Composite Manufacturing by using a novel modular 2.45 GHz Microwave Processing System

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ABSTRACT

A novel industrial microwave system for automated processing of carbon fibre reinforced plastics has been developed at Forschungszentrum Karlsruhe and tested for commercial use. The system integrates advantageously the basic processing steps as tooling, tempering of the resin and lay up, the impregnation of the fibres, pre-forming techniques as well as finally the process curing of the composite structures. Composites for aerospace applications in prepreg and wet technology have been successfully fabricated and investigated for quality and certification issues. Features of the system, as well results on the material investigations are presented. The use of microwaves shows new approaches on the process interaction for the fibre materials, precursors, resin systems, lay-up preparation etc. with direct consequences on the adjustable material properties. CFRP materials are heated volumetrically with microwaves, offering the opportunity of very high heating rates. In comparison to conventional heating where the heat transfer is diffusive and depends on the thermal conductivity of the material, the microwave field penetrates the material and acts as an instantaneous heat source at each point of the sample.

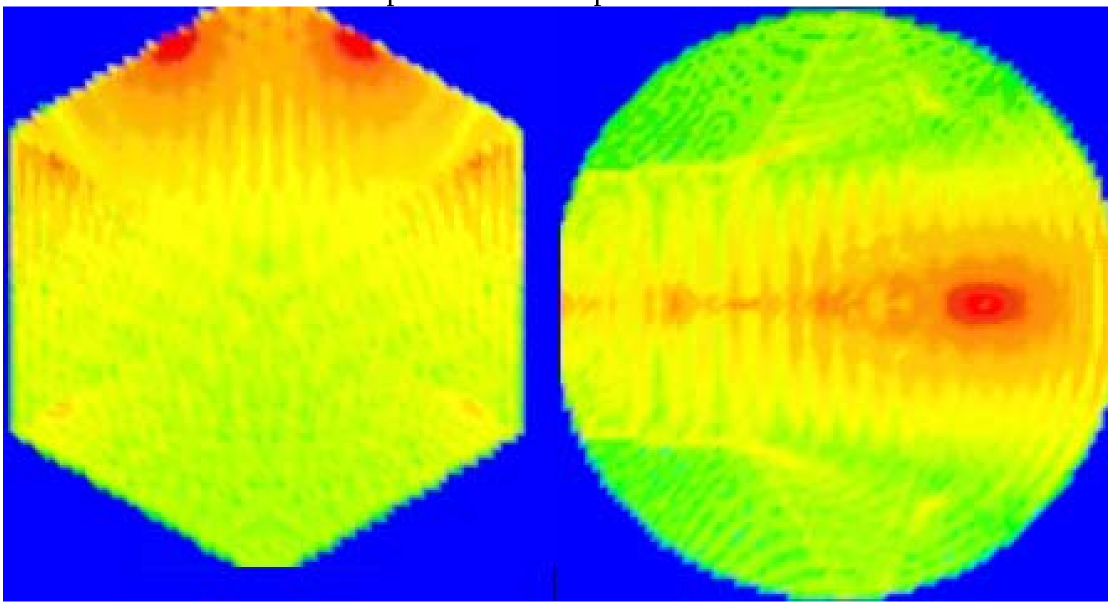


Fig. 1: Comparison for an optimized hexagonal applicator at 30 GHz. On the right, the field distribution within a cylindrical system is visualized [1]

The CFRP can be selectively heated, keeping the oven environment cool. Spatial temperature homogeneity is crucial for qualified material properties. The samples must be exposed therefore to an excellent homogeneous field distribution. The development of the microwave system has been assisted by extensive numerical simulations.

1.INTRODUCTION

Of all the heating systems the autoclave is today the most popular system for the composite field, as prepregs usually need a high pressure environment along the curing process for forming.

Concerns on this state of the art approach are

- Long process times
- Inherently energy inefficient system
- Major difficulties caused by large thermal gradients and slow heat up times
- Bag failures
- Complex expensive tooling
- High acquisition costs

A special alternative for heating can be microwaves, since microwave heating at 2.45 GHz and 915 MHz has been established as an important industrial technology about more than 50 years ago. The successful application of microwaves in industries, that always has to compete with conventional heating systems, has been reported e.g. by food processing systems, domestic ovens, rubber industry, vacuum drying etc.

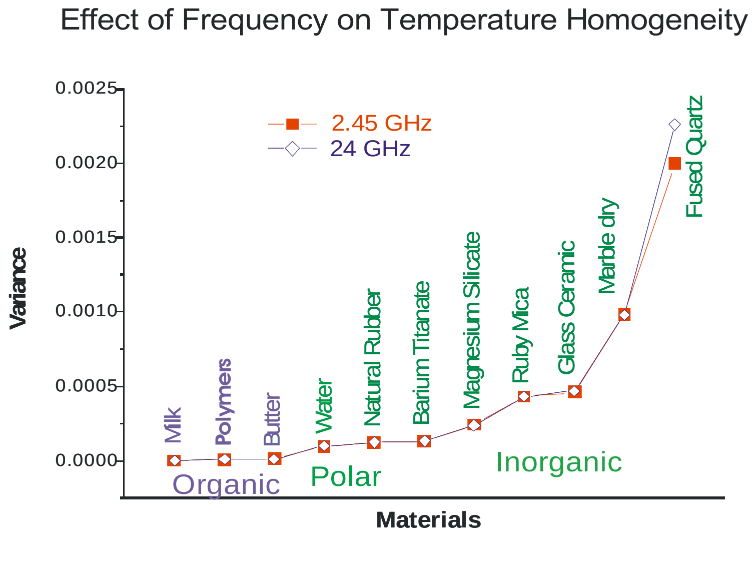


Fig. 2: For organic materials, the field conditions of the 2.45 GHz HEPHAISTOS-System result in an excellent volumetric temperature answer

A lot of individual technological solutions in industries, where the physical benefits of using microwaves result finally in commercial gain, have been developed. Investigations on heating

CFRP with microwaves have been undertaken for decades but failed due to the lack of a sufficient homogeneous electromagnetic heating field or reasonable costs for suitable sources and components providing industrial scale up.
The HEPHAISTOS concept originally developed and patented at FZK solves these long existing problems. These ideas have been tested successfully during collaboration at an early fundamental stage at DLR, Braunschweig.
Another important step for this novel technical development on the composite fabrication sector was the generation of a complex understanding of electrothermal behaviour for materials. This resulted in the development of codes for predicting the temperature answer of materials while exposed to electromagnetic field. It was shown, that under specific circumstances, process fields with vanishing thermal gradients,e.g. polymers can be applied for composite materials [2].
Detailed investigations and calculations of the normalised statistical variance of the volumetric temperature distribution being exposed to a homogeneous microwave field as in the HEPHAISTOS-System (Fig.2) show that the materials obey for the resulting temperature homogeneity (temperature answer) in a natural order: Organic, polar and then inorganic.
This shows clearly the enormous potential of this novel technological approach for fibre reinforced material applications, as well as e.g. adhesive joining. The results could even show, that the resulting temperature homogeneity achieved by the HEPHAISTOS-technology can not be improved by increasing the frequency (e.g.24 GHz), which usually gives the opportunity for finer resolved microwave field distributions.

2.THE HEPHAISTOS-SYSTEM

The developed microwave pilot system is named after Hephaistos, who is the builder and craftsman for the Greek gods, being also responsible since the past for oven and transportation technologies. The name HEPHAISTOS (**H**igh **E**lectromagnetic **P**ower **H**eating **A**utoclaveless **I**njected **STructures** **O**ven **S**ystem) stands as well for the technological concept of this microwave approach.

Fig.3: Hephaistos (Greek God), painting ca. 525 BC. He is also known as Hephaestus and Vulcan (Roman).

The current system integrates advantageously the basic processing steps as tooling, tempering of the resin and lay up, the impregnation of the fibres, pre-forming techniques as well as finally the process curing of the high performance laminate.

Distinctive physical and technological advantages of microwave heating compared to conventional heating are:

- Volumetric heating of composite materials: The microwaves penetrate instantaneously the materials and generate locally a specific heating content.

- Reduction of cycle times: Due to the volumetric Heating, the heating rates with a structure can be strongly increased gaining for a higher throughput of products.

- Selective Heating: Microwaves only heat the composite structure, the oven and components "keeps cool".

- Energy savings: Only the lightweight structure is directly heated. The oven will not be cooled actively, which results as well in reduction of cycle times.

- Rapid control of the process: Due to the instantaneous and volumetric heating within the composite structure processes can be applied, which are impossible in conventional ovens due to their inertia on temperature changes especially if local overheating occurs for exothermal reactions.

- Upscale: The HEPHAISTOS-technology can be applied for large structures.

- Automation: The fabrication process as well as control and sensoring can be adjusted very advantageously with the HEPHAISTOS-technology, such that overall optimizations of the process chain can be gained.

- Reduced hardware-costs of the heating system: Due to the use of standard industrial 2.45 GHz components, an industrial HEPHAISTOS-system is much more convenient than autoclave systems.

The most notable effect processing CFRP materials with microwaves is their volumetric heating, offering the opportunity of very high heating rates. In comparison to conventional heating where the heat transfer is diffusive and depends on the thermal conductivity of the material, the microwave field penetrates the material and acts as an instantaneous heat source at each point of the sample. The CFRP can be selectively heated, keeping the oven environment cool. Spatial temperature homogeneity is crucial for qualified material properties. The samples must be exposed therefore to excellent homogeneous field distributions. This is essential, as the carbon fibres imply a very high microwave reflectivity and the tendency for arcing and breakdowns at loose ends in areas of inhomogeneous microwave patterns. This problem is very severe and one of the major phenomena, that made microwaves not applicable yet for CFRP processing. A specific multimode applicator development aims to tackle these problems.

Monomode applicators involve only controllable field properties in small specific applicator regions, whereas multimode ovens promise, especially for frequencies higher than 2.45 GHz, the possibility for low field fluctuations in larger regions. Simulations and experiments have shown, that achieving high quality homogeneous field distributions over most of an applicator volume is not trivial, even at frequencies in the millimetre-wave regime (30 GHz). An industrial microwave oven for production needs is successfully designed, if the available processing volume containing uniform field properties is about the size of the whole cavity and reflections are minimized. Conceptions of novel millimetre-wave technology have been transferred by DELFI simulations to 2.45 GHz technology to realize these demands by providing a large part capability for CFRP processing.

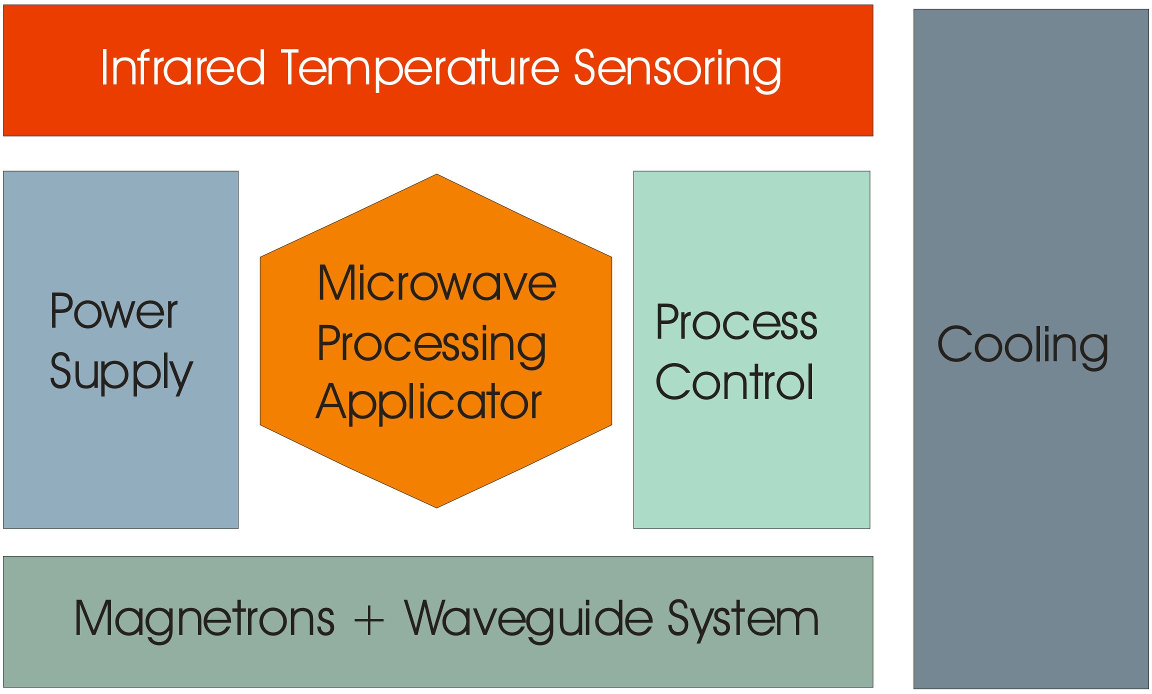


Fig.4: Schematic Set-up of the HEPHAISTOS-System

The main hardware contribution of the system development is realized for a specific modular applicator containment providing an excellent homogeneous electromagnetic field distribution. The fabrication process can be performed in pressurized environments up to 5 bar or at standard conditions. The processes are measured remotely by infrared sensors or shielded low-cost thermocouples.

The HEPHAISTOS-concept follows a two paths strategy:

1. as a stand alone processing system
2. as an upgrade system for existing autoclaves

The main goal lies at the development of stand alone systems for novel pressureless processes in combination with specific infiltration techniques, such as VAP (Vacuum Assisted Process)[4]. With this, the main profit can be drawn for industrial fabrication of high performance laminates, especially for wet injection technologies.

The upgrade system intends to insert a compact inset module into an autoclave system, changing the autoclave to a cool microwave system. The autoclave can still be applied as a pressure shell.

The technological developments at FZK-IHM together with EADS and IFB are joined with FZK-ITAS (Institute for Technological Assessments) to investigate and assess the possible development stages and scenarios for early optimizations of the full process chain [5].
Since the beginning of 2003, the HEPHAISTOS-CA1 [6] has been used as a pilot system at FZK to follow the fundamental systems HEPHAISTOS-SA (used in Braunschweig at 2001-2002) and HEPHAISTOS-BA (used in Karlsruhe at 2001-2003). Former basic investigations for CFRP heating have been performed since 2000 with a 30GHz gyrotron installation.

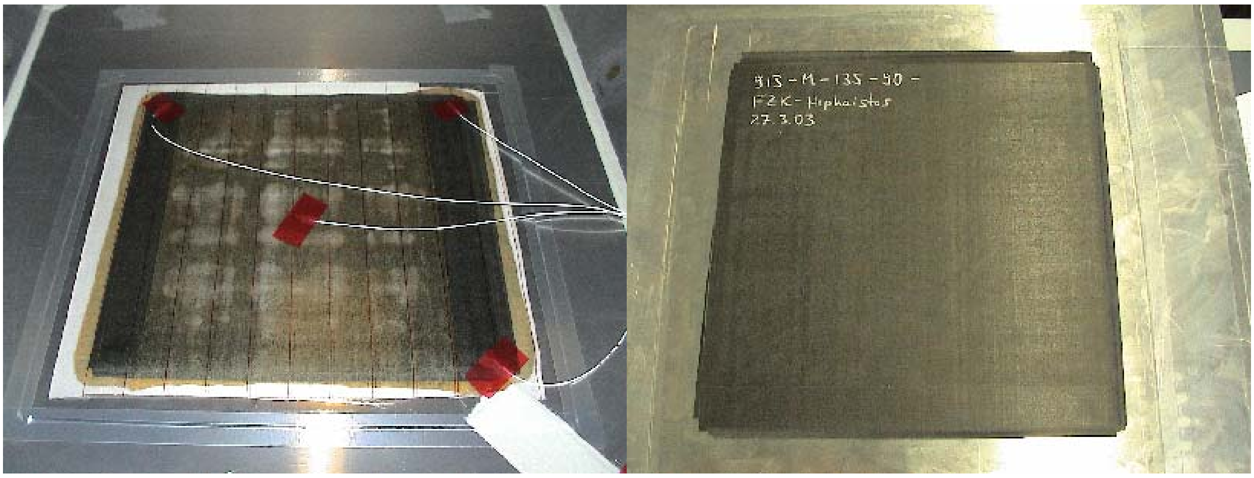


Fig. 5: Process setup: 1 bar vacuum bagged prepreg 913 system (left) and homogeneously cured sample (40cm x 40cm) after the process (HEPHAISTOS-CA1 System).

For the HEPHAISTOS systems, the microwave energy is transferred by a waveguide system and coupled into the applicators. The overall available microwave power for the CA1 system is 12 kW. The diameter of this system is 1 m consisting of one module with 1m length. The maximum size of a CFRP slab cured in this system was about 60cm x 80 cm x 1cm.

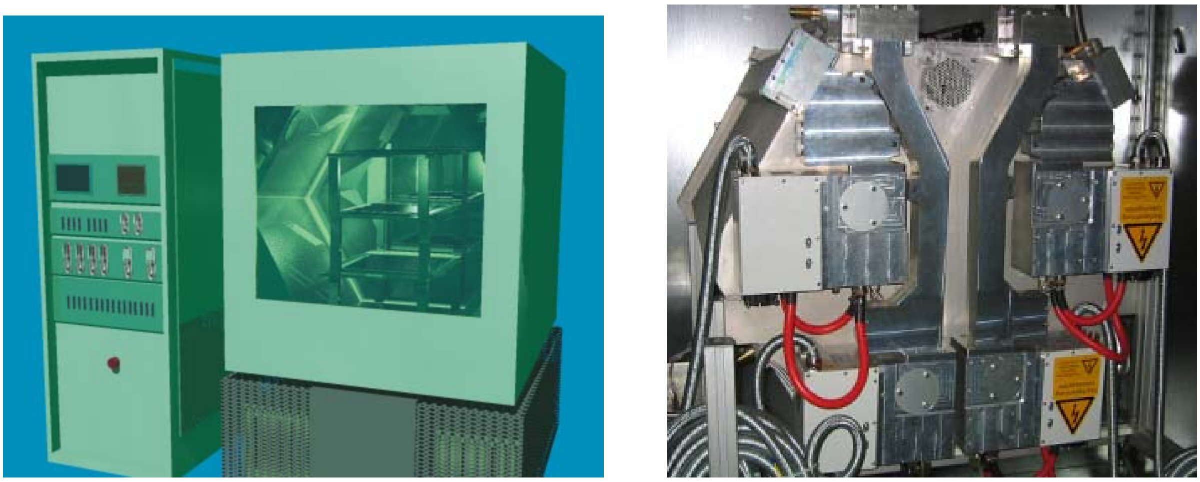


Fig. 6: HEPHAISTOS-CA1 as a stand-alone system (left), ultracompact magnetron units backpacked for an CA1 autoclave inset system (right)

The HEPHAISTOS microwave system containment is very compact and can be used as an inset to upgrade at low costs existing conventional autoclave systems. But because on the very cost-intensive nature for autoclave based composite processing technologies as pointed out before, autoclave-free approaches without pressurizing are most promising for future broadband industrial application.

2.1 Autoclave-free wet-technology applications A preferred approach is the wet or injection technology, where resin is drawn into a dry lay up of carbon fibre weaves like the VAP process. The produced parts show good surface detail and accuracy. The need for shipping and storing refrigerated prepreg is removed as well. The simple set up with a 1 bar vacuum bag reduces drastically the overall technological demands. Wet technology is a very cost-effective non-autoclave process, where high performance CFRP parts can be fabricated in nearly arbitrary shapes using simple process management in a not pressurized environment.

To inject resin into dry carbon weave, the resin as well as the lay up has to be preheated, to keep the resins viscosity low. After the injection phase, the curing cycle can immediately start. The complete process can be automated with the HEPHAISTOS system. A continuous monitoring and control for the cure cycles of composite materials is permitted.

2.2 Systematic Investigations for the technological development with composite materials Extensive work for processing and testing CFRP materials have been performed very fruitfully together in a joined collaboration with Institut für Flugzeugbau IFB, Stuttgart and EADS Corporate Research Center, Ottobrunn to finish a basic investigation program for the application of prepreg- und infiltration techniques.

Especially the following parameters have been investigated: Heating rates, resin systems, prepregs, textile semifinishes, infiltration techniques, difficult geometries and tooling materials [7].

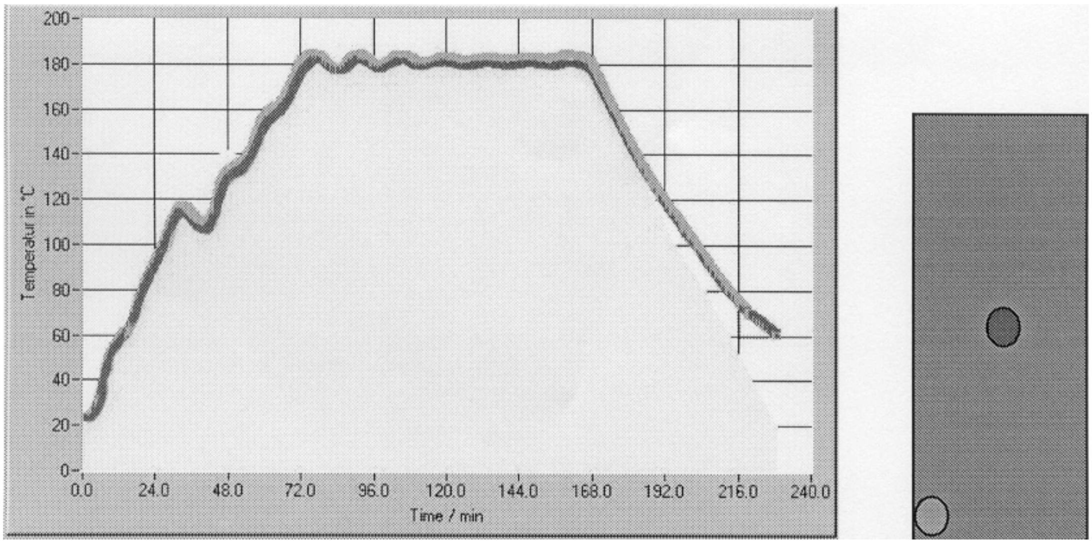


Fig.7: a 15 cm x 30 cm rectangular CFRP test plate processed and injected in the HEPHAISTOS-CA1 system (left). The temperature measured points are visualized in the right picture.

Fig.7 shows such a typical process in an HEPHAISTOS-CA system: the initial heating and tempering phase up to 110^{o}C, resin injection phase according the VAP processs, final heating for curing to 180°C and at last the cooling down phase of the sample. On the right picture, the measuring points in the centre and the edge of the sample can be seen. The temperature-time diagram shows clearly, that the temperature is homogenous during the dynamic heating as well in the stationary state, where the curing of the resin takes place.

Fig.8: A T-profile fabricated with the HEPHAISTOS-CA1 according the VAP infiltration technology and cured at 180°C

The process shown here has been performed as well in conventional systems: autoclave and convection heat oven (autoclave used without pressure) to obtain comparable measurements of the material properties. As a result, the investigations of the DMA, DSC, ultra sound and ILS-tests showed additionally to the process technical advantages significant enhancements of the material qualities for the microwave processed materials (see Fig.11-12)
A specific difficulty for the CFRP fabrication is the immediate change of the material thickness. To consider this obstacle, different tests in prepreg- and infiltration technique have been applied successfully at high heating rates (8°C/min).

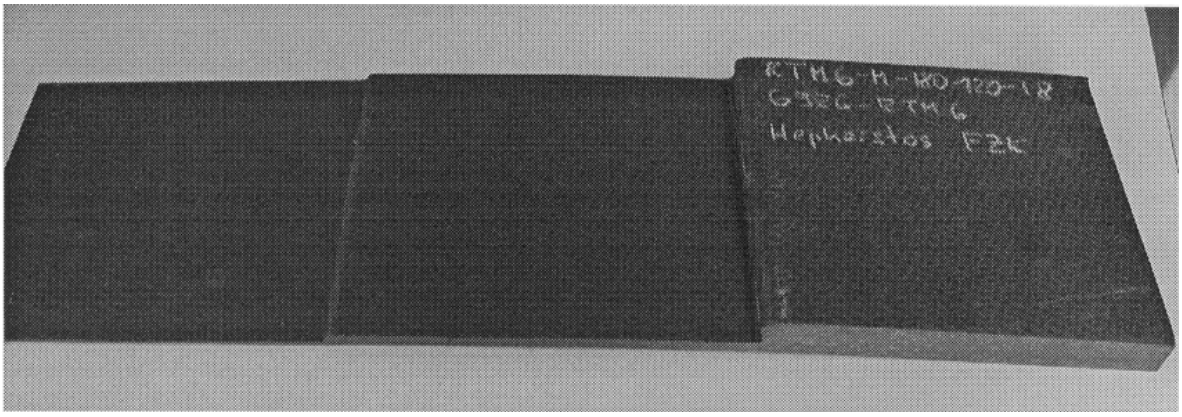


Fig.9: Large RTM6 injected CFRP Plate (60 cm x 20 cm) with integrated steps 2 / 6 / 20 mm.

As a result, Fig.9 shows a large sized CFRP plate (60 x 20 cm) fabricated in the HEPHAISTOS-CA1 microwave system. The curing was performed at 180°C using a standard RTM6 resin system.

Identical structures have been processed as well in prepreg. The used resin systems (e.g. 913) show a high exothermal reactivity. Due to the inertialess control of the microwave heating within the structure high heating rates can be applied without the danger of reactive overheating.

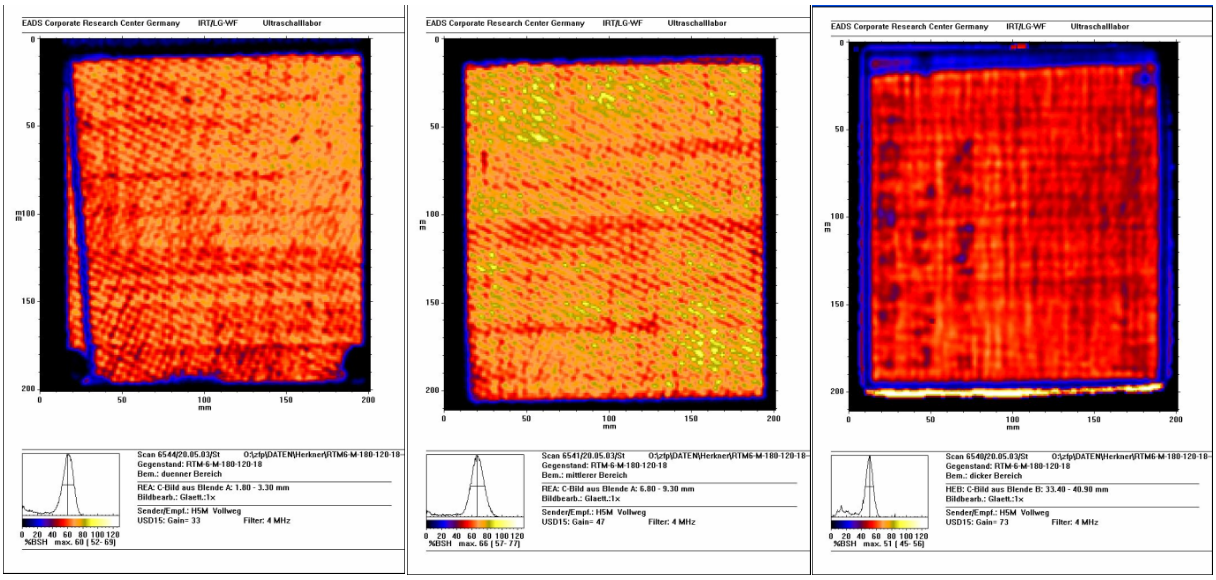


Fig.10: Ultrasound investigations of different sections of the step plate, left 2mm, centre 6mm, right 20mm thickness

It turned out by ultrasound scans, that all the different sections of the plates showed a high homogeneity. Extensive test series on aviation certification issues are currently ongoing.

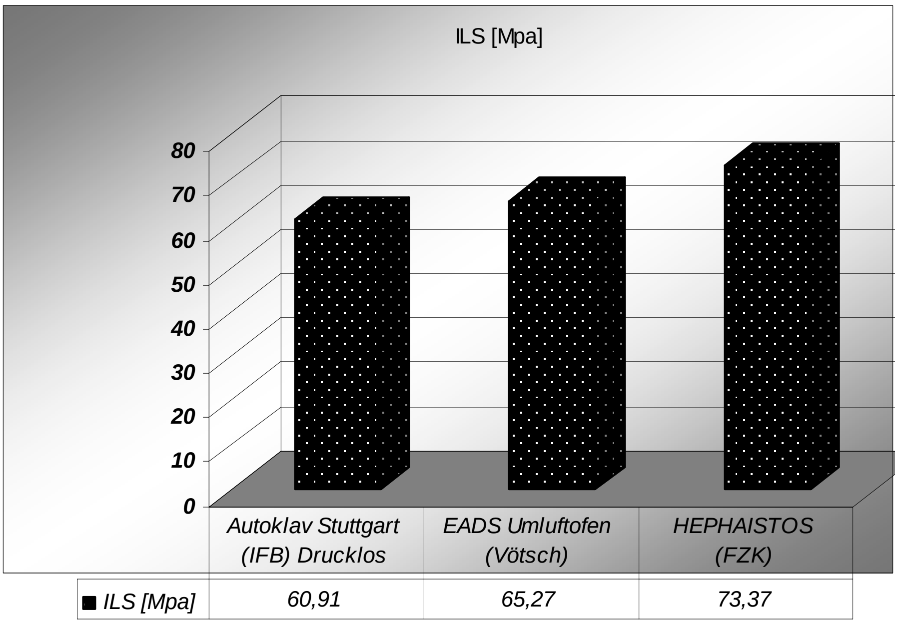
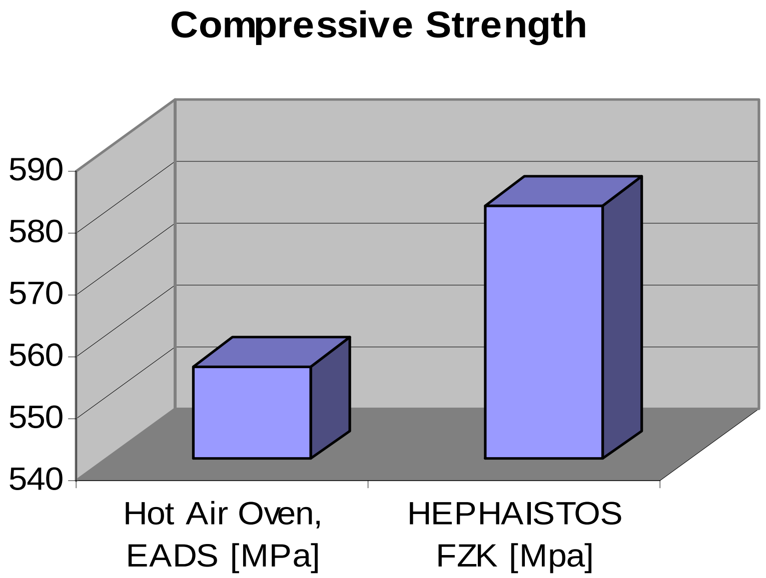


Fig. 11: Comparison of the averaged values for a test series of the interlaminary shear strength ILS with different oven systems using the VAP process



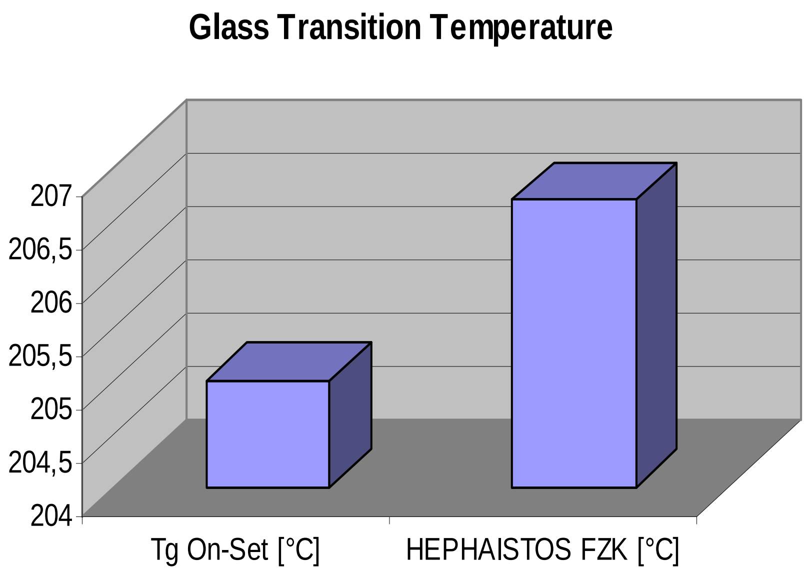


Fig. 12: Comparison of the averaged values for a test series for the compressive strength (up) and achieved Glass Transition-Temperature for the cured materials

3. SUMMARY AND OUTLOOK

In this paper, the motivations and advantages of a 2.45 GHz Microwave system for the fabrication of CFRP composites based on standard industrial components have been presented and discussed. The significant advantages of this new process as well as a comparison of the material properties with conventionally processed samples have been shown evidently. The material enhancements could be declared by theoretical considerations of the electromagnetic interactions with the laminate. To verify and optimize these effects, further detailed investigations are planned.

Fig. 13: The next step CA2 system is under current development

Additional potentials concerning the process control (reduction of cycle times) and the material properties of fabricated structures will be opened up due to optimized process steps and resin systems.The basic investigations could be finished successfully. Currently the scale up for production facilities and their technical specifications are worked out. A large system HEPHAISTOS-CA2 as well as a professional multi-usage system HEPHAISTOS-CA1P working under industrial guidelines are under development together with the Vötsch Company, Reiskirchen, Germany (http://www.v-it.com).

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