Process Improvement of Continuous Induction Welding of Carbon Fiber-Reinforced Polymer Composites

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1. Introduction

The joining of fiber-reinforced polymer composites (FRPC) in a material-specific manner still poses a particular challenge (Ref 1-3). Welding processes are suitable for thermoplastic FRPC (Ref 4, 5). The way in which the energy required for welding is introduced into the laminates determines the applicability and efficiency of a welding process. Since the carbon fibers (CF) provide a sufficient electrical conductivity, carbon fiber-reinforced polymer composites (CFRPC) can be heated by means of electrical induction (Ref 6). However, for this purpose, the CF must be arranged in the laminate in such a way that closed electrical conductor loops are provided (Ref 6-8). With the electric losses within the CF and between CF-CF junctions (due to dielectric hysteresis or contact resistance), heat is dissipated (Ref 6, 8-10). For continuous induction welding of thermoplastic CFRPC, an induction coil is moved along the weld seam to induce eddy currents into the CF (Fig. 1). Consequently, the thermoplastic matrix in the joining zone between the two adherends is heated above melting temperature. A consolidation roller following the induction coil applies the necessary joining pressure and reconsolidates the laminate.

The induced eddy current depends essentially on the spatial distribution of the magnetic field strength $\mathbf{H}$. For the case of a circular coil, this can be calculated using Biot–Savart’s law (Eq 1) (Ref 11). Here, $r$ is any point in space, $r$ is its distance from the induction coil, and $ds$ is the curve element of the conductor in the direction of current flow. Due to this fact, a gradient of the magnetic field strength results and from this, in turn, a decreasing temperature gradient over the laminate thickness (Ref 12).

$$\mathbf{H} = \frac{I}{4\pi} \int \frac{d\mathbf{s} \times \mathbf{r}}{r^3}$$ (Eq 1)

In addition, the inductive heating behavior is influenced by process parameters. These were investigated in more detail in (Ref 8, 13). With regard to the frequency $f$ of the magnetic field, the heat introduced by induction is proportional to the square of the frequency. An exponential dependence of the heating rate is demonstrated for the coupling distance, i.e., the distance between the inducer and the laminate surface, and the generator power. The higher the power and the smaller the coupling distance, the greater the heating rate. The dependence of the coupling distance can again be attributed to Biot–Savart’s law. The intensity distribution of the magnetic field is strongly dependent on the inducer geometry (Ref 6). In the center of a laminate with infinite size, the heating pattern on the laminate surface corresponds in principle to the mirror image of the inducer geometry. The influence of the textile and laminate parameters was investigated in (Ref 10, 14-18).

Due to these underlying physics, the resulting temperature distribution in-plane and in laminate thickness direction is

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The induction heating of a CFRPC laminate leads to a temperature gradient across the thickness of the adherend, with a pronounced maximum temperature close to the laminate surface facing the induction coil. Due to this temperature gradient, the polymer at the induction coil faced laminate surface will already be melted, before the polymer in the joining zone is melted. Consequently, the laminate will deconsolidate or the polymer at the induction coil faced laminate surface will even be thermally degraded (Ref 13). In order to be able to use induction heating for welding CFRPC laminates, a surface cooling by means of pressurized air was developed, which enables the temperature gradient to be inverted (Ref 19). By means of surface cooling, it is possible to control the temperature distribution in thickness direction and to prevent the melting of the polymer in the laminate region facing the induction coil.

2. Improvement Approaches

In order to increase the process speed and, simultaneously, to keep the bonding quality at autoclave level, the spatial temperature distribution within the laminate has to be adapted. For this purpose, three improvement approaches were developed within this study based on the three crucial heat fluxes influencing the continuous induction welding process (Fig. 2). The heat flux $Q_m$ describes the heat input resulting from the dissipated electric energy, the heat flux $Q_{\text{surface}}$ describes the heat that is removed by the surface cooling, and the heat flux $Q_{\text{Consolidation}}$ describes the heat that is removed by conduction through the consolidation roller.

The first improvement approach intends to adapt the laminate structure, so that the main heat dissipation is located in the joining zone. Consequently, the location of the maximum temperature moves from the induction coil laminate surface to the joining zone. Thus, a faster and more efficient heating is possible. In (Ref 20), an optimized metal susceptor was developed for this purpose. Another method to generate the maximum heat in the joining zone is based on a hybrid laminate structure consisting of alternating glass fiber surface tissue plies and CF unidirectional plies (Ref 21). Within this study, the adapted laminate should only consist of polymer and CF textiles.

The second improvement approach is aimed to increase the heat that can be removed from the induction coil faced laminate surface. For this purpose, the recently used surface cooling method, which is based on forced convection through pressurized air, was improved.

The third approach provides the initial research of the thermal and mechanical condition under the consolidation roller by means of simulation model. The roller and the laminate are represented within a multi-physics finite element method (FEM) model.

3. Adaption of the Laminate Setup

In order to reduce the number of possible laminate setup configurations, only laminates reinforced by CF fabrics, consisting of a polyamide 6.6 (PA66) matrix and providing a homogenous fiber volume content (FVC) of $\phi = 50\%$ as well as a laminate thickness of $h = 2.1$ mm, were considered for this study. By means of inductive heating trials, the induction heating behavior of laminates consisting of different CF fabrics was previously investigated (Ref 14-17). Based on these studies, the influence of laminate and textile parameters is known. Reinforcement fabrics differing in their textile parameters cause different inductive heating rates. In order to shift the temperature maximum from the laminate surface facing the induction coil to the joining zone, reinforcement fabrics that heat up slowly are positioned in the laminate area close to the inductor and reinforcement fabrics that heat up quickly are positioned in the region of the joining zone (Fig. 3).

According to (Ref 16), laminates consisting of twill weaved CF fabrics with an areal weight of 630 g/m² (Twill 630) showed the lowest heating rates. Conversely, laminates with twill weaved CF fabrics with an areal weight of 160 g/m² (Twill 160) and laminates consisting of non-crimped fabrics with an areal weight of 200 g/m² (NCF 200) showed the highest heating rates. In general, it was shown that a high areal weight of the reinforcement fabric leads to a slow inductive heating and a low areal weight leads to fast inductive heating. Additionally, the weave style has a significant influence on the heating rate.

To validate the adapted laminates, the same experimental setup as in (Ref 14-17) with a generator power of $P = 40\%$ and a coupling distance of $a = 5$ mm was used (Fig. 4). The used pancake coil consists of a copper tube with a diameter of Ø3 mm and has an outer diameter of Ø25 mm as well as two windings. On both laminate surfaces, the maximum temperature was measured by infrared cameras TIM 160 from Micro-Epsilon, Germany, and recorded by means of a GP20 data recorder from YOKOGAWA; Japan. The calculation of the heating rates was done according to (Ref 17). Four laminates of each kind were tested, in order to calculate averaged heating

![Fig. 1 Process design and crucial components of the continuous induction welding process for thermoplastic CFRPC](image1)

![Fig. 2 The three crucial heat fluxes influencing the continuous induction welding process](image2)
rates with respective standard deviations. For the adaption of the laminate structure, the same fabrics as in (Ref 16) were used (Fig. 5). Furthermore, conventional laminates made of Twill 630 (Laminate I), NCF 200 (Laminate II) and Twill 160 (Laminate III) were initially tested. The heating rates on the induction coil faced laminate surface as well as on the opposite surface of these three laminates correspond with the results known from literature. The heating rates on the induction coil faced laminate surface are bigger than the heating rates on the opposite laminate surface.

In order to compare the adapted laminates with the conventional laminates, the adapted laminates also provide a total CF areal weight of approximately 1,900 g/m², a laminate thickness of 2.1 mm, and a FVC of \( \phi = 50\% \). For the adapted laminate setups two concepts were used. The first concept provides adapted laminates made of Twill 630 on the induction coil faced laminate region and NCF 200 on the joining zone faced laminate region (opposite surface) (Laminates IV and V). The adapted laminates made according to the second concept provides also Twill 630 on the induction coil faced laminate region, but contain Twill 160 on the joining zone faced laminate region (opposite surface) (Laminates VI and VII). The NCF 200 plies were arranged with a \( \pm 45\^\circ \) fiber orientation. In contrast, all woven fabrics were arranged with a 0/90\^\circ fiber orientation. Each concept leads to two different laminate setups (Fig. 6). All adapted laminates in this study represent a fiber orientation. Each concept leads to two different laminate setups (Fig. 6). All adapted laminates in this study represent a fiber orientation. Each concept leads to two different laminate setups (Fig. 6). All adapted laminates in this study represent a fiber orientation. Each concept leads to two different laminate setups (Fig. 6).

The heating rates of the induction coil faced laminate surface of the adapted laminate setups of both concepts are smaller than the heating rates of the induction coil faced laminate surface of the conventional laminates made of NCF 200 (Laminate II) or Twill 160 (Laminate III), respectively (Fig. 5). However, the heating rates of the induction coil faced laminate surface of the adapted laminate setups of both concepts are bigger than the heating rate of the induction coil faced laminate surface of the conventional laminate made of Twill 630 (Laminate I). The adapted laminates 2x Twill 630 + 3x NCF 200 (Laminate IV) and 2x Twill 630 + 4x Twill 160 (Laminate VI) provide higher heating rates on the opposite laminate surface than on the induction coil faced laminate surface. Especially, in the case of the adapted laminate 2x Twill 630 + 3x NCF 200 (Laminate IV), the difference between the heating rates of the opposite and the induction coil faced laminate surface is 9.3 K/s, which corresponds to +11.56% of the heating rate of the induction coil faced laminate surface.

In order to validate that the adapted laminate setup 2x Twill 630 + 3x NCF 200 (Laminate IV) also provides a higher heating rate on the opposite surface compared to the induction coil faced laminate surface at other generator power levels, heating trials with different generator power levels \( P \) were conducted (Fig. 7a). These trials prove that the inversion of the temperature gradient is not dependent on the generator power \( P \).

Additionally, the induction heating behavior of the adapted laminate setup 2x Twill 630 + 3x NCF 200 was compared with the one of a Tepex® dynalite 201-C200(9)/50% from LANXESS Deutschland GmbH, Germany, which represents a commercial organic sheet. This commercial organic sheet provides a thickness of 2 mm as well as a FVC of \( \phi = 50\% \) and consists of nine plies of a CF twill weave with an areal weight of 200 g/m² each. The comparison between the heating rates shows that the difference in the heating rate can be turned from \(-23.1\% \) into +11.56% (Fig. 7b). Through the adaption of the laminate setup, the maximum temperature can be shifted to the joining zone and the induction welding process becomes more efficient. The heating in the joining zone is approximately 16 K/s faster with the adapted laminate structure. However, this increase cannot be directly transferred to the process speed of induction welding process. The assumed linear time–temperature curve is not valid for temperatures just below the melting temperature of the polymer. If the polymer becomes melted, deconsolidation will occur in the laminate and the contact resistances between crossing rovings will be become higher. Higher contact resistances result in a slower heating, since the induced energy becomes lower. Additionally, the heat transfer from the laminate to the surrounding is increased, if the temperature of the laminate is increased. Once the heat input and output reach an equilibrium, the temperature of the laminate will be constant. The change of the contact resistances, as well as the change of the heat transfer to the surrounding, will lead to a degressive shape of the time-temperature curve.

According to (Ref 4), the ideal welding temperature for semi-crystalline thermoplastics is 50 K beyond its melting temperature. For higher welding speeds, the difference between the heating rates of the induction coil faced and opposite laminate surface of 9.3 K/s is too low to achieve a temperature difference of more than 50 K, so that the polymer on the laminate surface will not be melted. Consequently, a surface cooling is still necessary for higher welding speeds, if the adapted laminate setup is used.

![Fig. 3 Methodology for the development of an adapted laminate setup](image-url)
4. Validation of an Advanced Surface Cooling

To analyze and improve the recently used surface cooling, common cooling methods were initially compared by means of a theoretical analysis of their cooling impact behavior (Fig. 8). As boundary condition always a one-dimensional, steady-state heat transfer process is considered. Furthermore, the laminate surface has always a temperature of 200 °C. The temperature of the environment in the case of free convection, the cooling fluid in the case of forced convection, or the heat sink in the case of conduction, was set to a constant temperature of 24 °C. For the current cooling method, the heat transfer coefficient $a$ was calculated for the volume flows 167 l/min and 304 l/min according to (Ref 22) (vertical impingement flow through single circular nozzle). For all other cases of convection, minimum and maximum heat transfer coefficients $a$ from (Ref 22) were used. For conduction, the thermal conductivity of steel (59 W/(m*K)) and copper (372 W/(m*K)) were used. The thickness of the heat sink was set to 1 mm. For the calculation of spray cooling, a heat transfer coefficient $a$ of 2,500 W/(m²*K) and 10,000 (W/m²*K) was selected according to the flow boiling of subcooled liquids (Ref 22, 23).
Cooling by means of the principle of heat conduction shows the highest heat flux density (Fig. 8). However, this cooling method is technically hardly feasible even for flat panels due to the required permanent and flush contacting of the laminate surface. Cooling by forced convection of liquids is—despite a theoretical high cooling performance—also not feasible for continuous induction welding. A contamination of the joining zone with the cooling liquid will result in low bonding strength or even no bonding due to two reasons. First, the liquid will also cool the joining zone, which impedes a melting of the polymer in the joining zone. Second, if the polymer is molten, the liquid will impede the diffusion process of the polymer across the interface, which is necessary for polymer welding (Ref 4).

The currently used cooling method works by means of a vertical impingement flow through a single circular nozzle, which is a special kind of forced convection of gases—the heat flow density \( q \) of the current method is slightly higher. As a compromise between cooling performance and technical feasibility, spray cooling provides a high potential, if a dry wall state is obtained. The term dry-wall state describes the operating point at which the entire amount of cooling liquid applied evaporates immediately when contacting the hot laminate surface.

In order to compare the cooling performance of the current cooling method with spray cooling, experiments with inductively heated CFRPC laminates Tepex® dynalite 207-C200(9)/50% from LANXESS Deutschland GmbH, Germany, with a polyphenylene sulfide (PPS) matrix were carried out. For this purpose the static induction heating test rig described in (Ref 16) with a coupling distance of 5 mm and a generator power of 20% was used (Fig. 4). The same induction coil as in the adaption of the laminate setup was used. The laminate was heated for 10 s by induction and was simultaneously cooled on the induction coil faced laminate surface (Fig. 9). The maximum temperature at the laminate surfaces in each trial was measured by means of infrared cameras and recorded by means of a GP20 data recorder from YOKOGAWA; Japan. The used infrared cameras TIM 160 from Micro-Epsilon, Germany, were operating in a measuring temperature range between 0 °C and 250 °C. If the heating goes beyond a temperature of 250 °C, the indicated temperature is limited to 250 °C.

To evaluate the cooling performance, the temperature difference \( \Delta T_{240°C} \) between the two surfaces of a laminate was determined once the opposite surface temperature has reached 240 °C (Fig. 10). By evaluating the cooling performance at an opposite surface temperature of 240 °C, the temperature limit of the infrared camera at 250 °C does not impact the evaluation.

Two spray cooling systems were used within this study. Spray cooling system 1 (Spray cooling system from Wabeco-Remscheid, Germany) is a cooling system for machine tools. Spray cooling system 2 (Preeflow eco-Spray from ViscoTec Pumpen- und Dosiertechnik GmbH, Germany) is actually used for precise metering of high-viscosity liquids. Both spray cooling systems are based on a two-substance nozzle with pressurized air as the flow fluid and water as the cooling liquid. Additionally, a vortex tube was tested within the frame of this study. For each cooling system five trials were carried out. Figure 10 shows the averaged time-temperature curves of the induction coil faced and opposite surface for each tested cooling system.

Within all trials the cooling has an impact on the temperature of both laminate surfaces. Both spray cooling systems show the expected significantly stronger cooling effect compared to the cooling with pressurized air and the vortex tube. Although spray system 1 shows the better cooling effect compared to spray system 2, extensive water deposits can be observed on the surface even with a minimally adjusted water output. An extensive water deposit can lead to a contamination of the joining zone with water. Compared to the spray cooling system 1 the spray cooling system 2 provides lower cooling performance. However, it allows a good controllability of the water quantity and thus controllable surface cooling without water residues on the laminate surface. Especially important for welding laminates with matrix of polyamide, which can absorb a relative high amount of water, is the ability to obtain a called dry-wall state.
CF-PPS laminates (Tepex overtops with a width of 12.5 mm. Both adherends are made of matrix will occur. The coupon consists of two adherends, which can be used several times, since no melting of the PPS temperature 220°C.

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By means of an infrared camera, the maximum surface thermocouples of type E were inserted into the welding zone. Although the temperature curves of the opposite surface resulting from pressurized air cooling and spray cooling system 2 are quite similar, the temperature difference is still significant. ΔT_{240°C} resulting from spray cooling system 2 is 23.4 K higher than ΔT_{290°C} resulting from pressurized air cooling. Due to this bigger temperature difference the process window of induction welding process could be enlarged and the robustness of the process could be enhanced. Therefore, spray cooling system 2 represents a promising cooling system due to the increased cooling performance compared to the recently used cooling method by pressurized air and due to the feasibility of a dry-wall state.

Subsequently, dynamic induction heating trials were performed to validate the cooling effect of spray cooling system 2. For this purpose, the experimental setup shown in Fig. 11 was used in combination with an induction welding robot. The induction power was supplied by the same induction generator as in the previous trials. A special coupon was manufactured to simulate a welding constellation of CF-PA6 laminates (melting temperature 220 °C). By simulating a welding of CF-PA6, the coupon can be used several times, since no melting of the PPS matrix will occur. The coupon consists of two adherends, which overlaps with a width of 12.5 mm. Both adherends are made of CF-PPS laminates (Tepex® dynalite 207-C200(9)/50% from LANXESS Deutschland GmbH, Germany), providing a melting temperature of the polymer matrix of 290 °C. Ten thermocouples of type E were inserted into the welding zone. By means of an infrared camera, the maximum surface temperature was measured between the induction coil and the consolidation roller. The coupling distance was set to 3 mm and the generator power was set to 70%. Each trial was repeated five times. The curves of the surface temperature within Fig. 12 represents the mean from the five trials. The temperature curves of the joining zone in Fig. 12 show the maximum temperature (mean from five trials) of two adjacent thermocouples.

In order to initially compare the cooling effect of spray cooling system 2 with pressurized air cooling within a dynamic process, the volume flow rate of air and the process speed were equal (Fig. 12a and b). The cooling by pressurized air with an air volume flow rate of 42 l/min at a process speed of 200 mm/min leads to a surface temperature of approximately 250 °C and a temperature in the joining zone between 304 °C and 278 °C (Fig. 12a). Both temperature ranges are too high for welding CF-PA6 laminates. The polymer in the joining zone will probably be thermally degraded and the polymer of the induction coil faced laminate surface will be melted. In comparison, spray cooling system 2 with an air volume flow rate of 42 l/min and a water volume flow rate of 6*10^{-3} l/min at a process speed of 200 mm/min leads to the targeted temperatures in the joining zone as well as on the laminate surface (Fig. 12b). By means of spray cooling, the temperature in the joining zone is between 276 °C and 251 °C. The temperature at the induction coil faced laminate surface is between 195 °C and 205 °C. Consequently, the PA6 polymer at the laminate surface would not be melted. Additionally, a dry-wall state was achieved on the laminate surface.

If the same temperatures in the joining zone and on the laminate surface should be obtained by means of pressurized air cooling at a process speed of 200 mm/min, an air volume flow rate of approximately 362 l/min is necessary (Fig. 12c). Compared to cooling with spray cooling system 2, cooling with pressurized air needs an air volume flow, which is 8.6 times higher, in order to achieve the same temperatures in the joining zone as well as on the laminate surface. Thus, water spray cooling 2 is more efficient than pressurized air in the case of dynamic cooling.

In the case of cooling by means of spray cooling system 2 with an air volume flow rate of 42 l/min and a water volume flow rate of 6*10^{-3} l/min, an increase in the process speed to 300 mm/min results in lower temperatures in the joining zone as well as on the laminate surface. However, the temperature difference between the joining zone and laminate surface is between 53 K and 64 K and a dry-wall state was maintained. In order to increase both temperatures, the induction generator power can be increased or the coupling distance can be reduced.

The conducted experiments prove that cooling by means of spray cooling system 2 helps to improve the performance of

![Fig. 8](image)

Comparison of potential cooling methods for surface cooling during continuous induction welding of CFRPC based on theoretical, thermal, one-dimensional, steady state analysis.

![Fig. 9](image)

Schematic depiction of the simultaneous inductive heating and cooling of the CFRPC laminate.

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The conducted experiments prove that cooling by means of spray cooling system 2 helps to improve the performance of
induction welding. For the same input parameters, cooling with spray cooling system 2 is more efficient than cooling with pressurized air. Further experiments with spray cooling and higher process speeds will be carried out in future.

5. Simulation of the Consolidation Phase

In addition to the controlled local energy input into the laminate and the enhanced cooling of its laminate surface, a more detailed look at the consolidation process is necessary to increase the process speed in continuous induction welding. For a detailed investigation of the thermal conditions in the region of the contact interface between roller and laminate, a thermal-mechanical simulation model by means of the FEM software Abaqus was developed (Fig. 13). The thermal material parameters used to represent the CF-PA66 laminates within the model are shown in Table 1. The roller diameter was set to \( d_{\text{roller}} = 42 \text{ mm} \) and the force applied to the roller was set to \( F_{\text{roller}} = 400 \text{ N} \).

To calculate the pressure distribution in the joining zone, the temperature-dependent compressive stiffness \( E_{33} \) of the laminate was determined experimentally according to DIN EN ISO 604:2003-12 with cylindrical specimens with a cross section diameter of 015 mm and a height of 18 mm (Fig. 14). The specimens were made of 2 mm thick CF-PA66 laminates (Tepex® dynalite 201-C200(9)/50% from Bond Laminates, Germany). Nine laminates were stacked and consolidated in the autoclave at 260 °C and 24 bar for 1 h to an 18 mm thick plate. Subsequently, the cylindrical specimens were cut from this consolidated laminate stack. The tests were conducted by means of a ZwickRoell testing machine type 1485, Germany, in combination with a temperature chamber. Since the maximum temperature of the temperature chamber is 240 °C, it is assumed for temperatures between 240 °C and melting temperature of the PA66 \( (T_m = 260 \text{ °C}) \) that the compressive stiffness \( E_{33} \) degrades linearly from 200 MPa until a residuum stiffness of 0.1 MPa is achieved at a temperature of 265 °C. For temperatures beyond 265 °C a constant compressive stiffness \( E_{33} \) of 0.1 MPa is assumed. Values below a compressive stiffness \( E_{33} \) of 0.1 MPa lead to numerical problems.

The experimentally determined values for the compressive stiffness \( E_{33} \) were also compared with calculated values based on micromechanics considerations according to (Ref 1). This comparison clearly indicates that an experimental determination of the compressive stiffness \( E_{33} \) is necessary. Thus, the experimentally determined temperature-dependent compressive stiffness \( E_{33} \) was implemented in the consolidation model. This allows the calculation of the pressure distribution in the joining zone dependent on the temperature distribution over the laminate thickness and the applied consolidation force.

In order to investigate the cooling effect of the consolidation roller, the worst-case scenario—all polymer over the cross-section is molten—was assumed. For this purpose, the initial laminate temperature was set to 280 °C. The simulation model shows that the elastic behavior of laminate and roller results in a 3D contact area (Hertzian contact pressure). However, this
The area is too small to dissipate sufficient heat from the laminate in the short contact time (continuous process) and due to the low thermal conductivity of the laminate in the thickness direction ($k_{\text{lam}} = 0.32 \, \text{W/(K*mm)}$) (Fig. 15). This prevents an effective influence of the roller on the temperature distribution in the joining zone.

For the subsequent investigation of the pressure distribution, an ideal, linear, steady temperature distribution in the thickness direction of the laminate was assumed (Fig. 16b). The simulation model shows that there is a maximum consolidation pressure at the instant center of the consolidation roller, which rapidly decreases in thickness and plane direction of the laminate (Fig. 16a).

Additionally, the material of the roller was changed from aluminum to an elastomer, which provides a lower stiffness ($E_{\text{elastomer}} = 5 \, \text{MPa}$, $\nu_{\text{elastomer}} = 0.4$) compared to aluminum ($E_{\text{aluminum}} = 70,000 \, \text{MPa}$, $\nu_{\text{aluminum}} = 0.3$). Due to the deformation of the elastomer roller, a significantly larger contact area between the top layer of the laminate and the roller results.

**Table 1** Thermal material parameters of the CF-PA66 laminates used for the simulation model

| Parameter                          | Value       |
|------------------------------------|-------------|
| Thermal conductivity $\lambda$     | 15          |
| Laminate:                          | 2.65, 0.32  |
| Heat capacity $c$                   | 500         |
| Laminate:                          | 1148        |
| Heat transfer coefficient $h$       | 22          |
| Between laminate and atmosphere    | 22          |
| Between roller and cooling fluid   | 716         |
| Between roller and laminate        | 2689        |

**Fig. 14** Determination of the temperature-dependent compressive stiffness in the thickness direction of laminate E33 for a TepeX® dynalite 201-C200(9)/50% CF-PA66 laminate from Bond Laminates, Germany
compared to the aluminum roller. Consequently, the elastomer roller leads to a more homogeneous pressure distribution in the contact area between roller and laminate. By means of this model, also the pressure distribution in the joining zone can be calculated (Fig. 17). Although the pressure distribution in the contact area between the roller and the laminate differs depending on the material of the roller, there is a comparable pressure distribution in the joining zone in both cases. The integral of the pressure over the roller path is the same in both cases. Accordingly, the roller material has a negligible small influence on the pressure distribution in the joining zone. However, the use of an elastomer roller can reduce the stress peak in the instant center and thus prevent possible laminate damage such as delamination resulting from interlaminar stresses (Ref 24).

In order to achieve a high bonding strength by means of induction welding, there initially has to be an intimate contact between the surfaces of the adherends, which represents the joining zone, and subsequently polymer healing at the interface between both surfaces has to take place (Ref 25, 26). Based on the pressure distribution in the joining zone, the degree of intimate contact $D_{ic}$ according to Lee and Springer (Ref 27) can be calculated (Eq 1). The degree of intimate contact $D_{ic}$ describes the contact conditions between two surfaces, which are pressed together with a pressure $p_{app}$ for a time $t$ and have the viscosity $\eta_m$. It is defined for the range between 0 and 1. A degree of intimate contact of 0 means that there is no contact between the two approaching surfaces. Once the degree of intimate contact is 1, a flush contact between the two surfaces is obtained. The initial surface roughness of the two surfaces is described through the variable $g$, which was set to 0.147 in this study according to (Ref 4). This value of $g$ represents a rough surface, which is the worst-case scenario for welding.

$$D_{ic} = g^{\frac{t}{\eta_m}} \left[ \frac{\int_{0}^{t} p_{app} dt}{\eta_m} \right]^\frac{1}{2} \quad 0 \leq D_{ic} \leq 1$$

(Eq 2)

As for simplification, the viscosity is assumed to be constant at the observed temperature range with $\eta = 100$ Pas. Hence, Eq 1 can be simplified (Eq 2).

$$D_{ic} = g^{\frac{t}{\eta_m}} \left[ \frac{\int_{0}^{t} p_{app} dt}{\eta_m} \right]^\frac{1}{2}$$

(Eq 3)

The degree of intimate contact $D_{ic}$ was calculated for different roller speeds and different forces applied by the roller (Fig. 18). The roller speed impacts the time $t$ and the applied force impacts the pressure $p_{app}$ in the joining zone.

If the roller speed $v_{roller}$ is increased beyond 400 mm/min in combination with a force of 400 N, the degree of intimate contact $D_{ic}$ will be smaller than 1. Due to the lower time during which the pressure is applied, no flush contact can be achieved for process speeds beyond 400 mm/min. If the process speed is constantly 200 mm/min and the applied force is increased, the degree of intimate contact is also increased. Consequently, an increase of process speed can be counteracted by an increase of the applied force.

Compared to a real, transient induction welding process, the viscosity will be increased during the consolidation, if there is no further heat input—since the temperature in the joining zone will be reduced due to heat transfer processes to the surrounding. An increasing viscosity leads to a smaller degree of intimate contact. However, the conclusion that an increase of the process speed can be counteracted by increasing applied force, is still valid for transient process.
6. Conclusion

The continuous induction welding process provides a fast, intrinsic and contactless heating of CFRPC laminates. However, up to date this outstanding advantages cannot be fully exploited due to the complex temperature distribution resulting from the physical dependent distribution of the magnetic field intensity. Therefore, an increase in process speed and a resulting increase in efficiency without a reduction in bonding quality is hindered by the temperature distribution, which is unfavorable for the process.

In order to improve the continuous induction welding process, three approaches were investigated in this study. The approaches aim on the improvement of the three crucial heat fluxes. The first approach involves improving the inductive heat input into the laminate by means of an adapted laminate setup. For two of these adapted laminate structures, an inversion of the sign of the temperature gradient was demonstrated in inductive heating tests. Further heating tests showed that this behavior can be reproduced with different generator powers. Compared to a conventional laminate, the temperature gradient between the induction coil faced and opposite laminate surfaces can be changed from $-23.10\%$ to $+11.56\%$ by an adapted laminate structure. Without the use of surface cooling, it is thus possible to melt the opposite laminate surface or the joining zone without the induction coil faced laminate surface exceeding the melting temperature of the matrix.

The second approach provides for the improvement of the surface cooling method, which is already in use. The theoretical analytical comparison showed the promising potential of spray cooling. Heating tests, in which the laminate surface facing the induction coil was actively cooled, confirm the result of the analytical consideration. However, this also revealed the requirements that have to be met by a spray cooling system. To avoid contamination of the joining zone with the cooling liquid, the application rate must be kept low enough to achieve...
a dry-wall state on the induction coil faced laminate surface. In this case, it is possible to achieve a significantly better cooling performance compared to compressed air cooling while maintaining the same temperature in the joining zone.

In the scope of the third approach, the consolidation phase was investigated in more detail by means of the developed thermal-mechanical simulation model. Due to the small contact area and the short contact time, the heat flow dissipated by the roller from the laminate surface is negligible. However, the simulation shows that the distribution and maximum pressure in the joining zone can be influenced by the material of the roller. The calculation of the degree of intimate contact shows that, at a constant applied force, an increase in the process speed means that an intimate contact of 1 can no longer be achieved. To compensate for this effect, the force applied by the consolidation roller has to be increased.

Each of the investigated approaches offers great potential for improving continuous induction welding of CFRPC. If all three approaches are used together, synergies will result. By adapting the laminate structure, the inductively supplied energy is introduced into the laminate in a more focused manner. Consequently, less energy has to be dissipated at the surface. The newly developed spray cooling system allows the laminate surface to be cooled more efficiently. Additionally, higher temperature gradients between the induction coil faced laminate surface and the joining zone (opposite surface) can be obtained, which increases the robustness of the process as well as the process window. The developed simulation model of the consolidation phase provided important insights into effects that lead to a reduction in weld quality when the process speed is increased. At the same time, however, measures can be identified that help to maintain the desired welding quality.

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