ASSESSMENT OF HYBRID HEATING FOR CURING OF CFRP STRUCTURES

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Abstract

In manufacturing of carbon fiber reinforced polymers (CFRP) a wide variety of technologies are used nowadays. Besides the significant potential to develop novel technologies that enhance cost and lead-time reduction, there is a need to develop a comprehensive assessment framework and models to assess these new technologies. In practice, technologies have been directly compared with each other blanking out their consequences on the rest of the manufacturing processes. To enable assessing new technologies of CFRP manufacturing processes a detailed activity-based modeling has been introduced allowing tracing each technology within the production chain.

Therefore, a systematic decision support framework has been developed by the German Aerospace Center (DLR) to establish the activity-based eco-efficiency assessment model (EEAM). Thus, decisions can be taken at an early development stage, if a certain technology proves being beneficial.

In the context of the H2020 funded project EFFICOMP DLR implemented this framework and the related EEAM to compare hybrid heating technologies in curing CFRP parts. These hybrid heating concepts consist of two combined systems, a water heated mold and an autoclave. The standard autoclave process is used as a reference process. It is compared to the stand-alone water-tempering process as well as a combined water-tempering inside the autoclave, employing the convectional heating capability of the autoclave. These three curing concepts are applied and recorded at DLR facilities.

The obtained data is used to parametrize the EEAM. The technologies are interchanged within a complete part manufacturing process chain in the assessment model, from fiber-cutting, to preforming, preparation, infusion, demolding and cleaning. Then the associated unit processes are defined to be considered for the comparison of the three technologies.

The results facilitate sensitivity analyses showing benefits and drawbacks of all used techniques and the further developments potential.

Keywords: cost assessment, composites, hybrid heating, composite manufacturing, autoclave, single line infusion, spring-in

1. Introduction

In recent years the use of parts made out of carbon fiber reinforced polymers (CFRP) has both increased in volume and broadened in fields of application. Along with this, traditional manufacturing techniques like hand-lamination and autoclave processing have been partly replaced or developed to increase productivity and quality of the components built. Especially, the need for higher volumes demands for more efficient processes, decreasing scrap rates and minimizing the ressources used to produce a product. These ressources can be materials, time, labor or energy, where some of these may be interdependent. Reducing the overall process time has been one major goal over the last years, since output numbers can be boosted, labor time per part is reduced and cost of energy is cut due to lower thermal losses.

This paper will take a look at a novel heating technique for curing of CFRP components, employing a water heated mold which is placed inside an autoclave. The idea is to combine the benefits out of two technologies. On one hand, the water heated mold is able to introduce energy much faster into the component, thus speeding up the thermal process massively. On the other hand, the autoclave is utilized as a pressure vessel to assure a high part quality, both for prepreg parts and infusion parts.

Furthermore, the structure characteristics and the part quality play a decisive role in evaluating novel technologies for CFRP manufacturing. Therefore, the structure geometry is examined to assure addressing the aimed quality. This includes the thickness determination and evaluation of structural spring-in phenomena for the different heating technologies.

To demonstrate the ability of this new heating technique a comprehensive assessment framework and models to assess this new technology are implemented. The eco-efficiency assessment model (EEAM) is a framework where complete production process chains can be modeled, including any unit processes of part manufacturing, like fiber cutting, preparing, tempering etc. as well as assembly processes for larger subassemblies. This allows to determine the benefits of a single technology within the process chain, while technologies have normally been compared directly, without taking into account their impact on the whole production process in general and the associated unit processes in specific.

2. Material and Methods

2.1. *Curing Methods Used*

The manufacturing of high quality composite parts takes different parameters into acount. In addition to a symmetrical layer structure or rather a directional fiber deposit and a sealed vacuum bagging, the necessary curing temperature as well as the curing pressure set thereby also play a decisive role. In order to ensure the latter, an autoclave is used for producing fiber composite components. An autoclave (gr./lat. self-sealing) is a gas-tight sealable pressure vessel which is used for the thermal treatment of substances in the overpressure range (Fig. 1). They are commonly used for the curing of building materials, vulcanizing tires and straps, as well as for the manufacturing of fiber composite materials. For the production of CFRP in autoclaves pressures of up to 10 bar and temperatures of up to 400°C are usually generated [Wießbach 2013].

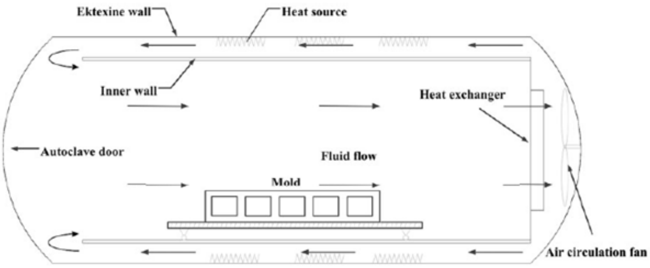

Figure 1: Autoclave environment [Wang et al., 2017]

The high pressure inside the autoclave is used to compact the individual laminate layers. The component is usually evacuated simultaneously in order to completely remove excess air from the fiber composite. Because of their high acquisition costs, these autoclaves are mainly used in aviation and space travel as well as professional motorsports such as Formula One. In the production of commercial aircraft, particularly large autoclaves are used, in which entire fuselage segments can be accommodated.

To ensure highly efficient manufacturing cycles for composite parts autoclave technology isn’t the exclusive choice. In case of large, solid molds, the heating and cooling cycles are very long due to the thermal inertia of the mold and finally the slowly advancing thermal convection in the autoclave. Efficient heating and cooling rates are not always possible. Therefore additional equipment (hybrid tempering) is necessary to speed up the processes and moreover out-of-autoclave fiber composite manufacturing is feasible too if no pressurisation is required.

The water tempering device (WTD) is a water-operated temperature control system which is predominantly used for infusion molding applications but also for other processes. They are ideal for temperature control during the production of high-quality articles. Furthermore it is used for operations far above the atmospheric boiling point of water with temperatures of up to 225°C. With their wide temperature and dimensional range which covers medium to very large capacities, they provide the basis for numerous special projects. Compared to heat transfer oil, the use of water as a circulating medium provides several technical and economic benefits – particularly when operating with higher temperatures. In addition to the benefits mentioned above, superior pump technology enhances the economic advantages of the WTD. The system used is mainly equipped with high-quality, multi-stage centrifugal pumps with a high level of efficiency, which can directly affect the system’s energy consumption (Fig. 2).

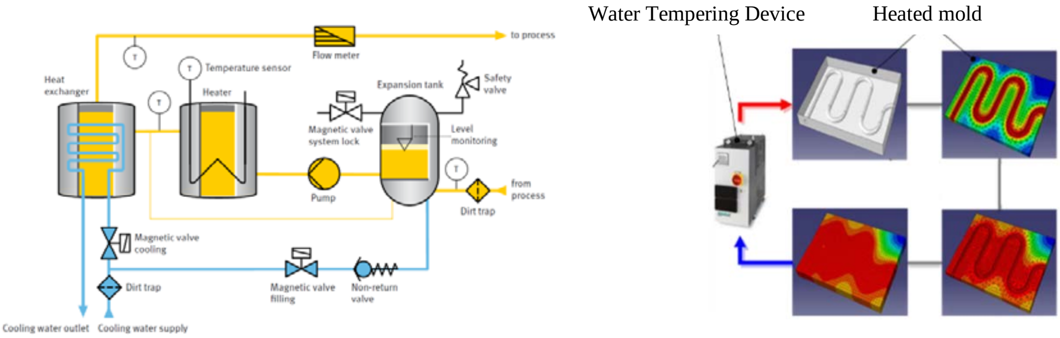

Figure 2: Functionality of water tempering device [Single/ DLR]

As already mentioned, the combination of the two systems offers further technical advantages. Firstly, the autoclave is able to generate the required pressure to compact the laminate which ensures a good laminate quality. Secondly the WTD allows the setting of different heating and cooling ramps and initiates the required heat input directly into the corresponding mold (Fig. 3).

Figure 3: Combined WTD and autoclave processing [DLR]

Since not every mold is usable for the combined process, a suitable mold design is necessary. In this case an aircraft leading edge segment mold made of Invar 36 is used. The special features of this mold are on one hand the used material and on the other hand the design of the drilled holes for the water flow through the mold (Fig. 4).

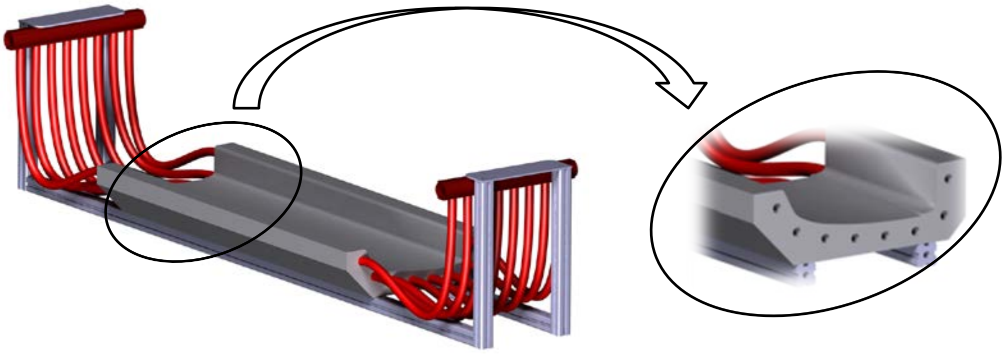

Figure 4: Leading edge invar mold with integrated water tempering [DLR]

An advantage of Invar 36 is the very low coefficient of thermal expansion which is similar to the one of CFRP. Thus it is guaranteed that the finished composite part at the end of the production process corresponds to the required design geometry. From the production-technological point of view the manufacturing of the through-holes is indeed complex and expensive. However, they are of crucial importance for the production process since they significantly influence the duration and efficiency of the production cycles.

In order to examine and compare the effects of different heating and cooling cycles several test specimens are manufactured on the leading edge mold. The prefabricated carbon fiber material (IMS65 E23 24K 830tex) is sewn to bidirectional and tridirectional dry fabrics. All test specimens have a symmetrical structure, but differ in their laminate thickness. For each production cycle 4 samples with a thickness of approximately 3, 5, 7 and 11mm are produced simultaneously.

In order to manufacture a fiber composite component a synthetic resin (usually epoxy resin) has to be introduced into the the fabric. In this case the resin Epicote EPS600, an one-component resin system which has almost the same properties as RTM6, is applied. The resin system is generally stored at -18°C, and must be preheated to 80°C before the manufacturing process starts.

In order to impregnate the fiber material with the resin an infusion method is used that was developed by DLR – the single line injection (SLI). In case of an resin injection or resin infusion the stacking is basically first evacuated and then the epoxy resin is sucked into the dry fiber material by means of the reduced pressure. This results in precompacting and prevents the preform of imperfections in the component by air inclusions. The special feature of the SLI procedure is that the evacuation and the subsequent infusion are performed by the same ("single") line (Fig. 5). After the fiber preform is evacuated, the switching between the vacuum pump and the resin reservoir is accomplished through a valve, since it is important to ensure that no epoxy resin gets into the vacuum pump. Finally the infused preform is cured at the appropriate pressure and temperature.

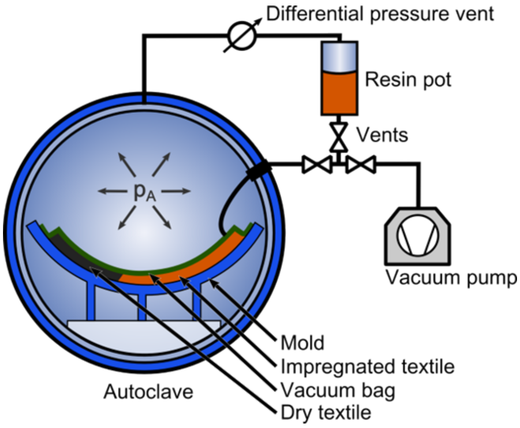

Figure 5: Single-Line-Injection (SLI) [DLR]

2.2. *Eco-Efficiency Assessment Model (EEAM)*

Based on the frameworks of life cycle assessment (LCA) as well as on process modeling, an integrated framework for modeling in LCA has been established in a previous work [Al-Lami & Hilmer 2015]. This systematic decision support framework has been developed by the DLR to establish the activity-based EEAM. Thus, decisions can be taken at an early development stage, if a certain technology proves being beneficial. Practically, a manufacturing process can be split into a set of unit processes (ISO 2006). For the manufacturing of CFRP these unit processes are illustrated in (Fig. 6).

Figure 6: Unit processes in SLI [Al-Lami & Hilmer 2015]

As it is shown in (Fig.6), SLI consists of seven unit processes. Within cutting the fabric plies are cut into the specified sizes for preforming. The preforming unit process includes the activities of laying up the fiber plies and preforming them within the specified geometries, which can include pressure and thermal applications. In preparing the requirements of the infusion as well as the tempering unit processes are fulfilled by setting up the mold, preparing the proper bagging, and connecting the different devices. Then the fiber is infiltrated by the matrix material in the infusion unit process. Furthermore, tempering is the unit process, where the composition of fiber and resin materials is cured to reach the aimed geometrical shape and mechanical properties. Finally, the CFRP structure is released from the mold in the demolding unit process [Al-Lami & Hilmer 2015]. However, within this paper only three unit processes are associated with the compared tempering systems as they are unshaded in (Fig. 6).

During manufacturing, data from each unit process are collected within a separated spreadsheet. These spreadsheets have generic table structure to facilitate the data collection. EEAM is developed as a user friendly model, while the assessment tasks are limited to distributing the Excel spreadsheet, collecting the data and documenting them. Finally, the user needs to activate EEAM, whereas no extra process modeling is required.

For inputs from all unit processes, this spreadsheet is structured generically as table. In practice, such Excel spreadsheets used to facilitate the data collection task for the field labors. Based on previous studies, about 330 input parameters within clearly distinguished categories are listed in this separate sheet today. These sheets are applicable for various manufacturing techniques of different CFRP structures and can be enhanced to facilitate any other.

After activating the assessment, EEAM collects these data under defined categories such as materials, labor, equipment, ancillaries and energy. On the other hand, CFRP associated economic characterization factors such as material prices and labor wage are gathered from data sources in advance. These characterization factors are uploaded within EEAM database and synchronized in each assessment to have up-to-date results.

EEAM connects a python-based tool with the Excel spreadsheets. This tool connects the sheets, collects the inputs, synchronizes them with EEAM database, and calculates the outputs. EEAM then presents the cost results statistically and visually.

3. Data Collection and Manufacturing Trials

In a first step, 3 tempering processes are to be examined and compared with each other. These include the standard autoclave operation, the heating with the WTD and finally the combined tempering process with autoclave and WTD at the same time. In order to keep the process as simple and reproducible as possible, the first tests are carried out on a blank mold. It is equipped with several temperature sensors which are located on the inside (no. 1 – 19) and on the outside (no. 20 – 24) of the mold (Fig. 7).

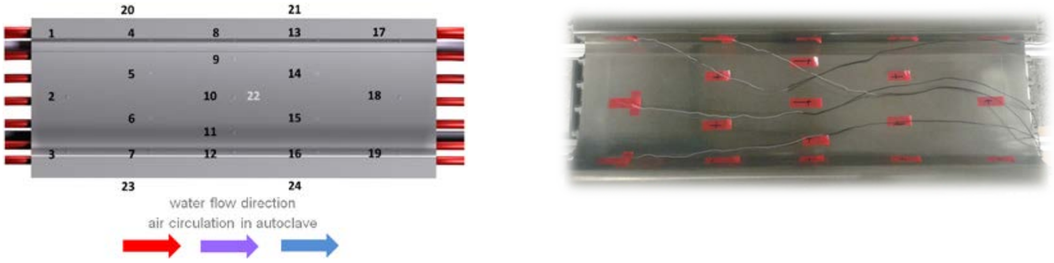

Figure 7: Position of temperature sensors on the mold [DLR]

All tests are performed with the standard temperature profile for the infusion and curing of RTM6. This means, the mold is first heated up to 120°C (infusion temperature of RTM6 and EPS600). When all sensors reach 120°C +/- 5K the heating process continues immediately to 180°C. After all sensors reach 180°C +/- 5K the mold will be cooled down to room temperature as quickly as possible. Figure 8 shows the data logs of the 3 performed tests. Since the temperature profile at all locations of the mold is approximately identical for each cycle (+/- 10K) and the diagram should remain clear, the evaluation was limited to only one temperature sensor (T10 - mold center).

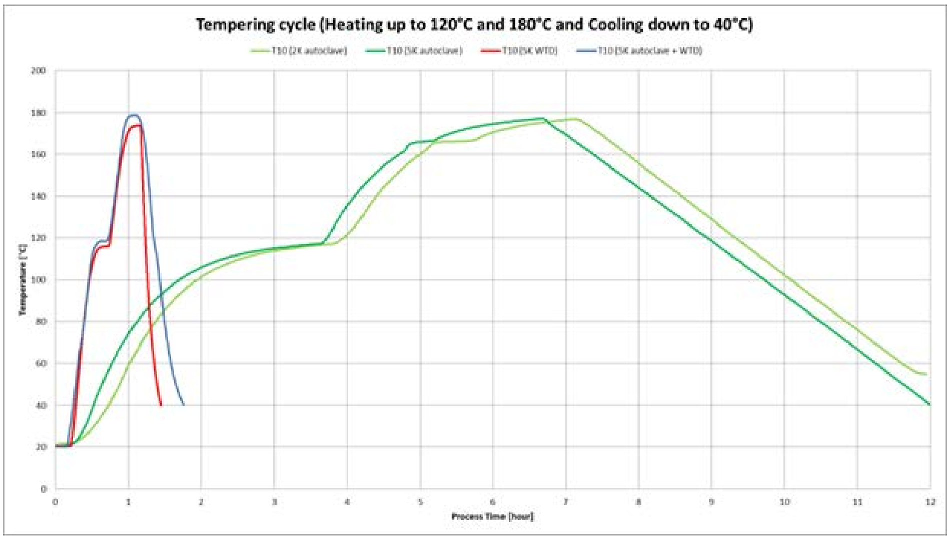

Figure 8: Tempering cycle without dwell times [DLR]

The autoclave tempering cycles (green lines) differ significantly from the ones with the WTD. The whole processes take more than 12 hours. Also a change of the tempering rate from 2K to 5K does not result in a process improvement since the heating and cooling power of the autoclave is not sufficient. It should be noticed though, that a lab-autoclave was used, which has very high heating and cooling power compared to an industrial standard autoclave.

In contrast, the two temperature curves with WTD support show significant time differences. The WTD tempering processes are more than 6 times shorter than the comparable autoclave ones. However, small differences occurs in the WTD processes. This results from the different circumstances during the WTD operation. The heat emission to the environment (room temperature) is very high when the WTD is operated individually out-of-autoclave. The predetermined temperature marks are not fully achieved. But the heating program can still continue due to the given specified tolerances (+/- 5K). During the hybirde heating of WTD and autoclave the ambient air temperature is the same as the mold temperature. Thus the exact temperature values are reached during the tempering process. The heat emission to the hot autoclave environment is therefore not as high as the heat emission to the ambient air out-of-autoclave. That is why the mold needs a little bit more time to cool down.

After the first tests have been carried out and initial findings on the behavior of the individual heating variants have been obtained, the second step follows. This involves the specimen manufacturing under various heating conditions. It will be investigated whether any effects with regard to different heating and cooling rates have an effect on the final component properties. Since the best results with respect to homogeneous mold tempering were achieved with the hybrid heating technology, the following specimen manufacturing will be performed like this. In this case heating and cooling rates of 2K/min, 5K/min and 10K/min are out. For each process 4 test specimens are manufactured with different laminate thicknesses of about 3, 5, 7 and 11mm (Fig. 9). On the one hand the infiltrability of different laminate thicknesses is to be represented. On the other hand it is to be investigated whether the different heating rates have any effect on the laminate or the part properties.

Figure 9: Preform positions in the mold (11mm, 7mm, 5mm, 3mm) [DLR]

The production of the composite parts is carried out with the same temperature cycle as the previous test runs. Only the dwell times for the resin infusion at 120°C and the resin curing time of 2h at 180°C are added in the manufacturing cycle. That is why the cycles will be extended, compared to the preliminary tests. Furthermore, the entire cycle is subjected to 4bar autoclave pressure (p_{absolute} = 5bar). This leads to a better compacting of the fiber material and, at the same time, to a higher quality of the manufactured fiber composite parts. During the tempering cycle 11 thermocouples log the relevant temperatures. 4 are positioned on the vacuum bag directly on the top of the preforms. The other ones are located on the inner and outer mold surface. Figure 10 shows the relevant temperature data logs. For each cycle two temperature curves are displayed in the diagram (2K/min – red; 5K/min – green; 10K/min – blue). The thick lines represent the average of the mold temperatures and the narrow ones the average of the temperatures measured on the composite parts. The curves with a tempering rate of 5K/min and 10K/min proceed in the same way. There is only a benefit of 10 minutes over the entire process. An evaluation of the graphs shows that although a target heating rate of 10K/min was specified, only maximal 7K/min has been reached. This is due to the high thermal inertia and the large volume of the mold. Unfortunately, the performance of the WTD used, as well as the performance of the autoclave, was not sufficient to meet these requirements. In order to achieve higher tempering rates, the systems would have to be improved or expanded. Significant differences occur between these two data logs and the one of the 2K/min data log. This cycle produces a delay of about 60 minutes. Furthermore, in all of the 3 data logs the temperatures on the preforms lead to an increased overshoot when they reach the 180°C mark. This is mainly due to the 11mm thick preform, which causes a short exothermic reaction due to the large amount of resin in the component. However, this chemical reaction disappears after a short time and is therefore not critical. What would be interesting here is what would happen with an even thicker preform with an even larger resin volume.

In summary, it can be stated that the tempering with 5K/min or 7K/min takes about 100min (300min process time – 80min infusion time – 120min curing time = 100min tempering time) (Fig. 10). Compared with the data log recordings from figure 8, the generated data are thus identical. The 2K/min tempering cycle runs about 180 minutes and thus takes about twice as long compared to the other two.

For the cost assessment associated data are collected and documented within the Excel spreadsheets for the different unit processes. Furthermore, modern energy measurement systems are implemented to have precise determination of the energy consumption. Other resource data such as equipment, material and energy prices as well as labor wage are uploaded to the EEAM database.

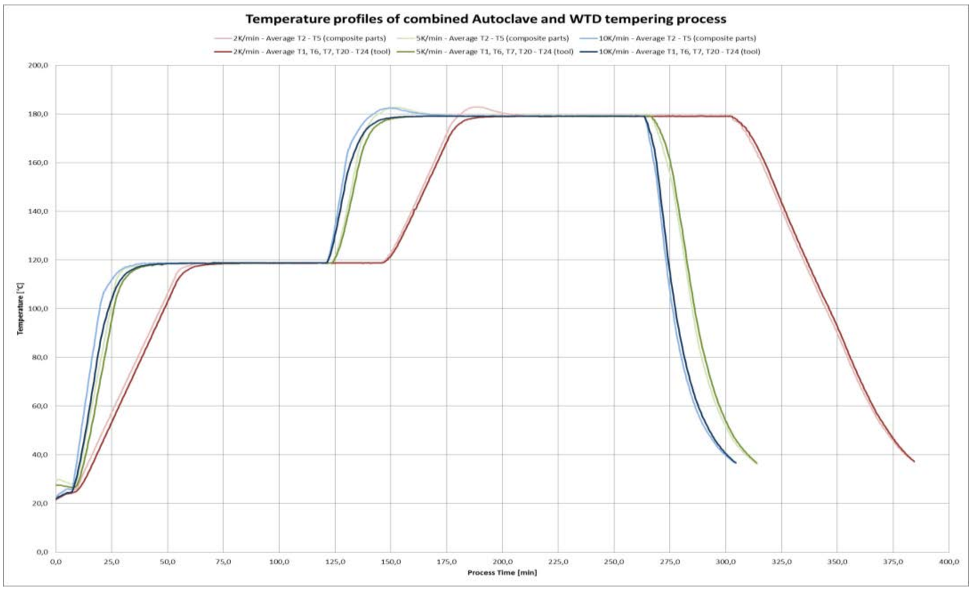

Figure 10: Temperature log during specimen manufacturing [DLR]

4. Results

4.1. *Technical Assessment*

In the following chapter, the manufactured parts are examined in more detail and possible effects are considered by the different production processes. For this purpose, the individual components are first measured manually with digital thickness measuring tongs. Secondly, a visual inspection is carried out and finally a 3D optical coordinate measurement is performed with the GOM ATOS system. Positioned on a rotary table, which is controlled by the GOM software, the individual parts can be digitally recorded from all sides. The GOM software subsequently combines all the individual images and generates a component file with all necessary geometry data and surfaces. These are combined and evaluated with the original design data.

By measuring with the measuring tongs at 10 measuring points per component only minor irregularities with regard to the part thickness can be determined. All components of a laminate thickness series show approximately the same thickness values (+/- 0,1mm) over the profile depth. There are slightly increased thickness values in the area of measuring point 2 and 7 (Fig. 11).

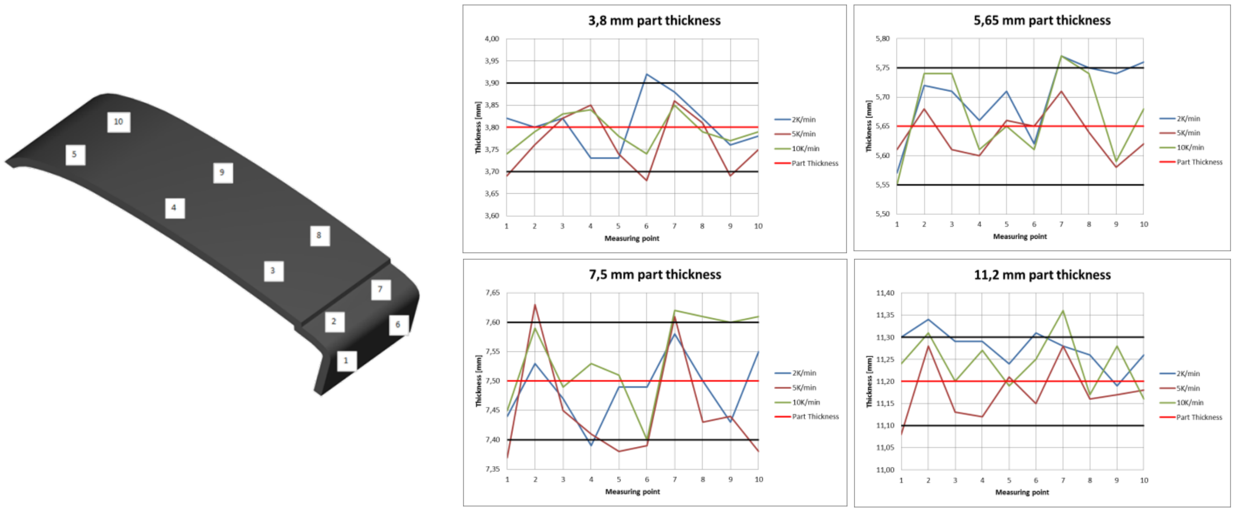

Figure 11: Thickness measurements locations on composite part and measurement results [DLR]

Figure 12: Fiber deflection in the radius range [DLR]

A visual inspection with regard to the laminate properties in the trimming areas shows no containment of porosities or any delaminations on the composite parts. Figure 12 illustrates the compressions of single layers occurring in the area of the radii transitions. The fiber layers were likely to be compressed during fixation of the vacuum foil and the evacuation of the components. This leads to a small bulging effect in the radi area and results in minor deviations of the laminat thickness. The bulging effect occurs mainly in thicker laminates with more layers than in thinner ones.

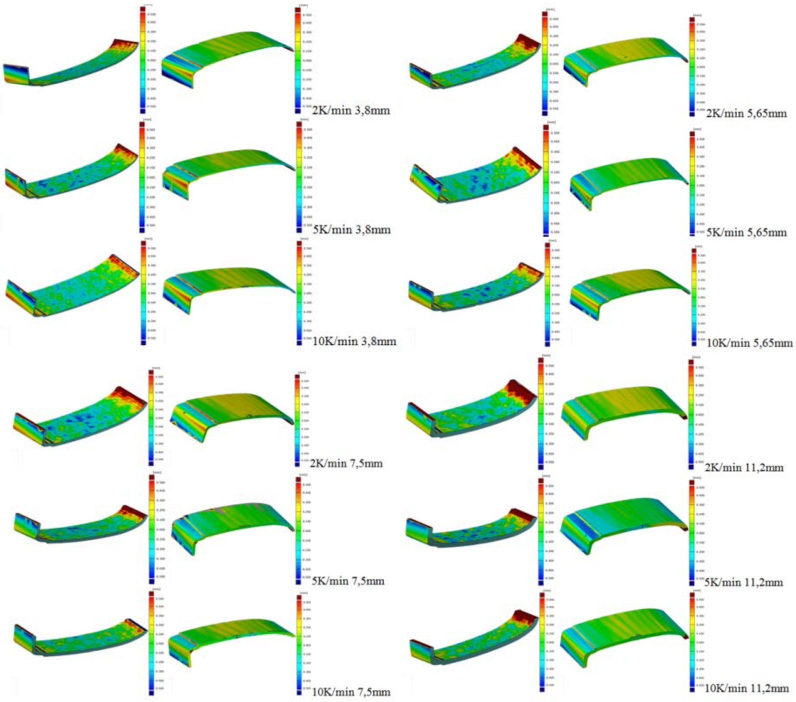

Figure 13: Geometrical deviations from the target geometry by optical scan [DLR]

Afterwards, the components are measured with the GOM ATOS in order to be able to determine the part thicknesses and deviations from the desired geometry. The previously measured thickness values can be confirmed by this optical measurement. Furthermore, the images will be compared with the already existing design data of the parts (target geometry). Figure 13 depicts the individual measurements with respect to the corresponding structural component geometries which are designed before with CATIA V5. In order to be able to compare the evaluation of the parts, the tolerance of the measurements was set to +/- 0,5 mm to the target geometry. The red color indicates that the surface of the designed part is smaller than the manufactured one. It is below the measured surface. Green means identical geometries respectively surfaces and the blue color implies that the surface of the designed part is bigger. The manufactured part surface is above the designed one. Therefore the greatest deviations occur in the region on the front edge at the radius of the components. This is to be explained by the fact that the parts produced here were cut a little smaller than the designed parts. This section can therefore be neglected. In the remaining area of the fiber composite structures the deviations from the target geometry are less than +/- 0,2mm. There are no significant differences due to the various heating cycles. The only abnormalities in the individual samples are the deviations in the extent of the spring-in effect of the 90°-flange. Due to the shrinkage of the resin the mold is manufactured with a 90,5° flange angle. Since various laminate constructions are used in this case, different flange angles are produced. On the one hand the spring-in effect decreases with an increase in the laminate thickness. This is because the individual layers are supported against each other [Kappel 2016]. The shrinkage of the resin during the cooling cycle has a minor effect on thicker laminates than on thinner ones. On the other hand the spring-in effect in the 5K/min tempering cycle is lower than in the other two cycles. In order to be able to make statements to this fact further test runs have to be completed (Fig. 14).

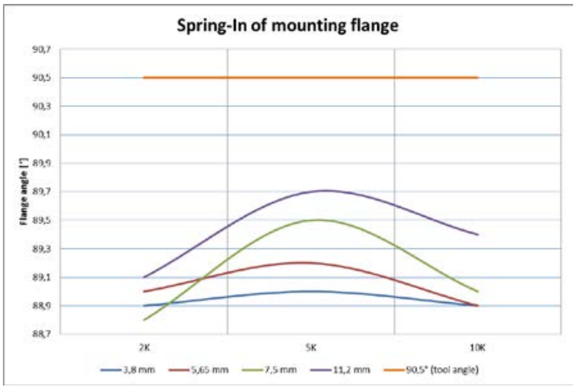

Figure 12: Spring-In effekt of manufactured composite parts [DLR]

4.2. *Cost Assessment*

For the selected curing methods used in manufacturing CFRP components, a cost assessment for the associated unit processes has been performed. Considering the preparing, infusion and tempering as they are illustrated previously, the cost is allocated under two categories, including the recurring and non-recurring costs. On the one hand, recurring costs represent all costs that occur repetitively within the manufacturing, such as labor cost, material cost, and energy cost. On the other hand, nonrecurring costs refers to costs that occur once such as equipment purchasing cost [Curran et al. 2004]. A comparison between the three heating technologies of the curing methods is therefore illustrated in (Tab. 1). However, since the CFRP parts produced with these three methods are identical, the material costs of fiber and matrix are excluded.

Table I. Heating technologies [DLR]

Parameter	Standard autoclave	Water tempering	Hybrid heating
Recurrent cost	165 €	113,44 €	172,81 €
Non-recurrent cost	391,12 €	42,29 €	240,07 €
Total cost	**556,12 €**	**155,73 €**	**412,88 €**

The results of this comparison show that the standard autoclave process has the highest total and non-recurring costs per part. The reason behind that is the high autoclave purchasing cost which is reflected on the costs of its operation time. The water tempering technology offers the lowest total, recurring and non-recurring costs. The reason behind the reduced non-recurring cost is the low purchasing cost of this heating system. Both energy consumption and preparing work time are less than what they are in autoclave and hybrid heating. Therefore, the recurring cost is the lowest. The hybrid heating system comes second in all cost categories. On one hand, the non-recurring cost of this system is lower compared to the autoclave, because the operating time of equipment for each part is reduced due to the reduced cycle time. On the other hand the preparing work is slightly more than of both other systems due to the combination of the two systems. Furthermore, the energy consumption of this hybrid heating is higher than the water tempering due to the autoclave implementation but less than standard autoclave due to the reduced cycle time.

5. Discussion

The technical assessment of the manufactured leading edge segments proves that the hybrid heating method utilizing the WTD and the autoclave does not have any negative effect on the part quality employing heating rates up to 7K/min. Both laminate quality, regarding porosity, as well as geometrical tolerances are similar to a conventional autoclave manufactured composite part.

The major benefit of speeding up the process was proven mainly by using the 5K/min heating ramp, because the equipment was not powerful enough to perform the 10K/min heating ramp, and the benefits in process time reduction were similar. Anyway, the very precise temperature control possibilities and the time saving potential of the hybrid heating were shown with the tests performed in this paper. The overshooting of the temperature reaching 180°C can be explained with the exothermal reaction of the resin system. A bigger and thicker component might produce a higher exothermal reaction, but with proper setting of the leading thermocouple, the WTD is able to control this, even actively cooling the certain area if needed. The investigation of heating rates above 10K/min might give an idea of even higher time-saving potential. And looking into thicker samples should be a next step towards structural CFRP components.

The cost assessment shows the cost reduction potential of the hybrid heating process of approximately 20% with regards to the three process steps preparing, infusion and tempering. This view should be broadened by integrating the other 4 unit processes into the calculation to give a more complete picture. Also, adding fiber and resin cost to the calculation will probably attenuate the advantage of the hybrid heating technology. Anyway, the cost is only one assessment factor. For a manufacturing company the time benefit of the much faster curing cycle might be the way to widen the bottleneck of the autoclave curing for higher production rates. The simple integration of a WTD into existing manufacturing infrastructures and its low investment cost may pay off quickly, when production time is the driver.

Acknowledgments

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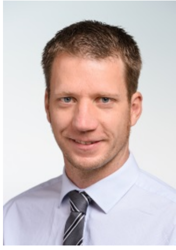

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Ali Al-Lami has done research on process assessment of composite production. His research work focuses on the eco-efficiency assessment as well as the implementation of Industry 4.0 technologies in this field. As a part of this work, he is working on the development of what is called the Smart-Work-Station (SWS) as the first real-time data collection system for eco-efficiency assessment in the composite production.
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