Electromagnetic Assisted Manufacturing of Carbon Fiber Reinforced Plastics

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OVERVIEW

This paper is dedicated to give an overview on latest research, made at the German Aerospace Center in the field of advanced manufacturing technologies for carbon fibre reinforced plastics (CFRP). The research work about preforming was done together with the Institute of Joining and Welding. To fulfil the industry's demand for time and energy efficient manufacturing methods, two innovative heat treatment techniques – inductive heating and microwave heating – were adapted to be used on the lab level within such thermal steps as resin preheating, preforming and curing of composites.

1. INTRODUCTION

1.1. Demand for CFRP

During the last couple of decades a continuous growth and development of the aerospace sector was going on. Recent market forecasts and analysis are predicting a further upturn, which already can be seen on launch of such innovative aircrafts as Boeing Dreamliner, Airbus A380 and Airbus A350 XWB. Permanent competition between manufacturers, increasing demands for comfort, aircraft performance and strict safety requirements are making further technical innovations necessary. Nowadays there are many possible strategies how to fulfil the demands and requirements of customers and authorities while keeping the structural mass of an aircraft low and its flight performance high. One of them is substitution of metals by carbon fibre reinforced plastics, e.g. for structural parts like fuselage, wing and tailplane. In comparison to former times, when reinforced plastics were used in cabin domain and fairings mainly, approximately 20% (A380) or 50% (A350, Dreamliner) of modern aircraft's structural weight consist of high-performance composites.

There are many composite manufacturing techniques available and well-known; however, all of them are containing at least one thermal manufacturing step. Within these steps energy is added to the composite in order to assert its mechanical properties. Commonly, convective ovens are used to introduce heat into the compound to ensure e.g. its preforming or curing. Unfortunately, due to slow heat conduction within parts and tools, conventional heating processes are suffering from thermal lag and are very energy-inefficient. Therefore the manufacturing capacity of conventional heating facilities based on convective heating is limited and large product quantities can not be handled, as required by the increased demand. These attributes are limiting the use of conventionally manufactured composites within an aircraft structure and increasing its production costs. To achieve future goals for the production rates, innovative technologies are required in order to speed up the production and therefore to reduce its costs.

Two very promising techniques were analyzed at the Institute of Composite Structures and Adaptive Systems at the German Aerospace Center in Braunschweig. One of them is microwave heating, which is based on volumetric energy generation directly within the product by such effects as dielectric and ohmic heating. In cooperation with industrial partners some microwave heating facilities have been designed and built. Subsequently some of the facilities passed the qualification process and are

already integrated into series production at the Airbus site in Stade.
Another innovative technique is inductive heating, which is under development at the Institute of composite structures (DLR) together with the Institute of Joining and Welding (Technical University of Braunschweig). It provides also the advantages of high heating rates and volumetric heating for local areas.
The main aim of today's work is to obtain better understanding of involved heating mechanisms, to assess existing production technologies and to adapt them to advanced heating techniques in order to provide the aerospace industry with tailor-made time- and energy-efficient facilities.

1.2. Manufacturing chain

The manufacturing process of carbon fibre reinforced plastics is subdivided into many steps. Since there are at least two components included into a composite, both have to be treated before they are joined to a part. This paper will focus on Liquid Compound Moulding (LCM) and PrePreg Processing Technologies. Fig. 1 shows manufacturing steps involved in a LCM process.

FIG. 1: LCM process chain

During the preforming step thermoplastic binder coated fabrics can be reshaped to obtain semi-finished products due to their handling advantages. Usually, the resin is stored at low temperatures and has to be defrosted to achieve the required viscosity before being injected into preformed fabrics. Within the curing phase the composite has to be heated until its complete polymerisation. The PrePreg manufacturing process depicted in Fig. 2 is similar to the LCM process, but since resin and fibres are already joined by the feedstock manufacturer, the resin preparation step and the curing steps vanish. All the manufacturing steps will be described more precisely later.

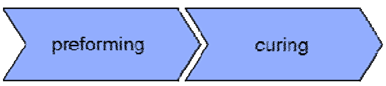

FIG. 2: PrePreg process chain

Each of these steps requires usually thermal energy, which is added by applying high temperatures to the assembly. The end of every step is reached after a predefined temperature level is achieved and the temperature distribution over the whole part volume is uniform. Since there are many heat sinks (e.g. tools, oven chamber) and heat sources (e.g. hot air) involved, the thermal boundary condition of a composite assembly is very inhomogeneous during the treatment. This disadvantage is magnified again by poor heat conduction property of fibres and resin. Therefore, by using conventional heating techniques based on hot air heating, convection and the subsequent heat conduction, the process time of each manufacturing step is too long and has to be reduced significantly to meet the increased industrial requirements. One of the possible solutions is a heating method, which generates heat inside the material and makes processes mostly independent from thermal boundary conditions and heat conduction properties of used materials. Following chapters of this paper will give an overview of such heating technologies, the work which has been performed and applications within the LCM and the PrePreg manufacturing chain.

2. PREFORMING

2.1. Local Preforming with Inductive Heating

A preform is defined as a preparation of dry fabrics for resin injection processes. Within the preforming step the single fabric layers are stacked and draped into desired shape and fixed in that position [1,2].
A common technique to prefrom the layers is the binder technologie. Fixing the fibre layers a thermoplastic adhesive or one component of the infusion resin is applying between the fibre layers. This binder can be melted by increasing the temperature. While decreasing the temperature afterwards, the binder viscosity decreases until it the layers become stabilized in the desired shape.
Melting of the binder can be performed by conventional techniques like ironing, convective or infrared heating, but especially for thick laminates it takes a long time to conduct the heat energy to the inner layers. Fig. 3 shows the difference in time needed to consolidate a standard frame laminate (20x Biax + 6x UD-layers) at a local point.

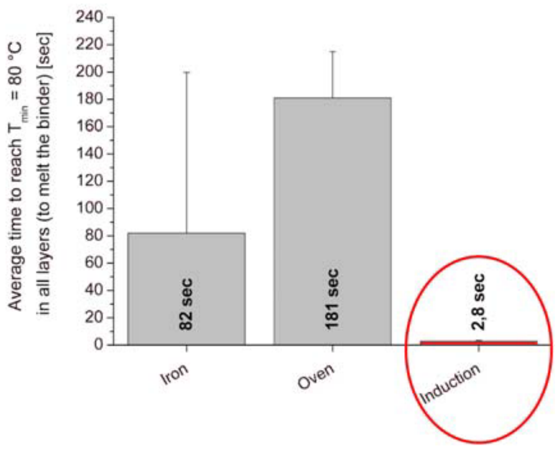

FIG. 3: Overview of preform heating processes

The other disadvantage of the state-of-art techniques is the relative low cooling rate: pressure must be applied until the temperature of the binder reaches a point well below the melting point. To overcome those problems, a new technique based on the application of electromagnetic waves (induction) is under development now: The main idea is that electrical energy can be transferred and transformed direct into carbon fibres by using inductors.
The advantage of induction heating is the achievement of high volumetric heating rates, compared to conventional manufacturing processes that rely on conduction, convection or radiation heat transfer [3]. Table 1 gives an impression of the maximum heat transfer rates possible by each method. The values are not specific for composites.

Table 1: Overview of maximum energy transfer [4]

Heat method	Energy transfer
Convection	0,5 W/cm³
Radiation	8 W/cm³
Conduction	20 W/cm³
Flame	1.000 W/cm³
Induction	30.000 W/cm³

The high energy transfer rate gives a first impression of the possible process acceleration. As the energy will be transferred volumetric in all layers within the magnetic field, it is also possible to heat up a thick stack in just one step. Tests have shown (Fig. 3) an acceleration factor of 30 for a 7 mm stack in comparison to ironing. Another important result is the much lower thermal scattering. A low scattering means a lower peak temperature and therefore less needed energy as well as less cool time.
To make this technology ready for composite production, an elaborative study has been performed in cooperation with Airbus Germany. The influence of parameters like kind of material, fibre orientation, stack-thickness, inductor geometry, frequency, thermal distribution in thickness and plane direction and much more have been analysed. In general, for inductive heating of carbon fibre composites, three different heat mechanisms can be divided [5]:

- Fibre Heating by Joule Loss
- Junction Heating by dielectric hysteresis
- Junction Heating due to contact resistance between fibres

It was found that in the used frequency range of 10 to 50 kHz, the fibre heating by Joule Loss is the dominant and most effective mechanism. That means that the electromagnetic waves will be transferred directly into the fibres. Getting a good efficiency it is necessary to have the possibility to induce an eddy current into the material. This is always the case if layers on top of each other have a difference in fibre orientation. This effect could not be reached if only UD layers with same orientation are used.
The heated area is limited by the position and size of the electromagnetic field which can be designed by modifying the coil geometry. For manual preforming it is most beneficial to fix the layers just punctual after draping e.g. a difficult radius so that a layer can be draped and fixed in several steps. This behaviour can be reached by using a U-inductor-core. Here the influenced spot like area has an elliptical shape of approximately 1 cm².

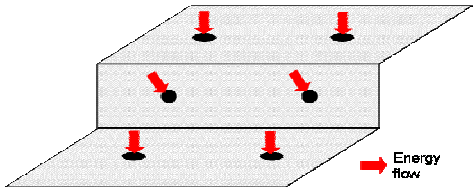

FIG. 4: Punctiform inductive heating

For automated preforming installations, where a whole area is normally draped in one step, it is beneficial to fix also the area in one step. To reach this, two different methods and inductors are available: One possibility is to use the spot inductor, which was described before, and move it over the surface. To speed this up, the inductor can be changed to a line-inductor. By moving this inductor a whole area – or in case of a complex gate inductor a whole preform can be fixed. A gate inductor is positioned around the cross-section of the preform. This is especially beneficial for continuous production.
After testing the manual preforming process successfully, a fully automated continuous preform

production line is under development at the moment. The first installation will be capable to preform H-shaped joining elements (Fig. 5), existing out of 12 single layers plus four gusset filler.

FIG. 5: H-shape joining element preform

A planned step further is to use this setup to manufacture curved elements with constant radius (in length direction) like simple frames (Fig. 6). Here, the same inductor-setup can be used; only the fabric guiding device has to be modified.

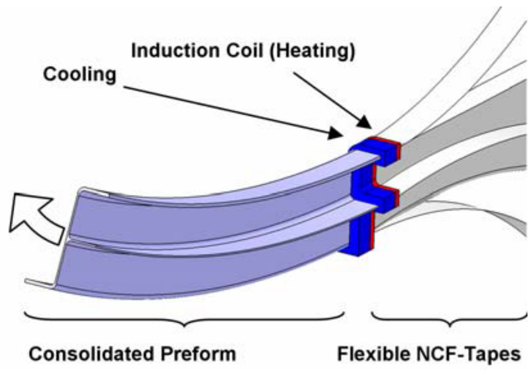

FIG. 6: Linear inductive heating for complex profiles

Also imaginable is a manufacturing line for real 3d-profiles with variable radius. The only difference here is again the guiding device which must get several actuators.

2.2. Global Preforming with Microwave Heating

The heat generation is based on slightly different mechanisms, than in case of inductive heating: instead of fibres, the binder drops are directly heated by dielectric effects. There is no sensible option to heat the assembly punctiform, so the whole part has to be exposed to the microwave field. Due to homogeneous boundary conditions over the part surface, the heat generation happens over the whole part volume.

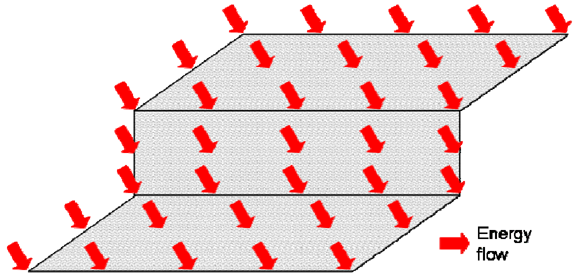

FIG. 6: Reshaped fabric heated by the microwave field and fixed over the whole volume

Unlike the inductive preforming, as described above, microwave based consolidation process allows complete melting of binder within the whole CFRP-part volume. Experiments with binder coated fabrics have been performed to prove the applicability of the method. Tests have demonstrated, there is no quality loss compared to established techniques as ironing or convective heating (Fig. 7).

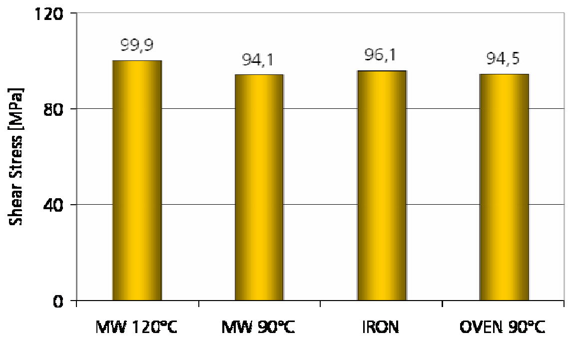

FIG. 7: Comparison of shear stress of samples produced with different techniques [6]

Despite the wave-like nature of microwaves propagation, it is possible to realize a uniform temperature distribution within a preform. Therefore, microwave heating can be used for fast preconditioning of large-scaled fabrics before their reshaping. This becomes important for designing of automatic facilities, since microwaves have been proved to be compatible with tools and auxiliary materials. To demonstrate the potential of microwave based preforming, an automated preforming facility has been built in close cooperation with Composite Technology Center Stade. Thereby the cycle time dropped to 20 minutes without any quality loss.

3. MICROWAVE ASSISTED RESIN PRE-CONDITIONING

Resin preheating is a necessary step for high-performance resin injection processes used by the aerospace industry. During the material storage, epoxy resin is exposed to a temperature of -18°C to prevent the early polymerisation. At low temperatures, the resin viscosity is too high and therefore it cannot be conveyed. To lower the viscosity microwave heating can be used, as shown by the research work at the Institute of Composite Structures and Adaptive Systems. Since thermosetting resins are partially lucent to microwaves, the high-frequency field penetrates the whole batch volume and generates heat volumetrically. As a result of volumetric heating high temperature gradients within a resin batch can be avoided. Therefore there is no risk of uncontrolled exothermic resin polymerisation while the preconditioning step, which leads to increased process safety. Through cooperation with partners from the aerospace and microwave industry a resin warming facility has been built (Fig. 8). Compared to conventional heating systems, which use heating by convection, the developed microwave warming facility uses microwaves to heat up the resin. The major advantage is volumetric heating, which causes a rapid temperature rise. Convectional resin heaters require about 6 to 9 hours to provide a homogeneous distribution of temperature, microwave facilities can achieve a time saving of about 90% while reducing temperature gradients within the resin batch as shown in Fig. 9.

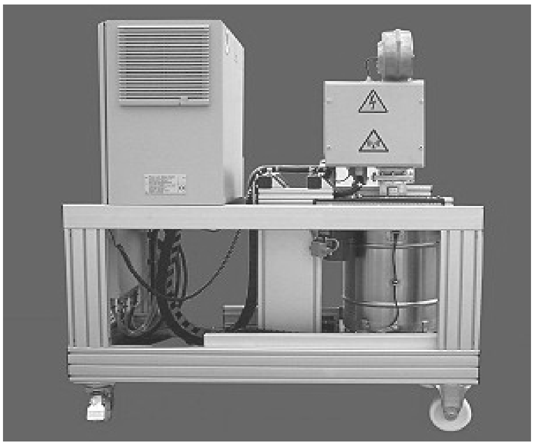

FIG. 8: Microwave resin heating facility

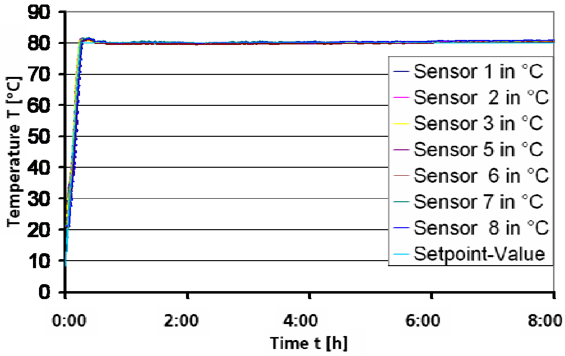

FIG. 9: Temperature detected by uniformly distributed sensors in a microwave heated batch

Due to excellent research results and good experience, microwave resin warming facilities are already used by the aerospace industry and will become state of art shortly.

Another application in the field of resin preconditioning is resin flow heating which was recently successfully tested. As shown on lab level, the quick heating of high mass flow of liquid resin is possible within short distance by using microwave radiation (Fig. 11). This effect is aimed to be used for pre-heating of injection resins. Especially in case of large structural parts, the quantity of required resin is very high. The usual technique is convective heating of the whole required resin to a temperature of approx. 80 °C before it's injection. By using a microwave flow heating facility (Fig. 10) just before the injection point, the pot-life of resin can be increased, since it's exposed to high temperatures for a short period only.

FIG. 10: Microwave flow heating facility

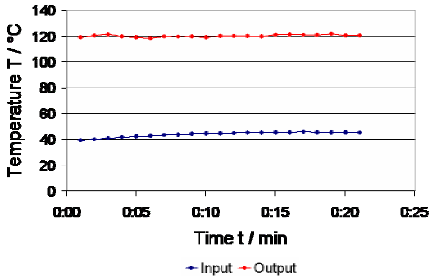

FIG. 11: Temperature raise of resin flow over a distance of approx. 200 mm

4. MICROWAVE ASSISTED CURING

The most energy-consuming step within every production chain is the curing of composites. Therefore, the integration of microwave heating technology is very promising at this stage. Microwave heating is selective, which means it depends on dielectric properties of materials, and requires no medium for energy transportation. Hence, there are precise temperature patterns possible with low thermal lag and low difference to the target temperature. By using microwave heating, cost-efficient curing processes are possible with substantial time and energy gain (Fig. 10).

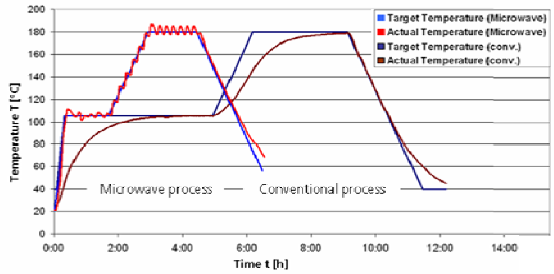

FIG. 10: Microwave driven curing vs. hot air driven curing

One of the aims of today's research work at the DLR is transferring of gained results to the industry. Accordingly to the state of the art, ovens or autoclaves are used to cure composites. Therefore a microwave heated autoclave has been designed and build in cooperation with the industry and set up at the Institute of Composite Structures and Adaptive Systems (Fig. 11). It can be heated with microwaves or conventionally and can be operated pressurized or not, therefore an excellent research facility with many capabilities is available now. The microwave autoclave is expected to fulfil the aerospace industry demands for fast and effective curing of preimpregnated carbon fibre reinforced plastics. In total 96 microwave sources – magnetrons – are integrated into the vessel, this concept is patented after being the main challenge of the project. Due to the allocation of magnetrons over the whole vessel surface, a homogeneous temperature distribution on the product surface can be achieved, as shown in the first basic trials. The technical data of the microwave autoclave is as follows:

- Diameter: 1600 mm
- Length: 4000 mm
- Packing Space: 8 m³
- Microwave Power: 96 kW
- Conventional Heating: 231 kW

FIG. 11: Microwave autoclave

An additional reduction of costs and complexity was achieved by adapting of conventional state-of-art tools for the new process. Therefore, the microwave heating can be applied to the most parts produced with LCM or PrePreg technology. Savings potentials of microwave autoclave assisted manufacturing compared to the state of the art will be proven shortly by simulating a series production on a lab level.

5. CONCLUSIONS

Within this paper the whole process chain of the LCM or PrePreg production was analysed with focus on thermal process steps. Due to industrial requirements, there is a demand for local as well as for global consolidation of the binder at the preforming step. For local consolidation, the inductive heating was successfully tested. This technology has the capability to speed up the process dramatically and to simplify the automation. To optimize the handling and storage capabilities of the preforms the microwave based preforming was tested on industrial level. With this technology, equal mechanical properties can be achieved in a much shorter time than with state-of-the-art techniques (ironing, convective oven). For the preconditioning of the resin, a microwave heating facility was developed and successfully tested. By using this facility, the preparation time of aerospace resins can be shortened down to 20 minutes. First systems are already in use by industrial customers. Additionally to that, a microwave resin flow heating facility was tested and promising results were achieved. Also for the curing of high performance CFRP parts, microwave heating systems are under construction now. Tests have shown that it is possible to increase the energy efficiency while decreasing the production time. The new developed microwave autoclave, beginning of operation soon, will further boost the efficient production of CFRP parts.

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