INNOVATIVE PROCESS CHAIN FOR THE PRODUCTION OF FIBER-REINFORCED FUNCTIONAL COMPONENTS BASED ON SANDWICH STRUCTURES BY ADDITIVE MANUFACTURING

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ABSTRACT

In the research project Additive Sandwich Manufacturing (ASM) an innovative generative manufacturing process for large light weight parts and components will be developed using additive and subtractive technologies for fiber-reinforced thermosets on the basis of polyurethane (PUR) which have to be adapted to the new process. A complete new process chain has to be developed including material mixing and application head, integrated printing and CAM software for 6-axis application and multi material application.

The complete process chain from the part design with an innovative data transformation for generative manufacturing up to the finish and quality control of the produced part will be explained in this paper. The aim of the collaborative project is the development of a novel generative process chain and the necessary software and plant technology for the production of complex, large-volume, medium and functional components. The paper describes the state of the art for 3D printing methods and the differentiation to the development project. One of the verification parts is a shear web of a rotor blade for wind turbines, which is a very large composite part with a sandwich layup.

The conventional manufacturing of the shear web will be explained, especially the used materials. The approach for material substitution is mentioned and the resulting challenges for the further material development. The project focusses on newly adaptable fiber-reinforced thermoset materials on the basis of polyurethane (PUR). This means a printable fiber paste for the face layers has to be developed and an in-situ expanding PUR-foam for the core material.

The complete machinery equipment for material delivery, application and finishing will be built up on the basis of the BladeMaker HSM 6-axis gantry at Fraunhofer IWES in Bremerhaven, Germany.

1 INTRODUCTION

Due to the increasing individualization of production goods as well as shortening product life cycles, additive manufacturing has achieved a high priority and a stronger focus in manufacturing industry. Existing processes and systems show a limited throughput and part size and most of the used materials and thus the components have low mechanical performance [1]. To close this gap for the production of lightweight components Fraunhofer IWES is developing an additive production process for the manufacture of large complex, medium strength functional components made of fiber-reinforced materials, in particular sandwich structures. The new process chain is based on the results of the BladeMaker project [2]. The work is part of German funded research project Additive Sandwich Manufacturing (ASM) and consists of 8 partners from research and industry. The consortium aims to achieve a significant contribution to the economical production of small quantities and individualized products made of fiber composite materials. Planned components are e.g. elements for rotor blades of wind power plants, machine parts for special engineering or components for automotive, commercial vehicles and rail vehicles.

Figure 1 shows the elements of a rotor blade. The two parallel parts in the middle of the blade are the shear webs, which are typical sandwich elements. In the project it is planned to manufacture the shear webs in real size. This offers the possibility to demonstrate the feasibility on industrial level on real sandwich structures. Due to the additively produced structures, the molding times, which are currently a critical factor in many rotor blade manufacturers, can be significantly reduced. Another advantage is that no extra molds are needed which means high investments and require a lot of storage capacity.

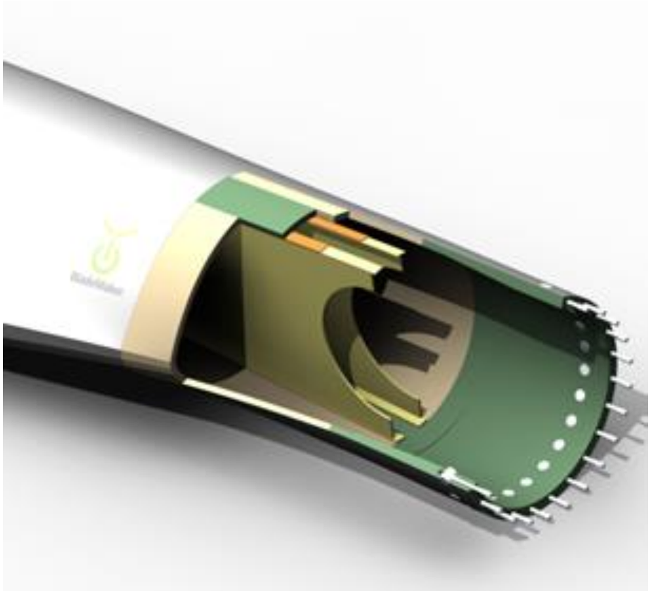

Figure 1: Elements of a rotor blade

2 STATE OF THE ART: MATERIALS AND PRODUCTION PROCESSES FOR ADDITIVE MANUFACTURING AND SANDWICH STRUCTURES

Additive manufacturing (AM) is one of the fastest growing economic sectors in the world. For example, global sales of AF goods have increased by approx. 400% within the last 10 years [1].
The main application area of AM is in the production of models for a better visualization of product ideas. Due to the state of the art, mechanically highly stressed components are very difficult to manufacture by additive manufacturing processes. Only for metallic products or in areas where high demands on the material properties in terms of strength and stability are not necessary, additive production is used for the production of user-supplied products. This is justified by the materials used in combination with the respective production processes. According to the state of the art, two processes play a fundamental role in the additive manufacture of functional components.

Fused Deposition Modeling (FDM)

In the FDM method, a plastic wire or granulate is fed to the print head, which is melted in the head and applied layer by layer. ABS, PLA or nylon is used as material. One advantage is that carbon or glass fibers can be added to the material. The workpieces produced this way have significantly poorer material and strength properties than conventionally produced CFRP and GRP parts. Reasons for this are the very low fiber length and non-directional fiber orientation as well as the use of thermoplastics as matrix material. Due to the short fiber length and the relatively low fiber content, these are not yet or hardly used for the strength increase in AM materials.

Selective Laser Sintering (SLS), Selective Laser Melting (SLM) and Selective Electron Beam Melting (SEBM)

The named additive manufacturing processes enable the generative production of metal and thermoplastic workpieces by applying powder layer by layer and sintered or melted at each desired point by a laser or electron beam at the desired points. This process is repeated until the 3D component is finished. However, these methods do not play a major role in the development as they are used only for metallic materials or thermoplastics without fiber reinforcements or with extremely short fibers.

Particularly in the case of the FDM method, progress has been made in recent years with regard to the reinforcement of carbon fibers or glass fibers. The following section presents examples which follow a similar approach to the planned development.

	MarkForged	*Cincinnati BAAM*	*3D Fibre Printer (Fraunhofer IPA)*	*ASM (Additive Sandwich Manufacturing)*
Matrix material	Thermoplastic	Thermoplastic	Thermoplastic	**Thermosets**
Printing axes	**3**	**3**	**6**	**6**
Variation of fiber content	✗	✗	✗	✓
Targeted reinforcement with continuous fibers	✗	✗	✓	✓
Manufacture of core structures with in-situ foams	✗	✗	✗	✓
Fiber volume content	ca. 10%	0%	ca. 10%	**> 30%**
Automated finishing process	✗	✗	✗	✓
Integrated non-destructive quality testing	✗	✗	✗	✓
Dimensions Workpiece	0.32 x 0.25 x 0.2 m	6 x 2.3 x 1.8 m	k.A.	**10 x 3 x 2 m**

Table 1: Differentiation of the development to the state of the art of 3D Printing

MarkForged: Mark X [1]

Currently the best known manufacturer of CFRP-3D printers in the industry uses the FDM method to create a basic structure of nylon. Contrary to the ASM project, MarkForged works with thermoplastics, which can be reinforced with very narrow CFRP prepreg. Furthermore, the printer is limited in the production possibilities due to its build volume of 330 x 250 x 200 mm and is therefore only used for smaller parts or parts which have to be joined later. An integrated quality inspection is already available but not a finishing process.

Cincinnati Inc.: Big Area Additive Manufacturing

The American company Cincinnati Inc. offers a printer that can produce large parts of carbon or glass fiber-reinforced plastic. The so-called Big Area Additive Manufacturing-CI (BAAM-CI) is capable of producing workpieces up to 6096 x 2286 x 1829 mm [3]. The diameter of the extrusion nozzle is 5 mm or 7.5 mm [3]. As usual for a FDM printer, the material will be extruded in three axes with a diameter. The carbon fiber or glass fiber is already in the granulate material. The contained fibers have a low volume part and a short length. According to the manufacturer, the printer is suitable for industrial applications and is already available.

Fraunhofer IPA: 3D Fibre Printer

In 2013, the Fraunhofer IPA published the development results for the 3D FibrePrinter, in which carbon fibers are impregnated with plastic. For this purpose, a special FDM print head has been developed which allows a few carbon fibers to be brought together in a nozzle with the plastic melt. The plastic melt then pulls the fiber at the same rate as it does itself by means of the principle of the water jet pump. The fibers are thus introduced uniformly and direction-oriented, but the fiber content is currently 10%. The print head is attached to a 6-axis articulated robot. In contrast to the planned development, a thermoplastic is used as matrix, which in contrast to thermosets, especially in combination with carbon fibers, represents the significantly poorer matrix material with regard to strength and temperature resistance of the composite material.

The following table provides an overview of the desired process improvements compared to the prior art in the production of fiber-reinforced components.

	Vacuum Infusion	*Hand Laminate*	*Conventional 3D-Print (FDM)*	*ASM (Additive Sandwich Manufacturing)*
Material properties E-Modul [GPa]	24 to 35	6,5	2,3 to 3,5	**12 to 15**
Material combinations	- Combination of resins and fibers with variable fiber volume content - Insert of foam elements or parts of other materials	- Combination of resins and fibers with variable fiber volume content - Insert of foam elements or parts of other materials	- Combination of resins and fibers with fixed fiber volume content	- **Combination of *resins and fibers with variable fiber volume content*** - ***Integration of in situ foams*** - ***Extrusion of pure resin*** - ***Insert of parts from various materials during the printing process***
Tolerances	0.1 to 0.4mm (finishing by robotic system)	0.1mm to 0.4mm (finishing by robotic system)	0.1 to 0.4 mm	**< 0.1mm**
Throughput (shear web)	11h	9h	not possible	**6.5h (Estimated time based on previously known values)**
Kg/h	42	46	estimated FDM: 0.1 kg/h	**75**
Dimensions (in m)	Free	Free	Currently limited to: 0.1x0.1x0.1	**Free, currently: 10x3x2**
Fiber volume content	Ca. 60%	Ca. 30%	Ca. 10%	**> 30%**
Process step reduction	- Separate mold construction necessary - Production of parts by hand - Separate finishing	- Separate mold construction necessary - Production of parts by hand - Separate finishing	- No mold construction necessary - Finishing as an outsourced separate process	- **No mold construction necessary** - **Integrated finishing** - **All-in-One Process**
Cost €/kg	12	10	n.a.	**8**

Table 2: Intended process improvements against the state of the art

3 DEVELOPMENTS IN ADDITIVE SANDWICH MANUFACTURING

3.1 Intended manufacturing concept in ASM

In the new process, the products shall be produced by applying individual layers of foam material or plastics reinforced with glass or carbon fibers by different extrusion heads. The reinforcement could be realized by cut fibers, mixed within the matrix, or separately applied continuous fibers. For the resins and foams the project focusses on thermosets based on polyurethane. In order to be able to apply these materials in a targeted manner, the print strategy and the associated processing programs must be generated in advance. To this end, various software elements have to be developed or adapted in the project. This includes the modeling of the material and structural properties as the starting point for the calculation of the print strategy. For producing the foam structures or the application of the fiber-filled resins, corresponding metering heads and mixing systems have to be developed by the industrial partners. In addition, the Fraunhofer IWES integrates or modifies machining processes with corresponding sensors in order to be able to manufacture components with suitable tolerances and surfaces for direct use. The Project "Additive Sandwich Manufacturing" aims the development and implementation of the necessary system technology and the adaptation of the materials to realize the process.

3.2 Cost model of the shear web in conventional manufacturing

The total production costs of a 40m shear web have been analyzed in the BladeMaker project. The production processes, the plant technology and the materials developed in the project will allow a reduction of the production costs of ready-to-use functional components made from fibre-reinforced plastics of 10 to 20 percent. In the example of a shear web for a rotor blade, the reduction results from the elimination of the mold costs of approx. 8% and lowering of waste by 5% for glass fibre blanks and resins due to the more precise application, compared to conventional processes. Thus, a significant contribution is made to the economical production of small quantities and individualized products made of fiber composite materials.

Further advantages can be made with the fully-automated system to lower the labor costs and achieve a consistent quality. The use of cheaper raw materials is another point to handle an increased throughput for composite components.

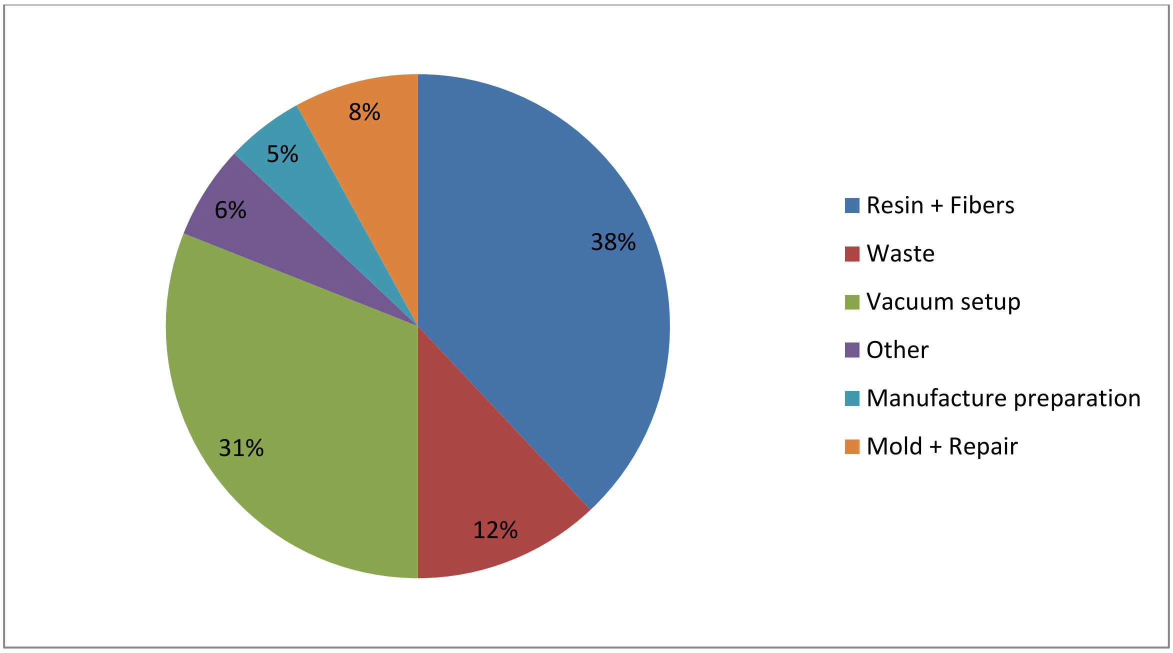

Diagram 1: Cost model shear web of IWT82- rotor blade

3.3 Process Chain of Additive Sandwich Manufacturing

The basis for this process should be a 6-axis working system that will allow the production of complex geometries. The six-axis system is required because of the new way of material layup compared to conventional 3D-print. Through the 6-axis system and the new material application one of the major challenges is the development of a new data processing module for additive manufacturing. Since the new method allows to realize reinforcement structures along the load direction in the component for the first time, the CAD data as well as the results from FE-analyzes and the necessary fiber alignment must be implemented into the data processing. This generated data model will be converted in such a way that it can be executed by the NC control of the machine. For further improvements in front of the production the process will be simulated by adapted CAD/CAM-Tools.

An important development focus is the data processing over the entire production process - from the 3D CAD data of the component to be produced, the generation of the printing strategy as well as the print data to the process control.

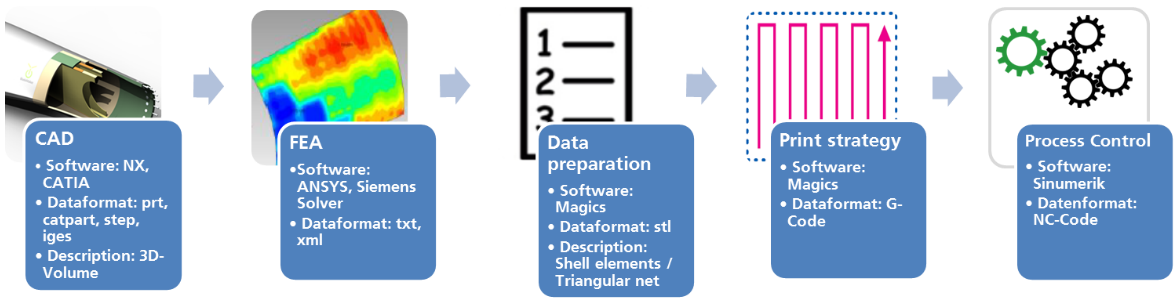

Figure 2: Structure of the Data processing

Beginning with the CAD-model which can be used in various data formats a Finite Elements Analysis (FEA) is integrated in the manufacture process. The results of the FEA, in particular the direction of the principal stress, will be used for the orientation of the fibers. In the data preparation these results are brought together with the software *Magics* by the company *Materialise* to get a sliced virtual part that can be printed in layers. The part will be described by shell elements with a triangular net. The printing strategy will also be generated by *Magics*. The resulting G-code is used by the process control, in this case a *Siemens Sinumerik*, to convert it to NC-code including all process data.

The system enables to vary the fiber volume fraction and the fiber length depending on the required mechanical properties for the component.

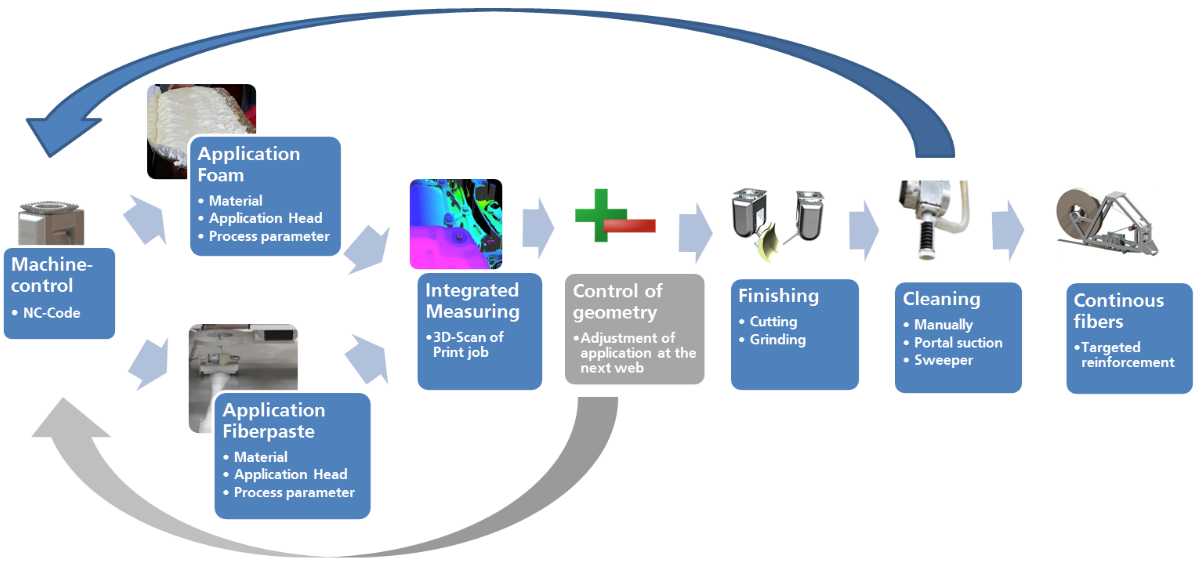

Figure 3: Process Chain of Additive Sandwich Manufacturing

Figure 3 shows the process chain for material application, beginning with the NC-code of the machine control. Depending on the desired component structures, two methods are available, in which the geometry is established either by extrusion of thixotropic thermoset with chopped fiber reinforcement or by extrusion of thixotropic foam for the production of sandwich structures.

Integrated measuring equipment will scan the applied web directly to control the geometry and adjust the material application on the next layer. After the material lay up a finishing process is integrated for cutting or grinding the final shape of the part. The step makes cleaning necessary, if continuous fiber shall be applied afterwards, to remove the dust from cutting and grinding to ensure a proper bonding between the layers. Additionally, the continuous fibers can be used as a targeted reinforcement for highly loaded areas. This increases the material efficiency for a component compared to conventional methods.

The essential distinguishing feature of ASM compared to additive manufacturing processes used today is the use of a newly developed extrusion mixing head with cut fibers and thermoset resins. An innovation is the combination with of an application head for foam materials with an application head for continuous fibers. By integrating these heads in a 6-axis CNC system, it is possible to realize complex geometries within sandwich structures. With this technique, the time-consuming and cost-intensive mold construction for composite parts is obsolete.

4 MATERIAL SUBSTITUTION FOR A SANDWICH ELEMENT OF A ROTORBLADE

This chapter describes the shear web of the BladeMaker rotor blade which is one of the verification parts for the development.

4.1 Description of the shear web in conventional manufacturing

The shear web is the major element in a rotor blade to adsorb shear stresses between the outer shells. Figure 4 shows the CAD-model of a shear web segment from the BladeMaker rotorblade. The segment is cut down to a length of 16 m with a width of 0.4 to 1.8 m and a height of 0.1 m.

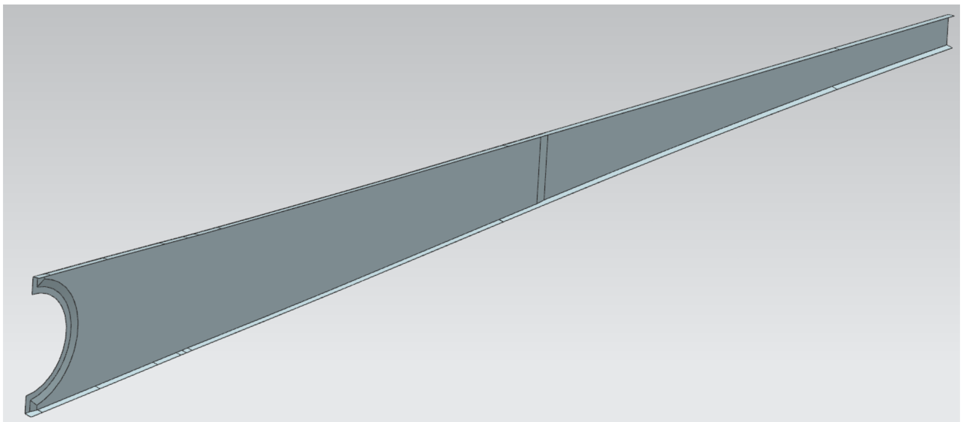

Figure 4: Segment of the BladeMaker shear web

The shear web is a sandwich construction with three face layers on each side and a foam core inside. For the face layers an E-glas, biax material from PD Glasseiden called KN G 800 M2 is used. It has an area density of 800 g/m² and a fiber orientation of ± 45°. For the matrix the epoxy system RIMR035c with the hardener RIMH037 from Hexion is used. The mechanical properties in the compound are shown in Table 1.

Type	Unit	KNG800M2 + RIMR035/RIMH037
E	[MPa]	10830
UTS	[MPa]	131.8
υ	-	0.568

Table 3: Mechanical properties of the compound

These values were determined by the Fraunhofer IWES material laboratory and are major requirements for the development of the new material for ASM. The core consists of a PVC-foam from Gaugler&Lutz called Airex C70.75. The thickness is about 20 mm at the root section and 6mm at the tip end. The mechanical properties of the foam are listed in the following table:

Type	Unit	AIREX C70.75
Density	kg/m²	80
Compressive strength	[MPa]	1.45
Compression modulus	[MPa]	104
Tensile strength	[MPa]	2.0
Tensile modulus	[MPa]	66
Shear strength	[MPa]	1.2
Shear modulus	[MPa]	130
Shear elongation at break	%	18

Table 4: Mechanical properties of the PVC foam AIREX C70.75 by Gaugler&Lutz [4]

4.2 Analysis of the shear web for material specification

One of the major load cases for a rotor blade is the maximum deformation due to high wind loads. For this load case a FE-model has been set up for the whole rotor blade and the displacement for the shear web was extracted from this analysis, shown in Figure 5. The maximum displacement is about 556 mm at the tip end. One goal is to achieve the same part performance with the material to be developed.

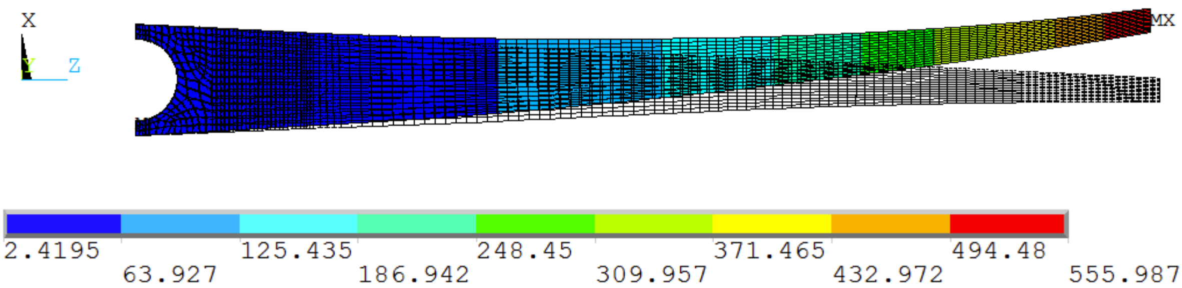

Figure 5: FE-model of the shear web

To evaluate the further material development in accordance to the shear web the conventional sandwich layup was analyzed analytically. In a first step, the engineering constants were determined with the classical laminate theory (CLT). The results are shown in Table 5.

Engineering constant		Sandwich layup Shear web
$E_{x,\ \mathrm{Tension}}$	[MPa]	1783
$E_{y,\ \mathrm{Tension}}$	[MPa]	1783
υ_{xy}	–	0.569
$G_{xy,\ \mathrm{Shear}}$	[MPa]	700
$E_{x,\ \mathrm{Bending}}$	[MPa]	6446
$E_{x,\ \mathrm{Bending}}$	[MPa]	6446
$G_{xy,\ \mathrm{Torsion}}$	[MPa]	700

Table 5: Engineering constants for sandwich layup of the shear web

The next step is to analyze the behavior of the sandwich layup for shear- and buckling strength. With these results the development of the reinforced fiber paste can be compared in a multi-layer compound like a sandwich to the conventional layup. If the materials performance is not sufficient, geometry changes might be necessary. But this could be easily realized by printing additional stringers for buckling stiffness for example to keep the weight of the part on the same level.

4.3 Challenges for further material development

The main component of the process development is the integration of the thermoset-fiber composite material. The aim is to develop adaptable resin / hardener matrix systems and foams based on polyurethane (PUR).

In a new on-line mixing process, on the one hand a homogeneous fiber distribution is to be ensured, on the other hand, both the fiber content and the processing parameters of the matrix systems can thereby be varied depending on the component and the process

In order to increase the mechanical strength of the produced components, cut glass fibers are added to the matrix. The processing of thermoset plastics with a targeted fiber content of up to 40% in an additive production process is associated with a high technological risk and represents a unique feature of the planned process. The fiber supply and also the mixing of the fibers with the matrix are one of the main challenges in the project. The fiber supply with chopped fiber versus fiber rovings is also part of investigation. Depending on the filament diameter and the cutting length, the mechanical properties can also be influenced positively [5]. For the further reinforcement of the component, reinforcing strips of continuous fiber are applied.

For the realization of the planned additive material, the aspects of the mixture and curing parameters of the starting components as well as the mechanical properties of the finished parts have to be considered. A particular challenge is the matching between application speed, viscosity during the application, pot life, thixotropy and curing time of the material for producing a homogeneous layer quality. The applied layer must have a sufficiently high degree of curing for the following layer application, but also a sufficiently high residual reactivity for homogeneous connection with the following layer.

5 DEVELOPMENT OF ADDITIVE SANDWICH MANUFACTURING CENTER

The complex shape of the intended product range and the way of material deposition requires a 6-axis robot system. Compared to today's proven processes, such as fused deposition modeling (FDM) or selective laser sintering (SLS), where the printing process takes place in only three axes, the new process with 6-axis is a paradigm shift [6] [7].

The lack of scalability options and at the occupation of large areas on the production floor is one of the key challenges for big 3D printer [8]. One major advantage of ASM is that the plant engineering and production processes are very scalable, plants can be offered in various sizes and with individually adapted additional functions (e.g. milling, grinding, etc.) according to the customer's requirements. SMEs can also flexibly respond to the needs of their customers.

The HSM-MODAL-6-axis portal from the BladeMaker project of the Fraunhofer IWES, shown in Figure 6, is used as basis for the new plant. It will allow the production of components with dimensions up to 10x4x4 m.

Figure 6: HSM Modal 6-axis double gantry portal from BladeMaker at Fraunhofer IWES at Bremerhaven, Germany

The material distribution of the PUR- fiberpaste and the PUR-foam is guaranteed by two dosing and mixing machines from the company *2KM*, Marienheide in Germany. Figure 7 shows the *PolyMix 2000* which is suitable for materials with a high viscosity up to pasty materials.

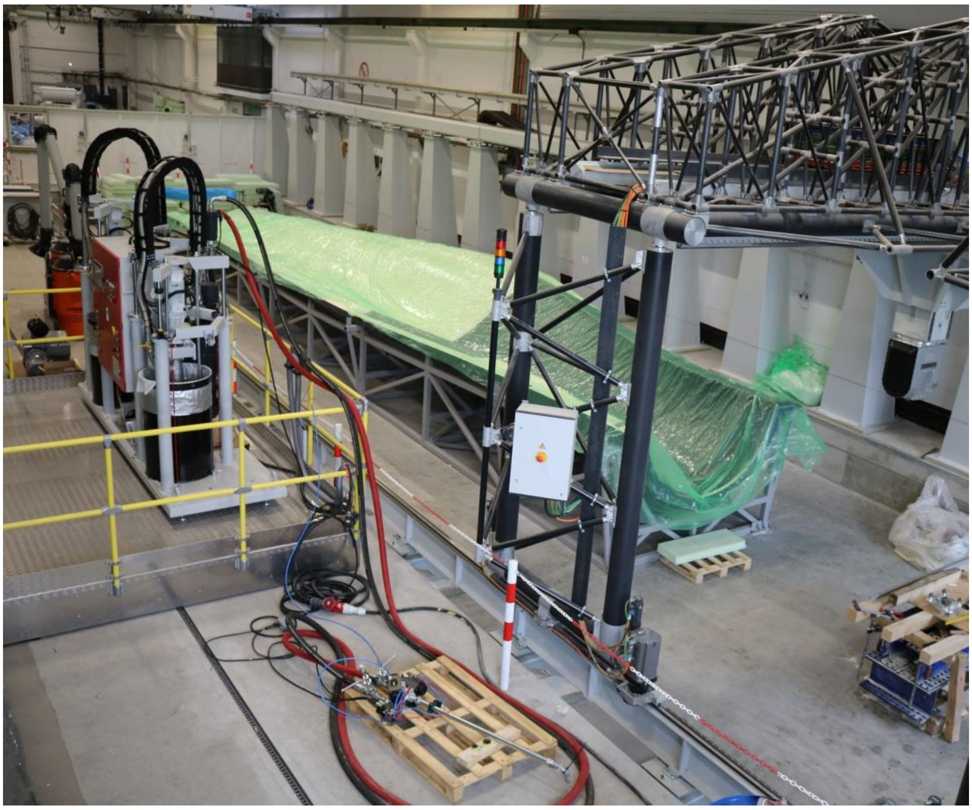

Figure 7: Dosing machine PolyMix 2000

The equipment is located on a heavy duty platform that can be connected to the gantry and moves alongside the gantry during the process. The material delivery will be realized with a piping system between the platform and the portal. The piping system will be installed in an energy chain to allow the movement over the whole workspace.

The dosing equipment is also integrated in the CNC-control of the HSM-MODAL-6-axis gantry for a fully-automated process during the manufacturing of the parts.

6 CONCLUSIONS

The paper describes the challenges in the development of a new 3D printing process in combination with a material to be developed that is suitable for the process as well as the parts to build. The scientific and technical prospects of success for the joint project described can be classified as very good. The development work is highly complex and requires excellent engineering expertise from different areas. If the project is finished successfully, the new production process will set new standards in the production of fiber-reinforced functional components. It offers enormous potential for optimization of the component properties and can lead to a significant improvement in the economy of the production of fiber-reinforced products by integration into industrialized process chains for use in serial production. The technology offers a very high economic and technical potential for manufacturing of complex and mechanically demanding components ever more favorable and flexible. The new process significantly shortens product development and production procurement times, eliminating investment in tools and molds. This results in a drastically reduced time-to-market at economically significantly reduced costs.

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