Suitability of thickness change as process control parameter for induction welding of steel/TP-FRPC joints

S. Weidmann, M. Hübner and P. Mitschang

Institut für Verbundwerkstoffe GmbH, Kaiserslautern, Germany

ABSTRACT
This study examines the influence of thickness change on bond strength of welded hybrid joints of physically surface-treated steel sheets and glass fiber reinforced polyamide 6. The quasi-static, discontinuous induction welding was used as joining method. The steel sheets were either treated by a parallel line shaped laser structuring, which is perpendicular to the load direction and has a line distance of 0.3 mm or 0.6 mm or by a compressed air blasting. Furthermore, the influence of joining temperature on bond strength was examined as a comparison. In both cases bond strength was determined using tensile shear tests according to DIN 1465. In addition, the void content in the laminate and in the joining zone was investigated by cross section images. A time-temperature-thickness change diagram was developed to gain insight into the processes during welding. Based on these findings, it can be stated that thickness change is suitable for process control and as a quality assurance feature in hybrid induction welding.

GRAPHICAL ABSTRACT

ARTICLE HISTORY
Received 7 January 2019
Accepted 6 March 2019

KEYWORDS
Induction welding; lap shear strength; hybrid joining; influence thickness change; process control; thickness change curve; surface treatment

Introduction
Thermoplastic fiber reinforced polymer composites (TP-FRPC) become increasingly popular as an engineering material due to their excellent lightweight design capabilities and their suitability for mass production [1,2]. Therefore, efficient and weight-neutral joining techniques for TP-FRPC as well as hybrid structures of metals with TP-FRPC are required [3]. There are many well established joining methods for TP-FRPC such as screwing, adhesive bonding and welding. The latter is particularly suitable for TP-FRPC because the structural integrity of the reinforcement is preserved and no additional material is needed. However, welding technologies must be adapted for multi-material concepts. A stable bond is generated by adhesion and a positive fit between the dissimilar materials. One concept for hybrid joining metal and TP-FRPC is to use the excellent inductive heating properties of metals [1,4]. When combining inductive heating with force application by a stamp, as shown in Figure 1, a bond is generated. In case of welding metals and TP-FRPC, the polymer itself is used as adhesive and no additional material is necessary. Typically, a temperature measurement is used to monitor and control the process. Monitoring of surface temperature can either be carried out contactlessly by an optical measuring system, e.g. a pyrometer, contact thermometers, or by means of...
thermocouples in the joining zone between the joining partners. Reliable optical temperature measurement in discontinuous induction welding is difficult because the welding equipment usually covers the joining partners completely. Contact thermometers cannot be used in most cases, as these are made of metallic elements that heat-up by induction and thus would falsify the measurement results. When using thermocouples, a temperature measurement in the joining zone is possible, but the thermocouples remain in the part as a foreign object. Therefore, the aim of this study is to investigate thickness change monitoring as an alternative in-line process control method. The thickness change is the difference between the thickness of both joining partners before and the thickness of the joint region after welding.

The influence of the thickness change on the bond strength was investigated for glass fiber reinforced polyamide 6 (GF/PA6) and steel (1.0338). Three different surface pretreatments of the steel partner were considered. The obtained results were then compared to experiments in which the joining temperature was used as control parameter. Thereby, the suitability of thickness change as process parameter was assessed.

Inductive heating

In induction welding, an inverter in combination with an induction coil generates an alternating electromagnetic field (Figure 2). This electromagnetic field induces eddy currents in an electrically conductive material, such as metal, which then heats-up by resistive losses. If the metal is magnetic, additional heat is generated by magnetic hysteresis. The electromagnetic field transfers electrical power without contact and generates heat directly in the metallic adherend. When enough power has been induced into the metal, it reaches the joining temperature which is above the melting point of the thermoplastic polymer matrix [5,6].

Inductive heating is significantly influenced by various physical effects [6]. In induction welding, as described in this paper, the following three effects are relevant. The Biot-Savart law, which defines the magnetic field intensity at a point in the area around the induction coil, the skin effect, which describes the penetration depth of the current density distribution in thickness direction in the conductor, influenced by the frequency of the alternating field around the coil and also by the magnetic permeability and electrical resistance of the conductor. A further phenomena is the edge effect, if the induction coil is located near an edge of the conductor, the eddy currents cannot distribute unhindered. Thus, the current density at the edge of the conductor increase, which leads to higher heat generation [5–7].

Another challenge in the inductive heating of metals is their good thermal conductivity. The heat generated on the metal surface is distributed well in the metallic joining partner, whereby the welding temperature in the joining zone may not be reached, since the heat generated at the coil facing metal surface homogenizes too fast in the entire metallic joining partner.

Induction welding

In the molten state, the polymer wets the treated metal surface and forms the connection mechanisms after cooling. The simultaneous application of a consolidation force on the joining zone improves a complete wetting of the metal surface by the polymer, which is shown in Figure 3.

In general the joining partners can be positioned in two ways relative to the induction coil: either the metal or the TP-FRPC is facing the coil. In this study, the metallic adherend is placed on top of the TP-FRPC, facing the coil side, to guarantee a high power-input into the metal due to a short distance between induction coil and metallic adherend. An additional advantage of this configuration is the better pressure distribution in the joining zone due to the solid state of the metal even at the maximum process temperature. To minimize process time, the
joining partners are cooled by forced convection with compressed air after heating. In hybrid induction welding of metals with glass-fiber reinforced thermoplastics, the TP-FRPC does not heat directly by induction, since the material is not electroconductive. If carbon fiber reinforced polymers are welded, the fibers can be used as heating elements, since they are electrically conductive [7]. If metals are welded to carbon fiber reinforced polymers, metals and the carbon fibers heat up inductively resulting in more complex heat generation.

**Influence of crucial process parameters**

In discontinuous induction welding, a number of important process parameters have to be taken into account. The most important parameters are the temperature in the joining zone and the thickness change, which are examined in detail.

**Temperature in the joining zone**

Heating the polymer to joining temperature is the basic prerequisite for any welding process. The aim is to form a layer of molten polymer which wets the metal surface. For good wettability, low viscosity is necessary, especially on rough metal surfaces. This requires a temperature far above the melting temperature, but also below the decomposition temperature, to prevent degradation of the polymer. The target temperature in combination with the holding time also determines the depth of the molten layer in thickness direction of the TP-FRPC. This is important, as on the one hand enough molten polymer must be available to fill all cavities of the structured metal surface, but on the other hand the structural integrity of the laminate must not be destroyed. In the literature there are only few indications of which temperatures should be selected for welding different types of TP-FRPC. Grewell et al. [8] give 50 K above melting temperature as a guide value for welding semi-crystalline thermoplastics. More often, other parameters which are related to temperature in the joining zone are considered, such as inverter power or holding time at joining temperature. **Figure 4** shows a typical profile of the parameters consolidation force, inverter power and temperature in the joining zone during welding.

![Figure 3. Schematic illustration of the wetting of a metal surface by molten polymer during pressure application.](image)

![Figure 4. Process diagram of consolidation force, inverter power and temperature in the joining zone during discontinuous induction welding.](image)

To investigate the influence of temperature on bond strength, first the challenge of temperature measurement must be solved. Since temperature measurement is difficult, many studies do not consider the influence of the temperature in the joining zone on the bond strength but the power input. For ultrasonic welding Harras et al. [9] and for laser welding Prabhakaran et al. [10] showed that higher
and lower power inputs lead to worse bond qualities. For ultrasonic welding, an energy of 2.2 kJ and for laser welding, a line energy of approximately 10 J/mm lead to highest bond strength. Another approach was chosen by Ageorges et al. [11]. Here, the influence of welding time on bond strength during resistance welding of carbon fiber reinforced polyethylenimine (CF/PEI) was analyzed. Short times did not result in a bond, longer times led to degradation of the polymer. Dubé et al. [12], on the other hand, carried out a temperature measurement during resistance welding of CF/polyetheretherketone (PEEK) and found that 440 °C to 450 °C are ideal. These studies confirm the assumption that an optimal joining temperature exists, while lower temperatures lead to an insufficient bond strength and higher temperatures to degradation of the polymer. However, they investigate the influence of temperature on bond strength for welding two similar TP-FRPC. The results can therefore only be transferred to the metal/TP-FRPC joints to a limited extent.

In hybrid welding of metals with TP-FRPC, there are only some studies that determine the influence of the joining temperature. Flock [13] used a temperature measurement during heat conduction joining on the surface of the metallic joining partner. They welded stainless steel, aluminum and galvanized steel with polyamide 66 (PA66) and polybutylene terephthalate (PBT), both of them containing 30% by weight glass fiber. It was found that all material combinations have the highest bond strength at 270 °C, except PA66 with aluminum or galvanized steel which reach the maximum strength at 280 °C. The investigated temperature range was from 240 °C to 280 °C for glass fiber reinforced PA66 and 230 °C to 270 °C for PBT, respectively. Jiao et al. [14] investigated the influence of laser power and focus diameter on the bond strength during laser welding of hybrid joints of stainless steel and carbon fiber-reinforced polyphenylenesulfide (PPS). It turned out that medium laser power and focus diameter are ideal. Katayama and Kawahito [15] investigated the influence of the combination of laser power (2–5 kW) and feed (5–15 mm/s) on the bond strength and came to the result of 2 kW and 5 mm/s as an ideal parameter set. In this case stainless steel was welded to CF-PA sheets, but no joining temperatures are reported. Krüger et al. [16] have investigated the ultrasonic welding of aluminum and CF/PA66 and determined the maximum strength at a welding energy of 1400 J. In laser transmission welding of polyethylene terephthalate (PET) and titanium, different laser powers (4–5.5 W) were investigated in [17] without measuring the temperatures. The maximum strength was achieved at 4.6 W. In [18], a laser welding process for CF/PA6 and galvanized steel was considered. Laser powers of 300 W to 500 W were examined without measuring the temperature, whereby the maximum strength was reached at 400 W. Similar to the studies dealing with two TP-FRPC as adherends [14,16–18], show that lower and higher energies lead to poorer results. Consequently, an optimum joining temperature respectively power input exists and has to be determined for each material combination.

**Thickness change**

The thickness change, that is, the thickness reduction of the laminate during the welding process, as shown in Figure 5, is the result of the parameters force, temperature, and holding time.

It is analyzed less frequently than pressure/force and temperature/power. Nevertheless, there are some papers on welding two TP-FRPC which are examining the influence of thickness change. Ageorges et al. [11] have studied resistance welding of CF/PEI. A larger thickness change of up to 0.2 mm leads to an increase in bond strength, which then remains constant up to 0.8 mm. Values higher than 1 mm will result in a decrease in bond strength. In this case, the joining partners had a thickness of 2.6 mm. Villegas [19] investigated the relationship between various process parameters, including the travel (comprehensive to thickness change) on bond strength during ultrasonic welding of 1.92 mm and 3.84 mm thick CF/PEI. Travel is defined in this work as a percentage of thickness of the as-manufactured energy director, i.e. 0.25 mm. They found an optimal travel for each investigated parameter set when varying consolidation force and amplitude, in summery larger and smaller travels led to lower bond strength.

The literature shows that different authors come to different results and that it is very difficult to estimate the influence of the thickness change on the basis of previous research. Furthermore, the thickness change is not included in any of the publications on TP-FRPC and metal welding mentioned in this paper. However, in many welding processes, such as resistance welding, the thickness change is used for process control [20,21]. Zhao et al. [22] investigated the displacement-controlled ultrasonic welding of carbon fiber reinforced PPS as a process control strategy. In their paper, they showed that displacement-controlled welding enables reproducible welds and thus represents the most promising welding strategy for thermoplastic composites.

In hybrid induction welding, evolution of thickness change during processing is influenced by a number of factors. These are the thermal expansion of the joining partners, the consolidation or
deconsolidation of the TP-FRPC laminate, the polymer squeeze out, void formation, intimate contact during the welding as well as the thermal expansion of the welding equipment. As a basis for a description of the physical processes during welding, the Duhamel-Neumann equation [23,24] can be extended. The strain during hybrid welding $\varepsilon$ can be described by

$$
\varepsilon = S \Delta \sigma + \alpha \Delta T + \beta \Delta X - \Delta e_{\text{consolidation}} + \Delta e_{\text{deconsolidation}} - \Delta e_{\text{SqueezeOut}}
$$

where:
- $\alpha \Delta T$ = Thermal expansion of joining partners and test rig
- $\beta \Delta X$ = Expansion of TP-FRPC due to crystallization of matrix polymer
- $\Delta e_{\text{consolidation}}$ = Consolidation pressure induced strain
- $\Delta e_{\text{deconsolidation}}$ = Deconsolidation induced strain
- $\Delta e_{\text{SqueezeOut}}$ = Strain in correlation with thickness reduction, affected by squeeze out
- $S$ = Material compliance = 1/E, where $E$ = Young’s modulus
- $\sigma$ = Applied stress
- $\alpha$ = Coefficient of thermal expansion
- $T$ = Temperature
- $\beta$ = Coefficient of volume shrinkage
- $X$ = Crystallinity of matrix polymer

A detailed description of the thickness change curves and their relationship to the quality of the welding of hybrid joints made of metals and TP-FRPC as also the resulting bond strength is still unexplored, as known to the author. In the context of this work a first interpretation of the curves was accomplished by connecting physical phenomena with the different phases of penetration. Thus, the thickness change can be defined as a control parameter or quality assurance attribute for induction welding in more detail.

**Adhesion and surface pretreatment**

Beside the process parameters, the adhesion of the polymer to the metal surface is decisive for the bond strength. In case of welding TP-FRPCs and metals two types of adhesion play an important role: specific adhesion, which is based on chemical and physical bonds, and mechanical adhesion, which results from the adhesive or, in our case, from the polymer flowing into (artificially produced) undercuts on the metal surface [25].

In [2], various surface pretreatments in combination with induction welding of CF/PA66 and aluminum were investigated, including acid etching with nitric acid. It was shown that a foam-like structure is formed in the oxide layer of the aluminum into which the PA66 flows. The generated interlocking results in higher strength and better resistance to weathering. In the field of welding metals and TP-FRPCs, metal structuring with a laser has become more established in recent years. In this way, undercuts are generated on the metal surface into which the polymer can flow, creating a form fit. Roesner et al. [26] have shown that this can greatly increase the bond strength during laser transmission and induction welding of various thermoplastics and steel. Cenigaonandia et al. [27] have investigated different types of structuring for laser transmission welding of PA6 and steel. As an alternative to laser treatment, mechanical methods for inserting structures with undercuts are also being investigated [28,29]. An overview of the influence of various surface pretreatments on the joint strength is given in Klotzbach et al. [4]. The metals were mild steel, stainless steel, and aluminum, which were sandblasted, treated by three different laser structuring methods and degreased (as a reference). The metals were welded to continuous glass fiber reinforced PA6 using laser welding and hot plate welding. Furthermore, they investigated a variation in pressure of 1 MPa to 6 MPa. The results of the study show that all three, the surface pretreatment, the pressure and the joining process, have an influence on bond strength.

**Materials and surface treatments**

Galvanized steel 1.0338 and glass fiber reinforced polyamide 6 (GF/PA6) were chosen as these
materials are usually used in the automotive industry. A more detailed characterization of these materials is shown in Tables 1 and 2.

A surface characterization was carried out by means of white light profilometer (‘MicroProf’ of the company Fries Research Technology, FRT). The profilometer has a lateral resolution of 1 μm and a height resolution of 3 nm.

Table 2 also shows images of the scanned steel surfaces with the corresponding roughness and structuring directions on the steel specimens.

The surfaces of the steel specimens were pretreated by compressed air blasting or laser-structuring. Blasting material was corundum (Geralast, grain size: 250–355 μm). The laser structuring was carried out in line pattern perpendicular to the load direction by a water cooled IPG 1000 W single-mode fiber laser. The focusing optics has a focal length of 330 mm, the resulting spot has a radius of 20 μm. Before welding, the metal specimens were cleaned in an ultrasonic bath with the cleaning agent Tickopur TR 7 for 15 min. Moreover, the steel and GF/PA6 specimens were degreased by isopropanol immediately before welding to obtain reproducible experimental conditions. Furthermore, the TP-FRPC were dried according to their data sheet at 80 °C for 12 hours before welding and degreasing to eliminate the moisture and receive reproducible conditions.

### Experimental set-up

The experiments were carried out on a laboratory induction welding test rig (Figure 1). The test specimens were placed horizontally on an aluminum tool, below the consolidation stamp. The steel and GF/PA6 specimens were fixed together with an overlap length of 12.5 mm using polyimide tape, according to DIN EN 1465. The stamp applies a constant consolidation force on the joining partners during heating and cooling. Figure 6 shows a schematic of the experimental set-up. The metal adherend faces the coil, which leads to an increased power input in the metallic joining partner. A further advantage is a more homogeneous temperature distribution in the joining zone, as the heat spots generated on the coil facing metal surface are homogenized in thickness direction because of the isotropic heat conduction of metals. The thicker the metal sheet is, the better the temperature distribution is homogenized in the joining zone. The maximum thickness change was defined by spacers, positioned beside the welding specimen. The spacers ensure that the consolidation stamp only welds the adherends to a specified thickness change and prevents further penetration of the metal into TP-FRPC.

The experiments were conducted with a circular pancake induction coil with a diameter of 35 mm and at a coupling distance of 5 mm. As induction inverter a TrueHeat HF 5010 by TRUMPF was used which generates a maximum output power of 10 kW at an output frequency between 50 and 800 kHz. The maximum current at the coil is 280 A at a voltage of 1500 V depending on the frequency. The welding process was in all cases performed under a constant power input.

All specimens were cooled after heating by pressured air with an air flow rate of 90 l/min. The temperature in the joining zone was measured by a

---

**Table 1.** Used TP-FRPC organic sheet.

| Fiber reinforcement/fiber vol. content | Glass fiber woven fabric, 3 layers symmetric twill fabric/ 47% vol. |
|--------------------------------------|---------------------------------------------------------------|
| Matrix-polymer                       | Polyamide 6 (PA6)                                             |
| Manufacturer identification          | TepeX® dynalite 102-RG600(3)                                  |
| Manufacturer                         | Bond Laminates                                                |
| Thickness                            | 1.5 mm                                                        |
| Density                              | 1.6 g/cm³                                                     |
| Melting temperature                  | 220 °C                                                        |
| Acronym                              | GF/PA6 1.5 mm                                                 |

**Table 2.** Used steel alloy with corresponding physical surface treatment.

| Steel    | 1.0338 |
|----------|--------|
| Surface pretreatment | Compressed air blasting | Laser structuring, 0.6 mm | Laser structuring, 0.3 mm |
| Thickness | 1 mm | 1 mm | 1 mm |
| Surface roughness | Ra: 2.92 ± 0.3 μm, Rz (ISO): 17.55 ± 1.4 μm | Ra: 15.53 ± 1.5 μm, Rz (ISO): 157.4 ± 19.4 μm | Ra: 35.51 ± 1.7 μm, Rz (ISO): 235.5 ± 13.4 μm |
| Acronym   | CAB   | L50.6 | L50.3 |
| Surface scan | | | |
thermocouple (Type E), which was placed between the joining partners before welding according to Figure 7. Figure 7 also shows the cut direction through the joining zone of the lap shear specimen in order to prepare micrographs. The thickness change was determined by subtracting the thickness of the joining zone after welding from the total thickness of steel and organic sheet as shown in Figure 5.

The bond strength was subsequently determined by lap shear tests according to DIN 1465. The dimensions of the joining partners as well as the overlap length are shown on the left-hand side of Figure 8. On the right-hand side of Figure 8, the test set-up of the tensile shear test is shown schematically. An universal testing machine Zwick 1485 was used. The testing force was measured on the traverse, the free specimen test length was 112.5 mm, the test velocity was 1 mm/min, and hydraulic clamping devices were used. To avoid additional stresses in the bond when clamping the test specimens, spacers with the same thickness as the joining partners were used to compensate the offset at the clamping points.

The final thickness change was measured by a caliper gauge before and after welding outside the test rig. To determine the course of the thickness change curves during welding, the test setup was extended by a KEYENCE displacement sensor model GT2-P12 with a measurement resolution of 0.5 μm and a display accuracy of 2 μm. The displacement sensor is mounted on the consolidation stamp and is directed orthogonally onto the surface of the aluminum tool. For statistical validation, five welds were performed with identical parameters. During heating and cooling within the process other factors, as described in chapter ‘Thickness change’, affect the measured thickness change. The chapter ‘Results’ shows and explains that this approach is nevertheless suitable for gaining a deeper insight into the physics of hybrid induction welding.

Results and discussion

To compare the adequacy of temperature and thickness change as process control parameter, their influence as well as the influence of different surface pre-treatments on bond strength were investigated in detail. Each test series consists of several parameter sets. The difference between the parameter sets within a series is the variation of the process parameter to be examined. At each parameter set, six specimens were welded, of which five were used for lap shear tests, and one specimen was used to prepare micrographs of the joint.
Influence of joining temperature

To evaluate the suitability of the joining temperature as a process control parameter, the influence of three different joining temperatures on bond strength was investigated for each surface treatment mentioned in Table 2. The results are summarized in Figure 9.

It is evident, that each surface pretreatment has its individual, ideal joining temperature. For LS0.3 and CAB a temperature of $290 \, ^\circ C$ leads to a decrease of the bond strength and have comparable bond strength at the lower and higher temperature. LS0.6 shows comparable results for each investigated temperature. The results of this study confirm the assumption made by Grewell et al. [8], that welding temperatures 50 K above melting temperature lead to good welding results. In contrast to the studies presented in the chapter 'Influence of important process parameters', in which there is a maximum strength at an optimum temperature and lower
strength at higher and lower temperatures, this typical correlation between temperature and strength could not be found.

Micrographs of welded specimens (CAB, LS0.6 and LS0.3) were prepared to investigate the void contend in the joining zone at different temperatures. It can also be seen in the micrographs that there is no direct correlation between joining temperature and void content. Here, too, each structuring distance has its individual joining temperature which creates the lowest number of voids. The evaluated micrographs are shown in Figure 10.

The results of the lap shear tests and micrograph analysis show the polymer temperature in the joining zone has to be clearly (+50 K) above melting temperature, but temperature is not the only parameter which defines bond strength and void content. In hybrid induction welding the bond strength and void content are also influenced by consolidation force, generator power and frequency, coupling distance, type of metal and FRPC and the surface pretreatment of the metal. The temperature distribution in the joining zone is inhomogeneous due to the inhomogeneous electromagnetic field. Nevertheless the results show that the polymer melts in the entry joining zone.

**Influence of thickness change**

The thickness change is the difference in thickness of the joining partners before and after welding, i.e. the path that the steel sheet is pressed into the TP-FRPC.

To investigate the influence of the thickness change, the surface-treated steel sheets described in Table 2 were welded to GF/PA6 1.5 mm and the bond strength of the hybrid joints was then determined. Thickness change was increased in 0.03 mm increments from 0.02 mm to 0.2 mm, the results are summarized in Figure 11.

At both structuring distances of the laser structuring a higher thickness change leads to higher bond strength. With a LS0.3, the highest bond strength is achieved from a thickness change of 0.14 mm onwards and for LS0.6 of 0.11 mm. At higher thickness changes, no significant increase in bond strength can be observed. A structuring distance of 0.3 mm results in higher bond strengths than 0.6 mm. This can be explained by the higher surface roughness (see Table 2). It is also noticeable that the standard deviation initially decreases with
increasing thickness change and increases again from a certain value.

The metal samples blasted with compressed air show no significant influence on the bond strength at higher thickness changes. The maximum bonding strength is achieved at 0.02 mm and 0.05 mm. At higher thickness changes, the bond strength decreases slightly and lies between 0.08 mm and 0.2 mm at a value of approximately 8 MPa.

Micrographs of the hybrid joints were made in order to evaluate the joining zone between steel and TP-FRPC. **Figures 12–14** show cross section views of hybrid welds with CAB, LS0.6 mm and LS0.3 as metal component and GF/PA6 1.5 mm for TP-FRPC. The specimens were welded with identical parameter settings. When comparing **Figures 13 and 14**, it is evident that a closer structuring distance and the associated higher number of cavities lead to more voids in the joining zone at identical thickness changes. As a result, more matrix polymer is required to fill the higher number of cavities of LS0.3 completely compared to LS0.6.

In **Figures 12–14** the micrographs at a thickness change of 0.02 mm and 0.05 mm show that these thickness changes are too small to prevent a deconsolidation of the TP-FRPC. Due to the experimental set-up, the spacers prevent a further penetration of the metal into the FRPC which leads to a pressure drop in the joining zone when the thickness change is reached, resulting in deconsolidation for small thickness changes. Furthermore, the cavities of the laser structuring are not completely filled with polymer, as not enough polymer is pressed out of the organic sheet into the cavities. This leads to low bond strengths as displayed in **Figure 11** (dotted line).

**Figure 12** show micrographs of CAB metal specimens. The area of contact between TP-FRPC in the joining zone is almost completely wetted with polymer at a thickness change of 0.02 mm onwards. Thus it can be stated, that for CAB only a short thickness change is necessary to achieve an intimate contact.

At higher thickness changes, there is no improvement of bond strength because lower surface roughness requires shorter thickness changes. A higher thickness change prevents a deconsolidation of the organic sheet.
Figure 13 show micrographs of LS0.6 metal specimens. Major voids in the joining zone as well as delamination of organic sheet disappear at thickness changes of 0.08 mm onwards, leading to an increase in bond strength.

Still, voids in the cavities of the laser structuring are present at a thickness change of 0.08 mm. Although the bond quality is imperfect in a visual evaluation, a stable bond is achievable with regard to the bond strength shown in Figure 11. A further increase of the thickness change to 0.11 mm and higher provides a void-free hybrid bond and a further increase in bond strength. A void free weld quality of the bond is thus achieved from 0.11 mm onwards. When comparing the visual evaluation of the weld with the results of the lap shear tests, it can be stated, that a void free bond correlates well with the highest bond strength.

LS0.3 shows a comparable behavior as LS 0.6. The micrographs of this configuration are shown in Figure 14.

At a thickness change of 0.02 mm many cavities are empty and a large part of the organic sheet is delaminated. From 0.05 mm to 0.11 mm there are less and smaller voids in the cavities and organic sheet. As a result, bond strength increases. A big improvement in bond strength takes place at 0.14 mm. This is caused by the dramatic reduction of size and number of voids in the joining zone. A void free bond is achieved at 0.2 mm, which correlates with a high bond strength and a small deviation.

While LS0.3 and LS0.6 are void free from a certain thickness change onwards, CAB specimens still contain voids in the organic sheet. When heating the metal, only the burr of the laser structured surface is in contact with the organic sheet. Due to the small contact area caused by the burr, the temperature of the metal can only transferred to the organic sheet in a minor extend. The lower heat transfer requires more time to melt the polymer. When welding CAB, the contact area is much bigger and thus the polymer melts earlier. In combination with a holding time constant for all experiments, this effect can lead to overheating.

Considering an example of a fractured surface of the joining zone of the lap shear test specimens after the lap shear test shown in Figure 15, it can be seen that the laser-structured steel surface is imprinted in the TP-FRPC surface. A closer view shows that the matrix polymer, which was pressed into the cavities of the laser structuring during welding, was partially pulled off from the TP-FRPC. Fiber breakouts of the TP-FRPC adhere partially on the fracture surface of the laser-structured steel, which indicates a good joint quality.

It can be concluded that thickness change is suitable as a control parameter. When welding laser structured metals, there is a clear correlation between thickness change and bond strength, which is validated by micrographs.

Analysis of the thickness change curve

Five GF/PA6 organic sheets were welded inductively with LS0.6 using a constant current output of 10 A, constant consolidation force of 300 N (without any spacers) as well as a maximum temperature of 290 °C, held for 60 s. The examined time dependent thickness changes and temperature profiles are shown in Figure 16. The diagram shows the development of 5 independent joining zone temperatures and thickness change curves, which is examined in more detail below.
The thickness change curves show four different phases.

Phase 1 begins with the welding process. The consolidation force is applied and the temperature in the joining zone is rising. At the beginning, the thickness change curve drops. This phenomenon can be explained by the thermal expansion of the materials. Both the organic sheet and the metal expand at this stage as a result of the energy input. Another phenomenon contributing to negative thickness change is void formation in the organic sheet, as shown in Figures 12–14, resulting in an increase in volume. A positive thickness change is achieved by the mechanism of intimate contact and the elastic-plastic compression of the matrix material until the melting temperature is reached.

Phase 2 is characterized by a rapid increase in thickness change until the graph flattens. The temperature rises to the defined joining temperature of 290 °C, which causes further thermal expansion of the joining partners, especially for metals. A large influence and turning the thickness change to positive values is the exceeding of the melting temperature and the associated melt formation and melt flow in the joining zone. For example, molten matrix polymer flows into the surface cavities and is pressed out of the joining zone (squeeze out) by the constant pressurization of the stamp, which is shown in Figure 17. Due to the constant power output, the consolidation stamp, made of aluminum, heats up and expands due to thermal expansion that affects the thickness change curve.

Due to the polymer squeeze out, the fabric reinforcement is compressed until a high packing density is reached and thus the penetration of the metal is slowed down. The flattening of the curve due to this effect marks the beginning of phase 3.

Phase 3 is characterized by a further, but slower increase of penetration. Due to the constant application of force, the molten matrix is still pressed out of the joining area.

Phase 4 starts when the inverter power is switched off and no further energy is induced into the metal. The joining partners cool down in this phase. In this phase a superposition of various phenomena influence the thickness change curve. First, the metal is pressed further into the FRPC because the matrix polymer is still in the molten state for a short time. As the temperature drops, a negative thermal expansion of the test rig and the joining partners occurs, which leads to an increase of the measured thickness change. Besides the change due to thermal expansion, the organic sheet shrinks due to the crystallization of the matrix polymer.
Conclusion
The results of this study show that thickness change reflects all effects on bond strength and void content. Welding temperature, consolidation force and surface preparation are influencing the thickness change at the same time and in a coupled way. Measuring the thickness change offers the opportunity to control the influence of the most important process parameters by measuring one single control parameter. Additionally, the thickness change can be measured easily with a high repeatability. Based on the results presented here, the following conclusions regarding induction welding of the metal with TP-FRPC are made:

- Temperature control in induction welding is difficult with optical measurement systems as well as contact thermometers and thermocouples in the joining zone.
- Each surface treatment has its optimum thickness change with highest bond strength.
- It can be assumed that the thickness change is suitable as a control parameter.
- The size and number of voids decreases as the thickness change increases.
- For compressed air blasted steel sheets, thickness changes of 0.02 mm are sufficient to ensure complete wetting of the surface by the polymer. In this case, even a small amount of melt is sufficient to create a nearly complete intimate contact between the dissimilar materials.
- For laser structured steel sheets, thickness changes of 0.11 mm for LS0.6 and 0.2 mm for L0.3 are sufficient to ensure complete wetting of the surface by the polymer as well as a void free bond. From these thickness changes onward, the bond strength increase only minimal.

This leads to the conclusion that measuring the thickness change is a simple and robust method for process control in discontinuous induction welding.

Acknowledgments
We want to thank our partners from the European research project 'FlexHyJoin'.

Disclosure statement
No potential conflict of interest was reported by the authors.

Funding
This study has been conducted in the frame of the research project 'FlexHyJoin', funded by the Horizon 2020 Research and Innovation Programme of the European Union, funding code no. 677625.

References
1. Mitschang P, Velthuis R, Didi M. Induction spot welding of metal/CFRPC hybrid joints. Adv Eng Mater. 2013;15:804–813.
2. Didi M, Emrich S, Mitschang P, et al. Characterization of long-term durability of induction welded aluminium/carbon fiber reinforced polymer-joints. Adv Eng Mater. 2013;15:821–829.
3. André NM, Goushegir SM, dos Santos JF, et al. Friction spot joining of aluminum alloy 2024-T3 and carbon-fiber-reinforced poly(phenylene sulfide) laminate with additional PPS film interlayer: microstructure, mechanical strength and failure mechanisms. Compos B Eng. 2016;94:197–208.
4. Klotzbach A, Langer M, Pautzsch R, et al. Thermal direct joining of metal to fiber reinforced thermoplastic components. Laser Appl. 2017;29:022421.
5. Marinescu M. Elektrische und magnetische Felder. Berlin: Springer; 2012.
6. Rudnev V, Loveless D, Cook RL, et al. Handbook of induction heating. Madisond Heights, Michigan, USA: Taylor & Francis; 2002.
7. Bayerl T, Duhovic M, Mitschang P, et al. The heating of polymer composites by electromagnetic induction – a review. Compos A Appl Sci Manuf. 2014;57:27–40.
8. Grewell D, Benatar A, Park JB. Plastics and composites welding handbook. Munich: Carl Hanser Verlag; 2003.
9. Harras B, Cole KC, Vu-Khanh T. Optimisation of the ultrasonic welding of PEEK–carbon composites. J Reinf Plast Compos. 1996;15:174–182.
10. Prabhakran R, Kontopoulou M, Zak G, et al. Contour laser - laser-transmission welding of glass reinforced nylon 6. J Thermoplast Compos Mater. 2006;19:427–439.
11. Ageorges C, Ye L, Hou M. Experimental investigation of the resistance welding of thermoplastic-matrix composites. Part II: optimum processing window and mechanical performance. Compos Sci Technol. 2000;60:1191–1202.
12. Dubé M, Hubert P, Yousepour A, et al. Resistance welding of thermoplastic composites skin/stringer joints. Compos A Appl Sci Manuf. 2007;38:2541–2552.
13. Flock D. Heat conduction bonding of plastic-metal hybrid parts. Aachen: Fakultät für Maschinenwesen der Rheinisch-Westfälischen Technischen Hochschule Aachen; 2011.
14. Jiao J, Wang Q, Wang F, et al. Numerical and experimental investigation on joining CFRTP and stainless steel using fiber lasers. J Mater Process Technol. 2017;240:362–369.
15. Katayama S, Kawaihito Y. Laser joining carbon plastic to stainless steel. Ind Laser Solut. 2014;29:22–30.
16. Krüger S, Wagner G, Eifler D. Ultrasonic welding of metal/composite joints. Adv Eng Mater. 2004;6:157–159.
17. Wang X, Li P, Xu Z, et al. Laser transmission joint between PET and titanium for biomedical application. J Mater Process Technol. 2010;210:1767–1771.
18. Jung KW, Kawahito Y, Takahashi M, et al. Laser direct joining of carbon fiber reinforced plastic to zinc-coated steel. Mater Des. 2013;47:179–188.
19. Villegas IF. Strength development versus process data in ultrasonic welding of thermoplastic composites with flat energy directors and its application to the definition of optimum processing parameters. Compos A Appl Sci Manuf. 2014;65:27–37.
20. Don RC, Gillespie JW, Lambing CLT. Experimental characterization of processing-performance relationships of resistance welded graphite/polyetheretherketone composite joints. Polym Eng Sci. 1992;32:620–631.
21. Shi H, Villegas IF, Bersee H. A displacement-detection based approach for process monitoring and processing window definition of resistance welding of thermoplastic composites. Compos A Appl Sci Manuf. 2015;74:1–9.
22. Zhao T, Broek C, Palardy G, et al. Towards robust sequential ultrasonic spot welding of thermoplastic composites: welding process control strategy for consistent weld quality. Compos A. 2018;109:355–367.
23. Hetnarski RB, Eslami MR. Thermal stresses – advanced theory and applications. Dordrecht, Netherlands: Springer Science + Business Media, B.V.; 2009. pp. 1–57.
24. Nemeth M. p. An in-depth tutorial on constitutive equations for elastic anisotropic materials. Hampton: NASA Center for AeroSpace Information, Langley Research Center; 2011.
25. Habenicht G. Kleben. Berlin: Springer Berlin Heidelberg; 2009.
26. Roesner A, Scheik S, Olowinsky A, et al. Laser assisted joining of plastic metal hybrids. Phys Proc. 2011;12:370–377.
27. Cenigaonaindia A, Liébana F, Lamikiz A, et al. Novel strategies for laser joining of polyamide and AISI 304. Phys Proc. 2012;39:92–99.
28. Müller S, Brand M, Dröder K, et al. Increasing the mechanical properties of metal-plastic-hybrids by improvement of the interface – a microscopic approach. In: Euro Hybrid Materials and Structures; Kaiserslautern, Frankfurt: Deutsche Gesellschaft für Materialkunde e.V. 2016. p. 184 ff.
29. Brand M, Kühn M, Müller A, et al. Enhancing the tensile strength in hybrid metal – FRP materials through various interlocking structure patterns. In: Euro Hybrid Materials and Structures; Kaiserslautern, Frankfurt: Deutsche Gesellschaft für Materialkunde e.V. 2016. p. 251 ff.