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Title: **Resistance seam welding of carbon fiber semi-finished products**

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ABSTRACT

The DLR preforming process for carbon-fiber textiles as part of the RTM-Process chain consists of automated draping, a new binder activation process through electrical resistance heating, consolidation inside a membrane press and trimming of the preform to net shape [1]. This paper investigates, whether activation by roller electrode, through electrical resistance heating, has the ability to replace conventional consolidation methods. Furthermore a model for the theoretical surface temperatures after activation was developed and compared to the measured temperatures. Different set-ups (variation of width, speed, number of plies and line loads) have been tested and the electrical efficiency and compaction of the preform has been measured.

STATE OF THE ART

On the used carbon-fiber textiles a powder binder is applied. During the process of binder activation, the powder binder is heated up under applied pressure until it melts and is then cooled down for crystallization. As a result the plies can be fixed to each other respectively be consolidated.

Consolidation with the help of a membrane press is energy inefficient and time consuming, since membrane and tool are heated as well.

Ultrasonic activation is able to compact lines on preforms with an aerial weight of 2660 g/m² at a speed of 0,037 m/s [2]. However with an even higher number of layers (> 8150 g/m²) the temperature in lower layers will not be sufficient for binder activation. Also other activation methods like induction and infrared heating cannot generate an even temperature distribution in through-thickness direction within very thick preforms.

PRINCIPLE OF ELECTRICAL RESISTANCE HEATING IN THROUGH THICKNESS-DIRECTION

An electrode can induce heat and apply pressure at the same time, which makes a consolidation of carbon fiber possible. This principle is shown in Figure 1. In this process the carbon fibers are heated by an electric current. In contrast to state of the art electrical resistance heating, the voltage is applied in through-thickness direction [3].

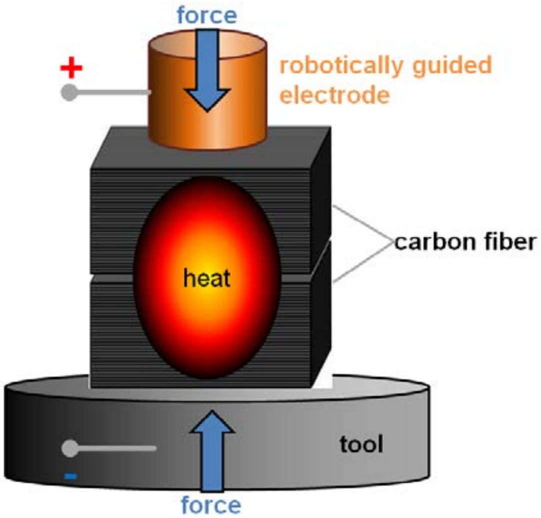

Figure 1: principle of electrical resistance heating in through thickness-direction [4]

ROLLER ELECTRODE AT DLR

With the setup of Figure 1 a local activation and therefore consolidation is possible. In order to activate lines of 30 mm width a roller electrode was developed at DLR Stade, which is displayed in Figure 2. By attaching the roller electrode to an industrial robot the consolidation of a wide range of geometries is possible (Figure 3).

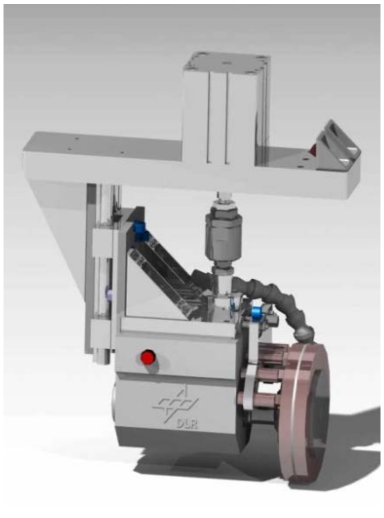

Figure 2: Roller electrode

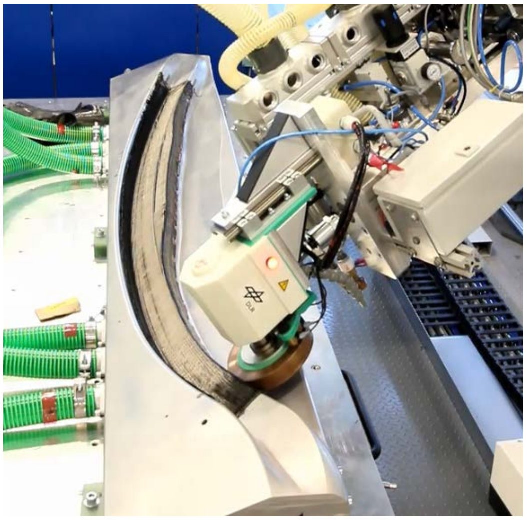

Figure 3: Robot guided roller electrode

DESIGN OF EXPERIMENTS

Four key figures were identified for an optimal process and can be seen in Table 1 under output parameters. Firstly and foremost the temperature of the preform should be between the binder activation temperature (102 °C) and a temperature which could potentially damage the fibers or their sizing. Secondly a homogenous temperature distribution within the preform is desirable. Thirdly a high compaction of the preform leads to good properties for handling and fine trimming. Finally the binder activation process should be as energy efficient as possible.

Beforehand four input parameters have been identified with the biggest impact on the output parameter, which determine the quality of the process. This is illustrated in Table 1.

With the help of a full-factorial experimental plan in total 17 configurations have been tested (see Table 1). In every test an electrical power of $P = 1000\,W$ was applied. For every input parameter a minimal and a maximal value was determined in pretrials.

	input parameters				**output parameter**			
Test No.	**Number of TriAx plies** n	**Consolidation speed** v	**Width of roller electrode** w	**Line load** p	**Mean temperature** $\bar{T}$	**Standard deviation of temperature** $SD(T)$	**Fiber volume content** $\varphi_{Preform}$	**Electrical efficiency** $\eta_{electr.}$
[ ]	[ ]	$\left[\frac{mm}{s}\right]$	$[mm]$	$\left[\frac{N}{mm}\right]$	$[{}^\circ C]$	$[{}^\circ C]$	[%]	[%]
1	4	10	12	40	140	18	39	28
2	10	10	12	40	141	12	44	46
3	4	20	12	40	147	23	38	31
4	10	20	12	40	103	12	38	58
5	4	10	30	40	101	8	38	23
6	10	10	30	40	90	9	40	43
7	4	20	30	40	78	16	37	30
8	10	20	30	40	68	4	37	53
9	4	10	12	100	121	5	42	18
10	10	10	12	100	113	6	43	34
11	4	20	12	100	109	13	43	24
12	10	20	12	100	98	10	41	45
13	4	10	30	100	69	7	36	18
14	10	10	30	100	70	2	41	31
15	4	20	30	100	59	7	37	22
16	10	20	30	100	53	4	39	40
17	7	15	21	70	77	4	39	33

Table 1: Summary of different tests carried out [5]

Temperature Measurement

The temperature was evaluated with the help of a thermographic camera. The temperature values were measured directly behind the roller electrode at the point “POI3” (see Figure 4).

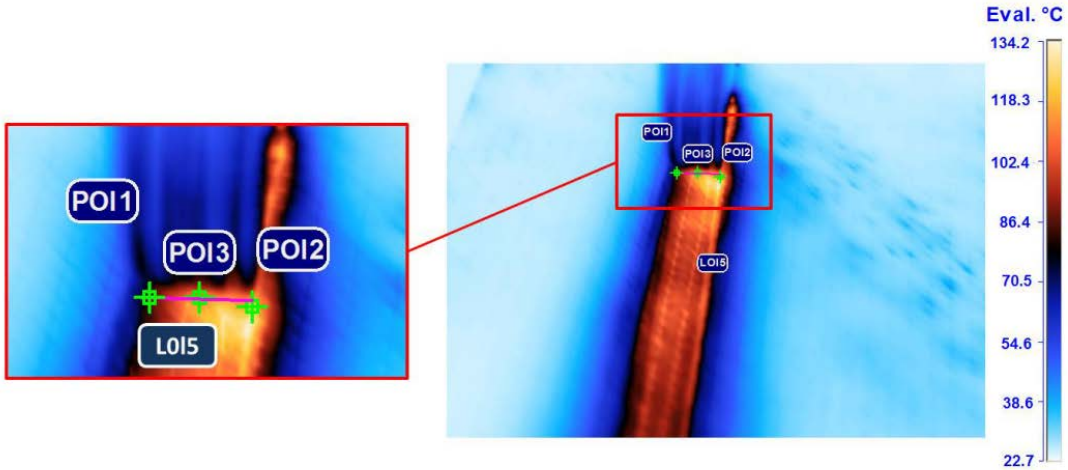

Figure 4: Temperature measurement with the help of a thermographic camera [5]

Measurement of compaction

The degree of compaction was measured with the help of a laser light sheet sensor. Although the fibers are not surrounded by resin the fiber volume content of the preform $\varphi_{Preform}$ (equation (1)) characterizes the degree of compaction. In this formula Aw_{fibers} stands for the areal weight of the preform, ρ_{fibers} for the density of the fibers and z for the thickness of the preform.

$$\varphi_{preform} = \frac{Aw_{fibers}}{\rho_{fibers} \cdot z} \cdot 100\% \tag{1}$$

Measurement of electrical efficiency

The electrical efficiency $\eta_{electr.}$ is an indicator for the amount of electrical energy, which is used for heating up the preform and respectively the share which is lost because of the resistance of the cables. An electrical resistance of the cables $R_{cable} = 0\,\Omega$ would lead to an electrical efficiency of $\eta_{electr.} = 100\%$. This can be expressed in formula (2). In this formula the resistance for the cables has been measured beforehand with $R_{cable} = 0{,}96\,\Omega$. The values for the overall resistance R_{total} are gained from the power supply during binder activation.

$$\eta_{electr.} = \left(1 - \frac{R_{cable}}{R_{total}}\right) \cdot 100\% \tag{2}$$

RESULTS

All the results are displayed in Table 1 under output parameters. With every setting the binder could be activated and the plies were adhered together, although in some cases the resulting temperatures were lower than the recommended binder activation temperature of 102°C.

Temperature measurement and distribution

With the different settings displayed in Table 1 temperatures from 53°C in test no. 16 to 147 °C in test no. 3 could be obtained. This is visualized in Figure 5. Most influential input parameter on the reached mean surface temperature $\bar{T}_{surface}$ is the width w of the roller electrode, followed by the line load p. With a smaller width w higher temperatures of the preform could be measured. This is reasonable since fewer fibers need to be heated up. Higher line loads result in lower mean surface temperatures $\bar{T}_{surface}$. This can be explained by a better heat transfer between fiber material and the copper electrode and a lower resistance of the preform [4], which leads to a lower electrical efficiency and therefore to a lower energy input in the carbon fibers.

The standard deviation of the temperatures ranged from 8°C to 28°C. The most influential factors for a more homogenous temperature distribution and therefore a smaller standard deviation were, with decreasing importance, greater width w of the roller electrode, more plies n and higher line loads p.

Measurement of compaction

Preforms with a fiber volume content $\varphi_{Preform}$ of 36% to 44% could be produced. The width w of the roller electrode and therefore the mean Temperature $\bar{T}_{surface}$ have the biggest influence on the compaction respectively the fiber volume content $\varphi_{Preform}$ of the preform. Since the compaction measurement was not performed directly after activation and in some cases the binder activation temperature was not reached, higher fiber volume contents seem possible with a higher energy intake.

Measurement of electrical efficiency

The results showed that in order to get a high electrical efficiency $\eta_{electr.}$ a higher number of plies are necessary. The influence of the line loads p on the electrical efficiency is less compared to the number of plies. Higher line loads cause a lower electrical efficiency $\eta_{electr.}$. Since higher line loads lower the electrical resistance of the preform the electrical efficiency decreases after formula (2). On the other hand do higher line loads benefit a more homogenous temperature distribution.

THEORETICAL MODEL FOR MEAN TEMPERATURE

For the calculation of the mean temperature $\bar{T}_{surface}$ a simplified model of the activation process was created. The model is divided into two phases. Furthermore the heat transfer due to radiation and convection is neglected, which is expressed in formula (3).

$$Q_{CF} = Q_{electr.} - Q_{conduction} - Q_{convection.} - Q_{radiation} \qquad (3)$$
$$Q_{convection.} = Q_{radiation} = 0$$

The first phase of the model assumes an instant heating of the preform in no time, with no heat flow. In the second phase the heat flow is calculated with the help of the semi-infinite plate model.

Phase I – instant heating with no heat transfer

The electrical energy $Q_{electr.}$ which is brought into the preform can be calculated with formula (4). In this formula P (here $P = 1000\,W$) resembles the electrical power, which is applied for the time t. The factor for the electrical efficiency η_{cables} takes into account, that a part of the electrical energy is lost through the cables.

$$Q_{electr.} = P \cdot t \cdot \frac{\eta_{cables}}{100\,\%} \qquad (4)$$

With this the theoretical temperature $T_{electr.}$ of the preform can be calculated in formula (5). In this equation the electrical energy $Q_{electr.}$ is obtained by formula (4), $m_{Preform}$ stands for the mass of the preform under the electrode and $c_{Preform}$ for the heat capacity of the preform. The Temperature of the carbon fiber before the heating process is resembled with T_{start} (here $T_{start} = 20°C$).

$$T_{electr.} = \frac{Q_{electr.}}{m_{preform} \cdot c_{preform}} + T_{start} \qquad (5)$$

Phase II – heat transfer between preform and electrode

For the heat transfer between preform and electrode the model of a semi-infinite plate is applied. For boundary condition a constant heat flow density was assumed $\dot{q} = -\lambda_{preform}\left(\frac{dT}{dx}\right) = \alpha(T_{electr.} - T_{start})$. Precondition for this model is a Fourier-number, which is smaller than 0.3. This is expressed in formula (6). In this formula $a_{Prefrom}$ stands for the thermal diffusivity (here: $a_{preform} = 2.09 \cdot 10^{-7}\frac{m^2}{s}$) and $t_{contact}$ for the contact time of the copper electrode with the preform. The contact time was calculated by $t_{contact} = \frac{d_{contact}}{v}$ with $d_{contact} = 0{,}0017\,m$. The characteristic length X can be calculated by $X = \frac{thickness\ of\ preform}{2}$.

$$Fo = \frac{a_{preform} \cdot t_{contact}}{X} < 0.3 \tag{6}$$

Next the Biot-Number of a semi-infinite-plate $\widetilde{Bi}$ can be calculated by formula (7). From literature the value for thermal conductivity of carbon fiber in through-thickness direction of $\lambda_{CF\perp} = 0{,}2\ \frac{W}{mK}$ [6] is obtained. The heat transfer coefficient between copper and the carbon fiber preform is assumed with $\alpha = 1000\ \frac{W}{m^2K}$.

$$\widetilde{Bi} = \frac{\alpha \cdot \sqrt{a_{preform} \cdot t}}{\lambda_{CF\perp}} \tag{7}$$

Finally the surface temperature $T_{surface}$ can be calculated with formula (8) [7]. Here $T_{electr.}$ can be obtained from formula (5) and T_{start} stands for the starting temperature of the copper electrode which is $T_{start} = 20°C$.

$$\overline{T}_{surface} = e^{\widetilde{Bi}^2} \cdot \left(1 - \mathrm{erf}\left(\widetilde{Bi}\right)\right) \cdot \left(T_{electr.} - T_{start}\right) + T_{start} \tag{8}$$

COMPARISON BETWEEN MODEL AND REALITY

In Figure 5 the measured temperatures of Table 1 and calculated temperatures out of formula (8) are compared. If one neglects test no. 1, model and reality show a good accordance, with a maximum deviation of 30.6 % in test no. 4.

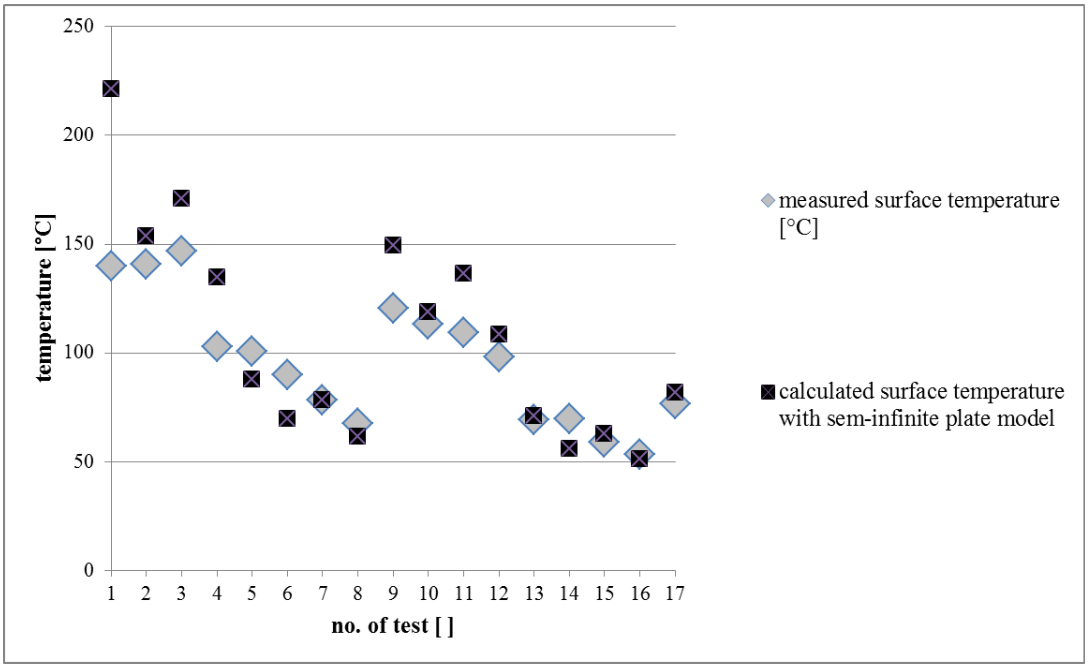

Figure 5: Calculated and measured temperatures of different tests

SUMMARY AND OUTLOOK

A preform could be binder-activated continuously with a roller-width up to 30 mm. Surface temperatures of up to 147°C could be reached. With shorter and thicker cables it will be possible to lower the cable resistance to activate even faster and to increase the electrical efficiency. With the help of the temperature model it is possible to predict the temperatures of the preform after consolidation. Fiber volume contents of the preform of up to 44% could be obtained. With higher temperatures even higher compaction rates seem possible.

In the future it is planned to test ultrasonic trimming of binder-activated preforms.

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