

# Application of Additive Manufacturing to Manufacture Removable Mold-Cores for the CFRP Production of Complex Geometries

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## Abstract

Carbon fiber reinforced plastic (CFRP) manufacturing often is an expensive, time-consuming small-scale production where most of the products and components are characterized by complex geometric properties. Especially for hollow components it is necessary to use removable mold cores, which are typically made of low-melting metal alloys, and used to shape the inner contour of the component.

To improve the time-consuming and costly process of mold-making, this paper describes the application of additive manufacturing (i.e. 3D-printing) for the production of mold cores. The outstanding advantage of additive manufacturing is the very flexible production out of a CAD model without further tools.

In the provided case study materials for additive manufacturing were selected and tested for their suitability to manufacture mold cores. For this purpose an exemplary mold core was produced with different additive manufacturing methods and used in common carbon fiber production processes. Since curing in the autoclave places the highest demands on the core, this process has been selected to test the mold cores. A special focus was on the analysis of the dimensional stability and accuracy by measuring the deviations of the inner cores after the autoclave cycle. The analysis was performed by using optical metrology utilising stripe light projection.

Finally this case study shows that additive manufacturing can lead to an increase in efficiency in the CFRP production but also that further scientific research and technological development are needed to realize the indicated potentials.

Keywords: 3D printing; Additive Manufacturing; autoclave; Carbon; CFRP; lightweight construction; mold; mold core; Rapid Tooling; small scale production;

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## 1. Introduction

The principle of lightweight construction exists almost as long as life on earth. For example light weight construction is used by nature in the formation of bones and plants. Thousands of years ago the Egyptians already used clay reinforced with tendons of animals or fibers to build temples. [1]

The modern era of fiber reinforced materials, especially carbon fiber reinforced plastics (CFRP), began in the 1950s with the desire of the aerospace industry for components that are light and stable at the same time. Therefore the challenge was to develop a technique that allowed a plastic and fiber to be combined. Scientists in all industrial countries tried to develop solutions to this problem, but it was in 1963 that engineers at the British Royal Aircraft Establishment made a real breakthrough. William Watt and his team combined carbon fibers with the polymer polyacrylonitrile and exposed it to a unique, multistage heating process. By reinforcing polymers with fibers a strong and light material could be created and used to fabricate versatile composites that were stiff, light, corrosion-proof, heat-resistant and tear-resistant. [2]

At the beginning the materials were only applied in the aerospace industry, but since 1990 CFRP has been increasingly used in several branches because of the possibility to adapt mechanical properties like stiffness and strength to the component's requirements. Especially in the last few years the market for fiber reinforced plastics grew rapidly. The demand for CFRP was 65.000 t in the year 2012. For the

next years a yearly increase of 13-17 % is predicted, so that an exponential increasing of the CFRP demand to 208.000 t is expected in 2020. That corresponds to 320 % of the current demand. [3]

The applications of CFRP are often very innovative and at high technical level [4]. Particularly due to the good ratio of weight to stiffness and the excellent mechanical properties CFRP products can be found in different industry sectors. Main areas of application are aerospace, wind power as well as sport, medical and rehabilitation industries [5]. The automotive industry is considered as an industry sector with high growth potential. But to achieve long-term growth the reduction of production and material costs is necessary. [2][6]

As CFRP manufacturing often is a small-scale production and in addition most products and components are characterized by complex geometric properties, the lead times and the production costs are high. This results from the fact that nearly every component needs an individual mold which has to be developed and manufactured in advance. Especially for tubular components it is necessary to use mold cores during the manufacturing process. These cores are typically made up from low-melting alloys and are used to shape the inner contour of the component. Thereby a core often has to be casted in a separate mold or is machined from solid materials. A further important requirement, which has to be fulfilled by a core, is that it needs to be removed after curing the CFRP component. [7]

Additive manufacturing provides the opportunity to quickly and easily create complex products and components. Especially with low quantities and individual shapes additive manufacturing is more efficient than conventional methods of manufacturing. Because of the aforementioned attributes additive manufacturing could also be used to manufacture reasonable removable mold cores for CFRP components. [8]

Against this background this paper shows the evaluation of application possibilities for materials, which can be used in additive manufacturing to manufacture removable mold cores. These mold cores should be suitable for common CFRP production processes. Since curing in the autoclave places the highest demands on the inner core, this process has been selected to test the cores.

## **2. State of the scientific knowledge and need for action**

### *2.1. Manufacturing processes for CFRP components*

Various manufacturing processes are available to manufacture CFRP components. Hand lamination is one of the simplest methods to produce a CFRP component. Alternately fiber mats are inserted into an open one-shell mold and resin is transferred and consolidated via hand rollers until the component's shape is thick enough. The components are commonly cured at room temperature and without pressure. But hand lamination is used rather rarely for high demand products because of the low fiber volume content of the products [9].

One of the most common manufacturing processes for highest quality products is the pre-preg autoclave process [6]. Pre-pregs are fiber fabrics, layings or mats which are already impregnated with the matrix. Duroplastics and thermoplastics can be used as matrix. In practice are mainly epoxy resins used as duroplastic matrix systems [10]. More than half of the carbon fibers are processed as pre-pregs and cured in autoclave [6]. An advantage of using pre-pregs is the possibility to define the ratio between fiber and resin in the pre-preg production process. Thus the fiber volume content can be precisely adjusted and is usually in the range of 60 %.

For processing the pre-pregs are put in a mold and in a foil under vacuum. The curing of pre-preg components occurs at high temperatures and under pressure in the autoclave, which leads to further infiltration of the carbon fibers and therefore to increased mechanical strength properties [11]. The pre-preg autoclave process enables the production of high-quality components under reproducible conditions of manufacture [12]. For a detailed description and further methods see relevant specialist literature such as [4] or [1].

### *2.2. Mold cores*

Molds that shape the component's outer and/or inner contour are required for all manufacturing processes of CFRP components. Depending on tool life, process temperature and pressure these molds can consist of steel, aluminium alloy, synthetic resin or plastics.

Mold cores shape the inner contour of the CFRP component during the manufacturing process. There are two different types of mold cores. Mold cores, which remain in the component after manufacturing and mold cores, which can be removed after manufacturing. In lightweight construction

remaining mold cores are often made of light PU foams or plastics. These mold cores already have the contour of the component to be laminated. By applying laminate layers to the mold core a very light and rigid structure is created [13].

In the following, only removable mold cores shall be closer considered because of the feasibility to use them for manufacturing hollow tubular components. There are different materials for mold cores depending on the manufacturing process of the CFRP component. According to the material also different approaches to remove the cores are used. A distinction is made between extracting, melting, destroying and releasing the mold cores. Extractable mold cores can be removed by changing the mold. These are often assembled molds of wood or metal [14] or air-filled elastic tubes. To melt out mold cores after the manufacturing process component and core are heated above the melting point of the core material, so that the core material flows out of the component. Here attention should be paid to the fact that the heating-up must not damage the manufactured component. Hard wax and low-melting metal alloys are ranking among the meltable mold core materials. [14] [15] [16] Destroyable mold cores have to be very brittle and have to break into pieces under mechanical stress. They are primarily made of plaster and similar materials. [14] The material for releasable mold cores is selected the way that it can be dissolved in water, alkaline or acid solution. Such materials are in accordance with the state of the art water soluble plaster, salts [14], ceramic mixtures [17] as well as water, alkali or acid soluble polymers [18].

### *2.3. Additive manufacturing*

Particularly in single-piece or small-scale production the manufacturing of molds and mold cores is very elaborate. Usually they are milled or cast in time-consuming and costly production processes.

Against this background additive manufacturing processes ought to be seen as alternative to avoid the conventional manufacturing processes of mold cores. Additive manufacturing is characterized by the layer build-up principle and thus provides the opportunity to manufacture complex parts or molds without tools. To start manufacturing the software of the additive manufacturing system needs only the 3D CAD data of the part to be manufactured in common STL format (Surface Tessellation Language). The software slices the part, which means in this context that the part is divided into a large number of thin layers. The manufacturing system uses these data and builds up the part layer by layer. The additive manufacturing processes can be distinguished by the material they process (powder, filament, liquid plastics or resin etc.).

Additive manufacturing processes can be quicker and more economic than conventional manufacturing processes, especially when it comes to manufacturing of small lots or individual single pieces. These factors are advantageous for manufacturing mold cores because time-to-market, availability and low costs are decisive for the competitiveness of a CFRP product.

In the field of rapid tooling additive manufacturing of molds to shape the outer contour of components and mold cores, which remain principally in the component, is already state of the art. But so far there are no approaches for additive manufacturing of mold cores, which can be used in autoclave processes with temperatures up to 160°C and pressures up to 0.6 MPa.

### *2.4. Optical metrology and digitization*

In order to being able to measure the deviations of the (geometrically complex) mold cores after the autoclave cycle, optical metrology using the stripe light projection principle represents a suitable method. The development of triangulation sensors using the stripe light projection principle for a 3D-digitization took place approximately 20 years ago. Nowadays high performance digitization systems are fully integrated into industrial manufacturing and metrology processes [19]. Typical fields of applications for the stripe light projection principle can be found in measuring the outline or the deviations of objects. Furthermore for the digitization of freeform surfaces the importance of the stripe light projection principle rises. Today areas of utilization can be found in tool and mold construction, the aerospace sector and in the automotive industry, where this technology is used for quality assurance, failure detection and rapid manufacturing processes [20]. To determine the exact distance between measurement object and sensor, optical metrology techniques use equidistant encoded light. Due to the decoding of the received light it is instantly possible to calculate the distance respectively the distance variation between sensor and measuring object / device under test.

Within the research for this paper a stripe light projection principle was applied, which encodes geometry by using triangulation. For the further considerations the focus is set on this principle. The

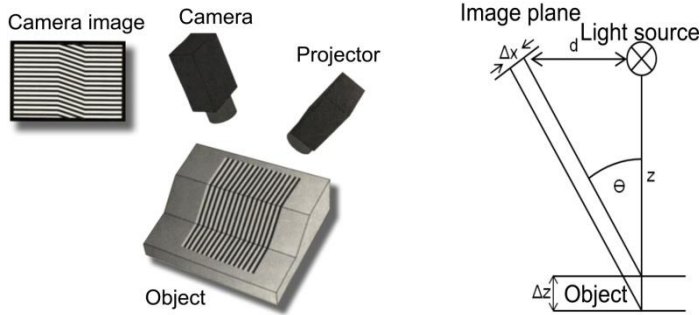


Figure 1: Setup and working principle of a triangulation sensor [20] [23]

common measurement range of the stripe light projection principle is between 2 mm and 5000 mm and reaches a measurement uncertainty from 2  $\mu\text{m}$  to 650  $\mu\text{m}$  [20]. The applied phase shifting technique thereby works in the following way: The measuring object is illuminated by a periodic sine wave light from one direction and observed from another direction [21]. Thereby it appears that a stripe pattern is moving over the surface of the object. To capture the necessary data for the digitization the procedure is recorded by two CCD-cameras, which are mounted in a laterally shifted position to the centered projector unit. Depending on the deformation of the equidistant stripe pattern according to the geometry of the object the system can calculate the 3D-coordinates for every pixel by using the triangulation (see Fig. 1) [22].

Often the dynamic phase-shift principle is applied for this purpose, where a periodic and approximately sinusoidal pattern is projected on the surface of the object [21]. The stripe pattern is thereby moved iteratively within one period. By the recorded intensity values of every pixel, the phasing is determined wherein at least three stripe pictures are necessary. From this reason only stationary objects can be digitized by this technique [22].

For the triangulation, shown in Figure 1 (simplified), the following mathematical context is valid for the change in position of the sensor:

$$\Delta x = \Delta z * \sin \theta \text{ with } \theta = \arctan \frac{d}{z} \text{ and } 0^\circ < \theta < 90^\circ \quad (1)$$

The measurement of the distance  $\Delta z$  can be traced back to the measurement of the lateral position  $\Delta x$  on a CCD-area sensor. The equation shows that with an increased triangulation angle  $\theta$  the sensitivity of the sensor towards the change of distance  $\Delta z$  rises [23]. Calculating the 3D-coordinates of every captured pixel the output to the corresponding software is a point cloud which represents the digital image of the object. For the digitization of an object it is often necessary that different views of the object are linked. This is caused by the dimension, the complex three dimensional shapes and the variable reflexivity of the object. The digitization of complex geometries becomes possible by linking the single measurement data (point clouds) from the different views to the object and transferring them into a common system of coordinates. To prepare an object for the digitization reference points need to be attached on the surface of the object. These reference points are necessary to define the system of coordinates of the object and make a transformation feasible. If the object has a reflecting or transparent surface, it has to be prepared with a contrast medium in addition.

## 2.5. Need for action

The market for fiber-reinforced plastics is innovative, showing rapid growth and the application areas are manifold because of the special material properties and numerous new developments. The development potential is far from being exhausted, so that further work should be pursued on topics such as optimization of manufacturing processes, automation and cost reduction.

There is no concept for manufacturing hollow tubular CFRP components by the autoclave process using a removable, additive manufactured mold core. The challenge is that the mold core has to withstand the high temperatures and pressures in the autoclave and subsequently has to be removed. Additive manufacturing is suitable for the manufacturing of such mold cores because of its advantages in small-scale production. The increasing diversity of materials and product quality enlarges the application areas of additive manufacturing. The aim of this case study is to evaluate the possibilities of

additive manufacturing for the manufacturing of removable mold cores regarding to the dimensional stability in the widely-used pre-preg autoclave process. For this purpose a list of requirements has to be compiled and, based on these requirements, potential materials have to be selected and tested in different autoclave processes. The detection of deviations of the autoclave processed mold cores compared to the CAD data should preferably be carried out by optical metrology using stripe light projection.

### **3. Material Selection and characterization of additive manufactured mold cores**

#### *3.1. Thematic scope*

The pre-preg autoclave process enables the manufacturing of CFRP components at a high quality level. As there is no suitable removable mold core for this process, this case study focuses on the pre-preg autoclave process. But the results can be used for the optimization of other CFRP manufacturing processes as well. If the mold core withstands the high requirements of the autoclave process it should be also suitable for other CFRP manufacturing processes. Especially CFRP components with epoxy resin matrix are cured in autoclave. Therefore the case study considers predominantly this matrix system.

#### *3.2. Approach*

Based on the defined thematic scope the approach was developed. Initially it is indispensable to set specific requirements for the mold cores. Afterwards suitable materials that can be processed by additive manufacturing were selected from the material classes polymer, resin-bonded sands and metals.

For the subsequent determination of the dimensional stability of the test specimens, these are placed as in the pre-preg curing under selected conditions in the autoclave. Whether and under which conditions a specimen is dimensionally stable, is determined by the comparison of optical measurements after the autoclave cycle with the CAD-models. Lastly, suitable concepts for removing the mold cores are considered.

#### *3.3. Requirements for mold cores*

The main function of the mold core is to give the component the inner shape during curing in autoclave. Thereafter the mold core has to be removed to obtain a hollow component. Insofar the mold core fulfills these essential functions in the defined test area, it is necessary to meet certain requirements in selecting materials. In summary the selection of a suitable mold core material depends primarily on these requirements:

- processable by additive manufacturing,
- temperature-resistant to the curing temperature (max. 180°C),
- pressure-resistant to vacuum and pressure in autoclave (max. 0.6 MPa)
- removable without damage to the CFRP component

#### *3.4. Material selection*

**Polymers** are the most widely used materials for additive manufacturing. Therefore available polymers should initially be considered. The structure and acting binding mechanisms in polymers are responsible for ensuring different thermo-mechanical behavior [24]. The characteristic values of glass transition temperature  $T_g$  and  $T_m$  melting temperature are determined in most cases by DSC (differential scanning calorimetry) and are usually specified in data sheets of additive materials. They serve as a rough guide for the selection of the mold core material. Another material parameter to limit the application temperature of polymers under thermo-mechanical stress is the heat deflection. It describes the ability of a test specimen to retain its shape under specified stress up to a certain temperature [25]. In this case study the HDTA (heat deflection temperature A) and HDTB (heat deflection temperature B) values were taken into account instead of other heat deflection values (like Vicat or Martens) for three main reasons: First, the heating rate of 1-3 K/min of the test procedure is in the range of a common autoclave heating rate of 2 K/min. Second, cover the maximum bending

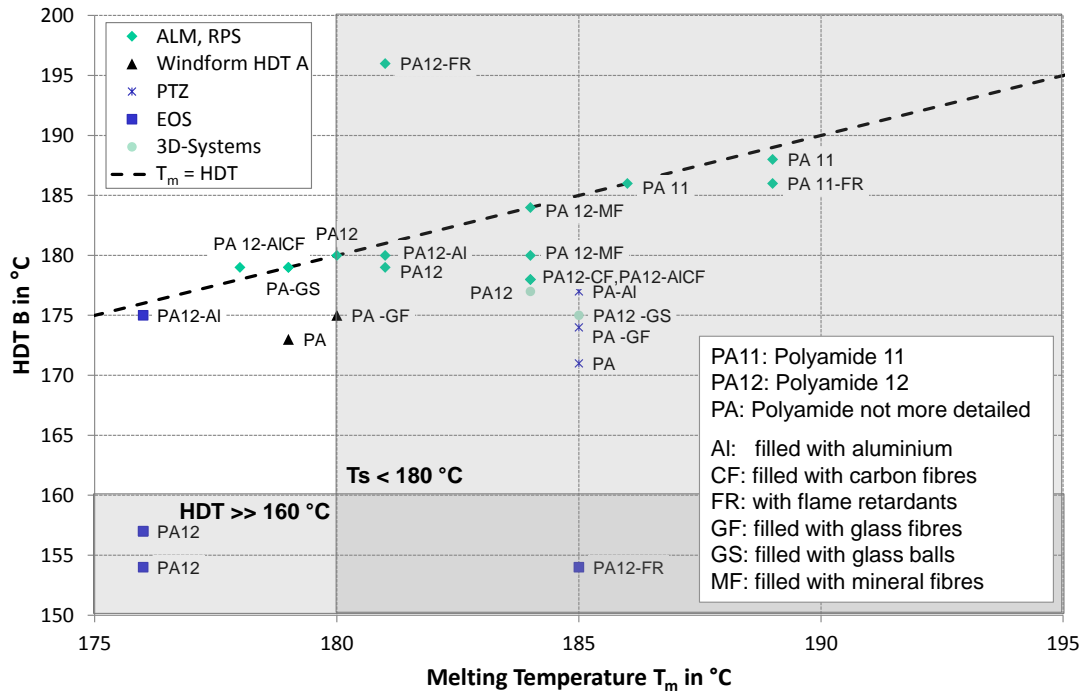


Figure 2: HDTB values and melting temperatures of current materials based on PA

stresses of 0.45 MPa (HDTB) and 1.8 MPa (HDTA) of the test procedure complies with the pressure in the autoclave (0.6-0.7 MPa). Third, the deformation of the test specimen is a critical failure mode because the mold core shouldn't deform during the autoclave process.

For the first rough limitation according to the resistance in the autoclave the consideration of the HDTB values is sufficient. The heat deflection of photopolymers, PS (polystyrene), ABS (acrylonitrile butadiene styrene), PC (polycarbonate) and ABS-PC-blend are not high enough. The remaining materials could have the necessary dimensional stability. These include PA (polyamide), cured photopolymers, PEEK (polyether ether ketone) and PPSF (polyphenylsulfone). PEEK and PPSF aren't removable without damaging the CFRP component and shall therefore not be further considered herein. Cured photopolymers are thermosetting polymers and not meltable. As the resistance to chemicals is similar to the matrix cured photopolymers aren't soluble without damaging the CFRP component.

Consequently PA remains in the class of polymers. But there is a wide range of materials for additive manufacturing based on PA. Figure 2 shows the HDTB values and melting temperatures of current materials based on PA and the related manufacturers.

With this figure the material selection can be made graphically. It is assumed an autoclave cycle with maximum curing temperature of 160°C and a pressure of 0.6 MPa. Subsequently, a post-curing process at 180°C takes place to melt out the mold core. The grey shaded area of the figure is out of the question because of a too high melting temperature or a too low HDTB value. For further investigations the two polymers polyamide 12 (PA 12) and polyamide 12 filled with aluminum particles (PA 12-AI) were selected.

**Resin-bonded sands** can be processed by additive manufacturing and have already been successfully applied in metal casting for some time. For financial reasons quartz sand is mainly used as basic material [26]. Organic binders can be synthetic resins such as phenol or furan resin [26]. To smooth the surface and increase the strength the mold cores can be infiltrated with epoxy resin, but at the same time it makes the decomposition more difficult. Therefore, furan resin-bonded quartz sand with and without infiltration were selected as material for the test specimens. Compared to phenol resin-bonded sands furan resin-bonded sands have a higher strength, which is necessary to withstand the pressures in autoclave. For the desired application it has to be tested, whether the temperature the pre-pregs can be maximally heated is sufficient to decompose the binder. If the binder does not decompose it is possible to destroy the mold core mechanically. Melting is not possible since the cross-linked binder is not meltable.

By 3D printing, selective sintering or selective melting components can be additive manufactured from **metallic materials**. The alloys and pure metals, which are used for additive manufacturing, have melting temperatures above 500° C and are very pressure resistant. For these reasons aluminum and steel are used as molds in the pre-preg autoclave process. But the additive processed metals, according to the current state of art, have a melting temperature far above the decomposition temperature of the epoxy resin matrix of CFRP components. Thus cores made of these materials are not removable without damaging the matrix. Both, releasing in acid or basic mediums, is no option because it takes a very long time and destroying the core mechanically isn't possible because of the high strength of the material.

Metallic removable mold cores could be additive manufactured, if alloys with a melting temperature in the range from 150° C to 200°C could be processed by additive manufacturing. Then the mold core could be melted out by heating. But it is not possible with currently available materials.

### 3.5. Characterization by optical metrology

The material selection has shown that there are two material systems of particular interest. On the one hand laser sintered polyamide (PA 12, PA 12-Al) and on the other hand 3D-printed sands (furan resin-bonded quartz sand). From these materials test specimen, as shown in Figure 3 (dimensions in mm), were manufactured and tested for suitability as a removable core in pre-preg autoclave process. The test specimen consists of a filled (left) and of a hollow area (right) in order to test the influence of the dimensional stability.

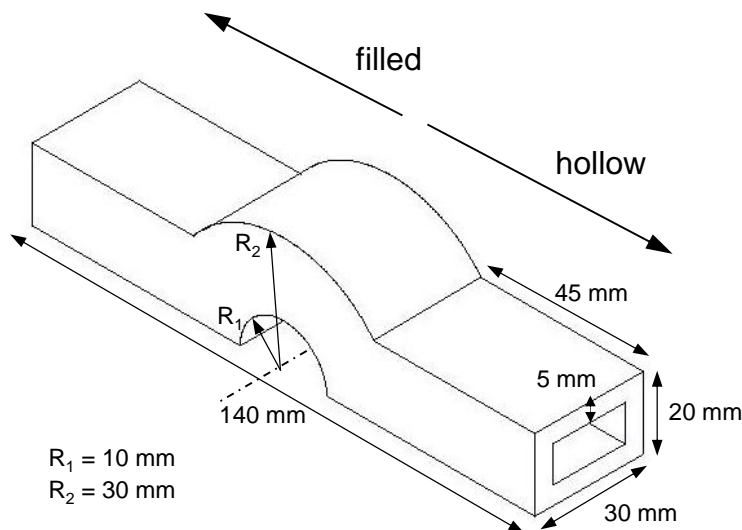


Figure 3: Test specimen

To check the dimensional stability the test specimen have been placed under different curing conditions in the autoclave. The characteristic values of the three performed autoclave cycles such as maximum temperature, holding period, vacuum and pressure in the autoclave are summarized in Table 1.

Table 1: Characteristic values of the performed autoclave cycles

Autoclave cycle	Max. temperature	Holding period	Pressure	Vacuum
1	130 °C	90 min	0,6 MPa	0,098 MPa
2	160 °C	60 min	0,3 MPa	0,098 MPa
3	168 °C	60 min	0,6 MPa	-

Before the measured deformations will be presented and discussed in each case, the following section describes the optical digitization of the specimen and the approach for the subsequent analysis of the dimensional stability and accuracy of the specimen.

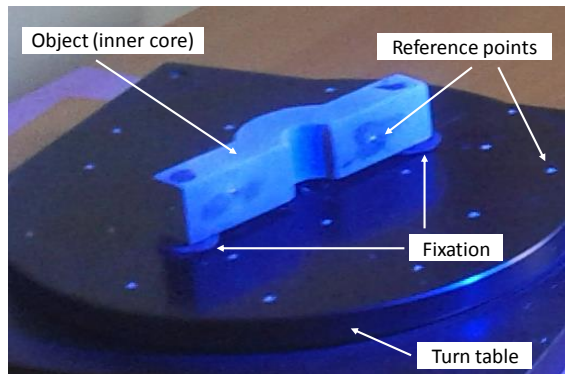


Figure 4a: Setup of digitization

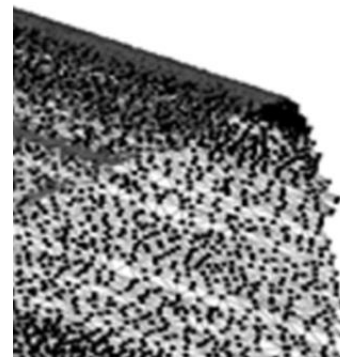


Figure 4b: Detail from the point cloud of a digitized mould core

The optical digitization is thereby a key technology for a successful and fast analysis of the dimensional stability and accuracy of the mold cores after the autoclave cycle. Thereby the digitization of the mold cores can be split up into three steps. The preparation of a mold core for the optical digitization is the first of them. As described in section 2.4, reference points have to be attached on the surface of the object and a treatment with a contrast medium has to take place in addition. After this, all reference points have to be cleaned from the contrast medium by using common cotton buds, so that the sensor can detect them.

The second step of the digitization is the generation of the point cloud by using a stripe light projection principle. Figure 4a shows a prepared mold core during digitization. For the presented research work a GOM ATOS COMPACT SCAN 5M sensor was used which has encoded the geometry by using triangulation. Figure 4b shows a cut-out from the point cloud of a digitized mold core.

The third step of the digitization is the processing of the generated point cloud and their transformation into a polygon mesh by using specific software. In the described work the 3D-data processing software "ATOS" as well as "GOM Inspect" were used to edit and post-process the generated point cloud. After these data transformation visual 3D images of the mold cores with accuracy values up to 0,02 mm were available.

For the following analysis of the dimensional stability and accuracy of the mold cores the comparison between the measured data and the nominal dimensions from CAD data were carried out. Using also the software "GOM Inspect", the deviations between the measured data and the nominal dimensions from CAD data could be derived from a full-field color deviation plot. Due to the color deviation plot, the analysis of the dimensional stability and accuracy e.g. warpage and shrinkage of the mold cores, were considerably faster and much more efficient compared to conventional measuring methods.

The results of the analyses of PA- and PA-Al-specimen after the autoclave cycle at 130° C, 0.6 MPa pressure and 0.098 MPa vacuum are shown in Figure 5 and Figure 6. In the filled area the deviation approaches zero or a maximum of 0.05 mm. Thus this area shows almost no change in shape and is sufficiently dimensionally stable. But in the hollow area a significant shape deviation can be seen. The open areas are incident due to heat and pressure. The incidence begins at the transition to the hollow profile and is more pronounced at the end of the specimen, at which the opening can be seen. The maximum deformation of the PA-specimen to the opening is about  $\pm 0.33$  mm and for the PA-Al-specimen at about  $\pm 0.20$  mm.

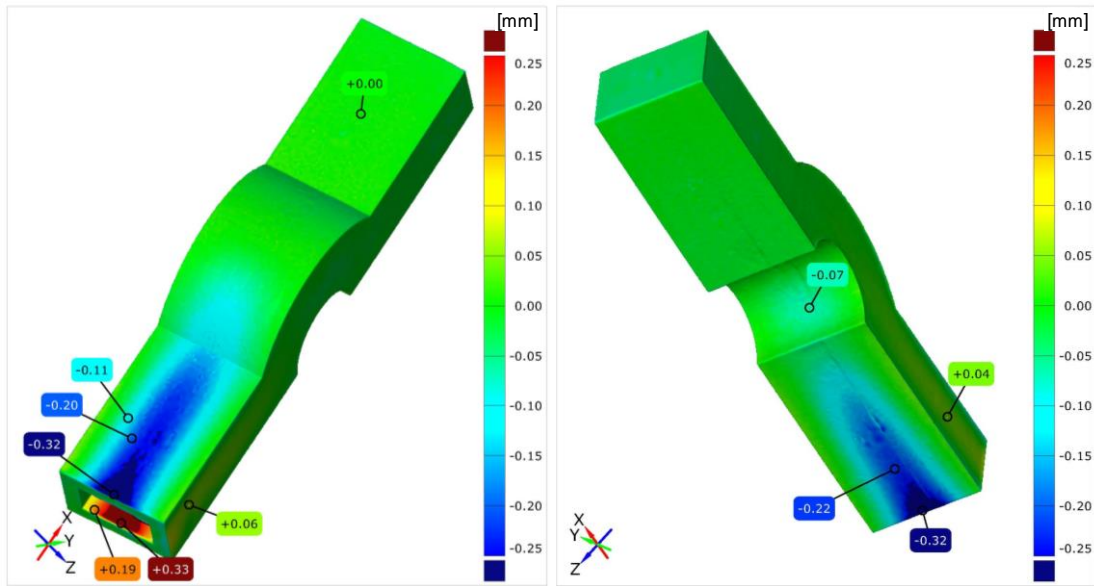


Figure 5: Deviations of PA specimen after autoclave cycle 1

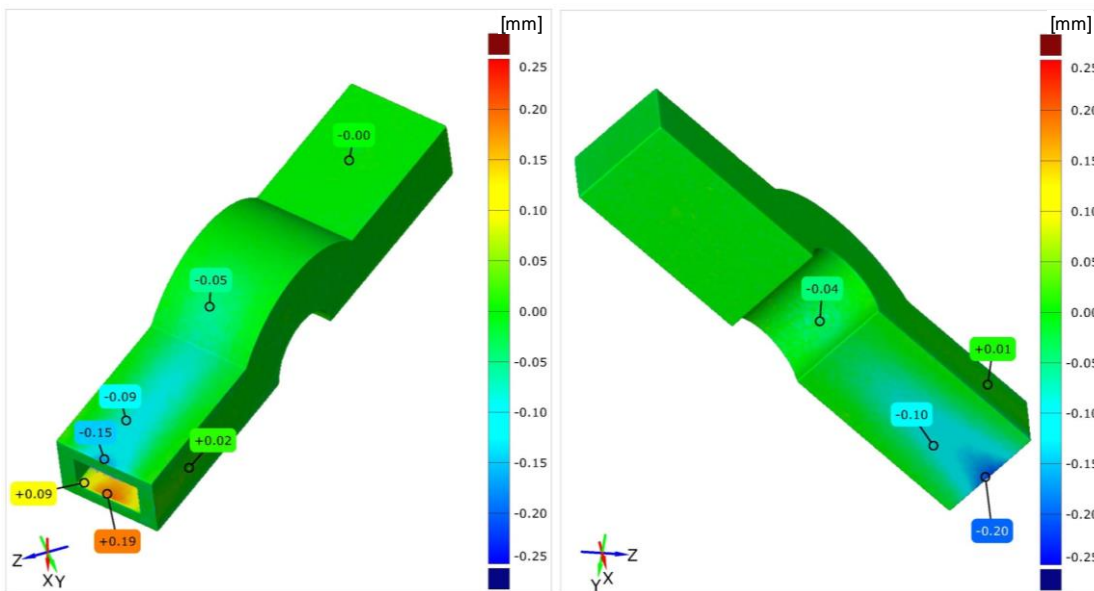


Figure 6: Deviations of PA-Al specimen after autoclave cycle 1

In Table 2 the shape deviations are compared according to the different performed autoclave cycles. The largest deviations were measured after the autoclave cycle 1 (130 °C, 0.6 MPa and vacuum). Here the autoclave temperature is lower than in the other cycles but the pressure difference is at the highest because an pressure of 0.6 MPa and a vacuum of 0.098 MPa are acting on the specimen. The holding period is in comparison the longest. The smallest deviation is observed in cycle 2 with the lowest pressure difference. Thus an increase in pressure has a greater influence on the deviations, than a temperature increase below the melting temperature.

Table 2: Different autoclave cycles and maximum deviations of the PA specimen

Autoclave cycle	Max. temperature	Holding period	Pressure	Vacuum	Max. deviations PA	Max. deviations PA-AI
1	130 °C	90 min	0,6 MPa	0,098 MPa	± 0,33 mm	± 0,20 mm
2	160 °C	60 min	0,3 MPa	0,098 MPa	± 0,07 mm	± 0,02 mm
3	168 °C	60 min	0,6 MPa	-	± 0,18 mm	± 0,11 mm

The mold cores manufactured from furan resin-bonded sands were also tested in autoclave processes under conditions of 130 ° C and 0.6 MPa as well as 160 ° C and 0.3 MPa.

After both autoclave cycles the not infiltrated mold cores were deformed and broke apart in the hollow area (see Fig. 7).

The infiltrated mold core also broke apart in the hollow area under conditions of 130° C and 0.6 MPa, but shows no optical changes under conditions of 160° C and 0.3 MPa. Regarding this specimens the analysis of the dimensional stability and accuracy indicated deviations up to 0.5 mm. Here, the filled area is with a deviation of up to 0.12 mm less deformed than the hollow area (see Fig. 8).



Figure 7: Broken specimen from furan resin-bonded sand (not infiltrated)

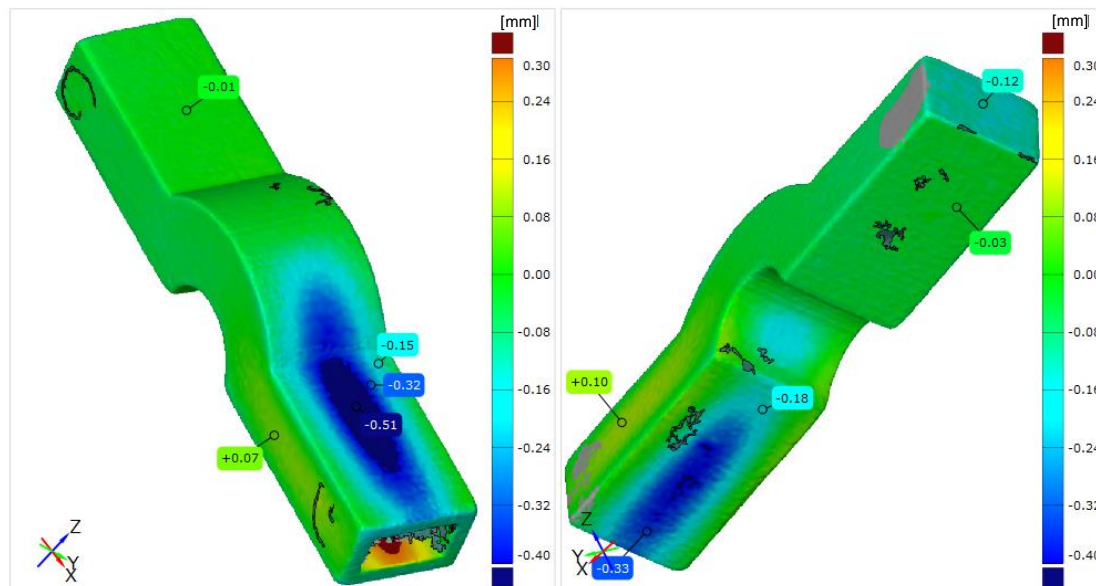


Figure 8: Deviations of the specimen from furan resin-bonded sand (infiltrated) after autoclave cycle 2

### 3.6. Results and discussion

The deviations of aluminum-filled polyamide were always less than that of polyamide. This is linked to the higher stiffness by the addition of a filler. In this way, the mechanical properties such as flexural strength and flexural modulus of PA-Al are greater than that of PA.

The influence of the vacuum on the type of deformation is obvious. Due to the fact that the hollow section was masked with tape and air was trapped under atmospheric pressure in the cavity, the vacuum and pressure affected the core surface unidirectional. Because of this the filled section of the core always had a better dimensional stability than the hollow section. Therefore the dimensional stability not only depends on the material but also on geometry. Closing of open surfaces or increasing the material thickness can be constructive measures to improve the mechanical properties of the mold core.

The values of heat deflection can be used as a rough guide for the selection of mold core materials. Temperature, pressure and holding period of the autoclave cycle as well as the geometry of the mold core have a significant impact on the deviations of the mold core. If the material is sufficiently stable to the conditions of the autoclave depends on the type of application and its specified tolerances. Furthermore in most cases an autoclave cycle with a lower temperature and longer holding periods can be chosen, in order to achieve the same curing conditions.

Overall, polyamides are suitable as material for mold cores with respect to their dimensional stability. However, they had to be heated convective for the removability by melting to higher temperatures than expected. The material only softened at an oven temperature of above 190 ° C, so that it could be partially removed from the CFRP component. In the convective heating the component and the mold core would have to be held continuously on this high temperature at which the polyamide is in a thermoplastic state to remove the core. In order to protect the component a heating is reasonable by which the mold core is heated more than the component. The dielectric and electric heating would make this possible. But the observed materials have no electric conductivity and have a high dielectric strength so that they cannot be electrically heated. As a consequence the removing of the polyamide mold cores is possible only to a limited extent.

Concerning the mold cores made from furan resin sands the experiments confirmed the higher strength of the epoxy resin infiltrated cores compared to the not infiltrated cores. The not infiltrated cores hadn't sufficient strength in the hollow area and were decomposed even at low pressure. The infiltrated cores were visibly deformed in the hollow area under pressure of 0.6 MPa, but had a very good pressure resistance in the solid area. With reference to the data sheet the flexural strength of the cores should have been sufficient for the autoclave pressure. However the strength also depends on the stress. Hence the data of the flexural strength give only a comparative value of the materials with each other and must be checked once again for each stress.

In summary the investigated sand cores were not suitable as removable core material for the pre-preg autoclave process, neither were the polyamide cores. Here the problem was that either the core had no sufficient pressure resistance to the autoclave pressure or couldn't be removed. An additional heating to achieve the decomposition temperature of the binder was not possible because the CFRP component matrix softens or decomposes by exceeding the glass transition temperature of epoxy resin.

## 4. Conclusion and outlook

In pre-preg autoclave process CFRP components with the best possible quality for innovative applications are manufactured. Here the pre-preg, a pre-impregnated fiber fabric, is cured at high temperatures and pressure. For manufacturing hollow components a removable mold core has to be used. For a mold core mandatory material properties are dimensional stability under the conditions in the autoclave and the removability without damaging the component.

By additive manufacturing complex components based on the CAD data can be manufactured quickly and without tools. Theoretically two material systems of the relevant additive materials had sufficient dimensional stability and promised to be removable without damaging the component. These were on the one hand laser-sintered polyamides and one the other hand 3D-printed resin-bonded sands. Polyamide 12 with and without aluminum filler and furan resin-bonded quartz sand with and without infiltration were examined in detail.

To determine the deviations of the mold cores after the autoclave process optical metrology was used. The case study has shown that the optical metrology is well suited to analyze the dimensional stability and accuracy of the mold cores. (The software makes the results available clearly in graphic form but it can also be presented in tabular form.)

The examination of the dimensional stability has revealed that the mold cores from polyamide in constructive unstable sections had only low deviations which were in the area of the manufacturing deviations. The furan resin sand models had great deformations in the unstable sections or were broken apart. All mold cores had a sufficient dimensional stability in the filled material sections.

The removability of all examined mold cores was not adequate. To melt out the polyamides the cores had to be heated above 190°C, a temperature only few pre-pregs will survive unscathed. In addition, this high temperature would have to be kept throughout the complete process of removal so that the polyamide not immediately solidifies again. The dielectric and electrical properties of the polyamide models were also not good enough to enable a carefully removal by heating the mold core faster than the CFRP component.

The sand cores were difficult to remove because either the core had to be broken out or the binder had to be decomposed. To decompose the binder, according to thermo-gravimetric analysis, a temperature of over 300° C would be necessary. Additive manufactured sand cores are, due to their poor removability, not suitable as mold cores for the pre-preg autoclave process.

It can be concluded that there is further need for research to use additive manufacturing for the direct manufacturing of removable mold cores. Further investigations should also consider the adhesive strength of the pre-pregs to the core material and the finishing of the cores' surfaces.

Other potential materials would be low-melting metal alloys. For example, tin alloys have a melting point in the range of 150° C to 180° C, but are not yet processed by additive manufacturing. They would be easier to melt out than polyamides since metals have a lower viscosity at the melting point. It might be possible to manufacture mold cores from tin alloys by selective laser sintering. However, other material classes that weren't in the focus of this case study, should be investigated.

Finally this case study shows the potential of additive manufacturing to lead to an increase in efficiency in the CFRP production. To realize the potentials further scientific research and technological development based on this case study are needed.

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