PROCESS PARAMETERS FOR INDUCTION WELDING OF METAL/COMPOSITE JOINTS

Peter Mitschang and Rudi Velthuis

INSTITUT FUER VERBUNDWERKSTOFFE GMBH
Erwin-Schroedinger-Strasse Bld. 58, 67663 Kaiserslautern, Germany
peter.mitschang@ivw.uni-kl.de

ABSTRACT

Material mix is one of the challenging topics of the future. One specific subtopic is the development of joining techniques being able to join thermoplastic fiber reinforced polymer composites (TP-FRPC) with light-weight metals to hybrid structures to reduce the specific disadvantages of the individual material groups and combine the advantages. Induction welding can be used to weld FRPCs as well as for joining of metal/TP-FRPC. This paper shows the development of a discontinuous induction welding to join carbon fiber reinforced polyamide (CF/PA66) and aluminum (AlMg3). The major goals are how does metal and polymer bond and what are the main parameters influencing the welding strength.

1. INTRODUCTION

The use of continuous fiber woven fabrics increased in the last years. More and more lightweight structures, especially those made of metal/TP-FRPC are of interest. These allow innovative product designs and developments in many different industrial areas. Hybrid lightweight structures formed with metal/TP-FRPC enable a new generation of products with applications in the automotive and aircraft industry. The development of joining techniques which are able to combine TP-FRPC with lightweight metals to form hybrid structures reduce the specific disadvantages of the individual material groups and combine their advantages [1]. When manufacturing metal/polymer structures, the surfaces of the partners to be joined are brought together, in order to create a permanent joint. Complex physical and chemical mechanisms take place on the interfacing surfaces. The joining partners are therefore usually treated before joining to improve the surface area properties. Some treatments and their effects are shown in Table 1.

Table 1: Surface treatment methods and their properties [2]

Method	**Treatment**	**Effect**
Cleaning, degreasing	• Washing with a solvent, like acetone	• Cleaning of the joining partners
Mechanical treatment	• Grinding • Sandblasting • Polishing	• Geometrical changes of the surface → roughness • Removal of contamination layers
Chemical treatment	• Etching in NaOH • Pickling in acid	• Change in the chemical structure of the surface (e.g. oxidation)
Physical treatment	• Plasma cleaning	• Removal of organic compounds • Surface activation

The adhesion models describe beside mechanical adhesion, due to penetration of polymer into pores on the surface of the metal joining partner, also specific adhesion. This specific adhesion is divided into physical, chemical, and thermodynamical mechanisms [2]. With the physical mechanisms the entire range of physical bonding forces, like dipole-forces, dispersion forces, and hydrogen bridges, takes place. Chemical bonds are formed due to functional polymer groups, which are able to build strong bonds with the metal partner. Specific surface and interface energies play an important role in the wetting and compatibility of the joints. This is also called thermodynamical adhesion.

2. TESTING METHOD AND INDUCTION WELDING EQUIPMENT

The materials used were aluminum (AlMg3), steel (DC01), carbon fiber reinforced PA66, and carbon fiber reinforced PEEK. The organic sheets were manufactured on a continuous compression molding machine at IVW. The metal sheets had a thickness of 1.0 mm, the carbon fiber reinforced sheets of 2.0 mm. As carbon fiber reinforcement a woven fabric with a 5H satin style was chosen and resulted in a fiber volume content of 48 %. To investigate the influence of the surface properties on the bonding, single-lap joints in accordance with DIN EN 1465 were chosen (Figure 1).

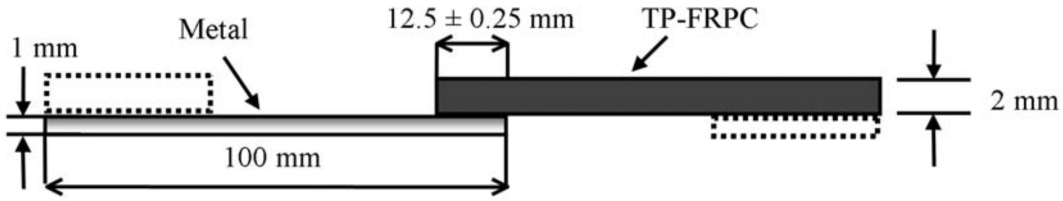

Figure 1: Single-lap joint in accordance with DIN EN 1465, sample width 25 mm

Two plates with a length of 37.5 mm, a width of 25 mm, and a thickness of 1 and 2 mm were attached on both ends of the sample to ensure a parallel load introduction. The free clamping length therefore is 112.5 mm. The testing takes place at a speed of 1 mm/min. The mechanical tests of welded samples were performed on a standard universal testing machine (1485, Zwick).

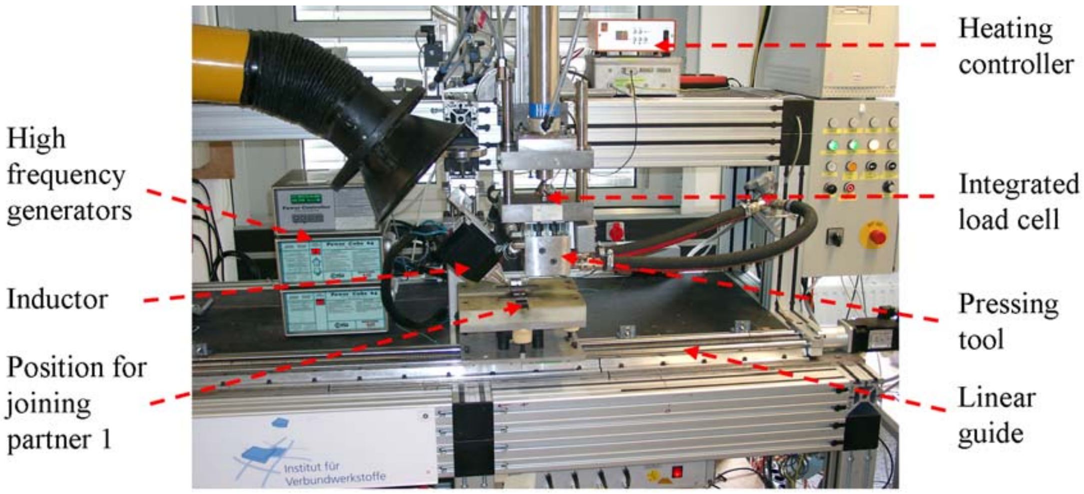

Figure 2: Overview of the equipment for discontinuous induction welding

Discontinuous induction welding equipment was set-up for manufacturing of the metal/composite-joints in accordance with DIN EN 1465 (Figure 2). The equipment consists of high frequency generators (operating frequency 800 kHz), an inductor head, a heating controller to press the samples at a required temperature, and an integrated load cell to determine and regulate the joining pressure. Variable process parameters are the generator power, the speed of transportation, the consolidation pressure, and the temperature of the pressing tool. Beside the direct process parameters the treatment of the specimens plays an important role.

Figure 3 shows that a further significant increase of the shear tensile strength can be achieved by combining the best pre-treatment methods. Compared to acetone treated samples (AT) the application of corundum blasting and additional polymer nearly doubles the shear tensile strength for both the AlMg3-CF/PA66 and the DC01-CF/PEEK.

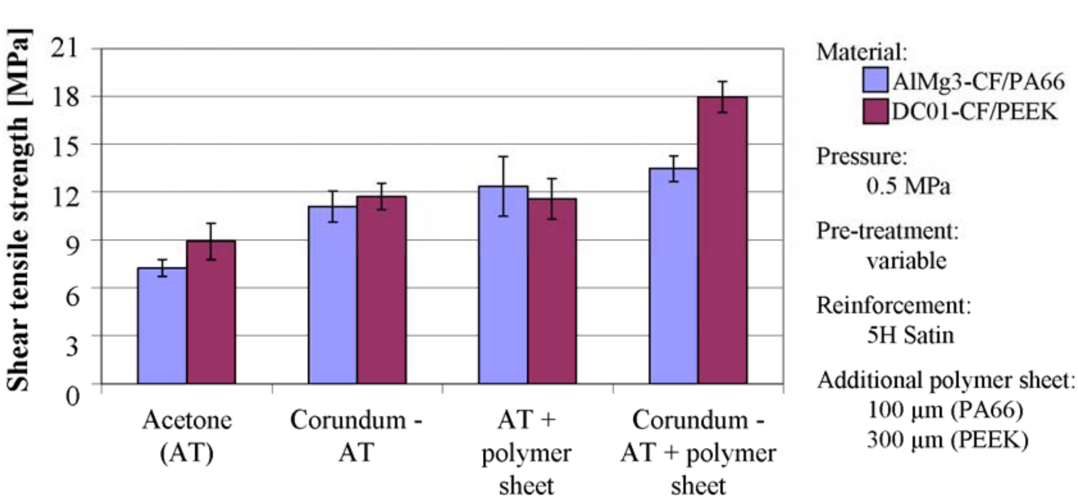

Figure 3: Influence of the combined process parameters on the shear tensile strength

Figure 4 shows a micrograph of the cross section of a sample, which was corundum blasted and had additional polymer. The formed polymer intermediate layer in the joining zone is recognizably smaller than the additional polymer sheet of 100 µm thickness before welding.

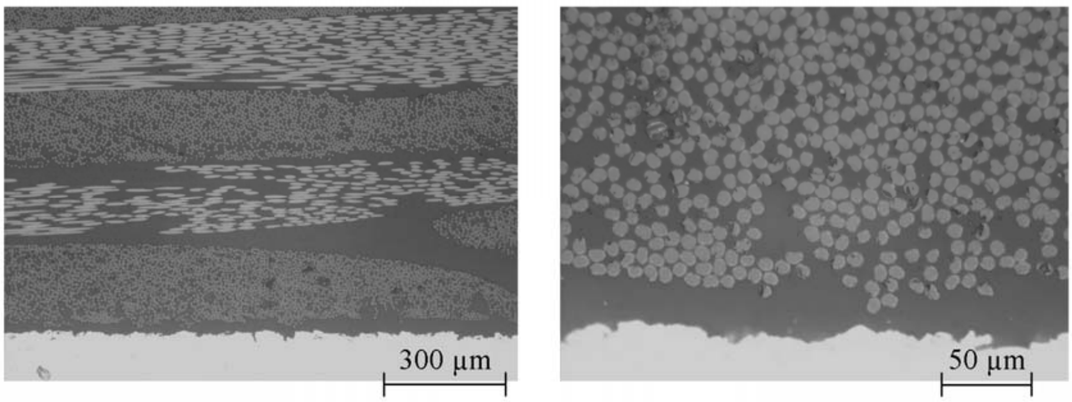

Figure 4: Micrograph of the joining area of a corundum blasted AlMg3 with an additional PA66-sheet (initial thickness: 100 µm)

3. HOLDING TEMPERATURE, HOLDING TIME, AND COOLING RATE

The tempered pressing tool enables pressing at a given temperature during a certain pressing time, and cooling with a given cooling rate.

The state of the art [3] seems to imply that the following settings should increase the shear tensile strength of both AlMg3-CF/PA66:

Table 2: Setting for welding AlMg3-CF/PA66

Parameters of the pressing tool:		**Exp. 1**	**Exp. 2**	**Exp. 3**
Holding temperature [°C]	A	280	10	140
Holding time [min]	B	7	0	2
Cooling rate	C	6 K/min	27 K/s	10 K/s

The three experiments with the above given conditions were performed to verify these observations.
In the case of experiment #1 CF/PA66 the high temperature of the pressing tool (above melting point of PA66) even at the relative low pressure of 0.5 MPa presses the polymer out of the joining area and carbon fibers are in direct contact with the AlMg3. Here no adhesion can take place so the shear tensile strength is very low (average 7 MPa). Experiments #2 and #3 were performed with a constant pressing temperature of 10 °C and 140 °C. Then the polymer was quickly cooled down below melting point T_M (see Figure 5).

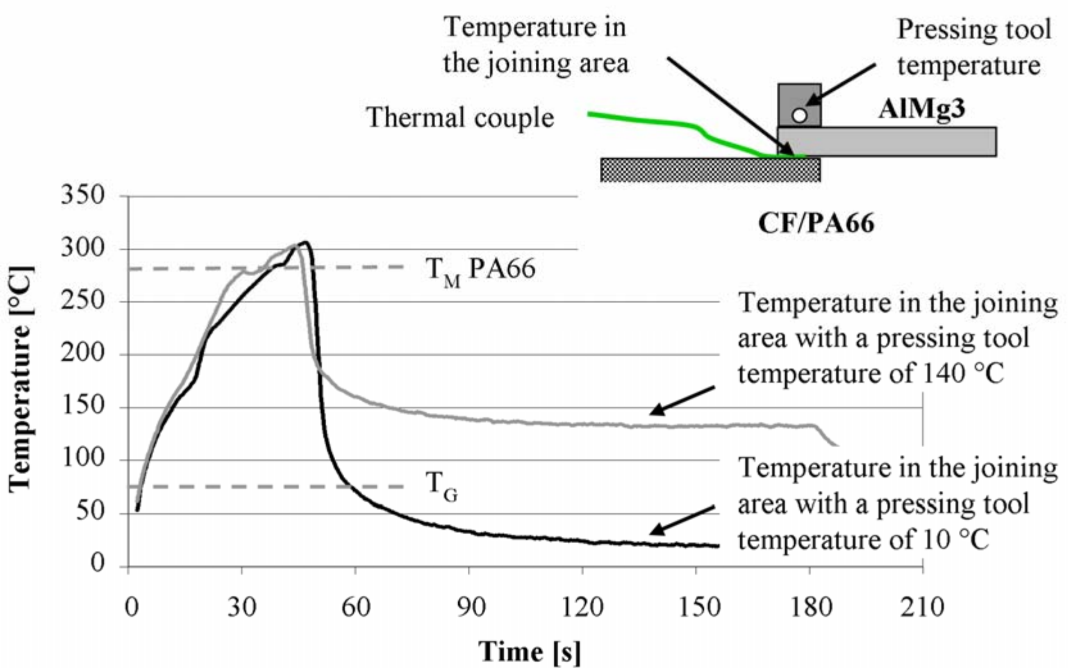

Figure 5: Temperature vs time in the joining area for corundum blasted AlMg3-CF/PA66 with additional polymer

These two pressing temperatures did result in slightly different shear tensile strength values up to 14.5 MPa (Figure 6). The values of crystallinity for the various settings vary only in a small range. This indicates a very fast crystallisation of PA66.

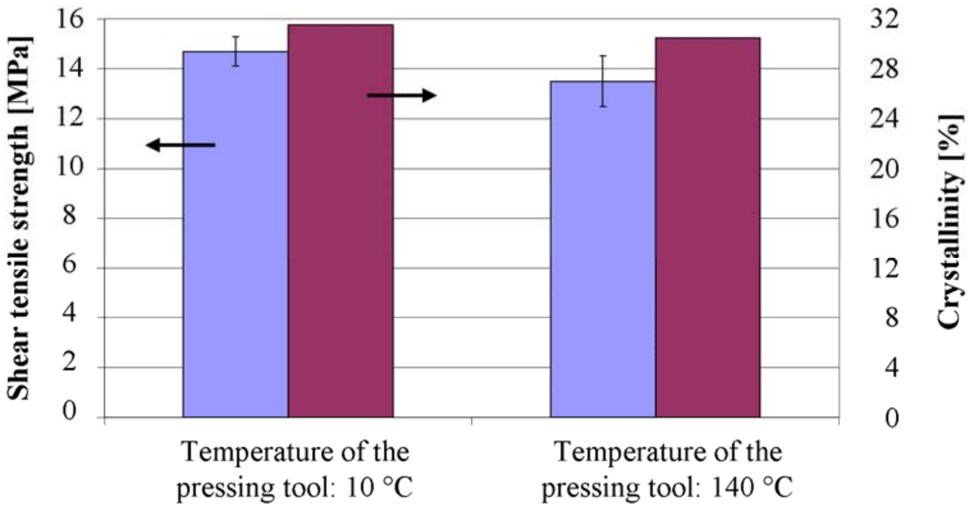

Figure 6: Shear tensile strength and crystallinity of corundum blasted AlMg3 and CF/PA66 with additional polymer pressed at 10 °C and 140 °C

The cold pressing temperature leads apparently to many quickly grown small crystals instead of slowly grown large crystals.

These experiments illustrate that choosing the appropriate processing conditions can increase the shear tensile strength. As the differences in crystallinity are very small no general explanation is found and further large scale investigations are needed.

4. DEGRADATION TEMPERATURE AND INFLUENCE ON THE SHEAR TENSILE STRENGTH

Ehrenstein [5] shows the dynamic thermogravimetric analysis (TGA) of PA66 with a heating rate of 10 K/min in oxygen, argon, and helium. In order to observe a similar behavior for the reinforced PA66 used, TGA-experiments with various environmental gases were performed (Figure 7).

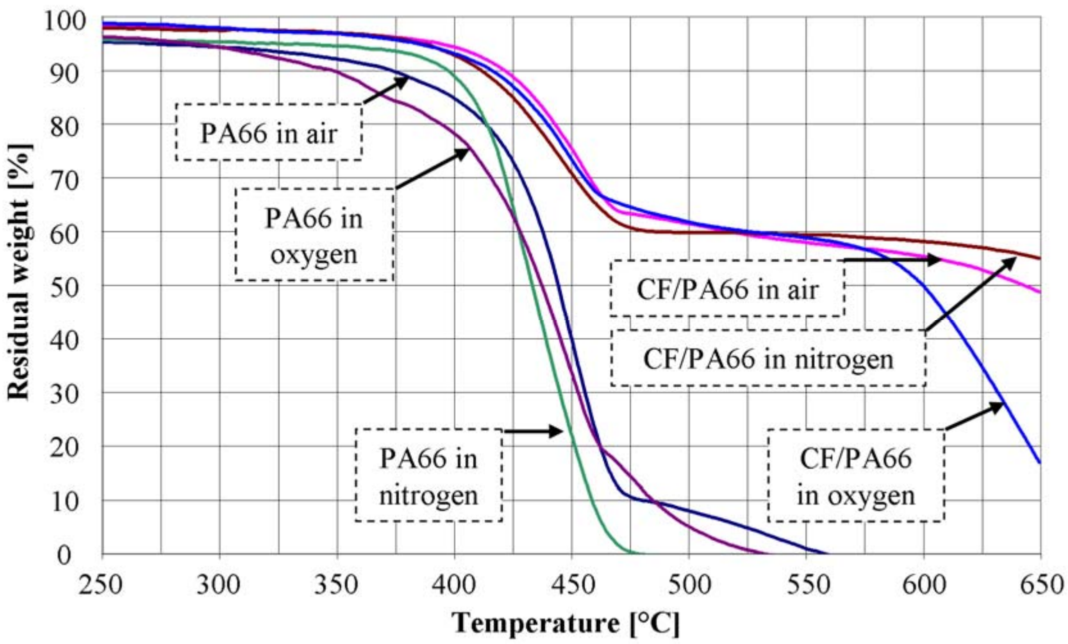

Figure 7: Thermogram of PA66, CF/PA66, at 10 K/min in various environmental gases (oxygen, air, and nitrogen). Specimen mass: 11-17 mg

Figure 7 shows an unexpected result for PA66. Although in [5] a large increase of the decomposition temperature for PA66 was observed, this behavior is not confirmed by the performed experiments. A closer look at the PA66-sheet thermogram illustrates that the oxygen influences the decomposition only to a low extent. The decomposition is therefore supposed to be mainly dominated by thermal degradation instead of thermal oxidative degradation. In the case of carbon fiber reinforced PA66 this effect is even smaller compared to the PA66-sheets. It should be noted that although between 300 and 400 °C a weight loss of only 5 % for CF/PA66 in oxygen, air, and nitrogen was observed, the molecular structure has significantly changed, but this cannot be determined by the TGA [6].

Moreover, at low heating rates (e.g. 0.1 or 1.0 K/min) a larger influence of the gases on the polymer is expected. On the opposite, heating rates of 300 °C/min for welding are normal and will even reduce the small effect of the environmental gas on the PA66.
Although the thermogram in the case of carbon fiber reinforced PA66 does not show an increase in the process window, several welding experiments with PA66 were performed in a nitrogen environment to observe a change in structural influences. The influence of the oxygen exclusion on the shear tensile strength of the single-lap joints is illustrated in Figure 7.

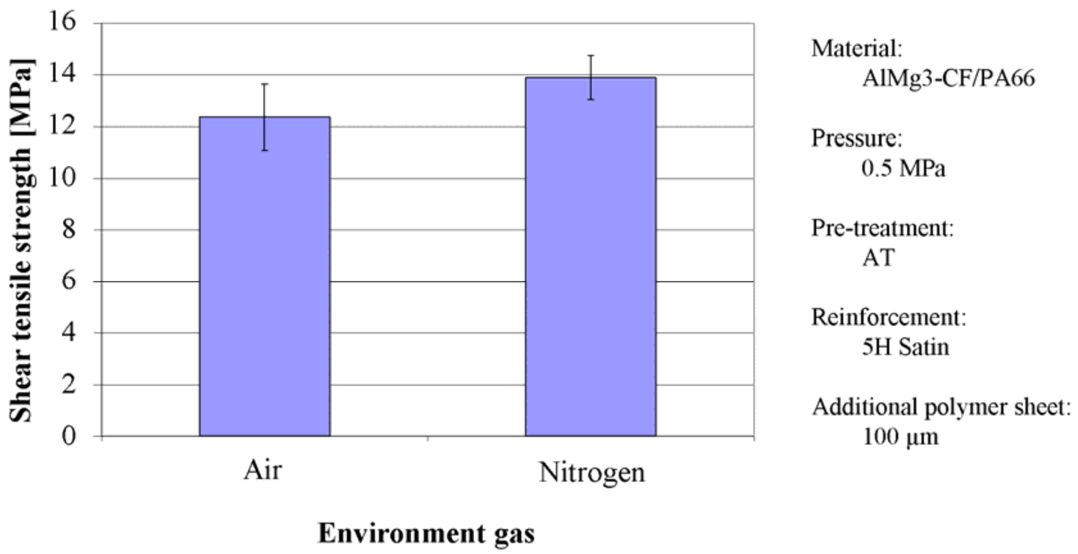

Figure 8: Shear tensile strength of AlMg3-CFPA/66-samples welded in an air and a nitrogen environment

The exclusion of oxygen leads to the same shear tensile strength for welding of AlMg3-CF/PA66 in air as the PA66 degradation is mainly thermally induced. For other polymer types (like PP) the thermal degradation is oxidative. Especially when the CFRPC-joining partner is the top joining partner and heating of the entire thickness takes place, the exclusion of oxygen can lead to better results. Locally higher temperatures can be obtained when heating the CFRPC-joining partner in the carbon fiber rovings, because these rovings are heated inherently and transfer the generated heat to the polymer.

In the case of welding of other thermoplastic materials (e.g. GF/PP) large quality improvements are expected as the manufacturing window is increased as is shown by TGA-measurements (Figure 9). The material used was a GMT (GF/PP).

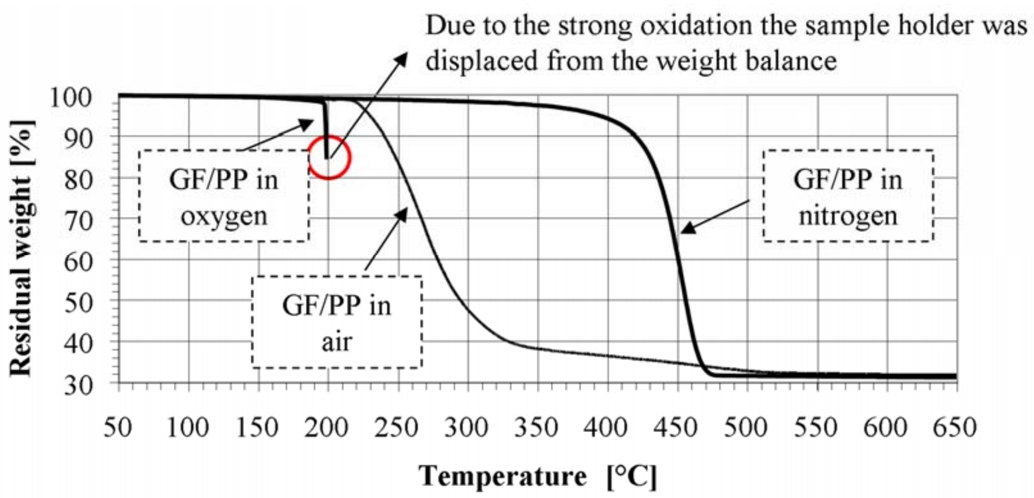

Figure 9: Thermogram of GF/PP in various environmental gases (oxygen, air, and nitrogen). Specimen mass: 12-16 mg

When GF/PP was heated in a nitrogen atmosphere up to 390 °C it shows a weight loss of 5 %, whereas for GF/PP in air the same weight loss of 5 % is observed at already 230 °C. The presence of pure oxygen even leads to displacing the sample holder from the weight balance, so the measurement was stopped at 200 °C. This phenomenon happened twice. This clearly shows that oxygen influences the polymer degradation. Oxygen exclusion by a shielding gas (like nitrogen) can be used to enlarge the process window for welding of GF/PP. The experiments show that the application of a non-oxygen environment creates new potential for welding. The gas nozzle can be located close to the welding zone and can also be used as a cooler.

5. BUILDING A MODEL FOR PREDICTING INDUCTIVE HEAT GENERATION

Analytical calculations and FE-simulations are useful to provide an insight into the equipment and process parameters that influence the induction heating. The obtained information enables the improvement of the process as the parameters are identified. Moreover, the calculations enable the application of a quality assurance using indirect measurements, e.g. measuring the temperature outside of the welding zone to obtain information about the temperature in the welding zone. First the material properties need to be determined to obtain reliable starting conditions for the calculations. Many of the needed parameters (e.g. thermal conductivity, and specific heat capacity) are not constant, but are temperature dependent, and therefore had to be determined experimentally. In [3] thermal properties are given for both AlMg3 and CF/PA66. These values are used for calculations and FE-simulation with the Ansys Workbench 10.0 software.

To compare the experimental results with an FE-model, CAD-models of the materials were created in SolidWorks 2005 and imported into Ansys Workbench 10.0. Here, an internal heat source can be assigned to the welding zone. By means of calorimetry the generated heat caused by induction heating can be determined (Figure 10).

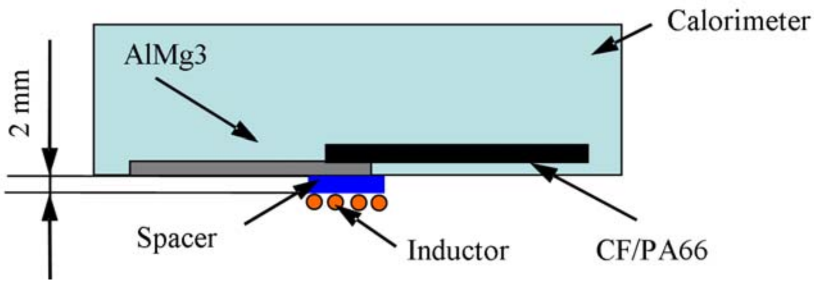

Figure 10: Experimental set-up for the calorimetry experiment

The samples are placed in a vessel containing a certain volume of water. Inductive heating is applied and the temperature change is measured. The generated heat can be measured by using the following equation:

$$Q = \Delta T \cdot (m_{Sample} \cdot c_{p,Sample} + m_{Water} \cdot c_{p,Water} + m_{Vessel} \cdot c_{p,Vessel})$$

Q	=	Heat stored in water [J]
ΔT	=	Measured temperature difference in the calorimeter [K]
m_x	=	Mass of the sample, water or vessel [g]
$c_{p,x}$	=	Specific heat capacity of the sample, water or vessel [J/(g·K)]

For the calculation of the generated heat the following conditions were used.

Heat capacity water:	c_p = 4.18 J/(g·K)
Heat capacity aluminum:	c_p = 0.90 J/(g·K)
Heat capacity vessel (PC):	c_p = 1.3 J/(g·K)

The heat capacity of the water is regarded to be constant in the applied measuring range. By recording water temperature in the vessel in respect to time, the heat transferred into the water is calculated, thus, the heat generation in the joining partner can be determined. The generated heat was determined and its value of 8.0 x 10^7 W/m³ was used as internal heat source for the overlap area of the AlMg3 to simulate the induction heating (Figure 11).

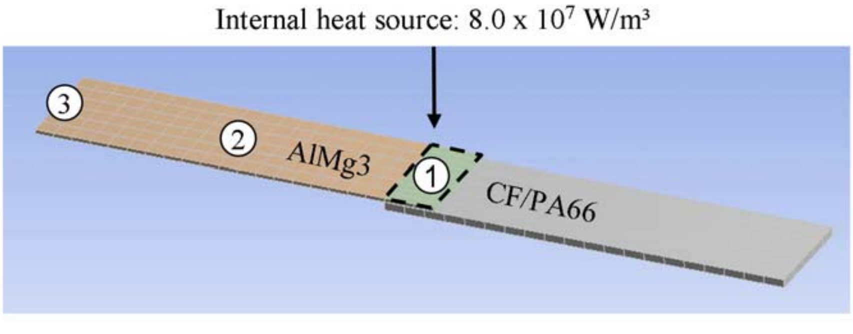

Figure 11: Mesh used for simulation of the heat transfer in AlMg3-CF/PA66-joint

The values of the measuring points one to three correspond very well with the measured values indicating that the used FE-model is able to predict the temperature distribution after applying an internal heat source. For the developed model the sample holder was also integrated. Figure 12 shows the temperature distribution after 50 seconds of heating and a view of the sample's cross section.

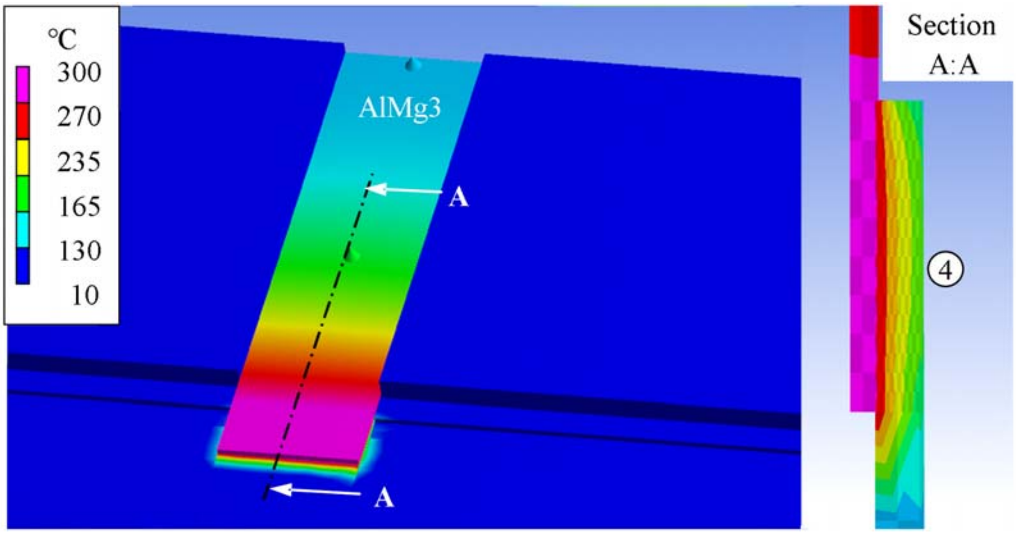

Figure 12: Temperature distribution after 50 seconds of heating with an internal heat source of 8.0 x 10^7 W/m³ and the temperature at position 4

Here it can be clearly observed that the thermal conductivity of the AlMg3 is much higher than in the CF/PA66. For position 4 a temperature of 150 °C was experimentally determined, the simulation leads to a value of approx. 165 °C.
The good correspondence between the experiment and the FE-calculations are also proven by comparing the results of heating after 50 seconds from the infrared camera observation and the FE-model (Figure 13).

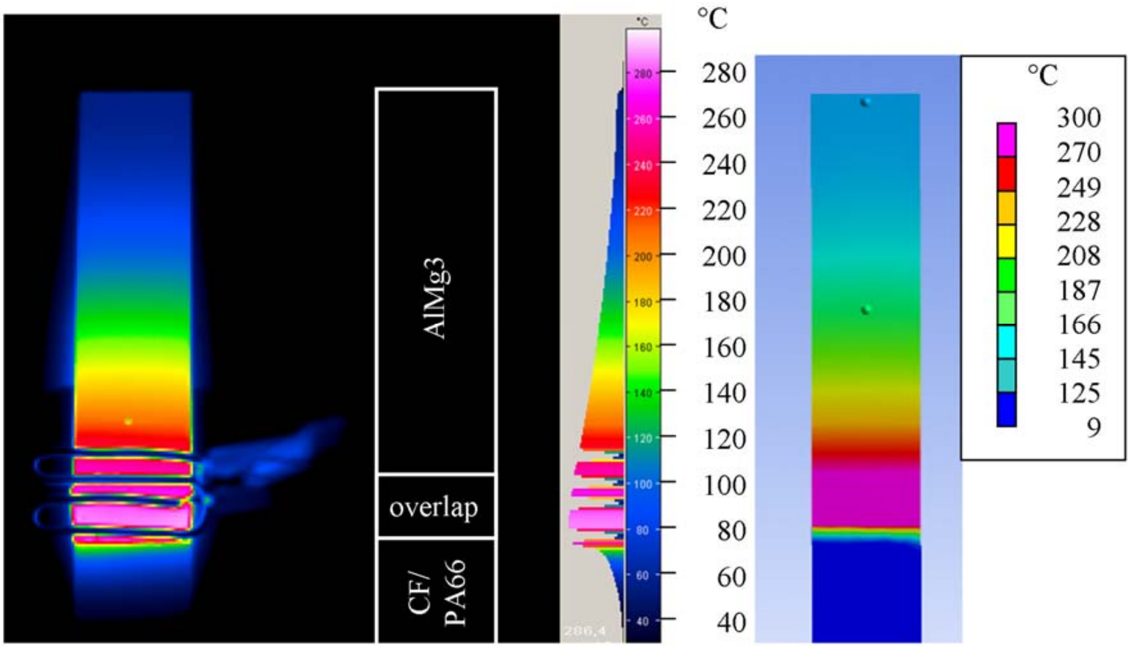

Figure 13: Temperature distribution after 50 seconds of heating with an internal heat source of 8.0 x 10^7 W/m³ and infrared camera observation

The thermal conductivity of the aluminum is more than 20 times higher than the thermal conductivity of the CF/PA66. The main heat is transferred into the metallic specimen while the composite part stays cool and solid. This gives the possibility to melt the polymer only in the welding zone. The rest of the composite part is still solid and able to carry loads. This is a very important requirement for designing handling mechanisms and welding tools.

Summarizing the results from the experiments, the analytical calculations and the FE-simulations, it was shown that a very good conformity between these three different methods was achieved and the FE-software can be used to predict the heat transfer into the joining partners. Finally, a prediction of the manufacturing parameters for the heating can be accomplished with this tool.

6. SUMMARY

Induction welding can be used to weld FRPCs as well as for joining of metal/TPFRPC. After evaluation of the achievement potential of this bonding type, it was concluded that the surface treatment of the metallic and the polymeric joining partner, as well as process conditions, influence the bonding quality. By combining several treatment parameters (corundum blasted with additional polymer layer) the bonding strength is almost doubled to 14 MPa for AlMg3-CF/PA66-joints. Further investigations of the process conditions show that for AlMg3-CF/PA66-joints the highest shear tensile strength values are achieved if the material is cooled down quickly. No significant change in the crystallinity was observed by DSC-measurements, so a fast cooling of the samples is possible. The shear tensile strength is only about 15 % less than that of adhesively bonded joints, but the samples need no additional curing afterwards.
Dynamic thermogravimetric analyses in various environmental gases were performed to increase the degradation temperature of the polymer. In the case of PA66 this did not lead to an increase of the process window as the polymer degradation is almost solely thermally controlled instead of oxidatively controlled. However, this kind of welding shows a large potential for welding of fiber reinforced olefins, like GF/PP. An increase of the degradation temperature from 230 °C in air to 390 °C in nitrogen was measured.
By means of calorimeter experiments and FE-calculations in Ansys the heating during induction welding were successfully reproduced.

7. ACKNOWLEDGEMENTS

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