INFLUENCE OF MAXIMUM TEMPERATURE AND COOLING PHASE ON THE LAP SHEAR STRENGTH OF INDUCTION JOINED GLASS FIBER REINFORCED THERMOPLASTICS AND STEEL

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Abstract

Induction joining of metals and thermoplastic fiber reinforced polymer composites is a promising technology for hybrid joining. Two important factors, which influence the joint strength, are the maximum joining temperature and the temperature range during which pressure is applied during the cooling of the parts to be joined. Therefore, this study investigates the influence of these different process phases independently and under repeatable, defined, and precise process conditions. To that, a laboratory scale press with high heating and cooling rates (1 K/s heating, and approx. 1.75 K/s cooling) was used to simulate the induction joining process. Lap shear tests showed, that an increase in joining temperatures from 250 °C to 290 °C leads to a significantly higher (47%) lap shear strength. Moreover, it was observed, that pressure must be applied around melting temperature. A temperature decrease under pressure from 270 °C to 200 °C in around 30 s leads to the highest strength of 15.33 MPa. In addition, the results show, that pressure does not need to be maintained during crystallization (temperature range from 180 °C to 160 °C). The results show, that in case of induction joining, that means that a short contact time of roller (continuous joining) or stamp (discontinuous joining) is sufficient and high process speeds are possible.

1. Introduction

Induction joining of thermoplastic fiber reinforced polymer composites (TP-FRPC) is a promising technology which has been used for decades to join thermoplastic fiber reinforced polymer composites. It is a very flexible process which can be used to create continuous joints with a length of up to several meters [1] or to locally join parts discontinuously. The processing of both glass fiber and carbon fiber reinforced materials is possible. Recently, induction joining has shown great potential for the manufacturing of hybrid components consisting of metals and TP-FRPCs [2, 3]. In addition, induction heating of metals is a well-established process for applications like surface hardening, sealing or melting [4]. For hybrid components, the polymer itself is used as adhesive and no additional material in the joining zone is needed. Moreover, the intrinsic heating of the metal by induction limits the melting of the polymer only to the joining zone. Thereby, the risk of thermal damages is reduced.
The induction heating process takes advantage of the ability of an electromagnetic field to transfer energy without physical contact. When an electrical conductor is placed in an alternating electromagnetic field (generated by an induction coil), eddy currents are induced. According to Joule's first law, a current flowing through a conductor causes the conductor to heat up. This effect can be used to heat an electrically conductive part, for example made of steel or aluminum, which is placed near an induction coil. A further factor responsible for induction heating is magnetic hysteresis, which is only possible if the conductor is made of a magnetic material (e.g. steel or nickel). The alternating

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electromagnetic field causes the elementary magnets to oscillate and the resulting friction is transformed into thermal energy.

In order to use induction heating in a joining process, the coil must be combined with some form of pressure application. During continuous induction joining, pressure is applied by a consolidation roller, which follows the coil, applying pressure to the joining area in order to create a strong joint. For discontinuous induction joining, a stamp is used to apply pressure to the parts after being heated by the coil. Both induction joining processes (see Figure 1) consist of a heating phase which results in a joining temperature T_j, which lies above melting temperature T_m and below degradation temperature $T_{d,}$ and a cooling phase during which pressure is applied while the polymer solidifies. In continuous induction joining, the time span of pressure application is a result of the process speed at which coil and roller move. It is usually in the range of only a few seconds. During discontinuous induction joining, the time span for pressing can be defined independently by moving the stamp. Usually, pressure is applied throughout the entire cooling phase.

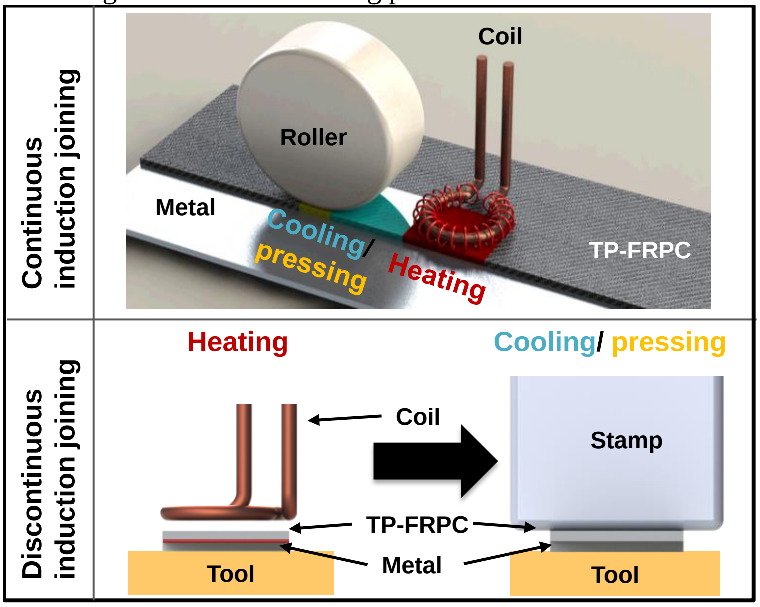

Figure 1. Schematic depiction of the continuous/ discontinuous induction joining

The timing of this sequence of melting under the coil and solidification under the roller/stamp is very important to enable a high quality bond without deconsolidation and voids. In addition, the joining temperature most probably has an influence on joint strength. Still, these two aspects have barely been covered for hybrid thermal joining processes in previous studies or literature. In case of polymer (composite) welding, there are several studies dealing with the relation of input power or temperature of the heat source with joint strength, such as [5,6] In [7], a simulation model taking into account T_j and the timing of pressure application is used to define a process window for continuous induction joining of carbon fiber reinforced thermoplastics. An experimental approach for the definition of a process window is presented in [8] for carbon fiber reinforced thermoplastics and in [9] for glass fiber reinforced polyamide 6 (GF/PA6) and steel or aluminum. However, these studies only deal with the optimization of temperature distribution and process speed without analyzing the optimum T_j or a suitable temperature range, during which pressure should be applied. To close this gap, this study aims at the investigation of the influence of T_j and the temperature range during which pressure is applied on the joint strength under repeatable, defined, and precise process conditions.

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2. Materials and methods

In this study, glass fiber reinforced polyamide 6 (GF/PA6) and steel (DC01, 1.0330) were used because this material combination is used in the automotive industry due to GF/PA6's sufficiently high mechanical properties and service temperature for structural parts. Its material properties are listed in Table 1.

Table 1. Material properties of GF/PA6

	Unit	
Fibers [10]		Roving glass
Fabric [10]		Twill (symmetric)
Area weight [10]	g/m^2	600
Yarn [10]	tex	1200
Density [10]	g/cm^3	1.8
Fiber content [10]	% vol.	47
Thickness per layer [10]	mm	0.5
Melting temperature [10]	°C	220
Glass transition temperature [10]	°C	60
Crystallization temperature (DSC)	°C	~170 °C

The crystallization temperature T_c was determined by differential scanning calorimetry and is regarded as being around 170 °C at the cooling rates present during the joining process.
Before joining, the surfaces of both materials were treated. The GF/PA6 parts were wiped with acetone while the steel parts underwent a preparation cycle consisting of the following steps:

1. Cleaning with acetone in an ultrasonic bath for 15 minutes at room temperature
2. Sand blasting with white corundum leading to a roughness of 17,84 ±1,96 µm in length-direction and 24,17 ±1,07 µm in width-direction
3. Cleaning with acetone in an ultrasonic bath for 15 minutes at room temperature

The sand blasting ensures constant surface conditions and increases adhesion by enlarging the metal surface.
Then, lap shear specimens were joined in a laboratory scale press to ensure repeatable, defined, and precise process conditions. In order to define the optimum T_j, the specimens were heated to different temperatures above T_m and below degradation. A suitable temperature range for pressure application was determined by applying pressure only during a certain period of the cooling phase. Different temperature ranges were chosen, of which one covers nearly the entire cooling process (T_m and T_c), some cover temperatures around T_m and others temperatures around T_c. Then, the lap shear specimens were tested in a Zwick tensile testing machine with the following parameters:

- 250 kN load cell and hydraulic clamps
- Free length: 23 mm
- Testing speed: 1 mm/s.

In addition, micrographs were prepared from several specimens in order to evaluate the bond quality regarding deconsolidation.

3. Experimental

In order to define the optimum T_j, and a suitable temperature range for pressure application, lap shear specimens were joined in a laboratory scale press. The overlap was set to 12.5 mm and the width to 25 mm according to DIN EN 1465, but the length had to be reduced from 100 mm to 50 mm, due to the limited size of the pressing tool. The experimental setup is shown in Figure 2.

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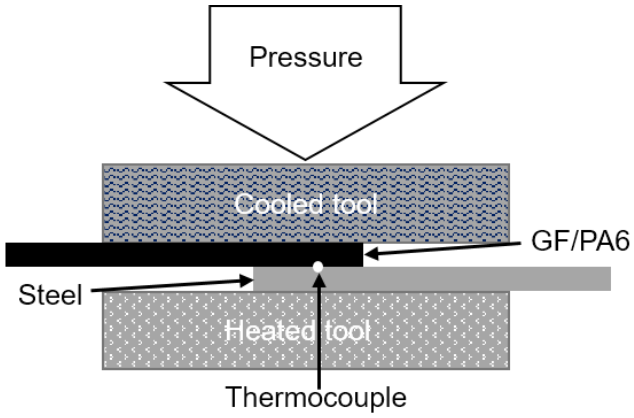

Figure 2. Schematic depiction of the joining process in the lab-scale press

The specimens were placed between the two plates of the press, which can be heated and cooled independently. The steel part was touching the bottom plate, which was heated to imitate the induction coil (heat source). The top plate was kept at room temperature and represented the surrounding air during the induction joining process. The specimens were heated to a defined joining temperature, which was supervised by a thermocouple in the joining zone. In addition, pressure was applied during defined periods of the joining process.
The lab-scale press offers high heating and cooling rates (1 K/s heating, and approx. 1.75 K/s cooling). Figure 3 shows, that the lab scale press can qualitatively imitate the induction joining cooling process while IJ's cooling rate is approximately twice as high (3,8 K/s) as long as the specimens are not subjected to free convection. In both processes, pressure is applied during solidification.

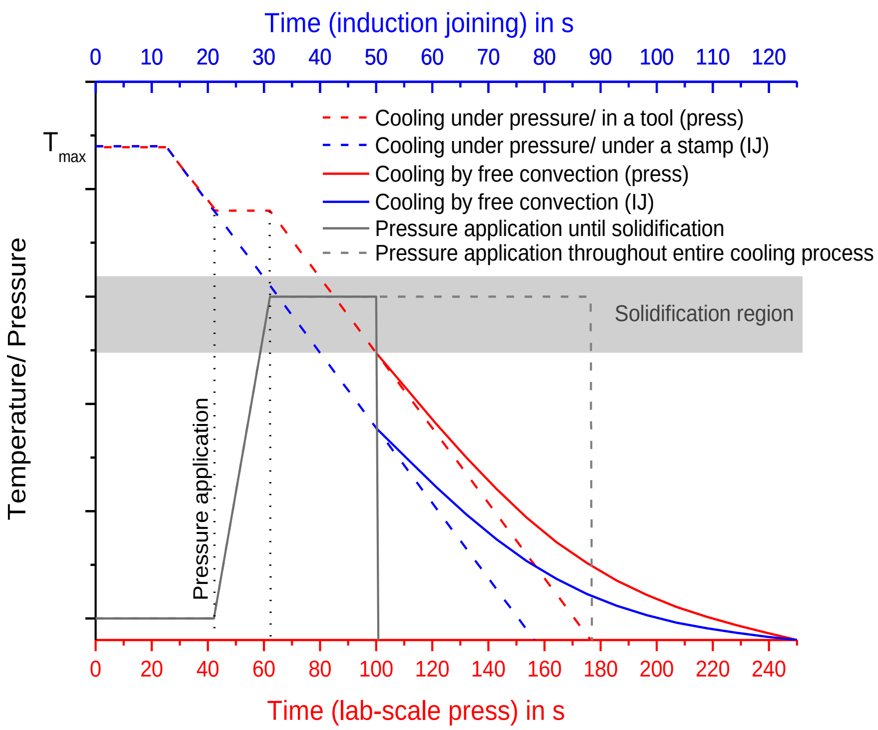

Figure 3. Exemplary comparison between the cooling process in a lab-scale press and during induction joining

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In order to investigate the influence of the maximum joining temperature on the lap shear strength, the specimens were joined using the process parameters listed in Table 2.

Table 2. Parameters of joining process to define optimum joining temperature T_j

Joining temperature T_j	Pressure	Temperature range of pressure application
250 °C	12.8 bar	30 °C to 250 °C to 30 °C
270 °C		30 °C to 270 °C to 30 °C
280 °C		30 °C to 280 °C to 30 °C
290 °C		30 °C to 290 °C to 30 °C
310 °C		30 °C to 310 °C to 30 °C
340 °C		30 °C to 340 °C to 30 °C

Pressure was always applied throughout the entire joining process, i.e. from room temperature to T_j back to room temperature.
The process parameters which were used to analyze the influence of the temperature range of pressure application on the lap shear strength are listed in Table 3. In these experiments, the pressure was reduced to 6.4 bar to enable a quick pressure application. During the remaining process, a clamping load of 1.6 bar was applied, in order to fix the specimens in the tool.

Table 3. Parameters of joining process to define suitable temperature range of pressure application

Joining temperature T_j	Pressure	Temperature range of pressure application
270 °C	6.4 bar	180 °C (T_c+10 K) to 160 °C (T_c-10 K)
		200 °C (T_c+30 K) to 40 °C (near to room temperature)
		200 °C (T_c+30 K) to 160 °C (T_c-10 K)
		240 °C (T_m+20 K) to 160 °C (T_c-10 K)
		240 °C (T_m+20 K) to 200 °C (T_m-20 K)
		260 °C (T_m+40 K) to 40 °C (near to room temperature)
		270 °C (T_m+50 K) to 170 °C (T_c)
		270 °C (T_m+50 K) to 200 °C (T_m-20 K)

4. Results and discussion

The results obtained from the lap shear tests are displayed in Figure 4. They show, that an increase in T_j from 250 °C to 290 °C leads to significantly higher (47%) lap shear strength. However, a further increase does not evoke a higher strength due to visible degradation and excessive melt flow.

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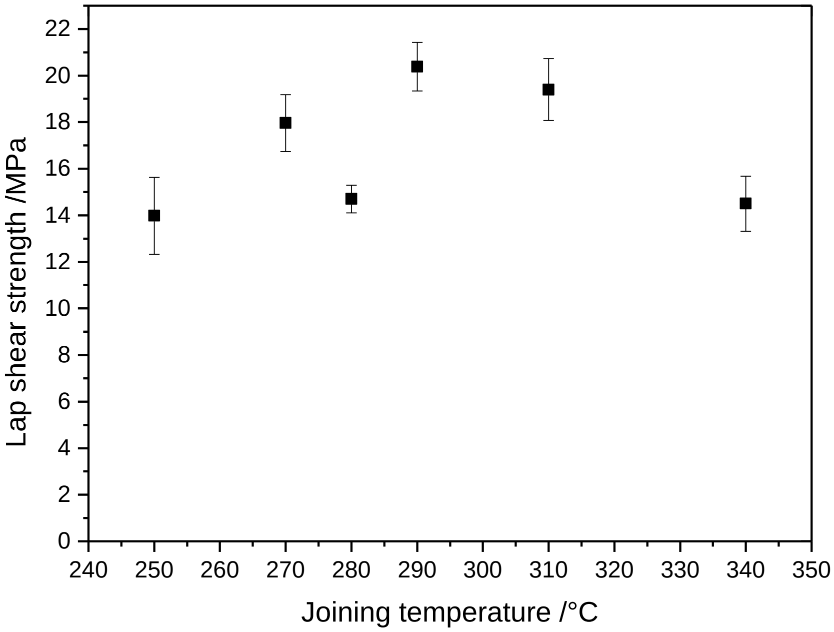

Figure 4. Influence of T_j on the lap shear strength of GF/PA6 and steel

Figure 5 shows the influence of temperature range under pressure on the lap shear strength. It can be observed, that specimens which were subjected to pressure around T_m show better results than specimens to which pressure was applied below melting but around crystallization temperature. The highest strength, 15.33 MPa, is achieved when pressure is applied from 270 °C to 200 °C

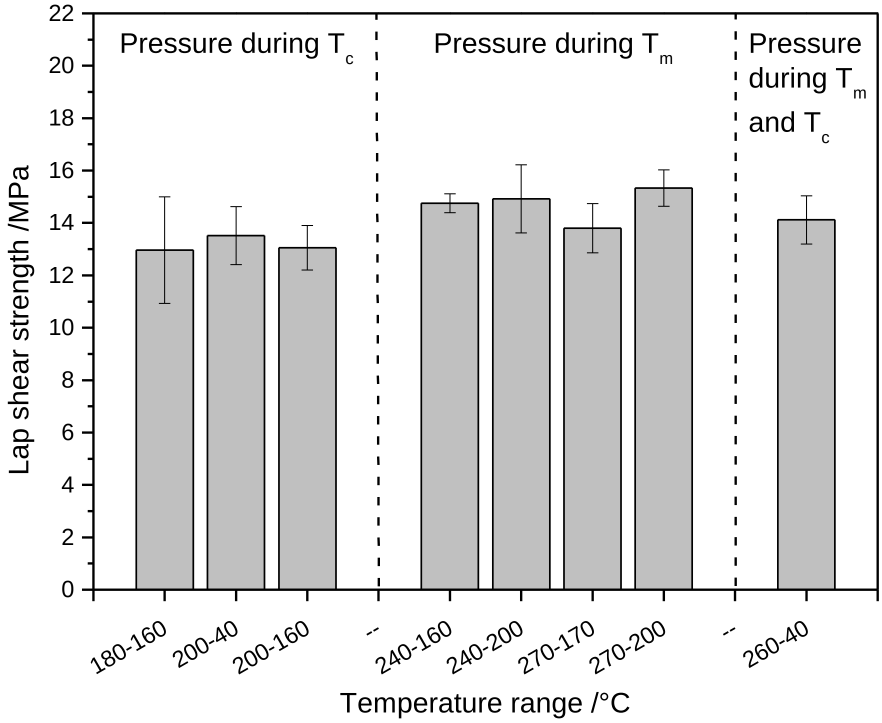

Figure 5. Influence of temperature range under pressure on the lap shear strength of GF/PA6 and steel

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These results are confirmed by the micrographs shown in **Figure 6** and **Figure 7**. While the specimen, to which pressure was applied from 270 °C to 200 °C (**Figure 6**), shows no deconsolidation, the specimen with pressure application from 200 °C to 40 °C (**Figure 7**) contains many voids within the laminate.

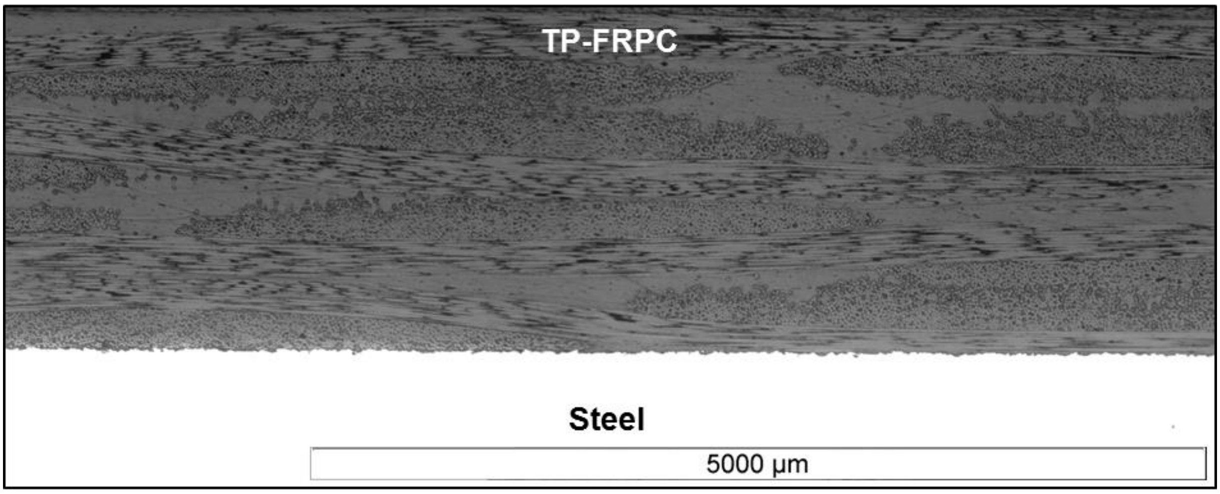

Figure 6. Micropgraph of a specimen to which pressure was applied from 270 °C to 200 °C (around T_m)

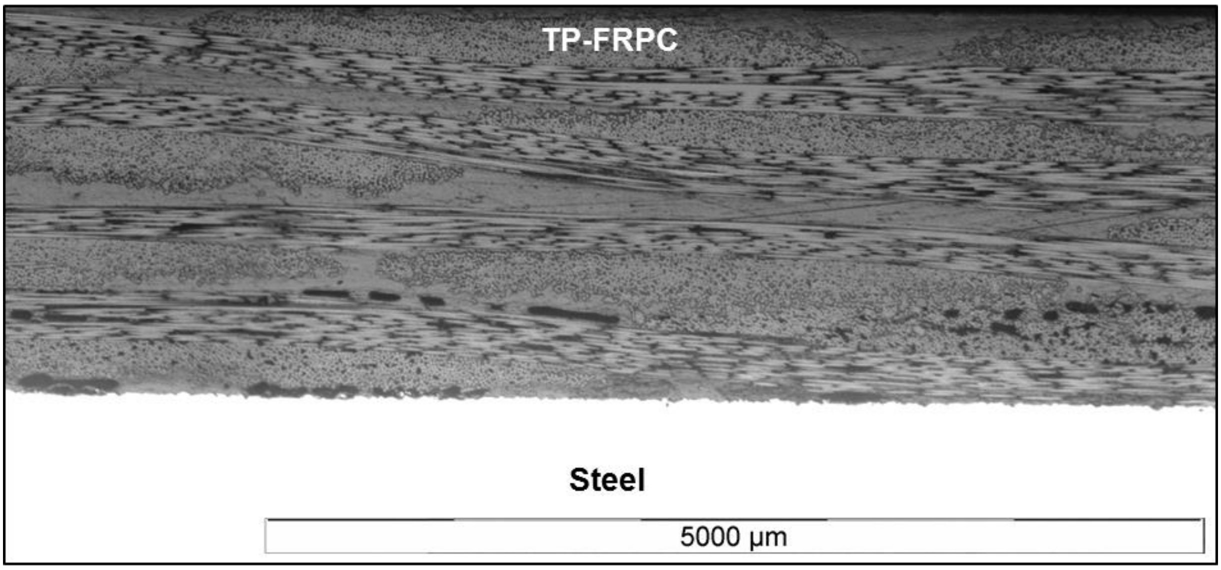

Figure 7. Micropgraph of a specimen to which pressure was applied from 200 °C to 40 °C (around T_c)

5. Conclusion

Within this study, the interdependency of joining temperature and the temperature range of pressure application and lap shear strength during induction joining of GF/PA6 and steel was investigated. In order to guarantee repeatable and precise process condition, the induction joining was simulated in a laboratory scale press with high heating and cooling rates.

It was found, that an increase in joining temperatures from 250 °C to 290 °C leads to a significantly higher (47%) lap shear strength. A further increase of T_j leads to visible degradation and excessive

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melt flow and thus to a reduced strength. Moreover, it was observed, that pressure must be applied around melting temperature. A temperature range under pressure from 270 °C to 200 °C leads to the highest strength of 15.33 MPa. In addition, the results show, that pressure does not need to be maintained during crystallization. In case of induction joining this means, that a short contact time of roller or stamp is sufficient and higher process speeds are possible. These findings can also be transferred to other hybrid joining processes with high heating and cooling rates.

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References

[1] T. J. Ahmed, D. Stavrov, H. E. N. Bersee. A comparison of fusion bonding techiniques: resistance and induction welding. *Proceedings of Sampe Europe International Conference, Paris, France,* April 5-7, 2005.
[2] P. Mitschang, R. Velthuis, M. Didi. Induction spot welding of metal/CFRPC hybrid joints. *Advanced Engineering Materials*, 15: 804-813, 2013.
[3] P. Mitschang, R. Velthuis, S. Emrich, M. Kopnarski. Induction heated joining of aluminum and carbon fiber reinforced nylon 66. *Journal of thermoplastic composite materials*, 22: 767-801, 2009.
[4] V. Rudnev, D. Loveless, R. L. Cook, M. Black, *Handbook of Induction Heating*, CRC Press, 2003.
[5] M. Hou, L. Ye, Y. W. Mai. An experimental study of resistance welding of carbon fibre fabric reinforced polyetherimide (CF Fabric/PEI) composite material. *Applied Composite Materials*, 6: 35-49, 1999.
[6] C. B. Bucknall, I. C. Drinkwater, G. R. Smith. Hot plate welding of plastics: factors affecting weld strength. *Polymer Engineering & Science* 20: 432-440, 1980.
[7] P. Mitschang, D. Maurer. Quality Controlled Induction Welding by Adapted Process Parameters. *Proceedings of Sampe Conference 2015, Baltimore, USA,* May 18-21, 2015.
[8] M. Hümbert, P. Mitschang. Characterization and modification of the temperature distribution during continuous induction welding. *Proceedings of the 16th European Conference on Composite Materials ECCM 16, Seville, Spain,* June 22-26, 2014.
[9] M. Hümbert, P. Mitschang. Interdependency of welding speed and distance between coil and roller during induction welding of metal and glass fiber reinforced polyamide 6. *Proceedings of the 20th International Conference on Composite Materials ICCM-20, Copenhagen, Denmark*, July 19-24 2015
[10] Bond Laminates GmbH, Material Data Sheet: Tepex® dynalite 102-RG600(x)/47% Roving Glass – PA 6 Consolidated Composite Laminate, Brilon, 2014.

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