INFLUENCE STUDY AND COMPACTION BEHAVIOR USING ULTRASONIC WELDING FOR PREFORMING ACTIVITIES

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Abstract

Preforming of bindered dry carbon fiber material is an important step in the process chain for the manufacturing of CFRPC parts. State of the art technologies used in the aerospace industry like vacuum processes have some disadvantages. An alternative continuous technology could be identified using ultrasonic welding. To use this technology it is important to understand the effects of the parameters to the material. Furthermore a comparison to other technologies is of interest to identify the technological potential.

The present report shows a study regarding the extent of the parameter influence of ultrasonic welding to the properties of the dry fiber preform for different pre-products. Furthermore a comparison study will show the differences to other technologies like the vacuum process or the use of heat presses.

As a result it can be said that influence of the parameters differs to a conventional ultrasonic welding process and that the extent depends on the material structure. Compared to other technologies where compaction force and temperature are applied simultaneously the ultrasonic preforming process is much faster and the compaction rate increases significantly for a static process.

1. Introduction

Carbon fiber reinforced polymer composites (CFRPC) aroused increasing interests for structural and non-structural parts not even in the aerospace industry, because of their great mechanical properties related to the low specific weight. This progress can clearly be seen observing the increasing material share of composites used in the new developed airplanes, like the A350 or the Boeing 787. Due to that fact a higher level of flexible automation to produce CFRP-parts is claimed by the industry to save costs, material and time as well as to achieve a more reproducible quality.

One important step in the process chain using bindered dry-fiber material for manufacturing of CFRPC-parts with infusion technologies is the preforming process, which is needed to obtain a certain fiber volume content and to stabilize the dry fiber preform to a claimed geometry for further processing [1, 2]. Thereby a certain amount of layers will be joined using the polymer based binders in between. Within the aerospace industry the so called sequential preforming [3] using bindered material is preferred towards stitching or sewing processes because of a lower disturbance of the fiber architecture and the possibility to reach a higher fiber volume content. To achieve a homogeneous

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densification and to avoid fiber undulations interim-preforming sequences will be performed after a certain number of layers.

State of the art technologies used in the aerospace industry like convection ovens or IR-beams in combination with vacuum-bags are discontinuously, not time efficient, expensive, difficult to automate and the use of a vast amount of auxiliary-material is necessary [4]. All these disadvantages make clear, that a development of an alternative process is of current interest. Ultrasonic welding was identified as an alternative cost efficient technology for joining layers with a small width in a seam welding process within the preform assembly [5].

The scope of the current work is to develop a continuous preforming process using ultrasonic welding for extensive parts. The concept is shown in figure 1. A sonotrode of the length l_{sono} should be moved relative to a stack of carbon fiber layers covered by a PTFE buffer foil with a certain feed velocity v along the x-axis. Thereby a specific weld pressure as well as an amplitude is applied perpendicular to the surface (z-direction) to generate the necessary energy to activate the binder. The PTFE foil must be used to prevent any surface damage or disruption of the fiber architecture.

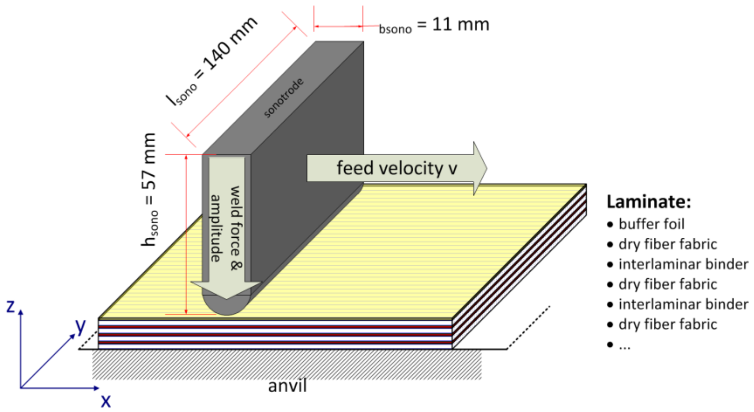

Figure 1. Concept of continuous ultrasonic preforming process

Before the use of this technology it is necessary to understand the mechanism of action and it is of interest how the process differs to the conventional ones (vacuum process). To do so an influence and a comparison study for a static spot-weld process will be presented in this paper. These experiments will provide the base to determine the parameters for a continuous process.

2. Material and Experimentation

2.1. Material

For the influence as well as for the comparison study four different dry carbon fiber materials were investigated. All materials have an integrated polymer binder system. This binder is for all materials except the Hexcel HiTape an epoxy powder. Additionally at the PrimeTex and at the TohoTenax material an interlaminar thermoplastic toughener is applied to improve the mechanical properties. For the HiTape the toughener also acts as a binder.
The HiTape as well as the TohoTenax material are unidirectional (UD) orientated. The difference can mainly be seen in the manufacturing process, where the HiTape passes through a special process for a better fiber alignment. The same process affects the PrimeTex material. The voluminous quad axial Saertex NCF is the only material without a toughener.
It is the aim to join stacks with an area weight between 600 g/m² and 700 g/m². Experiences from the manufacturing have shown that insufficient densification effects and an increasing undulation rate can

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be observed at higher values. Furthermore a higher numbers of layers would lead to a reduction in the feed velocity of the continuous process. The material properties can be seen in table 1.

Table 1. Used material for experiments

Material	Fiber	Area weight (g/m²)		Structure	T_{active} (°C)	Interlaminar material		Stack size
		With binder	Without binder			toughener	binder	
Hexcel HiTape	AS7 GP 12K (IM7)	134	142	UD	155	Thermoplastic, V800E		4
Hexcel PrimeTex	AS7 GP 12K (IM7)	220	229	0/90 fabric	155 | 105	Thermoplastic, V800E	Epoxy powder	3
TohoTenax UD	Tenax-J IMS 60 E13 24K	194	210	UD	200 | 110	Co-Polyamide	Epoxy powder	3
Saertex	Tenax-J IMS 60 E13 24K	1079	1101	quad. NCF	90	-	Epoxy powder	1

2.2. Test-Rig

For the use of ultrasonic welding electric voltage is transformed by a converter with piezoelectric actuators to mechanical oscillations. The amplitude is a product of the transmission ratios of the converter, the booster and the sonotrode [6].

The test rig consists of an oscillation unit and a generator provided by Herrmann Ultraschalltechnik GmbH & Co. KG. The system works at 35 kHz with an amplitude of 23.1 µm at an output of 100 %. The nominal power is at 600 W. The sonotrode for the spot welds follows the dimensions given in figure 1. Even the contact surface of the spot weld sonotrode is flat. Therefor the weld area has a dimension of 140 mm × 11 mm. The weld force is generated by a pneumatic system and is controlled by a proportional valve to ensure constant values. To monitor the process several sensors are implemented to measure the weld force (load cell, ±1 N), the degree of compaction (vertical aligned magnetic ruler, ±1 µm) and the temperature. To minimize the process disturbance “fine wire”-thermocouples with a diameter of 80 µm are used. The system records all values with a rate of 0.02 s.

For the comparison study the oscillation unit can be replaced by a heat stamp. The stamp consists of a flat surface (25 mm × 50 mm) heated up by three heating cartridges. To make a fast cooling down possible the stamp has a cooling gap for compressed air. By the use of a PID-controller it is possible to set the claimed temperatures at the surface with a precision of ± 5 °K.

2.3. Experimentation

2.3.1. Influence study

The aim of the influence study is to determine the reaction of the preforms made by different pre-products on the variation of the ultrasonic welding input parameters. These parameters are the amplitude a, the weld force p and the contact time t. The possible responses of the preforms are the temperature, the energy and the relative fiber volume content (FVC). The relative FVC $\varphi_{F\text{-}rel}$ is defined as the volume ratio between fibers and embedded air under a certain pressure. This value is calculated by the use of the materials grammage G_F [kg/m²], the numbers of layers n, the fiber density ρ [kg/m³] and the measured preform thickness d [m] (Eq. 1).

$$\varphi_{F-rel} = \frac{n \cdot G_F}{\rho \cdot d} \cdot 100\% \quad (1)$$

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To determine the described influences each material is tested with one stack defined in table 1. For the study a full factorized experimental design with a triple centered replica was created. The evaluation will be done by the design of experiments (DoE) tool modde by umetrics Lt. to show the influence shares of the parameters and to identify coherences between the parameters for each response. The parameters, their levels as well as the responses can be seen in table 2.

Table 2. Parameters and responses of the full-factorized experimental design

Factors / Parameters					Responses	
Name	Level			Unit	Name	Unit
amplitude	17.33 | 75	20.33 | 88	23.1 | 100	µm | %	temperature	°C
weld force	0.1	0.2	0.25	MPa	FVC | thickness	% | mm
contact time	0.8	1.4	2.0	s	energy	W

The range of the parameters was selected after some pre-trials to identify a proper process window. Especially the weld force is of peculiar interest. In common ultrasonic welding processes for thermoplastic material usually weld forces between 0.2 MPa and 0.6 MPa are applied to the material [7]. Due to the fact that the heat process differs to a conventional weld, because it depends on inter filament friction [5], there is no need for such high values. Furthermore pre-tests have shown that a weld force of more than 0.25 MPa leads within a continuous process to an intolerable fiber misalignment at the edges of the sonotrode.

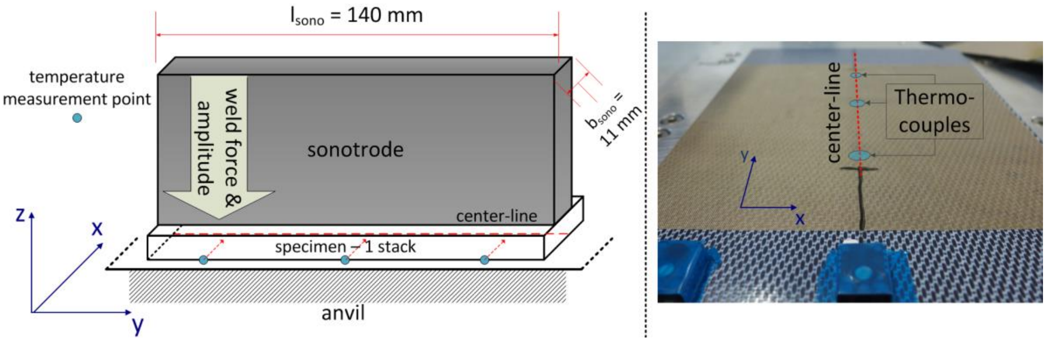

Figure 2. Experimental setup and thermos-couple positioning for influence study

The test execution is schematically shown in figure 2. The stack is placed under the sonotrode and the weld force as well as the amplitude is applied to the specimen for the claimed time. For the UD materials the fibers are orientated along the x-axis. The temperature is measured at three positions between anvil and specimen on the center-line of the sonotrode. Previous investigations have shown that in this area the lowest temperature can be expected. Furthermore the temperature on the bottom of the stack is responsible for a possible joint to further stacks. For the evaluation the temperature and the material thickness at the end of the process are used. For the energy investigation the average value over the process time will be calculated.

2.3.1. Comparison study

On the one hand the comparison study is an extension of the influence study to determine the compaction behavior with an increasing number of stacks. On the other hand it will be shown how other technologies are acting. Figure 3 shows the experimental setup for the ultrasonic trials on the left as well as the setup for the trials with the heat press on the right. Additionally preforming trials will be performed under the use of a vacuum bag in an industrial convection oven.

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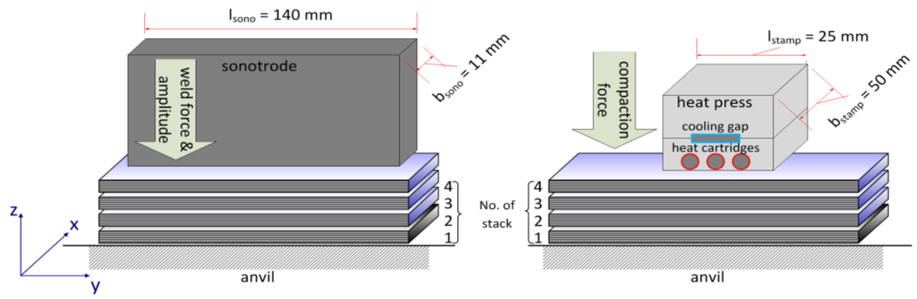

Figure 3. Setup for the comparison study: ultrasonic welding (left); heat press (right)

Each material has to be joined stack by stack under the use of different amplitudes and forces. The contact times for the ultrasonic trials are adopted from the influence study and their results observing the softening temperatures of the binders. The used weld forces for the ultrasonic process are also a result of the influence study. For the heat press compaction forces of 0.1 MPa, 0.2 MPa and 0.3 MPa are applied to the specimens. The temperatures for both kinds of specimens are measured between the stacks. The specimens will be unloaded after an uncritical temperature is reached. The HiTape material is tested with an UD fiber orientation and with a 0°/90°-orientation as well. All trials are performed three times for a better statistic.

With respect for a possible debulking of the textiles the relative FVC is measured 120 s after the trial is finished under the maximum vacuum pressure of 0.1 MPa. Experiences have shown that it is necessary to reach at least the claimed thickness of the final part as well for the preform using a vacuum infusion process. The claimed FVC within the aerospace industry is between 60 % and 63 %.

As a result of this test series the compaction behavior with an increasing number of stacks will be discussed. Furthermore the differences between the technologies will be shown as well as the influences of the welding parameters already investigated for one stack before.

3. Results and Discussion

3.1. Results of the influence study

The evaluation of the influence tests leads to several multi linear regression models (MLR) for each material and process answer. Figure 4 shows the parameters influencing the answers depending on these models. The diagrams present the significant coefficients for the single model terms in a scaled and centered way to clarify the influence shares.

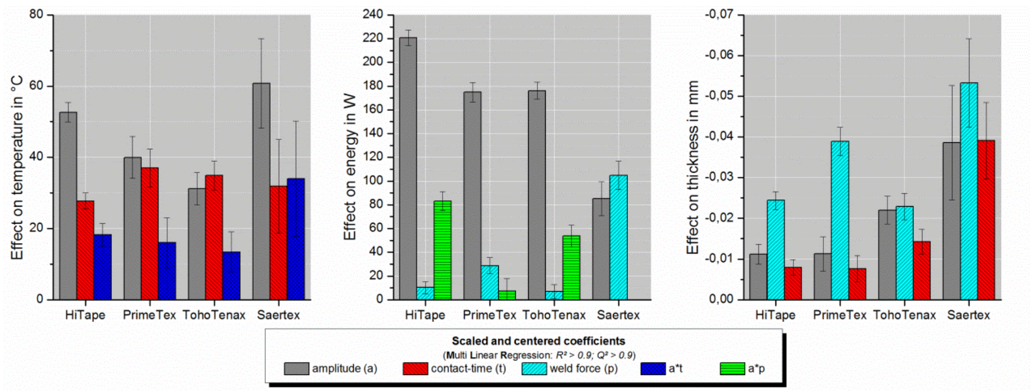

Figure 4. Scaled and centered coefficients of the influence study for each material

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Qualitatively the results are similar for all materials. Even the shares differs which can be explained with the material structure. In general the temperature is mainly driven by the amplitude and the contact-time and their interactions. The interaction leads to a non-linear progression between amplitude and contact-time. In contrast to conventional ultrasonic welding processes the variation of the weld force has no significant influence on the temperature within the value range. Of course an extensive increasing weld force leads to an increasing friction, but due to the fact that the temperature progression depends on the friction of free movable fibers, the effect is quite low. It is clear that increasing amplitude leads to higher heating rates. Therefore to establish fast processing the use of amplitudes around 100 % are recommended, especially because no disturbance of the fiber alignment could be observed as it was done in other investigation with 20 kHz systems [8]. Furthermore the results make clear, that the influence of the contact time is quite similar for all materials. Even the impact of the amplitude is significantly higher for the thicker Saertex material. This can be explained by the fact that more filaments contributes to the friction effects.

The laminate thickness, which is directly linked to the relative FVC, is affected by all three parameters. Thereby the contact-time has the lowest influence to the compaction. Obviously the values for the weld force and the amplitude differs. For HiTape and PrimeTex the influence of the amplitude is much lower than for the other materials. This could be explained with the already improved fiber alignment. Therefore the nesting effects are of lower intense. Indeed the weld force has the highest influence, but it is important to take the elastic effects into consideration. It is noticeable that already at low weld forces of 0.1 MPa (infusion pressure) for all amplitudes high relative FVC of more than 70 % could be observed. Therefore also for the continuous processing a low weld force is recommended.

The acoustic intensity J [6] (Eq. 2) describes the energy going through an area element per time unit.

$$J = \frac{1}{2} \cdot \rho \cdot c \cdot (2\pi f)^2 \cdot {A_A}^2 \quad \left[\frac{W}{m^2}\right] \tag{2}$$

In this equation f is the immutable frequency, A_A the amplitude, ρ the materials density and c the sonic speed. For the fact that the contact-time is just a multiplier to the energy the average values were recorded. This makes clear that there is no time influence to this response. Therefore the energy is mainly affected by the amplitude, the weld force and their interaction. The dominating factor is the amplitude. This correlates with equation 2 even under consideration of the nonlinear interaction factor. The weld force influences in interaction with the amplitude the material density ρ. This explains the role of the weld force as well as the influence of the interaction. One exception can be seen again observing the Saertex results. The process is very sensitive for this material and increasing weld forces lead to an instable process, which is responsible for the high scattering and the deviations within the regression models. This makes clear that especially for thick materials a lower weld force is recommended.

3.1. Results of the comparison study

The results of the influence study are impacting as already mentioned the values for the comparison study. Starting from the regression models the needed contact-times to reach the claimed temperatures at the bottom of the stack were calculated for each amplitude (75 %, 88 %, 100 %) and material. Furthermore the weld forces were reduced to 0.1 MPa. Additionally for the amplitude of 100 % a weld force of 0.15 MPa was applied to show the impact of an increasing value (except Saertex material because of instable behavior at increasing weld forces).

Figure 5 shows the temperature development for the ultrasonic welding and the heat press as an example of the TohoTenax material. Observing the ultrasonic specimens, for the first stack the heat rate corresponds with the results of the influence study. For an increasing numbers of stacks the heat rate increases as well. This is due to the fact, that the ultrasonic oscillations penetrate the stack below

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as well without an entire damping and more fibers contribute to the friction. Therefore between 9 and 12 layers (3 and 4 stacks) there is no significant difference in the heating behavior anymore. For further processing the contact-time could be reduced following these results. Further it can be pointed out, that an increasing weld force has as expected no significant influence to the temperature.

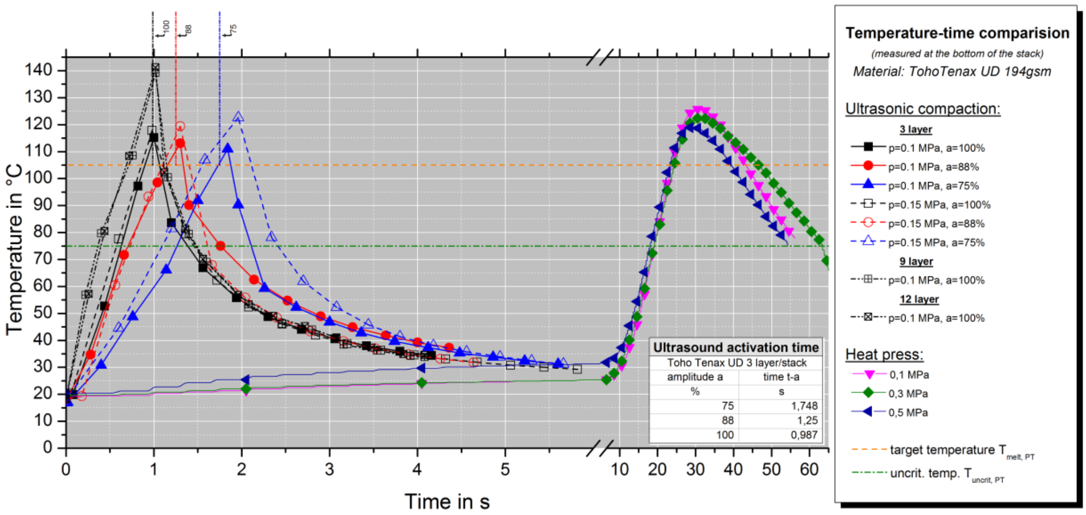

Figure 5. Temperature-time

Observing the results regarding the heat press it is clear, that the process needs substantial more time, whereby an increasing pressure do not have an influence to the heat rate. The whole process takes about 40 s for all materials, whereas for amplitudes of 100 % at the ultrasonic process the process is finished after 1.5 s. With decreasing amplitudes the process time increases.

The results for the relative FVC are shown in figure 6 for all materials and technologies after four preforming steps. For the combination of amplitudes of 75 % and the HiTape material no test could be performed. This is due to the fact that the reduced generator power does not last to achieve the claimed output for an already high condensed material (increasing density ρ). For all ultrasonic specimens the relative FVC is above the claimed 60 % with a low scattering. Observing the PrimeTex and the Saertex material the compaction rate is much too high. Therefore a decreasing weld force and a shorter contact-time is a possible adjustment.

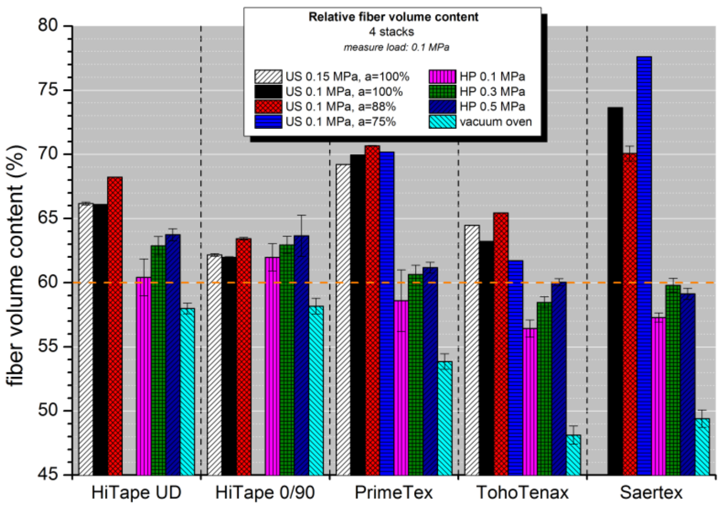

Figure 6. Relative fiber volume content for 4 stacks under 0.1 MPa pressure

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The calculated contact-times lead to a low difference between the trials with different amplitudes. Even for the 75 % Saertex specimens the FVC is much higher as for the higher amplitudes. This can be explained with a calculated contact-time that is placed with 4.05 s out of the design space of the influence study. Furthermore the increased weld force of 0.15 MPa has no significant influence to the relative FVC. The elastic effects seem to be predominant under the use of ultrasonic oscillations. For the HiTape specimens with a fiber crossed orientation the FVC is 4 % lower on average as for the UD specimens. This can be explained with a lower possibility for nesting effects.

Observing the alternative technologies it is clear that the use of the vacuum compaction does not lead to a satisfying FVC for any material. Especially for the TohoTenax material the results are extremely low, because of the high amount of binder material which cannot be distributed within the oven process. The results of the heat press trials show as expected an increasing FVC with an increasing pressure. For both configurations of the HiTape material the claimed FVC was achieved for all pressures. For PrimeTex at least 0.3 MPa must be applied to the material to reach the 60 % border, always having in mind that 0.1 MPa is the maximum possible compaction force under vacuum for the infusion. Observing the TohoTenax as well as the Saertex material even a pressure of 0.5 MPa does not lead to a satisfying result.

3. Conclusion

The influence study has shown that the temperature is mainly driven by the amplitude and the contact-time, whereas the degree of compaction is related to all parameters. However, the share of weld force to the remaining compaction is under the use of ultrasonic oscillations relative low and is dominated by elastic effects. The necessary energy for the process depends on the dense of the specimens and therefor on the compaction and the structure of the material. This makes clear, that an increasing pressure leads to an unstable process, if the generator operates at its limit.

The comparison with other technologies has shown the potential of the use of ultrasonic welding for a continuous stacking. The process is very time efficient and the claimed FVC could be achieved and exceeded partly to critical values. Using the vacuum compaction and the heat press it is only partly possible to reach the claimed values. The found values are the baseline for the parameter determination for a continuous processing.

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