 5 minutes.

Surface pre-treatment

Before starting the VARTM process, the steel and aluminum surfaces are completely pre-treated by laser irradiation. Therefore, a short pulse laser system (Powerline E Air 25, Rofin-Sinar, Nd:YVO4) with a wavelength of 1064 nm and a maximum power of 25 W is utilized. While structuring, the laser system operates in the pulsed mode and the laser beam is vertically positioned to and straightly focused onto the metal surface. Satisfying parameters, that means parameters which lead to a fine nano-structured and open-porous surface with various undercuts as well as with a good wettability and infiltration behavior, were determined by using scanning electron microscopy, atomic force microscopy, contact angle measurements and Focused Ion Beam investigations of fractured surfaces of shear tension specimens [13][14][15].

In this paper, the parameters leading to the best bond strength and corrosion behavior of steel-CFRP or, respectively, aluminum-CFRP specimens are shown. Constant parameters were the scan speed (800 mm/s), the hatch-distance (80 µm) and the repetition rate (1 time). The respective surface morphologies and the variable parameters are shown in Table 1.
Table 1. Parameter settings used for the laser pre-treatment of the steel and aluminum interfaces (left side) and resulting surface morphologies (right side).

| Parameter settings | Surface morphology |
|--------------------|--------------------|
| Current in A | Pulse frequency in kHz |
| Steel | 34 | 10 |
| Aluminum | 34 | 30 |

**VARTM manufacturing process**

The manufacturing process starts with the insertion of a metal sheet (steel or aluminum) into the tool cavity. Afterwards, six unidirectional carbon fiber textiles (HPT 320 C0, SGL) are placed, with respect to an alternating fiber orientation (0/90°). In order to protect the metal component against (contact) corrosion, a 0.2 mm thin glass fiber fleece (JM SH35, Saertex) is inserted between the metal and the carbon fiber textiles. After fabricating a preform, closing and evacuating the tool cavity, which is pre-heated to 80 °C, the hybridization is started. The resin system is injected through four sprues in the upper tool cavity at a constant pressure of 0.5 MPa and for an injection time of 3 min by using a RTM unit (iJect touch 2.0, Wolfangel). The resin saturates the fiber preform completely and generates a firmly bonded connection between the CFRP component and the metal surface while the curing process. In case of the laser pre-treated metal surfaces, the fine nano cavities are filled with the low viscous resin so that an additional mechanical interlocking between the nano-structured metal surface and the resin occurs in the curing process. To ensure a non-porous hybrid component, the excessive resin, escaping from the riser, flows into a so named resin trap which is connected to a vacuum pump. The completely finished and cured hybrid structures is removed from the tool cavity after a curing time of 42 min. The entire manufacturing process of the hybrid structure is shown in Figure 3.
Mechanical and ageing properties

After the intrinsic manufacturing process, shear tension specimens were cut out from the hybrid plates by waterjet cutting. Thereby, for each type (non-structured or laser pre-treated surface, with or without a glass fleece as an intermediate layer) and five specimens were cut out.

A part of the specimens was tested after a conditioning in normal climate (DIN EN ISO 291) and the other part was tested after an immersion test in a 5% sodium chloride (NaCl) solution (DIN EN ISO 53287). The influence of the electrolyte on the specimens was tested weekly and, in total, for four weeks. All shear tests were carried out in accordance to the German standard DIN 65148 and by using a MTS 810 table top test system.

Figure 4 shows the results of the shear tests on the steel-CFRP specimens in dependency of the surface condition (non-structured reference (REF) or laser pre-treated), the insertion of a glass fleece (GF) and the condition (in the as received condition or after an ageing in an immersion test in a 5% sodium chloride solution for 1, 2, 3 and 4 weeks). It can be seen that a laser pre-treatment of the steel surface has a beneficial influence on the shear strength.

In the as received condition, the shear stresses of the laser pre-treated specimens are at maximum four times higher than the shear stresses of the non-structured reference specimens. Furthermore, the insertion of a glass fleece has a positive effect on the shear stress. The non-structured reference specimens without a glass fleece reveal shear stresses around 8 MPa and the specimens with a glass fleece reach shear stresses around 14 MPa. It is assumed that the glass fleece lead to a homogenous interface thickness such that the applied stresses can be absorbed better by the interface. In addition, the glass fleece stabilizes, i.e. reinforces, the interface. The laser pre-treatment lead to shear stresses around 37 MPa (without a glass fleece) and 39 MPa (with a glass fleece). This improvement can be explained by the strong interlocking that occurs between the nano-structured steel surface and the resin during the infiltration and curing step of the VARTM procedure.

Regarding the development of the shear stresses while the four-week immersion test, it can be seen that the shear stresses of the non-structured reference specimens decrease with the duration of the test. In this case, the adhesion of the resin on the steel surface is as bad that the test solution can penetrate the interface and provoke crevice corrosion and, if the fibers of the CFRP component can get in contact with the steel, that means without a glass fleece in the
interface, lead to contact corrosion. By using a glass fleece, the decrease of the shear stresses is extremely high, because the glass fleece absorbs the test solution penetrating the interface, whereby the shear strength is significantly reduced.

If a laser pre-treatment of the steel surface is performed, the shear stresses are constant throughout the entire test period of the immersion test. The firm interlocking between the laser-induced nano structure and the resin lead to a durably strong bonding strength. Higher shear stresses obtained after 2, 3 and 4 weeks of the immersion test can be explained by the specimens’ position on the hybrid test plate, from which they were cut out. Close to the injection points, the laminate quality and therefore the interface quality is slightly better than in direct proximity to the riser.

Figure 4. Shear strength of the steel-CFRP specimens in dependency of the surface condition, non-structured reference (REF) or laser pre-treated, the insertion of a glass fleece (GF) and the ageing condition, in the as received condition or after an immersion test in a 5% sodium chloride solution for 1, 2, 3 and 4 weeks

Figure 5 presents the results for the aluminum-CFRP specimens. At first, it should be noted that no adhesion could be achieved for all non-structured aluminum-CFRP specimens. These specimens fail directly after the cutting process. By considering this information and the lower stiffness of the aluminum, which leads to a more flat force-path curve during the shear test, whereby the specimens fail at nearly the same path level than the steel-CFRP specimens, but naturally at lower maximum forces, the shear stresses revealed by a laser pre-treatment of the aluminum interface are very satisfying. In the as received condition, the specimens reach shear stresses around 30 MPa, without a glass fleece, and 26 MPa, with a glass fleece. It is assumed that the insertion of a glass fleece has no influence on the bonding strength and that the variation is caused by diversification resulting from the specimens’ position on the hybrid test plate (see above).

As already seen in the results of the steel-CFRP specimens, the exposure of the aluminum-CFRP specimens to the 5% NaCl solution has no influence on the shear strength. The shear stresses are constant throughout the entire test period. The laser pre-treatment lead to a firm interlocking connection between the laser-induced nano structure and the resin. Furthermore, a defect-free interface area is generated.
Figure 5. Shear strength of the aluminum-CFRP specimens in dependency of the surface condition, non-structured reference (REF) or laser pre-treated, the insertion of a glass fleece (GF) and the ageing condition, in the as received condition or after an immersion test in a 5 % sodium chloride solution for 1, 2, 3 and 4 weeks.

Fracture and ageing behavior

Regarding the fracture pattern of laser pre-treated steel- and aluminum-CFRP shear-tension specimens after the four-week immersion test, for both material combinations, without and with a glass fleece, no corrosion products can be detected. The failure behavior is cohesive/interlaminar and the laser-induced nano structure, shining through the resin layer or the glass fleece, respectively, is intact. The golden-brown color of fractured surface of the laser pre-treated steel specimens is no indicator for rust, but the typical appearance of the laser-induced generated iron oxide layer. The typical color of an aluminum oxide layer is white. Therefore, it can be noted that the interface is not penetrated by the test solution. The interface area is completely intact and contact corrosion does not occur – neither for the specimens with an isolating glass fleece, nor for the specimens without a glass fleece, i.e. without an additional corrosion protection.
Steel-CFRP

Reference | Reference + GF | Laser pre-treated | Laser pre-treated + GF

Aluminum-CFRP

No adhesion achieved | No adhesion achieved
Reference | Reference + GF | Laser pre-treated | Laser pre-treated + GF

Figure 6. Fractured surfaces of the steel-CFRP and the aluminum-CFRP shear-tension specimens after a four-week immersion test.

A side-view of the interface area of small steel- and aluminum-CFRP plates after the four-week immersion test by using a digital microscope (Figure 7) shows that it is still recommended to utilize a corrosion protecting glass fleece as an intermediate layer. Especially the aluminum-CFRP specimens locally reveal more pitting corrosion, which is typical for aluminum due to its porous natural oxide layer [16], if no glass fleece is used.

Steel-CFRP

Already failed
Reference | Reference + GF | Laser pre-treated | Laser pre-treated + GF

Aluminum-CFRP

No adhesion achieved | No adhesion achieved
Reference | Reference + GF | Laser pre-treated | Laser pre-treated + GF

Figure 7. Side-view of the interface area of the steel- and aluminum-CFRP specimens after the four-week immersion test by using a digital microscope.

Confocal laser scanning microscopy of the above seen steel- and aluminum-CFRP plates illustrate that the use of a glass fleece as an intermediate layer is highly recommended (Figure 8). If no glass fleece is used, the aluminum component locally shows deep holes (blue colored areas) caused by pitting corrosion. These holes are deeper for the specimens, which have no glass fleece as an intermediate layer. For the steel plates, this effect is hardly visible, because steel prone to surface corrosion instead of pitting corrosion.
Figure 8. Side-view of the interface area of the steel- and aluminum-CFRP specimens after the four-week immersion test by using a Confocal Laser Scanning Microscope.

Summarizing, the laser pre-treatment of steel and aluminum surfaces offers a promising possibility to improve the bond strength and the ageing resistance of steel- and aluminum CFRP structures by creating a mechanical interlocked and durable connection. Despite, a glass fleece is recommended as an intermediate layer to completely exclude contact corrosion.

3. Surface treatment for an insert concept

The load transmission in thin-walled structures made of CFRP is often realized by joining methods from the metal construction such as bolt connections. However, such a distribution of loads does not exploit the potential of the carbon fiber design as the loads are only selectively introduced pointwise and the fibers are interrupted and damaged [1][17]. According to a fiber-fare design of load transmission, a novel insert which bases on several piled metal layers was developed, the so-called Multilayer-Insert (MLI). The multilayer design (Figure 9) allows a considerably increased the contact area between the metal and the CFRP for an optimal distribution of load to each CFRP-layer [18]. The insert is designed to be built up during the AFP (Automated Fiber Placement Process) and can be adapted to the fiber orientation and to the size and the geometry to meet the load requirements. Therefore, a separate module for automated insert placement (AIP) is developed and integrated in a fiber placement head [19].

Figure 9. Design of a Multilayer-Insert: (a) conceptional setting and (b) exemplary specimen.

A central issue is in this case the surface pre-treatment of the aluminum layers. The pre-treatment has a strong influence on the process from both perspectives, the material science and production engineering, and must therefore be considered interdisciplinary. Here, the special requirements to avoid corrosion problems and guarantee a solid adhesion between aluminum
and CFRP are taken into consideration in [20]. Thereby, various coatings for aluminum that satisfy the previously mentioned requirements have been investigated. On the one hand, the coating should guarantee the adhesion between aluminum and CFRP and on the other hand, it should avoid the corrosion tendency between the two materials. In addition, the thickness of the coated aluminum must not exceed 125 µm to achieve the same thickness of a CFRP-layer and avoid thickening in the laminate. Given that an aluminum layer has a thickness of 100 µm, the coating should not exceed 12.5 µm. Furthermore, the coating must overcome the AIP process without damage to guarantee the corrosion protection after the production. Table 2 shows the coatings and some of their properties performed that are investigated.

| Coating | Used coating | Adhesion to aluminum | Corrosion protection | Thermal load capacity | Additional features | Coating thickness |
|---------|--------------|----------------------|----------------------|----------------------|--------------------|------------------|
| Anodized | Aluminum oxide Al₂O₃ | ++ | + | ++ | - High mechanical stress resistance (also for deformation) | 10 µm |
| | | | | | - Coat properties flexible adaptable by process parameters (coating thickness, pore size, postcompaction, …) | |
| | | | | | - Coat electrically insulating | |
| Chromium(III)-containing passivation | Surtec®650 trivalent Chromium oxide | + | o | ++ | - High suitability as adhesive surface for organical coats | ≈ 1 µm |
| Chromium-free-passivation | Nabutan®810 Titanium oxide | + | o | ++ | - High suitability as adhesive surface for organical coats | ≈ 1 µm |
| Epoxy primer | Cytec BR®127 epoxy basis | + | + | O | - Coat electrically insulating | 4 µm |
| Anodized + Epoxy primer | Aluminum oxide Cytec BR®127 | ++ | ++ | O | | 14 µm |
| Chromium(III)-containing passivation + Epoxy primer | Surtec®650 Cytec BR®127 | + | ++ | O | | 15 µm |
| Chromium-free-passivation + Epoxy primer | Nabutan®810 Cytec BR®127 | + | ++ | O | | 15 µm |

In the adhesion analysis, the energy release rates GIC are determined according to ASTM D 5528-01. In order to complete the adhesion analysis, tensile shear tests are carried out according to DIN 65148 where the interlaminar shear strength is determined. The corrosion tests are realized on the basis of salt spray tests according to DIN EN 60068-2-52 and the measurement of the open corrosion potential using a saturated calomel electrode.
Adhesion Analysis
The samples for the adhesion test are formed with a cross-ply laminate which consists of 0° and 90° layers. The laminate has a double-layer approach with four 0° layers in the center. One of the 0° layers is substituted by a coated aluminum layer, so the analyzed interface is exactly in the center of the laminate. The cross-ply laminate differs from the standard. This laminate approach is selected to reduce thermal stresses caused by the different thermal expansion coefficients of both materials.

It is shown in the adhesion analysis that the anodizing, the chromium (III)-containing and the chromium-free passivation provides the best adhesion properties (Figure 10). In the energy release rates, the values are significantly lower than the reference samples. Another illustration is shown in the interlaminar shear strength analysis. In this case, the chromium (III)-containing and the chromium-free passivation achieve higher values than the CFRP reference. This behavior is led back to the production of the samples. According to the norm DIN 65148, notches are cut in a way that they lead to stress concentration on the notch edges (Figure 11).

This is an already known issue in the shear-lap-tests. For this reason, the results can be accommodated only to a limited extent and permit only a qualitative statement. The values arising from the combination between anodizing and Primer BR®127 cannot be taken into consideration because of the long dwell time between both coating processes for logistic reasons. The adhesion properties of the anodizing process are reduced to a minimum after 48 hours. For completion within the framework of a further analysis, more samples have been coated. In this case, the dwell time was reduced to less than 48 hours. Additionally, the samples
were differently analyzed in a shearing tool in which rectangular samples are sheared off from the midplane. Due to comparability the samples with untreated aluminum were analyzed with the same method. In this event, the values for the untreated aluminum are 33 N/mm². The combination of anodizing and Primer are 17 % lower than the reference with 28 N/mm² [14].

Corrosion analysis
The samples for the corrosion tests are manufactured according to the mentioned standard. In this case, aluminum plates with a thickness of 1 mm and a size of 110 x 100 mm are coated. A laminate in the size of 50 x 100 mm is built up on half of the area of the coated aluminum plate and cured in the autoclave. The other half of the coated aluminum can be used to observe and evaluate the corrosion effects. In Table 3 and Figure 12 the results of the corrosion tests are shown. The passivation coating showed signs of corrosion even though an adequate corrosion protection is generally expected. Only the anodizing has a sufficient corrosion protection.

Table 3. Observations after salt spray tests.

| Sample/Coating                        | Observations after salt spray tests                                      |
|---------------------------------------|--------------------------------------------------------------------------|
| Uncoated reference sample             |  - Very strong surface corrosion                                          |
|                                       |  - Lot of corrosion residue, especially in the Al-CFRP-contact area        |
| Anodized                              | Aluminum oxide                                                           |
|                                       |  - Sporadically pitting corrosion                                         |
| Chromium(III)-containing passivation  | Surtec®650                                                               |
|                                       |  - Surface corrosion                                                     |
|                                       |  - Sporadically pitting corrosion                                         |
| Chromium-free-passivation             | Nabutan®810                                                              |
|                                       |  - Very strong surface corrosion                                          |
|                                       |  - Lot of corrosion residue, especially in the Al-CFRP-contact area        |
| Epoxy primer                          | Cytec BR®127                                                             |
|                                       |  - Filiform corrosion on aluminum                                         |
|                                       |  - Filiform corrosion/infiltration of the protective layer in Al-CFRP-contact area |
| Anodize + Epoxy primer                | Aluminum oxide + Cytec BR®127                                             |
|                                       |  - No detectable corrosion                                                |
| Chromium(III)-containing passivation + | Surtec®650                                                              |
| Epoxy primer                          |  - Light filiform corrosion in Al-CFRP-contact area                        |
| Chromium-free-passivation + Epoxy primer | Nabutan®810                                                              |
|                                       |  - Filiform corrosion in Al-CFRP-contact area                             |

The results shown in Figure 10 indicate that in relation to improve the adhesion properties the passivation coatings and anodizing can come into consideration. In view of the corrosion
analysis, (Table 3, Figure 11) only the anodizing and primer show adequate corrosion protection properties. For the use of aluminum inserts in CFRP, only anodizing as a coating can be considered because anodizing complies with both requirements, adhesion and corrosion protection.

![Image of coatings](image)

**Figure 12.** Results of the salt spray tests.

**Measurement of the open corrosion potential**

In order to measure the open corrosion potential, the aluminum plates with a thickness of 1 mm are coated in the same way like the samples for the salt spray tests. The difference is that the samples are not joined to CFRP, instead they will be used as an electrode in the galvanic cell. Finally, the results are contrasted and based on all the requirements, a recommendation for an appropriate coating is derived.

The measured electrochemical potential of the different coatings show the same tendency as already seen after the salt spray tests. It is unexpected that the electrochemical potential of SurTech650 is at the same level of the Primer BR®127, even though it showed weaker corrosion protection properties in the salt spray test (Figure 12).
The measurement of the open corrosion potential shows that the anodizing causes a reduction of the electrochemical potential difference of 440 mV in comparison to the untreated aluminum. This result coincides with the results from the salt spray test in which no signs of corrosion were observed. The same behavior can be seen for the combination of anodizing and epoxy primer BR127 and the epoxy primer BR127. The electrochemical potential difference to CFRP is 110 mV and 120 mV respectively. A different behavior is noticed on SurTec®650, even though the electrochemical potential difference of 105 mV to CFRP is similar to the previously mentioned coatings, the corrosion protection in accordance with the salt spray test is not satisfactory (Table 3). The coating Nabutan®810 owns the highest electrochemical potential difference to CFRP and reflects a high tendency of corrosion in the results of the salt spray test. Through the additional application of the Primer BR®127, the electrochemical potential difference decreases but is still the highest. Thus, the corrosion protection remains insufficient as shown in the previous tests.

4. Conclusion
The paper investigates multiple interfacial design concepts for CFRP-aluminum and CFRP-steel hybrid intrinsic composites. In particular, the key aspects joint strength, corrosion protection as well as manufacturability by single-step joining processes were addressed. In this context, different manufacturing processes (RTM, AFP, hot pressing) were discussed. The sector of surface treatments offers a wide range of processes, whereby chemical (anodizing, sol-gel coating, chromium and titanium passivation), physical (laser pre-treatment) and functional (primers and overmolding by polyamide inter-layers) approaches for steel and aluminum were investigated. The results of this study can serve as a guideline for the production of hybrid structures. Depending on the production process and the material combination different methods to increase adhesion and avoid corrosion are shown and can be taken into account for the design of hybrid structures. An overview about the advantages, disadvantages and characteristics of the mentioned methods and processes is presented below.
By using a sol-gel based silicate coating, an increased adhesive strength of aluminum-polyamide 6 joints was achieved. The subsequent functionalization of the ORMOSIL coating by different silane coupling agents yield increased adhesion, while amino group bearing silane showed the highest joint strengths among the tested silane coupling agents. It counts as an advantage that the subsequent functionalization is easily adaptable towards other composites based on chemically different polymer matrices. Beside improved adhesion, the ORMOSIL coating is promising to avoid corrosion due to its physical barrier properties. The applicable time span of the sol, determined by viscosity measurements accounts to 5 days and consequently suitability for production process chains is given.

A laser pre-treatment of steel and aluminum surfaces offers a promising possibility to improve, on the one hand, the bond strength and, on the other hand, the ageing resistance, i. e. the corrosion resistance, of steel- and aluminum CFRP structures. Due to the laser pre-treatment, a fine nano-structured and open-porous surface quality which is characterized by various undercuts is generated. During the infiltration process of the resin in the VARTM process, these small cavities are filled with the low viscous resin so that a firm mechanical interlocking between the resin and the metal surface, i. e. the laserinduced nano-structure, is generated. This strong connection lead to shear stresses which are up to 4 times higher than those of non-structured reference specimens. In addition, the connection is as firm and free of pores that the 5 % sodium chloride solution used in an immersion test is not able to penetrate the interface area so that the shear strength remains constant throughout a test period of four weeks. However, a glass fleece is recommended as an intermediate layer to completely exclude contact corrosion on cutting edges.

The process time of a surface pre-treatment by laser irradiation depends on the material, the laser system and the parameter settings, especially the scan speed, used. With the laser system utilized in this study, ablation rates of 0,6 cm²/s are possible. This short process time, the good automation capacity, practically no maintenance requirements and the excellent reproducibility qualify the laser pre-treatment for a large scale production.

The analysis of the surface pretreatments of the interface between aluminum and CFRP for AFP-processes shows that the combination of anodizing and the Primer BR®127 provides the best adhesion properties and corrosion protection. The electrochemical potential difference to CFRP is 105 mV and no signs of corrosion are observed in the salt spray tests. In further investigations, the transferability of the promising pre-treatment methods for different applications and complex structures should be investigated with reference to the adhesion and corrosion performance. Moreover, the pre-anodizing process can be optimized according to the properties needed. Through a parameter study, the adhesion properties can be improved. Furthermore, the shelf life of the combination between anodizing and primer should be analyzed. Finally, the chromium-free Primer BR®252 can be considered since it has been developed as an environment-friendly substitute of the Primer BR®127.

Summarizing, the selection of a surface pre-treatment method depends on the requirements of the respective application. A durably high joint strength and an effective corrosion protection are essential in the field of metal-CFRP hybrid structures. All presented methods lead to an increased joint strength and corrosion protection. By the laser pre-treatment and the anodizing or priming process higher shear strengths are achieved than by the sol-gel coating, but the last named procedure ensures superior corrosion protection. In many applications, the manageability of the pre-treatment procedure and the required processing time are key factors. In a large scale production, the pre-treatment process should be time efficient and practicable with a little manual effort. With process times of about 1 minute for coating itself and about 2.5 hours for subsequent heat treatment, the approach via a sol-gel coating shows an intermediate suitability, even though the process is highly automatable and convenient for large-scale production routes. The duration of the laser pre-treatment process strongly depends on the material, the surface area, the laser system and the parameters used. Nevertheless, the process time varies in a range of minutes and a complete corrosion protection can be easily realized by the insertion of an
isolation layer in the interface area. The anodizing and priming processes constitute a fast as well as easy pre-treatment procedure and reveal high joint strengths and adequate corrosion protection, but require partly highly toxic and environmentally harmful process materials, which should be avoided nowadays concerning labor safety and environmental protection.

Finally, it can be stated that the selection of a pre-treatment method does not only depend on joint strengths, corrosion performance and efficiency, but also on ethic principles as well as national and international laws and directives.

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