

INDUCTIVE PRE-BONDING OF STIFFENED STRUCTURAL COMPONENTS MADE OF CFRP USING THE EXAMPLE OF CO- AND SECONDARY BONDING PROCESSES

Hakan Ucan, Philipp Zapp, Deniz Akin
German Aerospace Centre (DLR). Institute for Composite Materials and Adaptive Systems,
Department for Composite Process Technology
Ottenbecker Damm 12, 21684 Stade, Germany

ABSTRACT

This paper presents a reliable and patented concept for the effective pre-bonding of stiffened elements on high performance structural parts. In a twofold bonding process, the irradiation of the alternating magnetic field heats the adhesive layer between the CFRP components and pre-bonds them together. The main bonding of the adhesive joint takes place in an autoclave under high temperature and pressure where it completely cures. The focus of this paper is on the pre-bonding process as a result of the enormous opportunities for development. That is based on the time-consuming heating techniques that are used in the current manufacturing process. Performed experiments show that the used concept based on inductive heating can drastically reduce the required time from 20 – 25 seconds per adhesion point to 2.5 – 3 seconds with the same or better pre-bonding quality as with actual state-of-the-art techniques.

Keywords Inductive Heating, CFRP, Pre-Bonding, Stiffening Elements, Stringer, Secondary Bonding, Co-Bonding, Fiber Bragg Sensors

1. INTRODUCTION

In the development of aircraft the topic of lightweight plays an essential role. More and more carbon fiber reinforced plastics (CFRP) find a steady growing demand in aircraft manufacturing and are equipped in their latest generation with over 50% of the total structure weight. This development is offset by labor-intensive manufacturing processes that cause very high costs for the components. This is the reason why it is important to provide rapid and cost-effective production processes today and in the near future. [1]

The structure coupling by means of classical joining process is and remains an inescapable issue. The challenge of this process is the effective bonding because in contrast to the decades of experience in metalworking the knowledge lacks in dealing with the material CFRP. Current bonding techniques based from today's perspective on the substance and form-fitting coincidence, and combinations of those. The adhesive technology as an integral joining method has been widely used for supporting aviation structures. In this case the bonding of thin laminates is particularly effective and a simple process, while with thicker laminates the design of the bonding points is complex and cost-intensive. [2] [3]

Looking at structural components the construction will be almost identical, primary structures stiffened in longitudinal (stringers) and traverse (frames) direction. In case of shell structures

with sufficiently high shearing modulus and buckling stability, the skin is reinforced with stringers in the longitudinal direction. This process involves in two steps in a material-logical adding. In the first step the stringers are pre-bonded with an aircraft certified adhesive film on the skin to avoid an unintentional movement and afterwards in a second stage bonded in an autoclave under high temperature and pressure. The elements that are responsible for the stiffening in the traverse direction, the so called frames, are riveted in a positive joining technology after the autoclave process (see Figure 1). [4]



Figure 1 Stringer and Frame Stiffened Shell Structure of an A350 [5]

The focus of this work was centered on the pre-bonding of the strings. In the current state of the art the adhesive film is warmed up with different heating technologies bases on thermal transport mechanisms like conduction, convection and radiation. A study of the literature on this subject indicates that several different electric heating techniques like heating mats or radiant heater can be used to pre-bond stringers. These technologies cause long cycle times. On the one hand the used heat transfer mechanism(s) plays an important role on the other hand the lack of automation and quality assurance is significant, too. With approximately over 480 aircrafts produced by Airbus per year and more or less 5 km bonded stringers per aircraft high costs are involved. [6][7]

This paper deals for the first time with the inductive pre-bonding of stringers on shell structures in secondary and co-bonding processes¹. It covers the main aspects of the phenomenology, material, technology and production specific parameters against the background of an innovative and effective feasibility.

2. TECHNICAL APPROACH FOR INDUCTIVE HEATING

The main advantage of induction heating is that the heat is generated directly in the workpiece. The inductor passes eddy currents into the CFRP material. Due to the resulting conductor resistance heat is generated. This heat generation and its operating principle on CFRP will be explained in detail.

¹ Secondary bonding (cured shell and cured stringers), Co-Bonding (uncured shell and cured stringers)

2.1 Theoretical Background and Operating Principle on CFRP

Inductive warming is based on the principle of induction from Michael Faraday. He was able to produce electrical current by moving a magnet through a coil of metal. The theory called it the *principle of generator*². Induction heating can be described on the basis of this phenomenon by two physical processes: the generation of an electromagnetic field and the existence of a temperature field created through the heat loss caused by eddy currents. A high-frequency current flows through a sink and generates an electromagnetic alternating field. In the electrically conductive process material thus an eddy current is induced. The penetration depth δ of the electric field is dependent from the operating frequency f , the electrical conductivity κ and the permeability μ of the used process material. The mentioned parameters can be assembled to the following formula (1):

$$\delta = \frac{1}{\sqrt{\pi f \mu \kappa}} \quad (1)$$

The eddy currents cause a joule heating within the conductor due to its resistance. The realistic electric power P in the process material is determined in this equation (2):

$$P = I^2 R_{\Omega} \quad (2)$$

Due to the electrical conductive properties of carbon fibers, inductive heating can be used with CFRP. The oscillating magnetic field induces high currents in the fibers, which in return set free their energy in the form of heat because of the electrical resistance. Besides this one, hysteresis- and capacitive effects are responsible for transferring energy from the magnetic field to the material as well. But these are negligible compared to the resistive effect. To aid the resistive effect it is necessary to provide closed loops made up of carbon fibers. This implies that a laminate of mixed layers performs much better than one of exclusively 0 or 90 degree plies. This behavior has been confirmed experimentally. These experiments also showed that the pre-compressing of the preimpregnated fiber material (prepreg) increases the efficiency of inductive heat transfer, because it reduces the electrical resistance at the intersection of two fibers. [8][9][10]

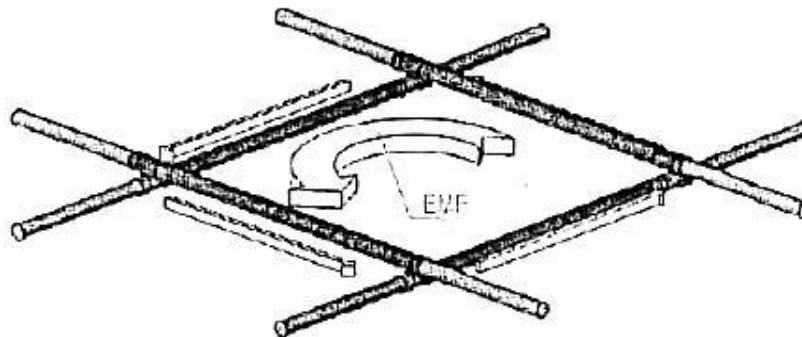


Figure 2 Operating Principle of Inductive Heating on CFRP [10]

² There exists also the *principle of transformer*, in this case the magnet doesn't move.

3. EXPERIMENTAL INVESTIGATIONS AND TEST EVALUATION

In this chapter, the automated induction cell and all other materials used for the tests are listed and explained. Then the second subchapter deals with the test evaluations and executions.

3.1 Automated Induction Cell with Integrated Measurement Technology

To achieve repeatable trials an automated two-axis portal system is used, which has a 1.8 m horizontal and 1.2 m vertical moving range. The inductors are attached to it using a spring system and a force sensor which allows for a high resolution force controlled movement upon the experimental setup reaching from 0 to 200 N contact force. The axes are controlled by a software Programmable Logic Controller (PLC) running on an industrial PC. On this platform data from each component including the induction generator is available and controllable, so freely programmable conditional movement sequences can be performed for all kinds of experiments (see Figure 3). [11]

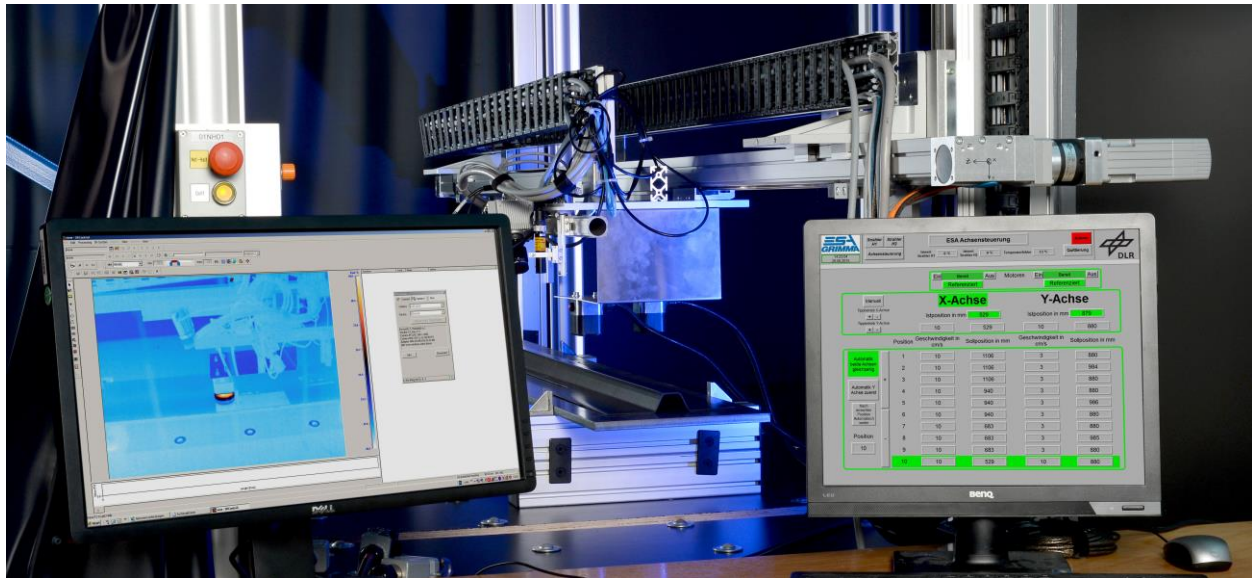


Figure 3 Automated Induction Cell with Integrated Measurement Technology

Underneath the x-axis a parallel 10mm thick steel plate simulates a typical invar mold used in CFRP aircraft manufacturing processes. On this flat surface a setup of a composite shell, adhesive film and stiffener can be arranged to heat it up inductively and measure the temperature simultaneously. This measurement is done by two different sensor systems: The Surface temperatures are measured by a thermographic camera, which is an A615 by FLIR. It has a resolution of 640 by 480 pixels and a frame rate of 50 Hz. To get online temperature values in between or even inside the composites during the induction process a more sophisticated sensor technology is required. [12]

Fiber Bragg gratings are able to measure either strain, temperature or both within a very thin fiber optic. If the fiber is applied in a way that no axial strain occurs, then only the temperature is measured, even in highly electromagnetically stressed environments. In the following experiments a *DI410* Fiber Bragg interrogator by HBM, Darmstadt, Germany is used. [13]

The induction hardware consists of a generator supporting up to two inductors. The generator is a *EW15* manufactured by IFF GmbH, Ismaning, Germany. It has a rated power of 15 kW and covers a frequency range of 8 to 18 kHz. The output voltage can be regulated by Pulse Width Modulation (PWM) and has to be set percentage wise. The resulting power depends on the inductive load of the setup (see Figure 4). [14]



Figure 4 Induction hardware manufactured by IFF GmbH

3.2 Test Evaluation

To investigate the applicability of inductive heating on pre-bonding processes of aircraft structures several experiments were done. At first small scale CFRP plates were made and pre-bonded by an inductively heated adhesive film. The form and size of the plates matched normed samples for tensile shear tests, which were performed for several different induction parameter sets and different temperatures. This should prove the basic feasibility and indicate the temperature range in which a provisional bond is established. Then two typical applications - co- and secondary bonding - were examined, where traditional pre-bonding methods were replaced by inductive heating. The main focus here was to investigate temperature distributions and the influence of frequency on the effective penetration depth. In the end all results were reflected in two full-scale experiments, where the inductive heating tested on A350 WXB panels.

3.2.1 Plant-specific parameter tests

In order to gather information about repeatability and random error in the measurements two series of repeatability test were performed. Each series consists of 15 induction cycles including measurements of the surface temperature, adhesive film temperature and actual power output. One series of experiments was done at 8 kHz (21% PWM) and the other one with 18 kHz (32.5% PWM), each for a duration of 3 seconds.

To investigate how changes in frequency affect the power absorption of the different materials some test similar to the co-bonding tests were also performed. This time the set power of the induction generator was set in a way that the actual power was always around 3 kW and the frequency was varied from 8 to 18 kHz. Again the three temperatures were recorded and evaluated to check for changes in the temperature distribution along the experimental setup.

3.2.2 Tensile Shear Experiments

To measure the mechanical properties of a provisional bonded structure several samples with 100 mm x 25 mm x 1.6 mm were made. Two bonded plates with an adhesive area of 1250 mm² make up one sample. The adhesive film used was of the type *FM300*. The samples were then heated up by induction with varying parameters. The temperature rise was recorded by a thermographic camera and assigned to the numbered samples. By the time those experiments were performed, there was no option to measure the temperature in between the plates. [15]

The samples were then tested by a *ProLine Z100* provided by Zwick GmbH & Co. KG, Ulm, Germany. The machine pulls the two plates apart with 10 mm/min and measures the resulting force. The maximum force indicates the quality of the bond. [16]

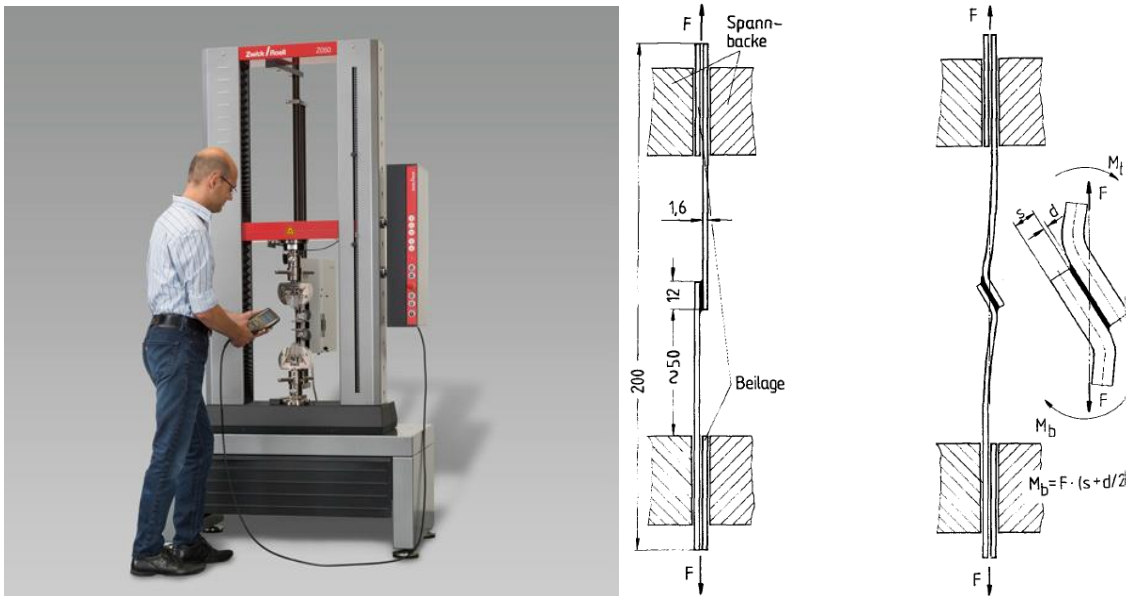


Figure 5 Proline Z100 (left), Tensile Shear Test (right)

3.2.3 Secondary- and Co-Bonding tests

The following experiments were done on the automated test stand described in chapter 3.1. They should reveal the temperature distribution of a typical stringer integration pre-bonding process during and after certain duration of electromagnetic induction. Furthermore how the parameters, especially power and frequency affect the temperature distribution. For each setup the ideal parameter setup heats the area around the adhesive film up to 50 – 60 C and keeps the temperature in the other areas as low as possible.

At first the temperature distribution of a co-bonding test setup during an inductive pre-bonding process was examined. To ensure that the adhesive film reaches a sufficient temperature to provide a good bond with the laminate, the temperature between a cured omega stringer made of unidirectional prepregand 6 mm thick wet prepreg plies was measured. These tests were done

without adhesive film in order to be able to reuse the experimental setup. The physical influence of *FM300* on the results is considered to be negligible. Another fiber bragg sensor was placed inside the laminate, just before the last layer. This provides additional information about the temperature distribution and can show if the material experiences a temperature too high for too long and therefore prevents the further use of the uncured material due to airbus regulations.



Figure 6 Trial setup with Omega stringer (1), prepreg laminate (2), tool (3) and the positions of the temperature measurements (on the left)

With the setup shown in Figure 6 the inductive warming process was done several times with varying power output and the measurements were taken. In between the tests the materials were cooled down to room temperature. After finishing the co-bonding test the prepreg layer structure used was cured in the autoclave following an *M21E* curing cycle. Both the stringer and the prepreg plate were then used in the secondary bonding experiments. Only using the exact same composite components makes the result of co- and secondary bonding comparable, since the influences of the prepreg layer structure and other properties on the induction process are considered to be not negligible. With both components being cured, the same testing with secondary bonding can be performed. Except for the second fiber bragg sensor which was placed in between two prepreg layers before. This was not possible with the new setup so it was placed between the mold and the CFRP plate. Measuring the actual power output, surface temperature of the stringer T_0 , stringer – skin temperature T_1 and skin – mold temperature T_2 , the co- and secondary bonding tests were all done with a 3 second induction cycle. The set power was varied from 20 to 55 % PWM.

4. RESULTS, OBSERVATIONS AND DISCUSSION

The evaluation in this part is concerning the coupon level tests. The aim was to set up the parameters of induction process for pre-bonding stiffener elements and to detect factors that may influence the process. The results should show the opportunities and profits of induction. Compared to conventional heating technology and obtained results should be taken to testify concerning optional applications.

4.1 Parameter Identification

The repeatability of the plant was in the focus of the first trials. The temperature data show a good correlation with the expected results. Next one of the results is presented, representative for both trials.

Table 1 Repeatability trials (f=18 kHz; t=3 s and 34.5% PWM)

#	P [kW]	T ₀ [°C]	T ₁ [°C]	T ₁₀ [°C]	Δ _{T1} [°C]
1	3	44.6	36.8	20.5	16.3
2	3	46.3	37.6	21.4	16.2
3	3	47.4	37.1	21.6	15.5
4	3.02	47	36.5	20.9	15.6
5	3.03	46.3	36.5	20.1	16.4
6	3.05	45.6	35.7	19.9	15.8
7	3.03	45.5	35.7	20.5	15.2
8	3.09	46	35.5	20.4	15.1
9	3.09	45.7	35.5	20.3	15.2
10	3.11	45.8	35.3	20	15.3
11	3.03	47.3	35.7	20.3	15.4
12	3.09	45.7	35.2	20	15.2
13	3.03	47.3	35.7	20.5	15.2
14	3.05	46.2	38.7	22	16.7
15	3.05	46.2	38.7	21.7	17

Average	46.19	36.41	15.74
Std. deviation	0.76	1.12	0.60

According to the theory the penetration depth rises equivalent to falling frequency. This is an important effect that had to be shown (see Figure 7). There are a lot of literature sources for dry fiber materials which show this but it is not shown for uncured or cured prepreg materials so far. This knowledge is fundamentally for an efficient process and for warming the correct areas (not the tool but the component!). The following diagram shows the temperature at several frequencies. The temperature sensors were placed on the top of the stringer (T₀) and between stringer – skin (T₁). The induced electric capacity and the time was always the same. [10]

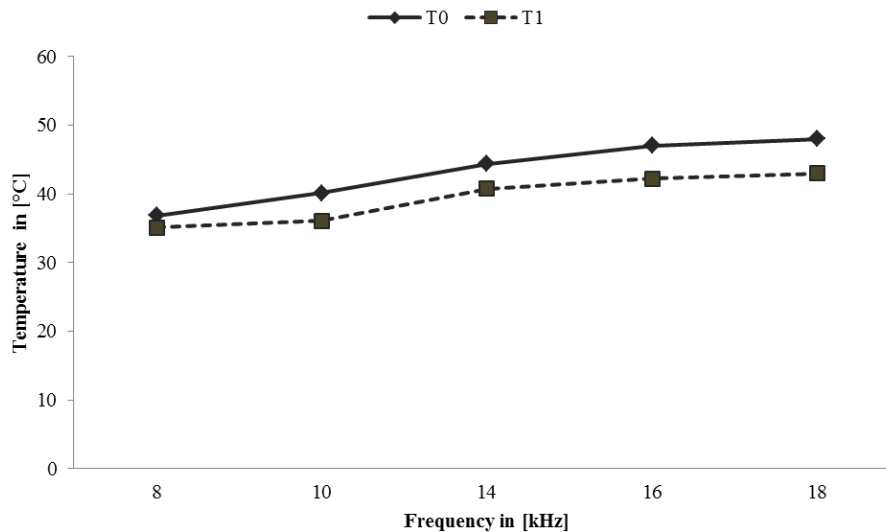


Figure 7 Frequency trials (P=3 kW, t=3 s)

The results confirm the thesis concerning the scientific theory. Figure 7 shows that the temperature in case of T_0 (surface stringer) and T_1 (stringer-skin) is rising equivalent to frequency. This can be explained in this way. The two sensors have only a few millimeters from each other and are warmed up by the electromagnetic field. The penetration depth is due to the low frequencies³ very high. This test series should indicate the influence of frequency changes and can be seen as a trend. It is planned to examine the frequency influence with an induction generator where frequencies can be set up to 100 kHz. On the other side the adhesive film begins to work at a temperature of about 45°C. That means that the temperature between stringer – skin (T_1) has to be 45°C at least, for fixing the stiffener elements. The results of the last test series confirm this.

As next the test series should proof the warming input by mechanical shear tension experiments like mentioned in 3.2.2 on coupon level. The results are shown in Figure 8. The quality of the adhesion rises with higher electrical power and with increasing processing time.

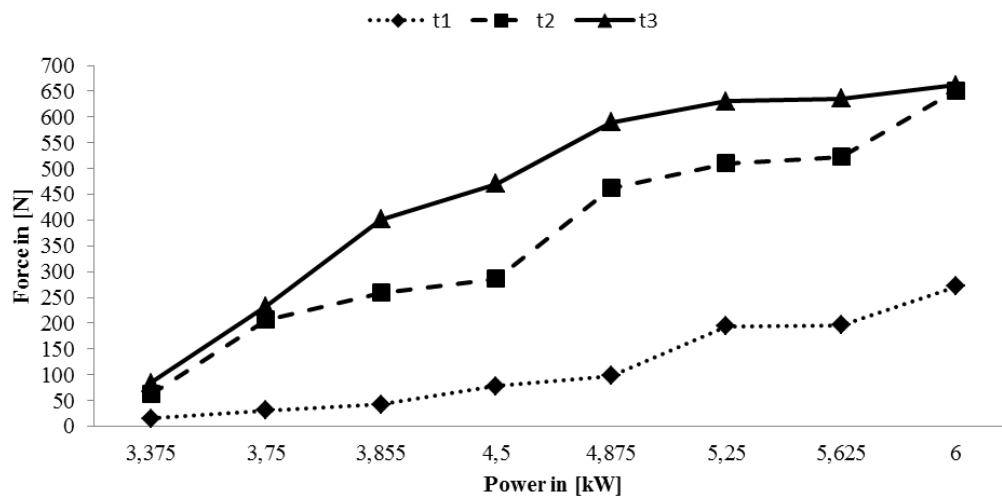


Figure 8 Analysis of the tensile-shear experiments with three different time steps ($t_1 < t_2 < t_3$)

Another figure (see Figure 9) shows a similar pendency between adhesion quality and temperature. This result also supports the thesis about the warming effect of the adhesive film: with higher induced electric capacity the heat generation rises and the adhesive film starts curing. Conspicuous is the rise at a temperature of approximately 50°C. At this temperature the adhesive film begins to jell. Because of this the shear tension forces rises especially in this area. This proves that the needed temperature reaches the area between the stringer - skin.

³ It has to be mentioned that 18 kHz is the highest adjustable frequency in the existing plant, but other plants could have a range up to 100 kHz.

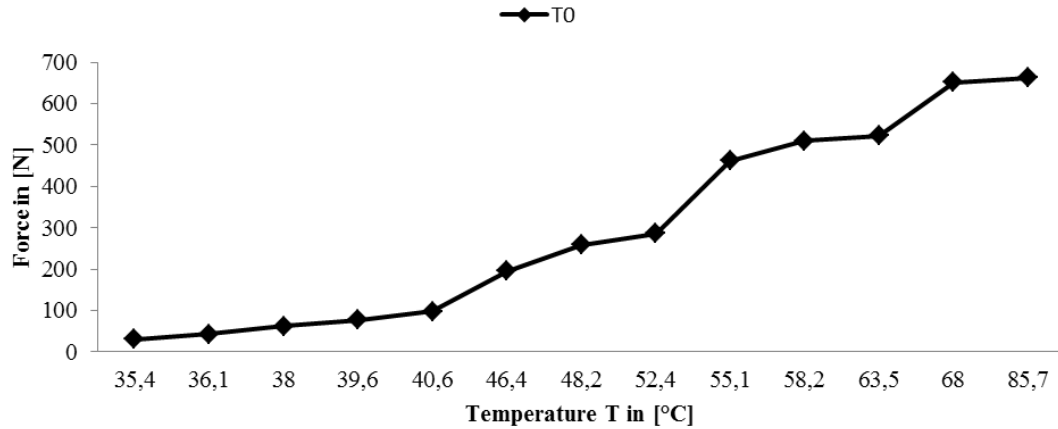


Figure 9 Tensile-Shear Experiments – Comparison Temperature / Force

4.2 Comparison of the Secondary and Co-Bonding Processes

Figure 10 shows the occurring temperatures during the inductive warming of co- and secondary bonding setups. It is obvious that the mean temperature at the sensor positions T0 and T1 is higher with the secondary bonding setup. The difference between T0 and T1 is higher as well. So the cured laminate seems to absorb more energy than the uncured laminate. This explains the higher mean temperature as well as the higher temperature difference since the stringer is the same and therefore absorbs the same amount of energy. The reason for the higher energy absorption could be the more compact fiber structure and the higher content of fiber volume, because it allows for more closed fiber loops and a better conductivity. This comparison shows that every setup needs its own setup. It is not possible to adopt setups between different processes and components without new measurements and parameter adjustments.

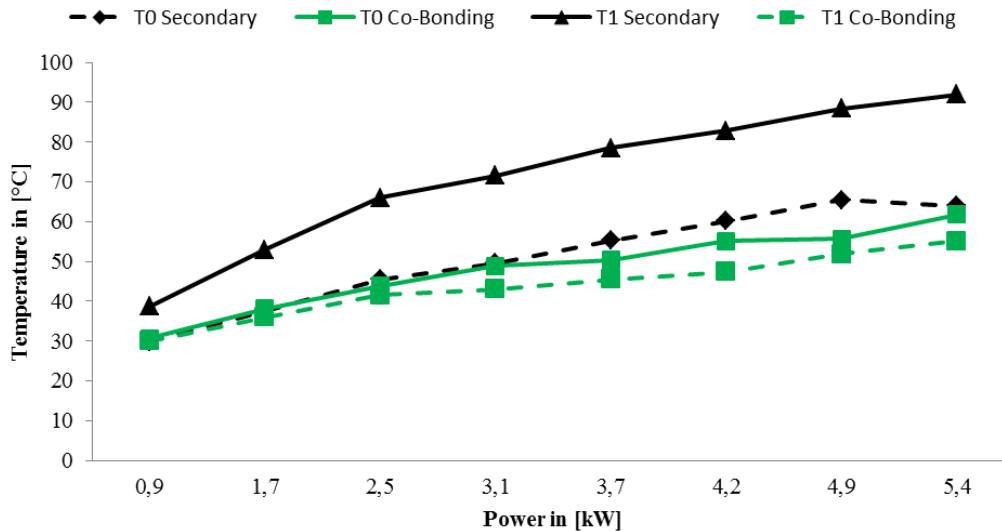


Figure 10 Comparison Secondary- and Co-Bonding Processes

4.3 Full Scale Tests

The induction pre-bonding technology was applied to bond stiffener elements in two full scale fuselage segments of the Airbus A350 XWB. The first fuselage segment had a constant thickness and the process was executed in a secondary bonding process. The second one had the original skin layer setup with ramps and was performed in a co-bonding process. The intention was to verify the transferability of the results so far from the trials to the full scale test. For the secondary bonding process the parameters had to be changed minimally⁴ because in the trials the differences in electrical characteristics between invar and steel materials are negligible and therefore ignored (see Figure 11). But conspicuous was the skin layer setup of the second fuselage segment with different thickness and directions. It may be noticed that the layer parameters play an essential role for the parameter setup of the induction process like mentioned before. The parameters needed to be reconfigured in a range of $\pm 5\%$ PWM in the co-bonding process because the ramps and layer directions of the second fuselage segment (see Figure 12) was more complex than in the trials. Finally it may be stated that both full scale tests have found a good agreement with the preliminary results.



Figure 11 Full Scale Pre-Bonding Tests A350 XWB shell - skin layer setup without ramps (constant thickness)

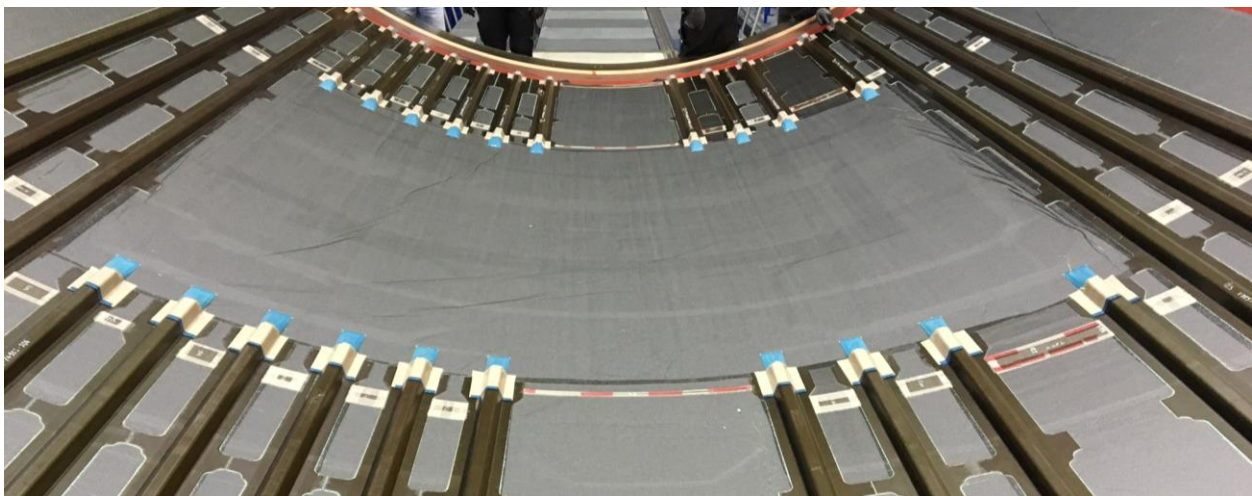


Figure 12 Full Scale Pre-Bonding Tests A350 XWB shell - original skin layer setup with ramps

⁴ The skin layer setup in thickness and direction was equal between the tests in the trials and the full scale tests.

5. CONCLUSIONS AND FUTURE PERSPECTIVES

The presented paper describes an innovative and effective method for the pre-bonding of stiffened structural components made of CFRP with focus on the stringer fixation. The processing speed inhibits this process stage due to the currently heating technologies. These were examined and partially integrated into the experiments presented in this paper. The results demonstrated that the process times took place within the range of 20 to 25 seconds (radiant heater) to several minutes (heating mats).

The aim of this study was to show that the induction technology is a possible efficiency-enhancing option in the process of the pre-bonding of components made of CFRP. The process was adjusted through trials to bond stringers in the secondary and co-bonding processes. The comparison of both processes showed that the preliminary results were expected but the inductive heating parameters cannot be transferred directly due to different material conditions. In both processes the pre-bonding time was between 2.5 and 3 seconds under consideration of all process specifications made by aircraft manufacturers. The required process time was 10 times faster than the current technologies. In order to verify the inductive technology the experiments were extended to two full-scale tests in secondary and co-bonding processes. The results of these tests have been found to be a good agreement with the preliminary results. In this way the reliability and the productivity of the process could rise significantly.

The next steps deal with automation and quality assurance of the inductive heating to make the pre-bonding process even more efficient and safe. Robotics and sensor technologies play an important role in this aspect.

Acknowledgements The authors would like to thank the European Community for its support of the investigation which was funded by the MAAXIMUS project. Further thanks go to our colleagues for the constructive discussions and to our partners Prof. Dr.-Ing. Christian Lammel as well as Ralf Schuster from IFF GmbH.

6. REFERENCES

1. M. Wiedemann, *CFK – Status der Anwendung und Produktionstechnik im Flugzeugbau*, Faszination Karosserie, Braunschweig, 2009
2. H. Schürmann, *Konstruieren mit Faser-Kunststoff-Verbunden*, 2. bearbeitete und erweiterte Auflage. Springer Verlag, Berlin Heidelberg, 2007
3. M. Flemming, G. Ziegmann, S. Roth, *Faserverbundbauweisen, Fasern und Matrices*; Springer-Verlag, Berlin Heidelberg 1995
4. R. W. Johnson, L.W. Thomson, R.D. Wilson, *Study on Utilization of Advanced Composites in Fuselage Structures of Large Transports*, Final Report, NASA, Washington, 1985
5. Airbus, www.airbus.com, 2011
6. A. Sauermann, *Method of connecting two fuselage sections with the formation of a transverse joint, and transverse joint connection*, Airbus Operations GmbH, Hamburg, 2009
7. T. Kruse, *Bonding of CFRP primary Aerospace Structures – Boundary Conditions for Certification*, CFK Valley Convention, Stade, 2013

8. A. Tewald, T. Walther, *Simulation der Induktionserwärmung beim Kunststoffspritzguß*, 15. CAD-FEM User Meeting, Kassel, 1997
9. T. Ströhlein, *Volumetrische Erwärmung von Kohlenstofffaserhalbzeugen*, PhD Thesis, Technische Universität Braunschweig, 2012
10. G. Benkowsky, *Induktionserwärmung*, Berlin: Verlag Technik GmbH Berlin, 1990.
11. Burster, *Datasheet -Zug-Druck-Kraftsensoren Typ 8523 Typ 8531*. Gernsbach, 2015
12. FLIR, *Datasheet - FLIR A315 / A615 Thermal Imaging Cameras for Machine Vision*, Nashua, 2015
13. HBM, *Manual - Interrogators for optical strain gages*. Darmstadt, 2015
14. IFF GmbH: *Manual - Betriebsanleitung für Geräte zur Induktiven Erwärmung*. Ismaning, 2015
15. Cytek Solvay Group. *Datasheet - FM 300 Epoxy Film Adhesive*. Tempe, 2015
16. Zwick GmbH & Co. KG, *ProLine Tisch-Prüfmaschinen Z005 bis Z100*, 2015