AUTOMATED PRODUCTION OF COMPLEX CFRP-COMPONENTS

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ABSTRACT

The present manuscript gives an overview of the approach of a project, launched at the Composite Technology Center GmbH in Stade, to develop concepts for a fully automated manufacturing process for complex CFRP-profiles. The targets of the project were, besides the development of the required resources (machines), the evaluation of economic feasibility, by comparison with today's state-of-the-art (fully manual process).

1. INTRODUCTION

The substitution of metallic primary structures with CFRP-parts gets more and more important in aerospace, but also in automotive applications. Due to the possibility of highly integrated structure design, suitable for distribution of forces, a massive weight saving is possible, which leads to a more economical operation of aircrafts and vehicles. In automotive, for example, a weight reduction of 8,5% through substitution of metallic with CFRP-structures would lead to a fuel-saving of 0,3l/100km. With regard to an average of 11500 kilometres travelled per year and per car and a production-rate of 17 Mio. cars per year in Europe, this would lead to a fuel-saving of 600 Mio. l per year only in Europe [1].

Especially in commercial aerospace there was an strong increase of structural CFRP-parts in the last decades. While CFRP-technology for structural parts entered commercial aerospace with the vertical tail plane made complete out of CFRP in the 1980s, the contingent of structural parts made out of CFRP reaches up to 30% today with the Airbus A400M [2]. The next step in CFRP-application for future aircraft-projects in commercial aerospace is to build a complete fuselage out of CFRP. This is indeed an enormous step for CFRP technology development concerning high volume production: Only with regard to fuselage frames, this would lead to rate of about 350 km of complex profiles per year!

As the today's state-of-the-art manufacturing for complex, curved CFRP-profiles with variation of shape over length is mainly manual, the development of an automated manufacturing process is absolute necessary to lower the recurring manufacturing costs essentially. A method to build complex, curved CFRP-profiles with a fully automated manufacturing process and its evaluation of feasibility for an high volume rate is the result of a project, which is described in the following manuscript.

2. ASSUMPTIONS CFRP-PROFILE

As the target CFRP-part for the project, a CFRP-profile with a complex Z-C-shape was chosen. The characteristics and complexities of the chosen example profile were defined as described in table 1. To fulfil the future requirements on production rate, a number of 135000 parts per year was defined.

The layup was chosen as typical for profiles which are used as a beam for bending loads: In the web-area +/-45°-layers, to fulfil the shear loads, and 0°-Layers, concentrated in the flanges, to fulfil the tension and compression loads. Thereby the 0°-direction is defined circumferential to the profile, along the flanges.

Characteristic	Value
Length	2500mm
Height (changing locally)	Variable, changing locally
Radius of profile curvature	Variable, changing locally
Local reinforcements	In web and inner flange
Joggles	In outer flange
Layup in outer flange and web	+/-45°
Layup in middle and inner flange	+/-45°, 0°

table 1: characteristics of CFRP-profile

3. CHOICE OF PROCESS

To produce CFRP-profiles, there is a choice of generally continuous and sequential manufacturing processes available. The mainly applicated processes and process-combinations are:

- *Pultrusion* (continuous process): continuous pulling of CF semi finished products, thermoplastic prepregs or dry products. The products are preformed in shape and curvature in a kind of rollforming process. Afterwards, the matrix is cured by hotpressing (in case of thermoplastic prepregs) or the dry perform is injected with thermoset resin by RTM-process.
- *Automated Fibre Placement (AFP)* (continuous/ sequential process): Automated placement of prepreg-tows with thermoplastic or thermoset matrix directly in the shape and in the curvature of the profile.
- *Dry Fibre Placement* (continuous/ sequential process): similar to AFP, in fact with dry fibre-tows. For injection of resin and curing an afterwards RTM-Process could be used.
- *NCF draping, preforming and RTM* (sequential process): draping of dry Non Crimped Fabrics into shape and curvature, injection of resin and curing by RTM-process.
- *Braiding, preforming and RTM*: (continuous process) Braiding of dry UD-rovings on a curved, shaped mandrel, injection of resin and curing by RTM-process

The process, which is chosen to develop a fully automated manufacturing process for complex CFRP-profiles, is draping of NCF with an afterwards performing step, combined with RTM-process (short: NCF+RTM). Generally, to bring CF semi-finished products into a strong curvature, dry products are more recommendable than prepregs, because of the better drapeability. In fact, with automated fibre placement technology, single prepreg tows are layed down on a shaped mandrel directly in the required direction, but the length of a layup-track of one tow on the mandrel is, regarding the +/-45°-layers of the basis layup, short, which will cause a long process time. An alternative of “classic” AFP is a fix AFP head in combination with a moving/ winding mandrel. But the risk of lower mechanical properties by cracking single CF-filaments due to strong deformation of relatively stiff prepreg-tows is very high.
Like the fibre placement technologies, the pultrusion technologies have a relatively high potential for fully automation, but due to the complexities of the example profile

(variation of height, radius of curvature, shape of profile), pultrusion technologies are not possible because they have their constrains of constant shape over profile length and of constant radius of curvature. Furthermore, to layup local reinforcements is not possible, too, by using pultrusion technology.
The braiding technology is a good method to build dry CF profiles which could be injected with resin and cured afterwards by RTM-process. Even variation of shape is possible, when special requirements are given. But only with braiding technology, local reinforcements are not possible. Furthermore, to build complex profiles like the stated example, the constrains of this technology are reached quickly. Another argument, which is in fact not validated fundamentally yet, is that due to the higher tendency of ondulations with braided CF products, lower mechanical properties could be expected in comparison with CF products, draped out of non crimp fabrics. But on this topic, new technologies, like UD-braiding, are in development [5].

techno	pot. autom.	Process time for 1 layer	Var. profile curvature	Var. profile height	Local reinf.	Joggles	C-type profile	Z-type profile
Pultrusion	++	++	--	--	--	-	++	++
AFP	+	-	+	+	+	-	++	+
DFP+RTM	+	-	+	+	+	+	++	+
NCF+RTM	-	++	+	+	+	+	++	+
Braiding+RTM	+	++	+	+	--	+	++	-

++ applicable very good
\+ applicable
\- limited applicable
-- not applicable

table 2: evaluation of processes for complex CFRP-profiles

As described in table 2, the NCF+RTM is the only today available technology, which handles all stated requirements on a complex profile. The disadvantage is the lack of potential for automation. This has stated the necessity to launch this project.
For injection and curing of complex shaped, dry CF-products, the RTM-process is a very good method. Especially with regard to the high production rate it is better to handle stiff tooling-parts instead of the relatively complex handling of vacuum-bagging in case of open-mould processes. Furthermore, due to a closed mould process with a fix cavity, complex parts with highly integrated design with high tolerances are achievable. The feasibility of RTM-process for high volume production was shown in the project “AutoRTM”, finished successfully at the CTC, too [3].

4. AUTOMATED PREFORMING PROCESS

4.1 Definition of performing process

In fig. 1, a rough overview of the whole process-chain, from draping of NCF, consolidation of dry sub-products to a final dry fibre-product, resin injection and curing with RTM until the necessary post-processes is given. To shorten the molding-time and therefore the occupied time of tools in case of complex CFRP parts, the manufacturing of a 3D shaped, dry textile product, the so-called “preform”, is necessary to ensure an economical process [4].

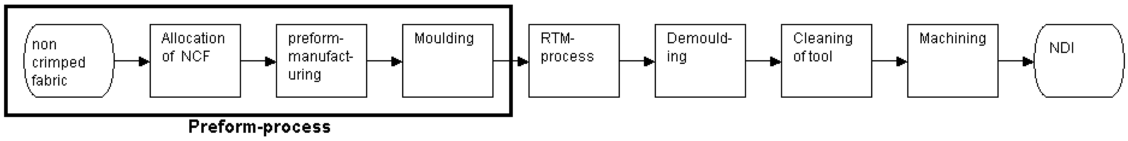

fig. 1: preform process in whole process chain

As already mentioned above, due to the complexity of the example part, it is necessary to apply a sequential method to build the perform in case of variation of profile-shape, radius of curvature and local reinforcements. Draping of NCF on a shaped, curved mandrel with an afterwards consolidation step for stabilisation is the only possibility to fulfil all stated complexities of the example part. Furthermore advantages are that the most available dry non crimped fabrics could be processed, high fibre volume contents are achievable, as well as good mechanical properties of the later cured part. The design of parts, manufactured with NCF is similar to parts, processed with prepreg-technology, the determination of mechanical properties is possible by testing plain coupons.
With regard to the high volume production, a high grade of automation and a reproducible process is required. With the complexity of the example part, it is not recommended to produce the complex preform in one sequence. It is more advisable to produce single sub-preforms, which are more easier, and consolidate all sub-preforms to the final perform, in an afterwards consolidation step. With this method, a automated, reproducible manufacturing process could be realised with less complex jigs and tools (fig. 2).

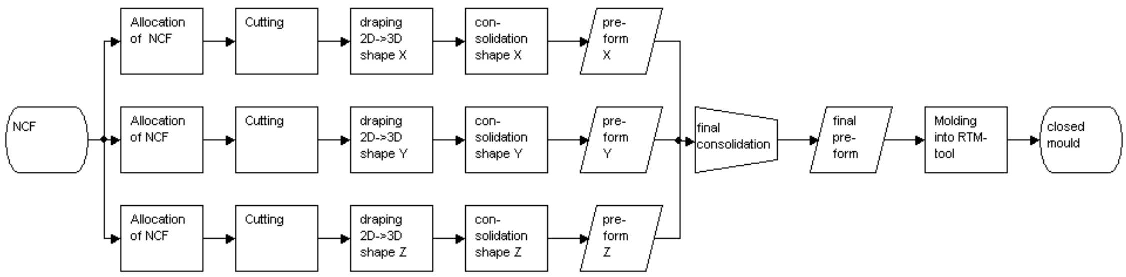

fig. 2: deateiled preform process for complex parts

4.2 General method for development of concept for automated performing

For every single subprocess described in fig. 2, a concept for 100% automated manufacturing had to be developed in the project. Beside the requirement on 100% automation, the reproducibility of every pass of the process had to be secured. Especially with handling of dry NCF-products this is in fact a big challenge.
The first step in development process is always to research different theoretically possible principles. These principles have to be evaluated concerning feasibility for 100% automation and reproducibility, and concerning realisability of above described complexities of the example part. Afterwards, the chosen principle has to be validated practically in trials. When the chosen principle is validated, the jigs, tools and devices, used in the validation trials has to be transformed in components and effectors for automated production.
This approach was applied for every single subprocess described in fig. 2 [6].

5. AUTOMATED RTM-PROCESS

To complete the automated process chain between „closing the mold“ and “delivery of cured part”, a short overview of the project “AutoRTM”, successful finished in 2006, should be given at this place:

The result of “AutoRTM” is a complete pilot plant to manufacture CFRP-fittings from allocation of semi-finished product to the demolded part. For achieving this goal, several new technologies, such as robotic handling tools, microwave performing and resin supply were developed.

In the first step fabric for the fitting is cut by a fully automated cutter. The blanks are commissioned by a robot with a special effector. This effector allows to collect the blanks although they have different sizes, without destroying the blanks laying next to them. In addition, the effector also accomplishes the draping of the material.

The next step is the preforming. At this, microwave technology is used for heating the material. This allows to increase efficiency and to decrease process time.

The finished preform is taken by a second robot with a vacuum assisted effector out of the preform mould and put into the open curing mould. The curing mould is transferred over a roller conveyor to the lid station and supplied with the lid of the RTM tool fully automatic. The closed mould is moved into a heating press and supplied with hoses for resin and vacuum connection by a docking station especially developed for this purpose. The advantage of this automatic docking station is in fact that no manual interference becomes necessary and that the volume of throw-away parts is remarkable reduced. With the developed system only two copper tubes of about 15cm length are wasted per injection, while during the serial process two resin filled hoses of minimum 2m length including screwed fittings have to be thrown away. After closing the press and completing the resin connection the injection is started over a fully automatic injection system with resin trap. The adherence of injection pressures and temperatures are permanently monitored and logged thereby. After, curing the automatic separation of injection lines takes place. The utilization of the thermal characteristics of the used single-component RTM 6 resin makes an absolutely clean and drip-free separation possible.

The tool is transferred into the lid opening station and opened up again by electrical driven mould opening cotter pins. Applying the required force for separating the lid from the mould is the major challenge in this step. The lid is taken off over elaborated kinematics and a third robot releases the finished part from mould with a suction gripper. After releasing the part from the mould the robot changes its effector for cleaning the mould. This cleaning effector works with a combination of air-jet and vacuum cleaner. Afterwards the curing mould is available for a further process [3].

6. VITRUAL PRODICTION PLANT

To evaluate the feasibility of the described production method for a high volume manufacturing of complex CFRP-frames, it is necessary to determine the recurring production costs. Therefore, a complete virtual production plant with respect to the production rate mentioned above, was designed with the “DELMIA Process Engineer” tool (DPE).

6.1 Description of product

The first step by designing a virtual plant is to define the product. Beside the part itself, which is described above, it is necessary to define different variants of cfrp-profiles. In the example, which was used in the project, the variants were defined as described in table 3.

Variant	Parts/year	Fraktion	Characteristic
I	73000	54%	Constant shape along the profile, no local reinforcements, all parts with the same curvature
II	43000	32%	Variation of shape along the profile, local reinforcements, all parts with the same curvature
III	11000	8%	Constant shape along the profile, no local reinforcements, all parts have different curvature
IV	8000	6%	Variation of shape along the profile, local reinforcements, all parts have different curvature

table 3: Variants of one-year-production of complex cfrp-profiles

A furthermore important information to calculate the recurring production cost of one CFRP profile of every variant are the material costs, which where defined as today's typical prices for NCF development material including overhead.

6.2 Processes and resources

For calculation of necessary machines, jigs, tools and devices it is necessary to define process times to determine the occupied time later. Together with specialists, for all steps of each subprocess, described in fig. 1 and 2, the process times where defined. Thereby, a high level of detail was taken into account. For the subprocess, described in chapter 4.3, for example, process times for bringing the draping effector in start-position, roll out of cut NCF layer, fixing of NCF-layer (startline), moving of effector during draping process over the mandrel, fixing of NCF layer (finish line) and bringing the back to start-position, process times in the accuracy of seconds where defined including all steps concerning quality insurance. This level of detail was applied through all subprocesses of the whole process chain, from allocation of semi finished product until final NDI. With this information, the total lead time of one part of every variant was determined.

Furthermore, the planning and design of all necessary resources (machines, effectors, jigs, tools and devices) with regard to the whole process chain was made together with experts from plant-engineering. Thereby, the acquisition cost of all resources were estimated, in case of the first machine including its development-costs and the price in case of follow-up orders. To determine the total amount of resources, a family-building was made for the effectors and tools, because of the fact that every profile of variant III and IV has different curvature. This leads to a minimum amount of different effectors and tools, independent from the capacity-analysis.

6.3 capacity-analysis, determination of amount of resources

The single process-steps with their process-times and the resources are attached to the DPE-tool. Afterwards, the single process-steps will be linked to the relating resources, used in the process-step. If every link is done, the analysing of capacity could start. Thereby, the maximum occupied time of every single resource is confronted with the available process time concerning the required production rate. The result is the total necessary amount of every different resource. Thereby, a availability of resources of 95% was assumed.

6.4 layout of virtual production plant

With the capacity-analyses and the calculated necessary amount of resources a pre-configuration of the production lines was done. Thereby, with the scenario described above, it is not necessary to have separate production lines for each family. The pre-configuration shows separate lines for the perform-manufacturing (one line for each sub-preform) and one common line for further RTM-processing and post-processes. Additionally, devices for transportation and storage are implemented in the layout. For final optimisation of the layout, a dynamic simulation is necessary. To evaluate the feasibility of an automated profile-production with the assumed production-rate in terms of production costs, the existing layout of the production plant with the high level of detail for the machines developed is more than sufficient.

6.5 production costs/ evaluation

The average prices for the resources is determined with the information from the specialists concerning the first machine including the non recurring costs for development and the follow-up orders:

$$\overline{I_r} = \frac{I_1 + (M-1) \cdot I_{2-M}}{M}$$

$\overline{I_r}$ Average invest for resource *r*

I_1 Invest for resource 1

M Necessary amount of resource *r*

Due to the fact, that in some cases special resources are only used for special profile-families, it is necessary to calculate the overall invest for every variant separately. The calculation of invest per variant was done in two steps: Step a) in case of resources, necessary for all profiles and step b) in case of resources, used only for special variants.

a) $I_{X1} = \sum_{r=1}^{r=R} \overline{I_r} \cdot \frac{n_X}{N}$ b) $I_{X2} = \sum_{k=1}^{k=K} \overline{I_k}$ $I_X = I_{X1} + I_{X2}$

I_X Invest for variant *X*

R Number of different resources, necessary for all variants

r Index of resource, necessary for all variants

K Number of different resources, necessary only for variant *X*

k Index of resource, necessary only for variant *X*

n_X number of pieces per unit of time for variant *X*

N Total amount of pieces per unit of time

With DPE ,the amortization costs per variant are calculated including work center costs with DPE by starting a script. Thereby, an amortisation time of ten years for every resource was assumed. By dividing the amortization costs of variant X through the number of peaces for variant X, the amortisation costs for one profile of variant X has been calculated.

The production costs per profile and variant have been calculated with those amortisation costs, the area costs, necessary for the resources and the material costs [7].

The results of this study are surprising: With a fully automated manufacturing of the described example part and the defined assumptions, it is possible to manufacture complex CFRP-profiles in the same pricing range, as comparable complex metal profiles, manufactured by milling process. Furthermore, in comparison to the manual serial manufacturing, which is the state-of-the-art process for those complex CFRP-parts, it is possible to reduce the non recurring production costs of about 22% and the recurring production costs even of about 55%! The reduction of lead time can be expected from 18,5 h (manual manufacturing) to less than 10 h (automated manufacturing).

7. CONCLUSIONS

With this study, a concept for automated manufacturing of complex CFRP-profile by automated draping of non crimped fabrics and preforming in combination of resin transfer molding process was developed and evaluated. The determined production costs in case of the assumed scenario validates definitely the economical feasibility of the researched concept, as the region of costs for similar metallic profiles could be reached. The enormous improvement in comparison to the manual manufacturing in terms of production-costs and lead time is shown, too.

Within this study, the necessary machines, tools and devices for a complete process chain, 100% automation, have been developed in a very high level of detail and proved in trials.

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