INFLUENCES OF TEXTILE PARAMETERS ON THE INDUCTION HEATING BEHAVIOR OF CFRPC

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ABSTRACT

This study addresses the experimental investigation of the influences of textile parameters on the inductive heating behavior of thermoplastic carbon fiber reinforced polymer composites (CFRPC). By means of stationary heating experiments different textile reinforcement fabrics which differ in the titer (linear density), the thread-count and therefore in their area weight as well as in the weave style, have been investigated. It was found that a lower thread count and a lower titer promote a fast heating of carbon fiber textile reinforced polymer composites by means of induction heating. Based on these results guidelines for an ideal adjusted laminate structure of a CFRPC organic sheet for induction welding are given. Additionally, a proposal for such an ideal adjusted laminate structure is presented.

1 INTRODUCTION

Lightweight design becomes more and more a key success indicator, e.g. for the efficient electric mobility. The main issue will be the reduction of the additional weight, which is derived by the implementation of heavy batteries in order to increase the vehicle's fuel range. For this purpose carbon fiber reinforced polymer composites (CFRPC) are particularly suitable since they provide outstanding strengths and stiffness in relation to their density. However, the application of CFRPC is still hindered by a lack of lightweight and economical joining technologies. For thermoplastic CFRPC the induction welding technology provides a joining technology which is suitable for mass production [1, 2]. By means of the induction welding technology, eddy currents can be induced into CFRPC laminates since the carbon fiber is electrically conductible. These eddy currents cause an intrinsic and physical contactless heating of the adherends. If the generated heat is high enough, the polymer of the adherends will melt in the joining zone. Through the application of a consolidation pressure onto both parts in the range of the joining zone a bond can be achieved.

Based on this technology the continuous induction welding process was developed at Institut für Verbundwerkstoffe GmbH (IVW) (Figure 1). The welding equipment for this process comprises an induction coil, a consolidation roller, and an optical temperature measurement device. Through a movement of the induction coil relative to the adherends, heat is generated step-by-step along the welding seam in process direction. Once the induction coil has heated the polymer in the welding zone above the melting temperature, the water-cooled consolidation roller applies the consolidation pressure and cools down the laminate around the contact area. The distance between the induction coil and the consolidation roller (*b*) is fixed during the welding process. By means of an optical temperature measurement device, which is mounted behind the consolidation roller, an online monitoring system is provided.

In order to implement the relative movement two possible strategies for process design are feasible. One assembly strategy provides the movement of the adherends, as shown in Figure 1. In this case the welding equipment is fixed. The other process design variant provides the movement of the welding equipment, whereas the adherends are fixed.

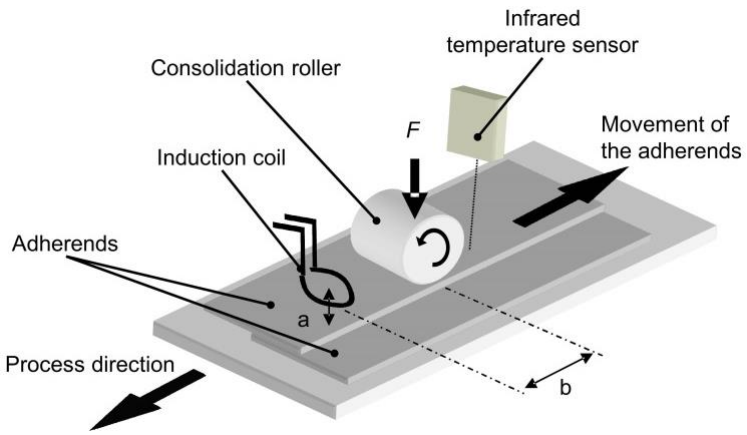


Figure 1: Schematic representation of the assembly of the induction welding process.

The continuous induction welding process for organic sheets made of CFRPC provides additional benefits, e. g. a high flexibility and mobility, small capital expenditures as well as the possibility to join complex components [1]. Nevertheless, the enormous potential of this technology is not completely exhausted yet. One major drawback, which comes along with the induction heating, is the unfavorable temperature distribution in thickness direction of the upper adherend. Due to the distribution of the field intensity of the electro-magnetic field the melting temperature of the polymer is attained first on the surface which is faced to the induction coil. Shortly thereafter the polymer in the joining zone attains the melting temperature. Since the surface faced to the induction coil is molten, the application of the consolidation pressure by the consolidation roller is affected or even impossible. Consequently, delamination or degradation of the polymer can occur.

Therefore, IVW has enhanced the continuous induction process by providing an active cooling of the surface by means of a compressed air jet during the induction heating. Thus, the polymer of the surface faced to the induction coil stays solid whereas the polymer in the joining zone can be molten. Since the maximum cooling rate of this method is physically limited also the maximum process speed is limited. In order to improve the efficiency of the continuous induction welding process, it is primarily necessary to further increase the process speed as well as the quality of the joint.

One possible approach to achieve these objectives deals with the adaption of the laminate structure of the organic sheet. A CFRPC organic sheet consists of a consolidated stack of multiple layers of carbon textile reinforcement fabrics which are impregnated with the same kind of polymer. Since the intensity of heat generation due to induction depends on the textile reinforcement fabrics [2], it is expedient to adjust the temperature distribution in thickness direction of a CFRPC organic sheet by adapting the lay-up of the textile reinforcement fabrics (Figure 2).

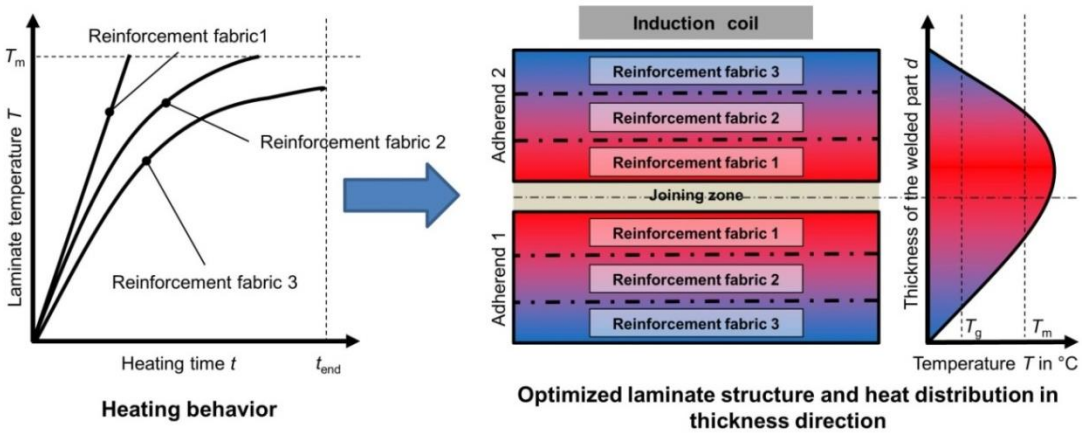


Figure 2: Concept for the optimization of the laminate structure based on the results of the heating-up tests of different reinforcement fabrics with varied textile parameters regarding the implementation of higher welding speeds.

Within this study the influences of textile parameters of the reinforcement fabric on the heating behavior of a CFRPC component are systematically investigated by means of static heating experiments. Thus, an ideal adjusted laminate structure of a CFRPC organic sheet for induction welding can be set up in order to ensure very high welding speeds as well as that the polymer can be melted locally in the joining zone. However, the polymer on the surface of the laminate, where the consolidation pressure will be applied, will not melt

2 HEATING MECHANISM FOR CFRPC

The induction heating is based on the phenomenon that a magnetic alternating field is produced around a coil which is supplied with an alternating current.. If an electric conductible material is exposed to this electro-magnetic field eddy currents will be induced into this material. In the case of CFRPC the eddy currents are induced in the electric conductible carbon fibers. However, it is essential that the fibers provide cross junctions so that electrical loops can be evolved. This requirement is met in the case of textile carbon reinforcement textiles. [3]

The generation of the heat due to the eddy currents underlies three different mechanisms (Figure 3) [4]. These three mechanisms can be separated into one fiber heating and two junction heating mechanisms. The fiber heating mechanism is also known as Joule losses. Due to the fiber's electrical resistance which is determined by their resistivity, length and cross-sectional area, heat is generated within the fiber if an eddy current runs through it. The junction heating mechanisms occur between fiber-fiber junctions. The first junction heating mechanism describes the heat generation due to the contact resistance between two fibers which are in contact at the junction. If two fibers are not in contact at a cross junction, since there are separated by a thin layer of matrix, the second junction heating mechanism occurs. This mechanism is based on dielectric hysteresis. It appears if the matrix is dielectric. In this case the matrix behaves as capacitor and resistor which are connected in a parallel circuit.

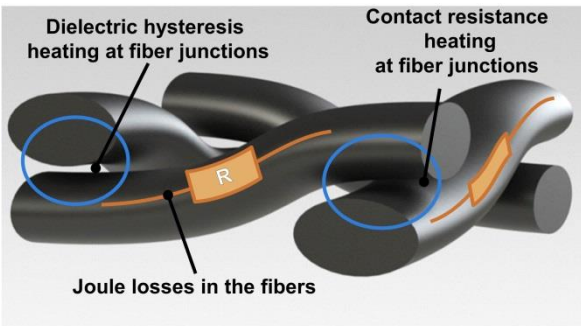


Figure 3: The three heating mechanisms which affect the heat generation during the induction heating of CFRPC.

3 MATERIALS

The heating experiments were carried out with several specimens consisting of different carbon fiber reinforcement textiles (Table 1). These textiles differ from each other in the titer (linear density), the thread-count and therefore in their area weight as well as in the type of the weave style. All heating experiments were carried out with specimens with a matrix consisting of Polyamide 66 (PA66) (Ultramid A4H, BASF).

No.	Weave	Area weight in g/m²	Titer Warp direction in tex	Titer Weft direction in tex	Thread-count Warp direction in Threads/cm	Thread-count Weft direction in Threads/cm	Matrix	Producer
1.	Twill 2/2	200	200	200	5	5	PA66	Made by IVW
2.	Twill 2/2	160	200	200	4	4	PA66	
3.	Twill 2/2	245	200	200	6.1	6.1	PA66	
4.	Twill 2/2	285	200	200	7	7	PA66	
5.	Twill 2/2	400	400	400	5	5	PA66	
6.	Twill 2/2	630	800	800	4*	4*	PA66	
7.	Plain	200	200	200	5	5	PA66	
8.	Satin 5H	290	200	200	7*	7*	PA66	
9.	±45° non-crimp fabric	200	800	800			PA66	
10.	Twill 2/2	200	200	200	5	5	PA66	BL

Table 1: Different carbon fiber reinforcement textiles (* values are rounded).

The specimens made by IVW were produced by means of a film-stacking in combination with an autoclave process. Within the autoclave process nine organic sheets with different textile reinforcement fabrics were produced with the measurement 400x150 mm^2 (Figure 4). Subsequently, four specimens with the measurement 150x100 mm^2 were cut out of each sheet.

Additionally, an industrial common organic sheet (ICOS) was also tested to exclude the influence of the lab scale production process. This organic sheet material is a TEPEX® dynalite 201-C200(9)/50% produced by Bond Laminates (BL). Here, also four specimens with the same measurements were used for the heating tests.

Before the experiments were carried out all specimens were dried in an oven at 90°C for 12 h.

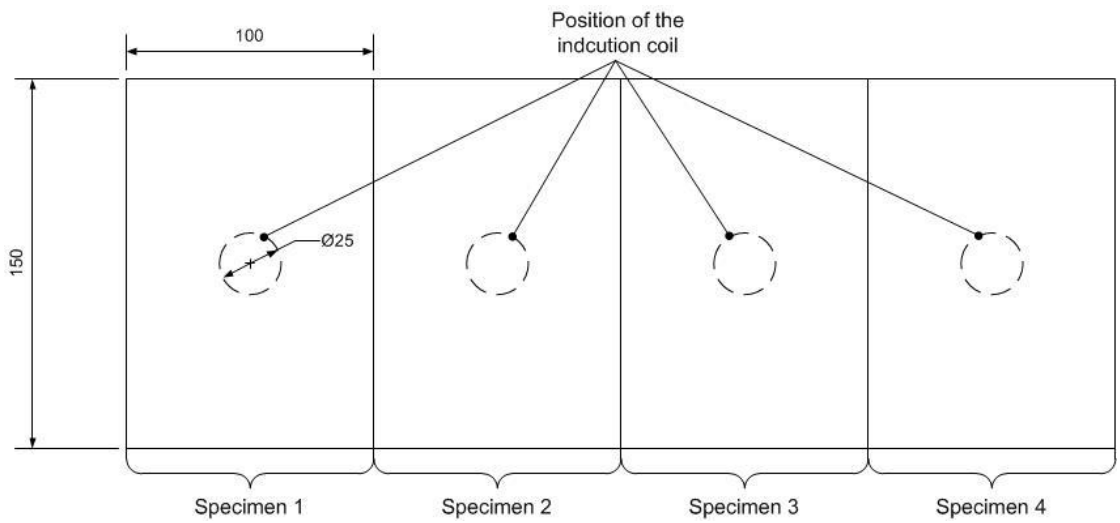


Figure 4: Schematic representation of a sheet produced in the autoclave where four specimens were cut out. The specimens were heated in the center, where the diameter of the coil is depicted.

The fiber volume fractions of the specimens made by IVW are between 49% and 58% (Figure 5). The fiber volume fractions were determined by means of a volumetric calculation. Due to imperfections which result from the manufacturing process the deviation of the fiber volume fractions are relative high. The thickness of the specimens is between 2.0 mm and 2.3 mm.

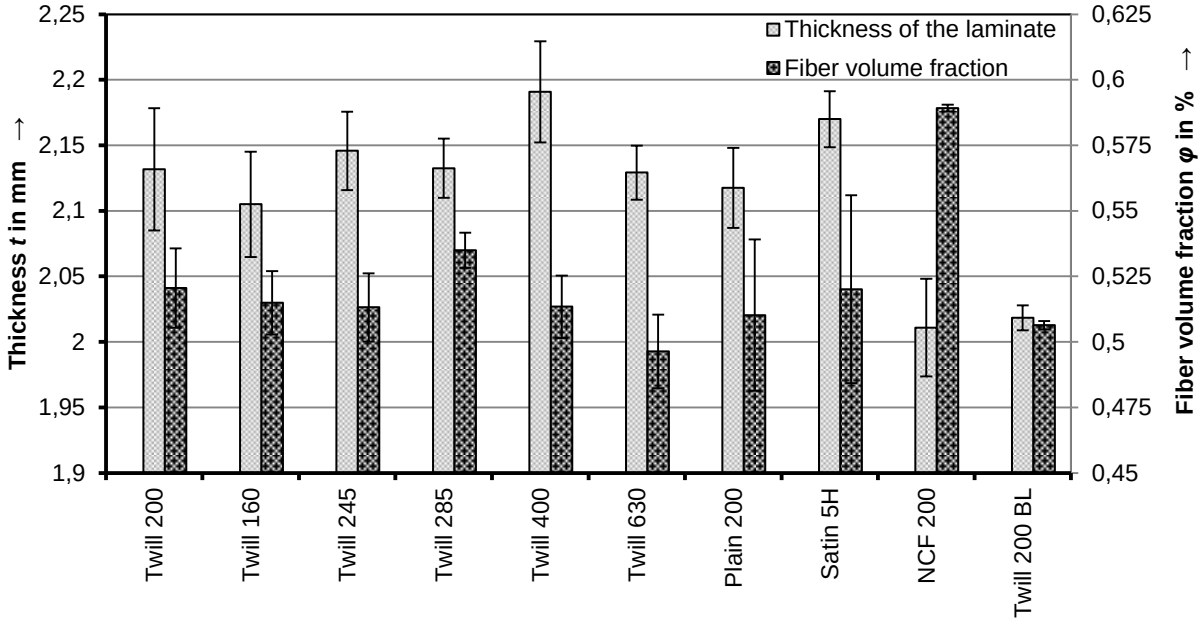


Figure 5: Laminate thickness and fiber volume fraction of all specimens. Note: The zero point on the thickness as well as on the fiber volume fraction scale is suppressed.

4 EXPERIMENTAL SET-UP

Since the heat transport due to convection is different between the top and the bottom surface in the case of a horizontal mounted plate, the specimens were mounted vertical for the heating experiments (Figure 6). The experiments were conducted by means of a circular pancake coil with a diameter of 25 mm and a coil-laminate distance of 5 mm. As induction generator a CEIA Power Cube PW3-32/400 was used. In order to exclude an influence of the selected generator power, all specimens were heated with a generator power of 15% as well as of 40%. The maximum temperatures of the surfaces of the specimens were measured by means of two TIM 160 infrared cameras from MICRO-EPSILON with a field of view of 48°. Both infrared cameras were connected with a YOKOGAWA recorder GP20 to enable the recording of the measurement. The measurement of the maximum temperatures of the two surfaces starts automatically once the induction generator is operating. Hence, the different heating rates of the induction coil faced surface and the opposite surface can be determined. To prevent deconsolidation a maximum temperature of 180°C on the surface faced to the induction coil was chosen as stop criterion. The infrared camera on the side of the induction coil provides a lateral point of view. Thus, the hot spots under the induction coil can be measured. If the infrared camera would be positioned with a rectangular alignment to the specimen's surface these hot spots would be covered by the induction coil.

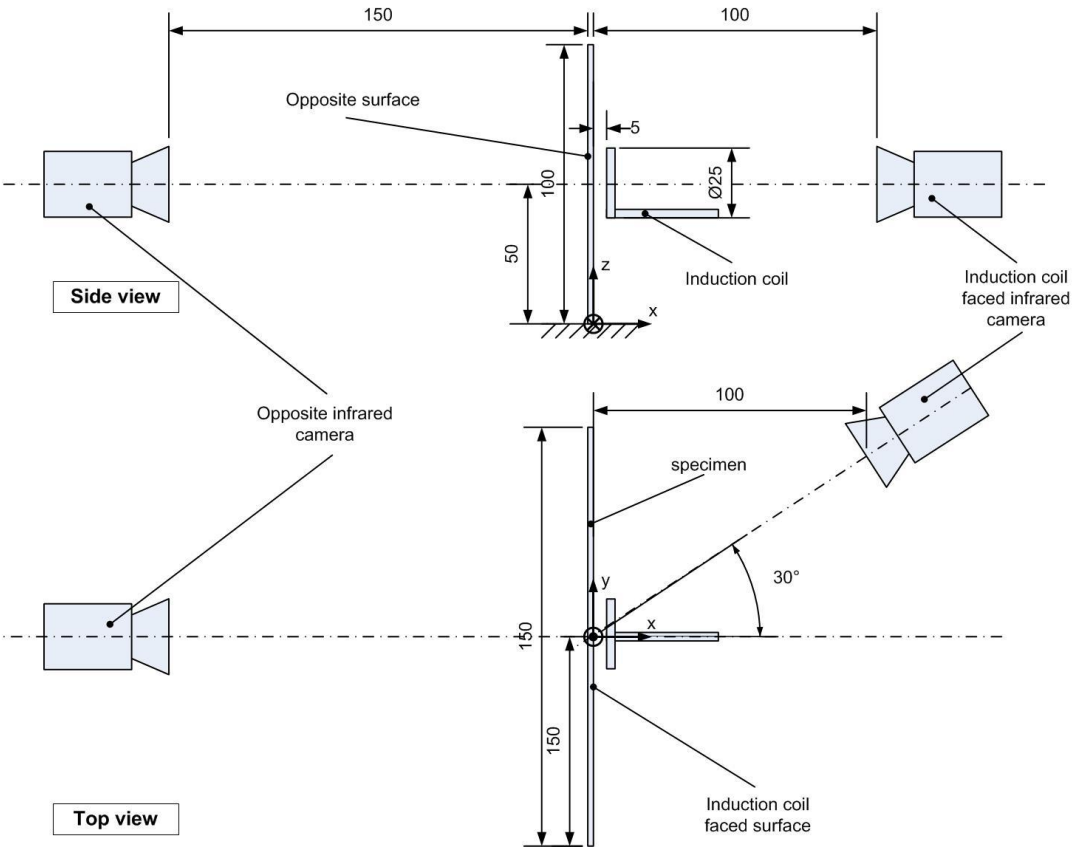
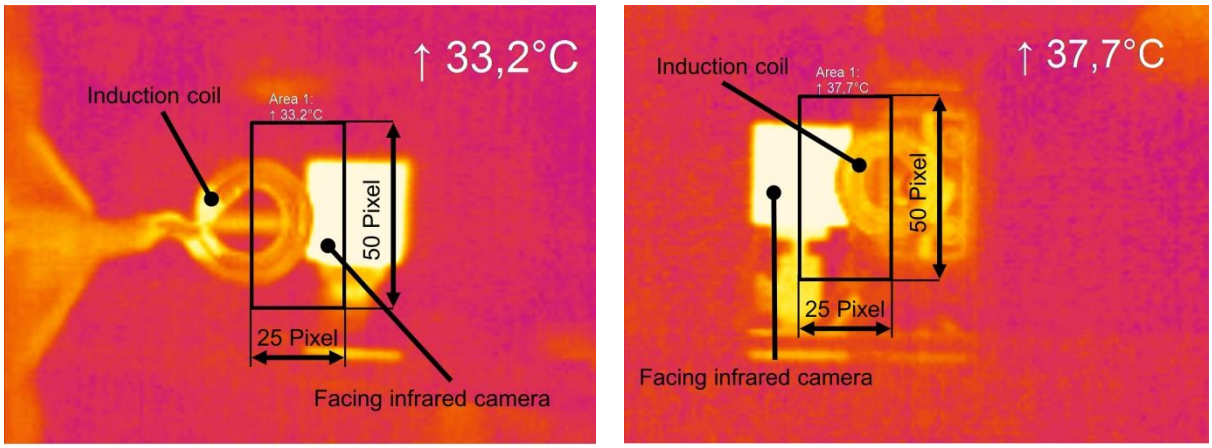


Figure 6: Schematic depiction of the experimental set-up for the heating experiments.

The measurement fields of the infrared cameras were adapted to ensure that the same position of the specimens is measured in all heating experiments (Figure 7). The size of the measurement field is 25x50 pixels. Since the surface conditions of the specimens were different, also the emissivity of each specimen differs. In order to exclude an observational error, additional tests with an emissivity tape were carried out. The used emissivity tape has an emissivity of 0.95 and was applied on both surfaces of all specimens.



a) b)

Figure 7: Point of view of the infrared cameras which measures the maximum temperatures of the induction coil faced surface of the specimen (a)) and of the infrared camera which measures the maximum temperatures on the opposite surface of the specimen (b)), if no specimen is mounted in the jig. The measurement field of both infrared cameras comprises the same area of the specimen.

5 RESULTS & DISCUSSION

Using emissivity tape the heating rates are lower compared to uncovered laminates because the heat has to transfer through the tape by conduction. Thus, the emissivity tape behaves like a thermal isolation. However, the standard deviations of the heating rates are smaller and the tendentious differences of the heating rates between the specimens with different reinforcement textiles keep equal. Since the error is constant for every specimen and the aim of this study is to gain the relations of heating rates, all experiments were performed with the emissivity tapes on top of the laminate.

Heating rates with a generator power of 15% compared to a generator power of 40% show that the difference of the heating rates between both surfaces is significantly increasing with generator power. It can also be stated generally that the heating rates are approximately three times higher with a generator power of 40% than with a generator power of 15% (e. g. cf. Figure 8 and Figure 9). Therefore, the tendential difference of the heating rates is not influenced by the generator power.

Influence of the thread-count

In order to determine the influence of thread-count on the heating rate four twill textiles with different threads-counts are compared. The heating rates which were determined with a generator power of 15% seem to be equal for different thread-counts (Figure 8). Nevertheless, an influence of the thread-count can be seen at a generator power of 40% (Figure 9). Since the heating rate is lower with a generator power of 15% compared to 40% the temperature distribution within specimen is more homogeneous at 15%. Thus, the influence of the textile parameters on the heating behavior is slurred by the relative long heating time. Another indicator for this fact is the difference between the heating rates of the induction coil faced surface and the opposite surface. Through a higher generator power this difference will increase, because there is less time to equalize the different temperatures of both surfaces. Hence it can be stated: The smaller the thread count the bigger is the heating rate.

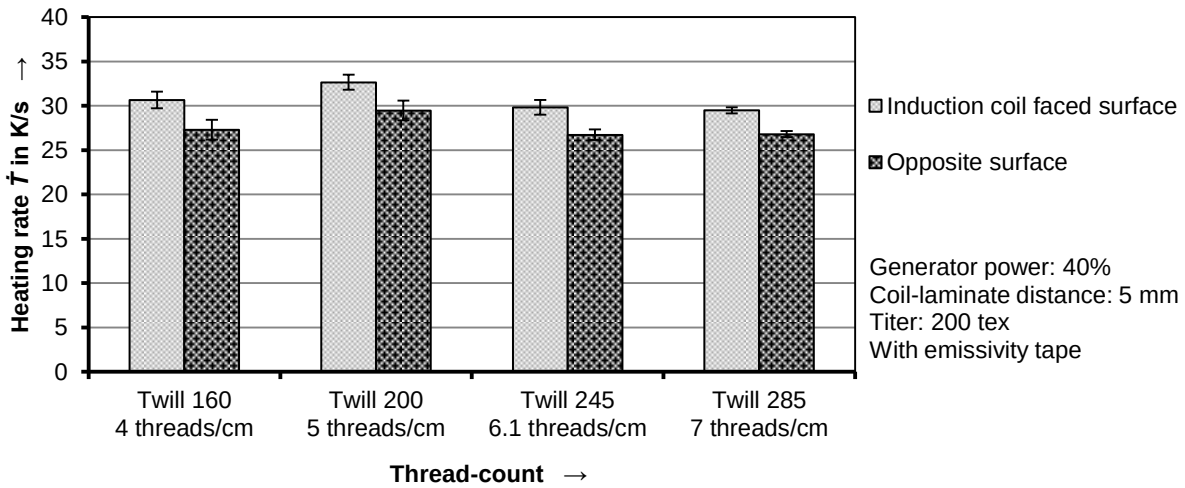


Figure 8: Heating rates dependent on the thread count at a generator power of 15%.

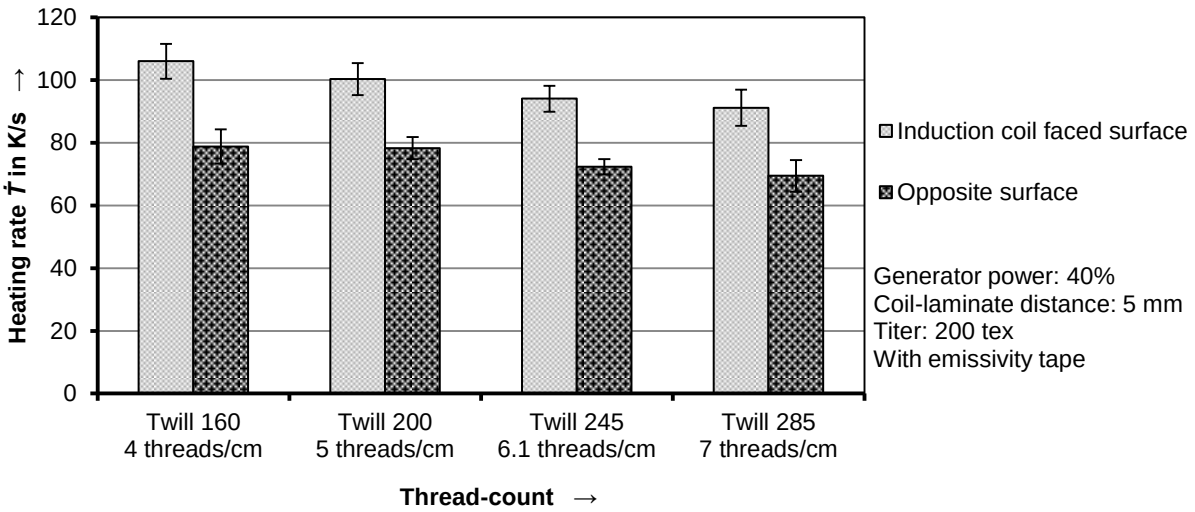


Figure 9: Heating rates dependent on the thread count at a generator power of 40%.

Influence of the titer

Also the influence of the titer was investigated by comparing the heating rates of four twill textiles. However, there are each two pairs with the same thread count which have to be distinguished. With a generator power of 15% as well as of 40% an influence of the titer on the heating rates is noticeable. The influence of the titer is stronger at a generator power of 40% (Figure 10). It can be stated: The smaller the titer the higher the heating rate.

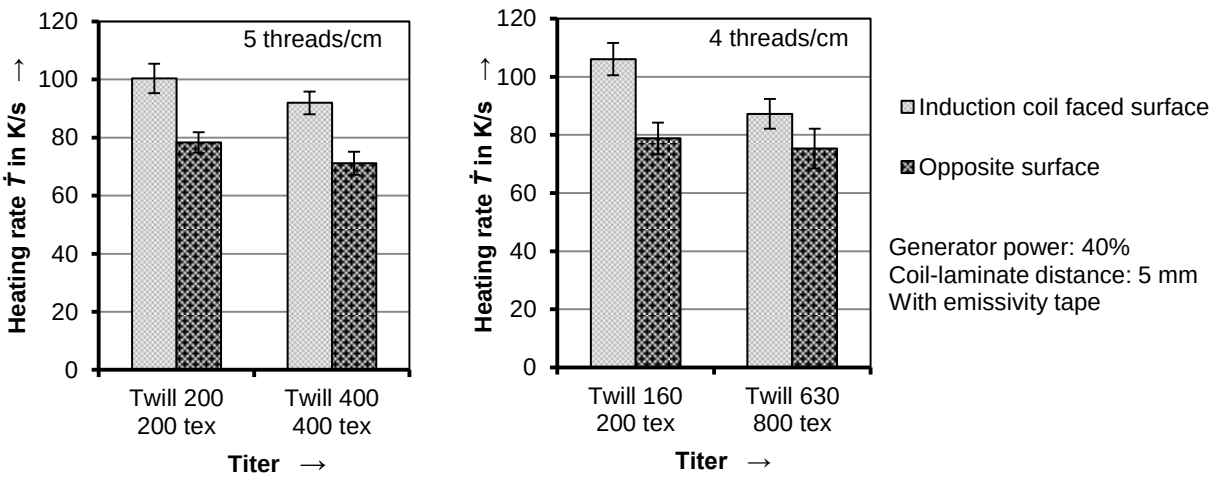


Figure 10: Heating rates dependent on the titer at a generator power of 40%. The left diagram compares two fiber reinforcement textiles with a thread-count of 5 threads/cm and the right one compares two fiber reinforcement textiles with 4 threads/cm.

Influence of the weave

In order to determine the influence of the weave style the heating rates of specimens made of twill, plain and non-crimp fabric (NCF) with a ±45° fiber orientation are compared (Figure 11). All of these specimens have a thread-count of 5 threads/cm and a titer of 200 tex. Additionally, the heating rates of specimens made of a satin 5H and a twill, both with a thread-count of 7 threads/cm and a titer of 200 tex, are plotted. The tendency of the differences between the heating rates is the same for a generator power of 15% as well as for a generator power of 40%. Different than stated by Rudolpf et al. [2] the heating rates of the specimens made of a NCF are higher compared to the heating rates of the specimens made out of the other four weaves. A possible reason for this phenomenon could be the

higher fiber volume fraction of the specimens made of NCF. Considering the standard deviation of the heating rates an influence of the weave style cannot be stated. One reason could be that the generator power of 40% is still too low in order to see significant differences between the heating rates. In further heating experiments the influence of the weave style will be investigated in connection with a higher generator power.

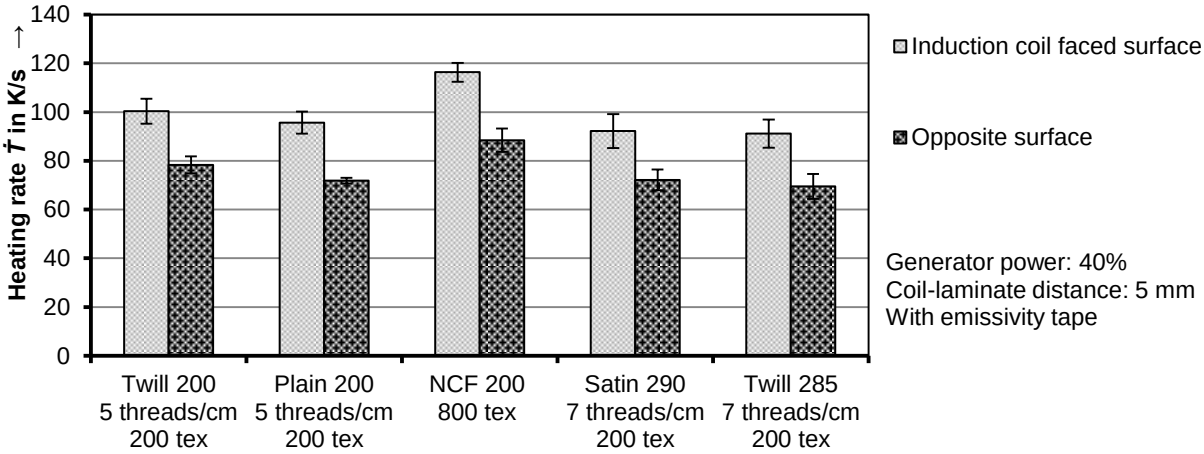


Figure 11: Heating rate dependency on weave style at a generator power of 40%.

Influence of the lab scale manufacturing process

To determine the influence of the lab scale manufacturing process, heating rates of a specimen made by IVW are compared to heating rates of an industrial common one (Figure 12). Both specimens provide the same textile parameters (twill, thread-count: 5 threads/cm, titer: 200 tex). Taking into account the slightly higher fiber volume fraction of the *Twill 200* compared to the *Twill 200 BL* and the standard deviation, no remarkable influence of the lab scale manufacturing process can be seen.

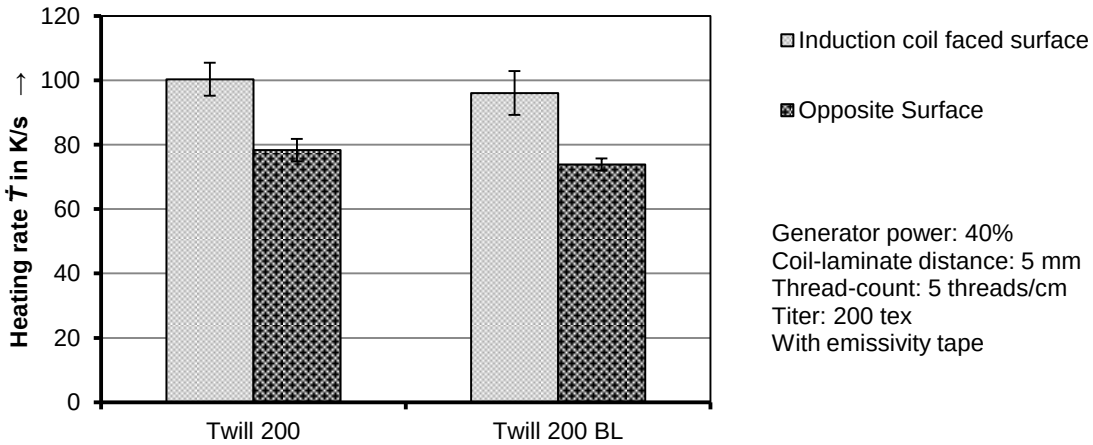


Figure 12: Heating rates dependent on the manufacturing process at a generator power of 40%.

6 CONCLUSION

The results which are gained through the comparison of the heating rates are summarized in Table 2 and Table 3. These results can be used as guidelines for the development of an ideal laminate structure for induction welding.

Boundary conditions	Heating rates	Standard deviation of the heating rates	Relative difference between the heating rates of	
			both surfaces	different reinforcement textiles
Generator power ↑	↑	↑	↑	↑
Using emissivity tape	↓	↓	Constant	Constant

Table 2: Summary of the influences of the boundary conditions on the inductive heating behavior.

Parameter	Influence on the heating rate
Thread-count ↓	↑
Titer ↓	↑
Weave	Further experiments are necessary
Industrial or lab scale manufacturing process	No influence

Table 3: Summary of the influences of textile parameters on the inductive heating behavior.

According to the stated guidelines a suggested laminate structure can be build-up as shown in Figure 13. It is consisting of two layers of Twill 630 fabric as well as of four layers of *Twill 160* fabric. This laminate provides a thickness of 2.1 mm and a fiber volume fraction of 50.8%. The laminate structure represents the best case regarding a minimum difference between the heating rates of the induction coil faced surface and opposite surface (cf. Figure **10**). For a generator power of 40% the estimated difference of the heating rate between top and bottom surface is in the range of $\Delta\dot{T} = 6$ K/s. Compared to the mono textile laminates, this difference between the heating rate of the top and bottom surface is about 50% lower in the case of *Twill 630* and approximately 75% lower in the case of *Twill 160*.

In a subsequent study it is intend to manufacture this ideal laminate and to validate this assumption. Additionally, with this ideal laminate structure welding tests will be performed in order to determine the bonding strength of the joint as well as the temperature distribution during the welding process.

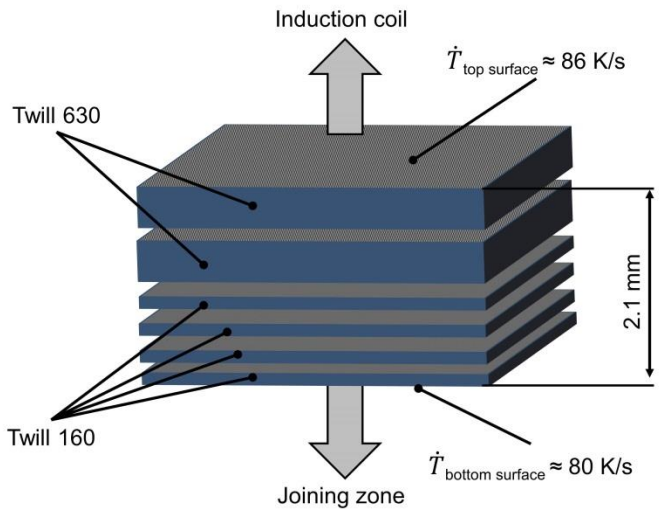


Figure 13: Example for an ideal adjusted laminate structure of a CFRPC organic sheet for induction welding.

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