1 Introduction
Thermoplastic polymers have many advantages for their use in composites. They allow short cycle times, offer a high toughness, have an unlimited shelf-life, and a good chemical resistance. Moreover, they are weldable [1]. Since they are combined with other materials in many applications, for example in the automotive or aerospace industry, joining technologies play an important role. Compared to other joining methods such as adhesive bonding or mechanical fastening, welding has some significant advantages. In contrast to adhesive bonding, welding does not require any solvents and in addition, the necessary surface treatment is less intensive. When rivets or screws are used, the reinforcing fibers are destroyed. By welding, only the polymer is melted and the integrity of the reinforcement is not influenced [2].

To further improve composite welding, a new concept for induction welding of carbon fiber reinforced thermoplastics was developed. It allows intrinsic heating of joining partners that contain carbon fibers. By cooling the partner that faces the induction coil, melting of the whole part is prevented.

2 Continuous induction welding of carbon fiber reinforced laminates
Every composite welding process is based on the melting of the polymer and the subsequent consolidation and bonding in a welding zone. In order to melt the polymer, continuous induction welding uses an electromagnetic field generated by a water-cooled coil that is connected to an oscillating circuit fed by a power supply unit.

The electromagnetic field, shown in Fig. 1, induces eddy currents into an electrically conductive workpiece [3]. This is then heated by these eddy currents until the polymer is melted. Afterwards, the two partners can be joined. In order to ensure a good quality of the weld, pressure is applied by a compaction roller after heating [4].

Since many reinforced polymers are assumed to be nonconductive, a susceptor, e.g. a metal mesh, is used to locally heat the welding zone. In this susceptor, Joule heating occurs due to its resistance [5]. In case that the susceptor consists of ferromagnetic particles, the electromagnetic field causes a vibration of its magnetic particles. This vibration results in the heating of the susceptor by magnetic hysteresis[6].

Although a susceptor allows easy heating of the welding zone, its use is not always favorable. It still presents a contaminant that weakens the joint by inducing high stress concentrations [6]. Moreover, the contact between a metal mesh and carbon fibers can cause corrosion that destroys the joint integrity [6].

To overcome these problems, the intrinsic heating of the workpiece itself was investigated. Since carbon fibers are electrically conductive, they can heat the laminate without a susceptor, as it is shown in Fig. 1. The only condition is, that the fibers form closed electrical circuits as they do in a weave [4]. Three different heating principles can be identified. Joule heating in the fibers and contact resistance heating at fiber junctions are both based on resistive losses [5, 7]. Dielectric hysteresis losses heat the polymer between two fibers at their junction [5, 8]. The first heating effect is dominant in weaves because of their good fiber contact [5, 9], while the second effect is important for unconsolidated materials [10].

2.1 Challenges and Objectives
Susceptor-less heating presents a challenge that requires a thorough investigation. Due to two
physical effects, the temperature gradient of a carbon fiber reinforced laminate during inductive heating is not favorable for the welding process. The first phenomenon is the so called skin effect. It describes the distribution of an alternating current in a conductor. The maximum of the current density is always on the surface and decreases towards the center of the conductor \[3\]. The skin effect is characterized by its penetration depth, which is the distance from the surface at which the current density drops to 1/e of its initial value \[3\],
\[
\delta = \frac{1}{\sqrt{\pi \mu_0 \mu_r \sigma f}}
\]
with
\[f\]: frequency of the electromagnetic field, \[\mu_0\]: magnetic constant, \[\mu_r\]: magnetic permeability of the conductor, \[\sigma\]: electrical conductivity.

The second effect is that the intensity of an electromagnetic field is inversely proportional to its distance to the coil. The field at a certain point outside the coil is expressed by the Biot–Savart law \[11\],
\[
\vec{H} = \frac{1}{4\pi} \oint \vec{l} \times \vec{I} \, d\vec{s} \frac{1}{r^3}
\]
with
\[\vec{H}\]: magnetic field intensity, \[\vec{l}\]: current, \[d\vec{s}\]: curve element of the conductor in direction of \[\vec{l}\], \[\vec{r}\]: displacement vector from the conductor element to the point.

This drop in field intensity with increasing distance leads to a temperature gradient in the welding zone, which is displayed in Fig. 2. The top of the laminate (coil side) is heated clearly faster by a stronger electromagnetic field. In order to melt the polymer in the welding zone, the laminate must be heated and melted through its whole thickness. That causes deconsolidation in the upper laminate. Moreover, thermal damage can occur on the top surface due to overheating. To avoid that, the field intensity has to be diminished by a reduction of the generator power. That leads to an even weaker field in the welding zone and, subsequently, to a reduced process speed.

Hence, the main objective of this work was the control of the temperature field in thickness direction. To investigate this, heating experiments have been performed and a three-dimensional process model was developed, so that the influence of significant process parameters could be assessed. To evaluate the quality of the welds, micrographs and tensile-shear-tests were made.

2.2 Implementation of a localized cooling

One possible measure to reverse the unfavorable temperature gradient caused by susceptorless heating is to reduce the temperature on the top surface. Since there is no possibility to reduce the field intensity locally near the coil, the surface must be cooled actively \[12\]. Common cooling agents are air, water, and oil. To avoid unwanted reactions between the cooling agent and the material, air was chosen. It is supplied by a nozzle for compressed air, which was installed in the center of the coil. It is shown by Fig. 3. This nozzle directs an impinging air jet to the laminate which cools the surface subsequently.

For welding purposes, this cooling was attached to a welding head, which was mounted to an industrial robot. In Fig. 4 the components of this welding head are displayed.

Again, the nozzle is in the center of the coil. In addition, there is a roller that reconsolidates the laminate after the melting of the polymer in the welding zone. A thermal camera allows a temperature based process control.

3 Simulation and experiments

In order to compare the heating behavior of uncooled and cooled specimens, heating experiments were performed. The examined specimens consisted of a carbon fiber weave with a PEEK or a PPS matrix. The material properties of the single components are listed in Table 1.

These components were processed to laminates, which were then cut into specimens. Table 2 contains the properties of the laminates.
In addition to the experiments, the heating behavior was modeled. As software code, Comsol Multiphysics was used. Since the purpose of influencing the heat distribution in the welding zone is to improve the weld quality, mechanical characterization had to be done. Therefore, lap shear tests based on DIN EN 1465 \[13\] were performed with CF-PPS laminates.
3.1 Heating experiments

For the heating experiments, square specimens with an edge length of 100 mm were used. They were positioned above a coil with a cooling nozzle in its center. To be able to monitor the temperature on both sides of the joining partner near the coil, a second plate was added. The temperature on both sides of the specimen was recorded by two pyrometers. Moreover, the surface on the opposite side of the coil was monitored by a thermal camera. The experimental setup is illustrated in Fig. 5.

For these experiments a CEIA Powercube 32/400 was used as generator. It offers a maximum absorbed power of 2800 W and a nominal frequency of 400 kHz. Both materials, CF-PPS and CF-PEEK, were examined. Since they showed the same heating behavior, the results can be applied qualitatively on both materials.

As a first step, the specimens were heated without surface cooling at different generator powers. Fig. 6 shows exemplarily the progression for CF-PPS heated at 10%, 20%, and 30% generator power and 2 mm coupling distance.

It can be observed that the coil side always reaches higher heating rates, which are represented by the gradient of the heating curve, than the opposite side. For CF-PPS heated at 2 mm coupling distance, the rates range from 15 K/s (10% generator power) to 48 K/s (30% generator power) on the opposite side and from 17 K/s (10% generator power) to 59 K/s (30% generator power) on the coil side. Since the heating rates are higher on the coil side, the temperatures reached on this side are also higher and a temperature gradient between both sides can be observed. With increasing heating rate, the difference in heating rates between both sides is growing, too. That leads to an increasing temperature gradient.

These findings are applicable to all specimens.

To investigate the influence of the impinging air jet, the heating curves of CF-PPS with 30% generator power and 2 mm coupling distance are displayed in Fig. 7. Three different volume flow rates were used: 304 l/min, 240 l/min, and 167 l/min.

The temperature at the coil side remained below the temperature on the opposite side and below welding temperature, which is about 50 °C above the melting temperature, approximately 330 °C in case of CF-PPS. For all three volume flow rates, the heating rate on the opposite side remains approximately the same. On the coil side, however, the impinging air jet influences the heating rate more significantly. With a volume flow of 167 l/min, the heating rate is higher than with 240 l/min and 304 l/min. But there is no significant distance between the latter two.

The general finding of the heating experiments is summarized in Fig. 8. There, the heating of the coil side of CF-PEEK with 3 mm coupling distance, 20% power, and a volume flow of 304 l/min is displayed.

It can be observed, that the temperature of the cooled coil side can be decreased below welding temperature and thereby the laminate is prevented from deconsolidating and thermal damages on the coil side. This can also be confirmed by a cross-sectional analysis. In uncooled samples, such as shown in Fig. 9, many voids and delamination are visible through the whole thickness of the laminate. In cooled samples, in contrast, the influence of the cooling becomes obvious. The first few layers, which are directly affected by the impinging air jet, are still consolidated. A cooled sample is presented in Fig. 10.

3.2 Simulation of the heating behavior

For further research, a computational model of these heating experiments was developed. Induction heating is a process with a high degree of complexity. Therefore, simulation is a powerful tool that helps to understand and predict material behavior.

The software, that was deployed, is, Comsol Multi Multiphysics 4.1. The simulation of the experiment incorporates a harmonic electromagnetic analysis and a transient thermal analysis, which are fully coupled. Its methodology follows the flow chart displayed in Fig. 11.

After building the model (see Fig. 12), which includes the geometry, material properties, all boundaries, and the mesh, the eddy current distribution is calculated in a harmonic electromagnetic analysis. The equation, which is underlying this step, is a time-harmonic Maxwell-Ampère formulation [14],

\[(j\omega\sigma - \omega^2\varepsilon)A + \nabla \times (\mu^{-1}\nabla \times A) = J_e \quad (3)\]

with
\( j \): induced current density
\( \omega \): angular frequency
\( A \): magnetic vector potential
\( \mu \): magnetic permeability
\( J_e \): external current density.

This quasi-static approach can be used, because the wavelength of the 400 kHz generator is 750 m and thus clearly larger than the thickness of the used laminats. Subsequently, a transient temperature field is determined for a static case. It is described by

\[ \rho c_p \frac{\partial T}{\partial t} = k \nabla^2 T + Q \quad (4) \]

with
\( \rho \): density
\( c_p \): specific heat capacity at constant pressure
\( T \): absolute temperature
\( t \): time
\( k \): thermal conductivity
\( Q \): heat source.

The simulation is done in several time steps from \( t_i \) to \( t_{\text{he}} \). The latter stands for the heating time. As heating mechanism, Joule heating is applied, because the surface cooling prevents deconsolidation. Moreover, the contact resistance between warp and weft is low enough, so that Joule heating may be assumed [5]. Two additional assumptions are (1) a homogenized anisotropic material model and (2) free convection at the outer faces.

For the calculation of the heat generation caused by a magnetic field, different material properties are necessary. Values that could not be found in literature or calculated from given values were determined by experimental characterization. The employed material properties are summarized in Table 3.

In order to validate the simulation, experimental temperature curves were compared to curves derived from the simulation. In Fig. 13, a good compliance can be observed. Moreover, the model offers the possibility to simulate heating patterns. Fig. 14 shows, that these patterns correlate very well. The cold spot in the center of the coil, the hot region caused by the global current loop, and the colder surrounding area can be predicted precisely. Only the shape of the heating pattern is slightly different. The square-like shape, derived from the experiments, is caused by current flowing along warp and weft rovings which are arranged in 0° and 90°. This behavior cannot be calculated with a homogenized material model.

### 3.3 Tensile-shear-tests

Based on the knowledge that was generated by the heating experiments and the simulation, the cooling concept was used for welding samples. They consist of CF-PPS and have a thickness of 1.3 mm with an overlap of 13 mm and a width of 25 mm. Each series consisting of eight samples was cut out of two welded plates. Fig. 15 and Fig. 16 show the welded samples. On the surface of the uncooled laminate (Fig. 15) a massive heat distortion is visible due to the overheating of the material near the coil. The cooled laminate (Fig. 16), on the other hand, is not damaged by overheating thanks to the impinging air jet.

All samples were tested according to DIN EN 1465 [13]. The uncooled samples reached average lap-shear strength of 27.08±1.51 MPa (see Fig. 17). The lap-shear strength of the cooled samples is slightly lower, 25.67±3.85 MPa, and has a higher deviation. But one can realize, that the lower values in Fig. 17 result from an edge effect at the beginning of the specimen. The lap-shear strength of the last five samples is 28.32±1.13 MPa. These higher values at the end show the potential of the surface cooling. A good surface quality can be achieved while keeping the same strength. Moreover, the welding speed could be doubled by using the impinging air jet.

### 4 Summary and outlook

Within this work, unfavorable temperature gradient during susceptorless induction welding of carbon fiber reinforced thermoplastics was addressed. The resulting problems could be solved by the development of a surface cooling (patent pending). To that, an impinging air jet was used. The efficiency of this method was proofed by heating experiments. In addition, a process simulation was built to gather a deeper understanding of the process. By lap-shear tests, the potential of the surface cooling – a better surface and a higher process speed with the same mechanical properties as uncooled samples- was shown.
In the future, further optimization is necessary to improve the reproducibility of the new welding process. Moreover, the new process will be extended to a wide range of materials and welding applications.

**Fig. 1**: Physics of induction welding of carbon fiber reinforced thermoplastics

**Fig. 2**: Temperature gradient in the upper laminate

**Fig. 3**: Implementation of a surface cooling

**Fig. 4**: Welding head with surface cooling

**Fig. 5**: Setup of the heating experiments
Fig. 6: Heating behavior of CF-PPS without cooling at 2mm coupling distance and different generator powers

Fig. 7: Heating behavior of CF/PPS with cooled surface at different flow rates, 2 mm coupling distance, 30% generator power

Fig. 8: Comparisons of the temperatures with uncooled and cooled top surface

Fig. 9: Cross section of a CF-PEEK sample heated with 3 mm coupling distance and 20% generator power

Fig. 10: Cross section of a CF-PEEK sample heated with 3 mm coupling distance, 20% generator power, and 304 l/min surface cooling

Fig. 11: Flow chart of the induction heating simulation

Fig. 12: Components of the simulation model
SUSCEPTORLESS CONTINUOUS INDUCTION WELDING OF CARBON FIBER REINFORCED THERMOPLASTICS

Fig. 13: Comparison of simulative and experimental heating curves

Fig. 14: Verification of predicted heating patterns

Fig. 15: Samples welded without surface cooling

Fig. 16: Samples welded with surface cooling

Fig. 17: Lap-shear strength of the uncooled samples

Fig. 18: Lap-shear strength of the cooled samples
Table 1: Components used for the specimen manufacturing

<table>
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<tr>
<td>Supplier</td>
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PEEK

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PPS

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Table 2: Manufacturing processes of the laminates

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Table 3: Material properties used in the simulation [15–21]

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<tr>
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<td>Fiber volume content in x-direction [%]</td>
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<td>25</td>
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<tr>
<td>Fiber volume content in y-direction [%]</td>
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<td>25</td>
</tr>
<tr>
<td>Calculated electrical conductivity in x-direction [S/m]</td>
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<td>$1.39 	imes 10^3$</td>
</tr>
<tr>
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<table>
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References


[8] P. Berlin; O. Dickman; F. Larsson "Effects of heat radiation on carbon/PEEK, carbon/epoxy and


