MATERIALS AND PROCESS SOLUTIONS FOR LIGHT WEIGHT STRUCTURES IN AERONAUTIC AND AUTOMOTIVE INDUSTRY

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Summary

Material science enabling e.g. light weight structures has a long history in Bremen. Advanced materials and material combinations as well as innovative technologies and processes are developed and applied in various industrial areas as aeronautics, aerospace, automotive, (wind-) energy and others. The presentation and the associated paper will give an overview about successfully introduced material solutions and highlight actual developments. A special focus will be on technologies applied or investigated for transportation industries as e.g. electro deposition painting or assembly processes like bonding incl. surface preparation.
Lessons learned from cooperation within the Bremen material network will be discussed and opportunities for future materials and technology developments presented. Possible synergies of a close co-operation in material science, considering inputs, needs and requirements from all affected stakeholders as industry, universities, research institutes and small and medium enterprises will complete the picture.

1. INTRODUCTION

In Bremen you can attain your goals quicker than elsewhere. In every aspects. Nowhere else can one meet so many decision makers, corporations and world-class brands within a mere 327 square kilometers – a small area with enormous advantages. Because what is being created here is strong and dynamic mix of industries, know-how and technologies from which you can benefit – contacts are made faster, new perspectives revealed and useful partnerships made possible.

Another aspect is the convenient location directly beside a major port and global flows of goods. Travel from Bremen to the other parts of the world has been going on since the 11th century. In 1358 Bremen joined the Hanseatic League and its port grew into the hub of international trade. The first steam ship line was established in 1847 and emigrants hoping for a better life in the New World boarded the ships in Bremen in ever increasing numbers. Between 1830 and 1974, more than 7 million people departed Europe from Bremen, but not only from the port.

The origins of Bremen Airport date back to the establishment of the ‘Bremen Airship Aviation Association’ (Bremer Verein für Luftschiffahrt – BVL) in the year 1909. The Aviation Association and the Norddeutsche Lloyd shipping company were jointly commissioned by the Bremen government to create an airship port. On 16 May 1913, the Association was commissioned by the Bremen Senate to establish an aviation base. This marked the birth of Bremen’s airport. In 1928, one year after the spectacular Lindbergh flight, three pioneers successfully tackled the first non-stop Atlantic crossing from east to west by plane. The aircraft’s name? “Bremen”, of course.

For more than 100 years aviation industry is based in Bremen and is one of the key industries today. As Germany’s smallest state, Bremen boasts a high concentration of competencies within a small region, as evidenced by the more than 100 enterprises in this industry which are domiciled here. The strength of the economy is accompanied by a strong scientific competence based in the Bremen University of Applied Sciences and University of Bremen (which is entitled 'University of Excellence').

Structural and systems design, flight physics, aircraft assembly, wing fittings, test facilities – Bremen is home to the entire process chain for high-lift systems. These high-lift wing systems are one of the most important technologies of the future. They enable the world’s biggest passenger airplane, the Airbus A380, to take off and land and make it possible, for example, to take off and land at angles that reduce the amount of aircraft noise in the vicinity of the airport. The courage to embrace new technologies is a definitive characteristic of aviation companies in Bremen. Carbonfibre reinforced plastics (CFRP) are lightweight, tough and corrosion-resistant materials without which tomorrow’s aircraft construction would be inconceivable. Production technologies for highly integrated components are being developed in Bremen to this very end.

Other industries are likewise benefitting from further improvements in these production technologies and the more cost-efficient production processes that ensue as a result. One of them is the automotive industry. Today, Bremen gives you an efficient and high-performance network comprising more than 600 automotive suppliers and has long since become a high-tech center of excellence with long-established companies. Here you will find the best know-how for any solution in automotive engineering. The Bremen plant of Mercedes Benz, with a workforce of more than 13,500, produces over 200,000 vehicles a year, including the entire C-Class range as well as the CLK, SL and SLK models. This makes it the company’s second largest plant in Europe. As a centre for the car industry, Bremen continues to expand. More and more new areas are being earmarked for companies willing to invest. In addition to a well-known steel producer (Arcelor) that has specialised at its Bremen plant in making special steels, e.g. for the automotive industry, there are also many companies in the state of Bremen that process novel and conventional materials.

Whereas major companies in Bremen generally have their own R&D departments that also focus on innovative materials, small and medium-sized enterprises often lack the human resources and expertise for using new materials, and for that reason are reticent to use them. The scientific expertise required to assess and develop new materials, to optimize known materials, and to manage production processes appropriately in respect of the materials used, is so advanced in the state of Bremen, in both the materials science and process engineering fields, that the state has become an academic and research cluster in 'Materials Science'.

Four extra-university research institutes form the core of this cluster of excellence: the Bremen Institute for Applied Radiation Technology (BIAS), the Bremen Fibre Institute (FIBRE), the Fraunhofer Institute for Production Engineering and Applied Materials Research (IFAM) and the Institute for Materials Science (IWT). Other major facilities include the University of Bremen's Institute for Microsensors, Microactuators and Microsystems (IMSAS) and the departments of Ceramics and Computational Material Science (CMS). These key institutes in the field of materials science, as well as the departments of Physics/Electrical Engineering, Production Engineering, Mathematics/Informatics, Biology/Bionics, Geosciences and Chemistry enjoy a strong reputation and renown at national and international level in fields such as surface engineering, polymer engineering, adhesives technology, general materials science, metal materials, composite fibre materials, ceramics, laser welding, simulation and modelling.

2. MATERIALS AND PROCESS SOLUTION FOR AUTOMOTIVE AND AERONAUTIC INDUSTRY

Automotive as well as aeronautic or aerospace industry are pioneers in light weight design. On the first view these industry have a quite big overlap in the field of enabling materials and processes. Similar low weight materials as aluminum or magnesium alloys resp. CFRP materials are in use. Also similar technologies as bonding, welding, painting,… are applied. But on a second view in a deeper requirement comparison of the applied materials and processes two main differences can be observed. Due to the high car production rate (several hundred thousand per year, compared to several hundred aircrafts per year), main drivers for the development of new automotive materials and process solutions are time and costs. Eave if these requirements are also important for aeronautic and space industry, especially the material weight and the reliability (long term performance) are key influencing factors. A overview about materials and process requirements in aeronautic industry with special focus on surface technology and environmental requirements is given in [1].

In this chapter three examples for the development of common technologies

- Base coat clear coat systems
- Electro deposition painting
- Generic understanding of corrosion mechanisms will be discussed.

2.1. Base coat / clear coat

The classical setup of aircraft external paint systems is shown in figure 1. It will be applied on the basic protection system. The external paint primer and the external top coat provide adhesion and resistance against UV radiation and fulfil the aesthetic wished from the airliner. The optional intermediate coat allows and easier paint stripping by the use of chemical paint stripper. Other functionalities as erosion protection or anti-static properties are provided by additional coatings [1].

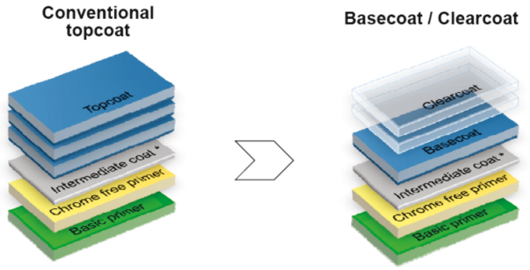

FIGURE 1: Setup of external paint system. Left classical top coat system, right base coat clear coat system [2]

The main time consuming steps in the external painting process are masking and de-masking operations as well as the drying process. With increasing complexity of the external livery the number of paint steps (incl. masking, de-masking and drying) increases. That's way the process time for external painting of a single aisle aircraft can vary from 6 days for a so called standard system (1 colour for background, 2 colours for decoration, paint system: primer and topcoat, standard design) up to 8-13 days for an extra high system (complex design, paint effects (several mica colours) combination of at least two high livery items) [3].

As already widely applied in automotive industry Airbus has also introduced a base coat clear / coat system (figure 1 right site). The high pigmentation of the base coat provides good color and opacity performance. So the required colors can achieve hiding in one single paint step. Compared to classical top coat systems, the drying time is reduced before a second color or clear coat can be applied. After application of the base coat, the external aircraft surface is coated with the clear coat. The clear coat provides final protection against various environmental impacts and produces a smooth finish. Other advantages of base coat clear coat systems are:

- Reduction of paint thickness
- Reduced material consumption results in less solvent emission
- Reduction of defects and easy repair
- Higher resistance to surface soiling, reduce the amount of cleaning with less detergent,
- Reduce direct maintenance cost by increasing interval between repairs [2]

2.2. Electro deposition coating

Electro deposition paint (EDP) processes are used in automotive industry to applied basic protection. In contrary to aircraft application that requires a surface protection on single part level, complete assembled car structures (various materials including bonding or sealant beads) are treated in the EDP bath. The general EDP process is described e.g. in [4] or [5]. The paint is deposited from an aqueous solution to a conductive part. Depending how the voltage is applied and whether the part to be coated is the positive or negative electrode two processes can be distinguished, anodic- or cathodic EDP. Even if EDP is a well established process it is still subject of an actual research and development work (e.g. [6], [7].

For application in helicopter production today one EDP system is qualified. For application in aircraft industry EDP is still under development. In the focus of investigation are anodic-EDP systems (not cathodic-EDP as applied often in automotive industry). Due to the good barrier function of EDP systems and the dense paint film today's EDP systems pass most of standard corrosion test as salt spray test or filiform test or media exposure tests. The main need for material improvement is the long term stability. In figure 2 results from a specific climate test (temperature change beween+80°C to -40°C, dry / wet variation) are shown.

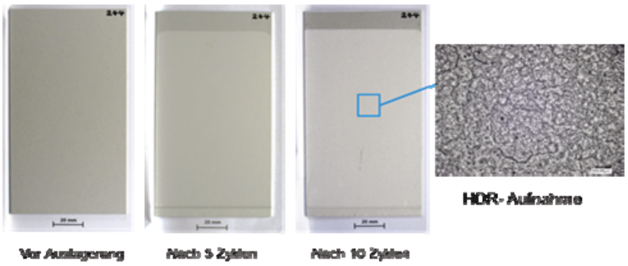

FIGURE 2: Coating failure after thermal cycle test

The test was developed to simulate in-service condition in aircraft. The qualified corrosion protective systems pass this test without any problem. The EDP system failed already in the begin of the climate test. Here some common development work with material supplier is needed to develop the EDP process to technical maturity for aircraft application.

2.3. Understanding of corrosion mechanism

Understanding of surface protection (degradation) mechanism is key to ensure long term stability and performance of future aircraft structures. To meet future challenges for aircraft surface protection systems coming from new materials resp. material combinations as

- improved metal alloys,
- carbon fiber reinforced plastics (CFRPs),
- multi functional materials, or
- materials made from renewable resources,

today unknown effects and boundary conditions need to be considered. To meet on the other hand the expectations to reduce aircraft development time and cost experimental investigations used in combination with chemical and physical (sometimes probabilistic) modelling approaches utilizing feedback from actual in-service maintenance data have to be used in a sensible way to predict material performance and behavior under in-service condition. Special attention must be paid to the acquisition of specific, precise, and representative input data.

Similar to the aeronautics industry, the automotive industry has developed a vehicle test pyramid and uses, as well, a combined approach of simulations with experimental tests and in service maintenance data. The main difference in terms of surface protection test and validation methods between the automotive and aeronautics industry is full scale vehicle validation under real in-service conditions. For automobiles and ground vehicles, full scale validation under in-service conditions is possible, but for sure this is not the case for either aircrafts or aircraft components. This fact of aircraft testing emphasizes further the need for a reliable and robust understanding of surface protection materials and processes. [8].

3. MATERIAL SCIENCE FOR AERONAUTIC AND AUTOMOTIVE INDUSTRY

Several hundred scientists are conducting research materials science issues in Bremen. These scientists are highly connected. Another special feature is the interdisciplinary nature of research in Bremen. Scientists of production engineering, physics, electrical engineering and of chemistry, biology and mathematics are co-operating on materials science innovation topics.

The innovation potential is high and, the portfolio wide: The core competencies include the entire process chain for the development of materials, ranging from materials synthesis to manufacturing processes and component design, including analytics, characterization as well as material testing. Collaborative Research Centers (CRC) funded by the German Research Foundation (DFG) might be just one example for the networking in the city.

The term “innovative materials” means the production, study and application of materials along complete value chains (materials, semi-finished product, component, system, application, disposal and recycling). In this context, it is important to know that this is not only focused on the development, manufacturing, coating, processing and application of new materials, but also on the extended use of known and optimized materials.

Material science is targeting cross-cutting technologies across all industries. Tailored material properties enable the design and development of enhanced product quality at potentially reduced cost.

Beyond the “traditional” material science competencies, another pioneering profile on "smart materials and components” has been established. Expertise in production technology, information and communication technology, logistics, robotics and systems engineering are merged in this case.

The scientific expertise for the evaluation and development of new and optimized materials is outstanding in Bremen with respect to materials technology and processing. Material science in Bremen is characterized by a close integration and co-operation of intra- and extra-university research institutes: Four non-university research institutes - Fraunhofer Institute for Manufacturing Technology and Applied Materials IFAM, the Foundation Institute of Materials Science IWT, the Bremen Institute for Applied Beam Technology BIAS, the Fiber Institute Bremen FIBRE - as well as the Bremen Center for Computational Materials Science BCCMS and the Laboratory for Precision Machining LFM are key contributors to materials research in Bremen.

The research work is relevant to a variety of industry segments; Focus is on the automotive, aviation and aerospace industry and the shipbuilding industry, general engineering and especially the wind energy.

Research results and technological developments shall be transferred to industrial applications efficiently, providing sustainable and environmentally friendly use of resources.

Lightweight construction in transportation is targeting increased efficiency and decreased use of resources. Employing different functional materials, meaning the right material in the right place, requires the combination of materials with different properties. Lightweight and rugged materials for transportation areas and e.g. wind turbines, joining technologies for multi material designs and corrosion resistant, non-toxic, self-healing and self-cleaning coatings pose central challenges for material science.

Multifunctional products, light weight design and miniaturization accomplished by intelligent material combinations and joining technologies offer huge potentials for innovation. On the material side, research activities focus on light metals as well as on composite materials. Over the last decades, especially fiber reinforced plastics have attracted attention due to high mechanical performance at low specific gravity.

Adhesive bonding is one of the key enabling technologies to lightweight design, especially when combing different types of materials. The core competency bonding technology includes development and characterization of adhesives, design and simulation of bonded and hybrid-bonded joints including their testing and qualification. Planning and automation of resulting industrial production processes and their reviews complete the profile. Current research activities do focus on accelerated adhesive curing at moderate temperature conditions and, at atmospheric pressure ideally.

Coating technologies are another focus of material science in Bremen. The integration of new functions is an important aspect when developing new paint systems, without compromising on values like decoration and surface protection. Examples of research and development projects for functional coatings in this sense with possible utilization in automotive, aerospace and energy production are:

- anti-icing coatings,
- drag reducing coatings,
- anti-contamination coatings,
- self-repairing coatings

Another important aspect of paint technology is the improvement of cost and quality. Again, research programs do center on accelerated cure techniques (e.g. UV cure, infrared cure), the development of new quality control methods as well as application techniques.

The coating technology for new lightweight materials like carbon fiber reinforced plastics (CFRP) is a challenge for both, automotive and aerospace industry. Due to the different thermal expansion of fibers and surrounding matrix resin, changes of the topography of the CFRP-surface occur. In case of automotive parts this phenomenon leads to an unwanted visibility of the fiber-structure at the surface ("telegraphing"). In the aerospace industry this behavior may be one reason for paint cracking which leads to higher maintenance costs. So, work is focused on the investigation of route courses for these phenomena and, on developing new test methods for these effects and, on measures to improve coating performance, eventually. [9].

Customized surface modification like surface preparation or functional lining enlarges the field of industrial application for a variety of materials or even permits their application. Long term stability of bonds and coatings and early recognition of any degradation and corrosion and validation of aging tests and process integrated surface analyses are –of course- part of the research activities.

Lightweight construction is a key technology for the future. A key role has been played by fiber containing materials, where glass, carbon or natural fibers are the most prominent types. In order to improve the characteristics of the FRP, e.g. weight and surface appearance, research is performed on developing innovative resins, designing and producing structural elements, improving their surface properties and, automated bonding and assembly techniques, eventually. By tailoring the interface between fibers and matrix resins, optimized materials can be achieved.

One production step for fibrous components is their layup in molds, where large volumes of release agents are employed to improve the releasing process of the component from the mold. Such release agents might cause serious issues in subsequent production stages, especially for bonding and coating steps. As a first step to overcome this problem, a deep-drawable release film has been developed allowing manufacturing FRP-parts without employing release agents. The film is an elastic, extremely flexible polymer film covered by a release layer of 0.3 microns only. So it can easily be applied to complex molds. Experiments demonstrated that large CFRP-components can be produced using prepreg techniques in an autoclave with temperatures of a 180 C.

Current research also focuses on repairing CFRP components, targets being: quick and easy repair methods, keeping the strength of the repaired component being comparable to the original part and a non-destructive testing method confirming the quality of process and part [10].

Larger components may differ significantly in some cases -due to the relevant production processes- from the specified geometry. So, the method of joining them is adhesive bonding. Besides the actual joining function adhesives can also provide other useful functions such as complete filling and sealing of different gap geometries, planar force transfer, strain/deformation absorption and hence protection of the substrates and electrical insulation.

Another challenge is posed concerning the higher automation of assembling large components. Automated assembly of large components within specified production tolerances requires high precision measurement and control methods. Many of the processes that are established for the mass production of smaller products have technological limitations when it comes to processing large structures. This means for example that "teaching" robots is not economically viable under these conditions.

There is currently a need for intelligent systems adapting individually to the relevant component geometry and production situation. Large flexible components must be automatically positioned and their shape modified.

High demands are placed on introducing new technologies or modifying existing ones. Applying multifunctional materials, materials with optimum characteristics and maximum potential for light weight design at the right place, all this is asking for new technical solutions, e.g. new joining techniques like adhesive bonding. There is an increasing need for process and product developing scientists to cooperate with experts in the field of simulation. Modeling tools can reduce the development cost as well as the time-to-market significantly.

The best choice of materials combined with optimum production processes, an indispensable prerequisite to achieve high quality and thus be successful on the market will be an appropriate qualification of the people being involved.

4. COLLABORATIVE NETWORK OF SMALL AND MEDIUM-SIZED ENTERPRISES IN ECOMAT

The aeronautic and aerospace industry's research requirements create a unique environment for research and development in Bremen. With this potential in mind, a partnership between the large aerospace and aeronautics corporations based in Bremen was created along with local research institutions and institutions from the University of Bremen. In order to utilize the driving power of the local, medium-size manufacturing companies, the research partnership was extended by the collaborative network of small and medium-sized enterprises. EcoMaT, the research center for eco-efficient materials and technologies was born.

In order to tap into this rich background, more than 15 small and medium-sized enterprises have currently formed a cooperative research and development alliance to explore shared areas of interest. Mainly the cooperation concentrates on joint development and application of innovative material concepts, light weight structures, integrated measuring technology, process optimization in the direction of lean and robust processes as well as continuous education for the companies' employees in these fields. Improved efficiency in these areas benefits not just the environment but also the bottom line.

This network of medium-sized industrial enterprises has developed from various branches of industry: the provider of heat treatment services; automation equipment for automotive and aerospace; metal forming; simulation and generation of virtual realities for the optimization of assembly processes; laser and video metrological system solutions; processing of fiber-reinforced plastics. The companies in the network connect in an ideal way the existing technology clusters unique to Bremen: aerospace, maritime technology/logistics, wind energy and other “green” technologies, automotive, engineering and robotics, and materials innovations.

Because the companies operate in very diverse markets, they are able to complement one another where thematically overlapping areas of interest exist thereby encouraging cooperation rather than competition. This creates fertile bilateral but also multilateral cooperation, where existing resources are shared. For example, a provider of job training for professionals can jointly use the machinery and equipment in the workshop of a partner in the network. By coordinating the hours of operation, the training company potentially has the use of state-of-the-art equipment for educational purposes and the equipment owner can be pleased at the increase of his equipments billable hours.

As the network started to develop, it became obvious that it makes sense to offer amongst the network partners the shared use of means of production, as well as testing and measuring equipment. In cross-company development projects, it almost always turns out that the formation of joint project teams working together in one place produces better results at a much faster pace than using a decentralized approach. Short distances, little bureaucracy and timely information delivery are crucial.

Within the network, there is great interest among the small and medium-sized enterprises for an open, cross-industry exchange among employees; gradually developing an informal "think tank." This further encourages and supports the network partners in developing a culture of "open innovation" which can create the “disruptive innovations” which are crucial to significant development. Through interdisciplinary observing, questioning and associating the companies manage to generate novel project ideas. Within the network these are then further developed into products with potential for economic success.

To achieve this, the companies organize workshops in the form of idea camps that use innovative methods such as the World Café or Design Thinking. Through the application of systematic methods, the employees of the various network companies can quickly find approaches and solutions for new developments that meet the requirements and needs of their customers and thus achieve the desired economic success of the company.

Under these conditions, distinctive project ideas were developed together. These are currently being pursued in the network, developed and evaluated as to their market potential. Some of the projects include: the development of nano-technological wear protection for press components; research in the field of optical measurement methods for heat distribution in heat treatment and hot-forming processes to improve the quality and prediction of material properties; the optimization of assembly / forming applications for lightweight components (e.g. in the automotive and aerospace industry).

The established structures of the collaborative network are used in EcoMaT to enhance cooperation between medium-sized industrial enterprises and research institutes and universities as well as the large aviation and aerospace corporations to the automotive industry. It is expected that through this extended association the potential for new developments in the field of lightweight materials and technology will be greatly increased.

5. ACTUAL RESEARCH FOR AERONAUTIC AND AUTOMOTIVE INDUSTRY

As far as expertise and collaboration between the research community and industry is concerned, materials science is perhaps the most important field of technological research in Bremen. There are strong partnerships between large companies and Bremen’s research laboratories, as well as intensive collaboration among the various research institutes. One major issue in Bremen in respect of ‘Innovative Materials’ concerns how to transfer outstanding scientific expertise, including the know-how of large industrial companies, into small and medium-sized enterprises. Commercial exploitation of what are often excellent scientific results has been achieved only in isolated cases so far. Another key issue in the cross-cutting field of ‘Innovative Materials’ is the need to improve skills in small and medium-sized enterprises with special reference to potential selection of alternative materials, and especially in the dimensioning and design of innovative materials for specific applications. Improving the interaction of measurement and simulation techniques is of special importance here.

Within this context, one key element in Bremen's further advancement is the conducting of innovative, market-based projects in the field of new materials. For pooling existing expertise in Bremen from industry and science in the field of innovative materials and surface technology is the technology center EcoMaT arise in the Airport City of Bremen. EcoMaT stands for "Center for Eco-efficient Materials & Technologies" and is in close proximity to Bremen Airport and to major industrial partner Airbus.

In EcoMaT the research topic deals with the question of the efficient and effective use of materials and the development of new materials. For other issues such as the design of products and segments by integrating new material properties by the convergence of sensor technology and materials as well as materials of construction are fairer to the fore. The application-oriented focus thus also includes the associated processes and the integration of technological knowledge in manufacturing processes.

Under one roof, around 500 people from the business and scientific will research and develop together. This technology will be viewed and analyzed from an application-oriented perspective through multidisciplinary and intersectoral cooperation. Short distances and joint projects can be used to accelerate innovation processes across industries already in an early stage of development. The proximity also allows the sharing of laboratories and facilities. Results from the R&D activities are not only for improving future products and applications there are also benefits for training and teaching for future human resources.

[1] Lohner H., Kröger-Kallies B., Fangmeier A.: Aircraft surface protection – Principales, application, future trends. Deutscher Luft und Raumfahrt Kongress, Bremen, 27.09 – 29.09. 2011. urn:nbn:de:101:1-201207206293

[2] Le Blanc, L. The new basecoat-clearcoat external paint systems for AIRBUS application. SURFAIR Conference, Biarritz, 10.06. - 11.06. 2010

[3] Lahidjanian D., External painting of single aisle aircraft in Hamburg. Deutscher Luft und Raumfahrt Kongress, Bremen, 27.09 – 29.09. 2011

[4] W. Machu, Elektrotauchlackierung, Verlag Chemie, Weinheim, 1974

[5] Nanetti P. Lack für Einsteiger. Verlag Vincentz Network GmbH & Co KG, Hannover 2009

[6] Collinet-Fressancourta, M., Nunsb N., Bellayerc S., Traisnela M.: Characterization by TEM and ToF-SIMS of the oxide layer formed during anaphoretic paint electrodeposition on Al-alloys. *Applied Surface Science*, 277, (15), 2013, p 186–191

[7] Schramm C. Maul R., Weiss H., Heckel C.: Use of metallic pigments as electrodeposition paint pigments. *European Patent* EP1877499

[8] Lohner H , Hack T.: Impact on industry. Corrosion Aluminium Alloy Corrosion of Aircraft Structures - Modelling and Simulation, Ed.: DeRose J.A., Suter T., Hack T., Adey R.: Ashurst, Southampton, WIT Press (2013), 181-186

[9] Volkmar Stenzel, Nadine Rehfeld: Funktional Coatings, Vincentz Network, Hannover (2011)

[10] DVS*-Richtlinie 3310: Qualitätsmanagement in der Klebtechnik