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Processing and Quality of Continuous Fiber Reinforced Thermoplastic by Direct Extrusion

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ABSTRACT

Thermoplastic sheets with continuous fabric or roving reinforcement offer the possibility of short cycle times. Conventional production solutions require double belt presses processing semi-manufactured plastic sheets or powders. An improvement of continuous fiber reinforced thermoplastic (CFRT) sheet production can be achieved through reduced energy consumption, increased output, improved impregnation and waste reduction. This work presents a high potential process applying a direct extrusion technology. It enables the impregnation and consolidation of woven textiles in an extrusion die with continuous throughput. A novel production line was developed and investigated for process capability. This extrusion process allows the production of CFRT sheet starting from thermoplastic granulate and woven textile in one single production line integrating plasticization, impregnation and sheet forming.

Index Terms - fiber reinforced thermoplastic, lightweight design, energy efficiency

1. INTRODUCTION

Lightweight design with fiber-reinforced plastics is a method for weight reduction in vehicles and aircrafts. Thermoplastic sheets with continuous fabric or roving reinforcement offer short processing cycle times in comparison to processes based on thermosetting matrices. Continues fiber reinforcement improves significantly the mechanical properties of components. The demand is consistently growing. Increases for CFRT of 17% p.a. and 5 % p.a. for GFRP are expected. The growth can only be achieved by tapping the potential of savings of 30 percent until 2020 [1]. While only a fifth of these savings can be contributed by the material, especially the cost of fiber filaments and the further processing to fabrics, most improvements are achievable in the production processes. Potential savings are valued at 40 percent. The replacement of thermosets by thermoplastics offers the possibility for shorter cycle times [1]. Another obstacle for establishing serial processes is insufficient quality of the laminate. Improved composites especially require a reduction of the porosity content and an increased wetting of the fiber structure with the thermoplastic melt. Current production solutions for CFRT require high pressure provided by discontinuous presses or double belt presses for improving quality. An improvement of CFRT sheet production can be achieved by reduced energy consumption, increased output, improved impregnation and waste reduction.

2. THERMOPLASTIC IMPREGNATION PROCESS

During impregnation process, the reinforcement material has to be effectively wetted with the matrix material. Numerous authors [2-6] already examined this mechanism. D'Arcy's law is used for describing the matrix flow velocity on an idealized reinforcement textile.

$$\bar{v} = \frac{dz}{dt} = \frac{K}{\eta}\frac{dp}{dz}$$

z	flow distance
t	impregnation time
K	permeability
η	viscosity
p	impregnation pressure

Permeability is anisotropic depending on fiber orientation, weave, fiber radius and impregnation direction. It defines the required pressure for impregnation in a given time. Influencing factors vary for every reinforcing fabric and must be characterized experimentally. A distinction is made in flow parallel and perpendicular to the roving, which is usually occurring as a combination of both.

$$K_{\perp} = C_1 \left(\sqrt{\frac{\varphi_{fmax}}{\varphi_f}} - 1 \right)^{5/2} \cdot R^2$$

C_1	experimental validated factor
φ_{fmax}	maximum fiber volume ratio
φ_f	fiber volume ratio
R	fiber radius

$$K_{II} = \frac{8R^2}{c} \cdot \frac{(1-\varphi_f)^3}{\varphi_f{}^2}$$

c	experimental validated factor
φ_f	fiber volume ratio
R	fiber radius

Factors c and C_1 are calculated by Gebart based on the Navier-Stokes equation [7, 8]. It allows the modification of Kozeny-Carman model to fit into experimental validated parameters. [8] As shown in Fig. 1 the permeability is changing during the whole impregnation process.

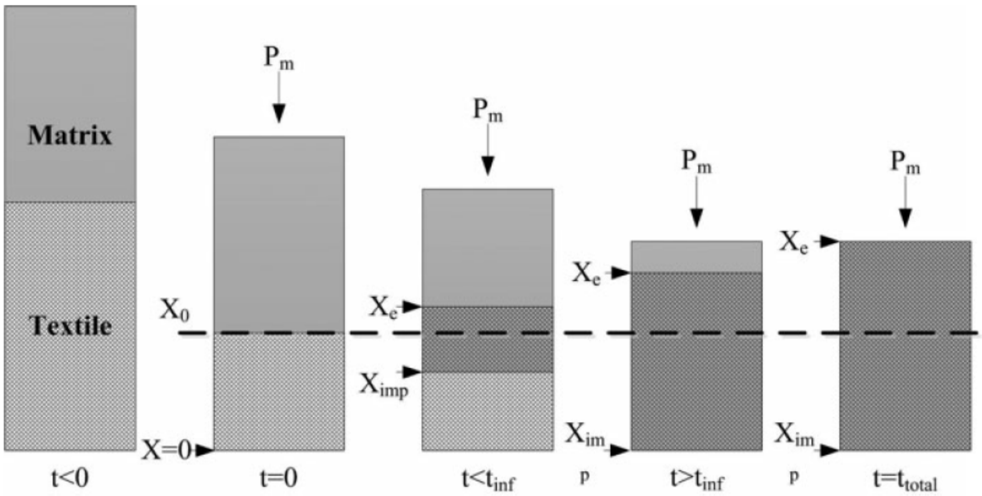

Fig. 1: Fiber relaxation during thermoplastic impregnation process [9]

This effect has been examined by Michaud and Manson [6]. During impregnation the polymer is forced by external pressure into the textile. Applying pressure leads to compression of the reinforcement material and to an increase in the fiber volume fraction. By infiltrating the matrix into the fiber bundles, the textile starts to expand to its later volume. Industrial production of

CFRT's needs cooling of the wrought material at this point, which leads to another change in volume and pressure. By reaching the recrystallization temperature shrinkage of the matrix increases non linear and leads to an decrease in impregnation pressure. [9]

In state of the art production cycle the pressure provided for impregnation owed to the wish of high fiber volume ratios is very high. As shown in Fig. 2 the amount of pressure necessary to reach a certain amount of fiber volume ratio.

$$\Delta p = \frac{\eta(T) \cdot z^2}{2 \cdot K(p) \cdot \Delta t}$$

$\eta(T)$	viscosity as function of temperature
z	flow length
$K(p)$	permeability as function of pressure
Δt	impregnation time

It's calculated for polypropylene and glassfiber reinforcement with a fiber diameter of 9 μm an impregnation time of 3 s and impregnation length of 0,2 mm.

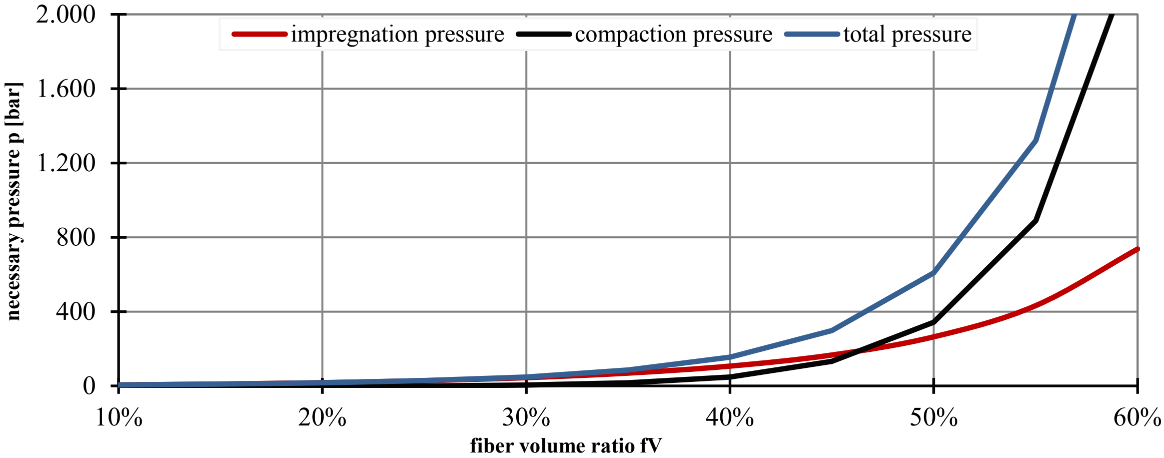

Fig. 2: necessary pressure to reach a certain amount of fiber volume ratio

The diagram shows the effects of different amounts of pressure at impregnation quality of CFRT's. The red graph shows the calculated amount of pressure necessary to infiltrate the fiberbundles with matrix. The pressure provided leads to a compaction of the bundle and therefore a decrease in permeability. Overcoming the lowered permeability requires an increase in the pressure provided. An iterative calculation leads to total amount of pressure necessary. If this pressure cannot be provided the reinforcement material won't be impregnated completely and voids remain in the CFRT.

Fig. 3 shows a conventional production cycle of CFRT components.

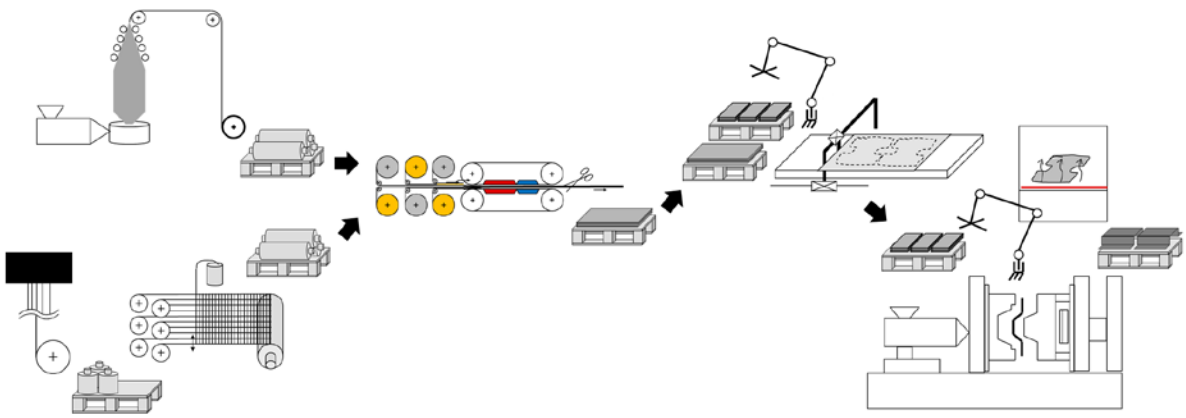

Fig. 3: conventional production cycle of CFRT components

Displayed is the film stacking process. Hereby the polymer granules need to be fused in an extrusion blow moulding machine and shaped into film. Separately the production of the reinforcement material takes place. Both materials are stacked up and joint by a double belt press. The matrix needs to be fused again and is pressed into reinforcement material to reach the status of CFRT sheet. Those sheets need cutting in required shape by laser or waterjet. The shaped sheets are heated again in an oven und brought into an injection molding machine. By overmolding the component is functionalized for it’s later purpose and finished.

3. DIRECT EXTRUSION PROCESS

This study describes the direct extrusion process which belongs to the field of direct feed method. The plastic melt is applied in a wide-slot distribution tool on a reinforcing layer and yet consolidated in the tool as shown in Fig. 4.

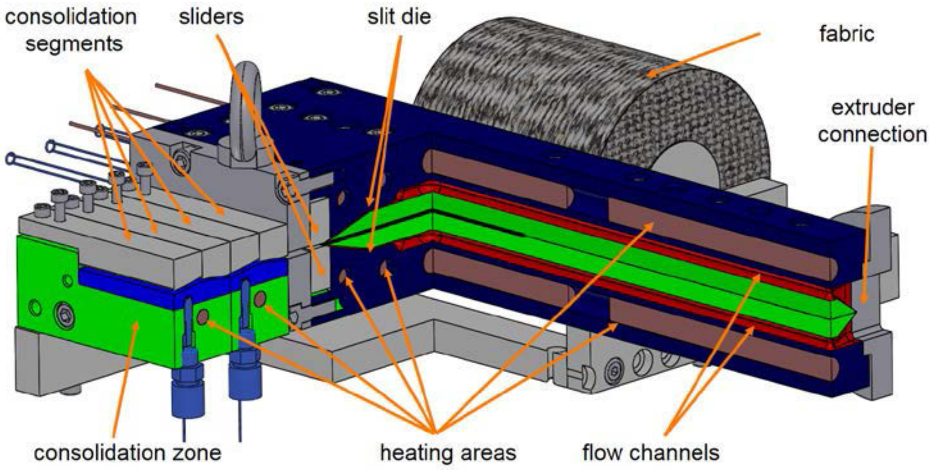

Fig. 4: Direct extrusion die (cut open)

The melt provided by an extruder can be applied on one or on both sides of the woven layer. This is influencing the impregnation path and the pressure needed for consolidation, but also effects the void content in the resulting CFRT. The impregnated semi-finished product can be consolidated by the use of a siphon unit. In this case the impregnated fabric belt moved by a sinusoidal cavity. The compression of the melt films above and below the textile semi-finished product allows the consolidation by increasing local hydraulic pressure. The resulting fiber volume ratio can be adjusted through extruder output and haul-off velocity of the textile woven. The gap height can be varied by sliding elements to generate sufficiently consolidation pressure even at high production speeds.

Main advantages of direct extrusion are in the range of energy saving and material protection. The following calculation example shows the difference between the production of CFRT in the direct extrusion process and the continuous film stacking. The specific fuse enthalpy have to be overcome by direct extrusion process only once. In the extruder, the pellets are melted and further processed in melt form state to organic sheets. The material can thus be processed more gently, whereby the degradation is reduced. Typical specific fuse enthalpy is 0.16 to 0.34 kWh/kg for a polypropylene. For a direct extruded organic sheet this results in the required power for processing of one-kilogram PP to organic sheet and an average efficiency of 0.7 to 0.23-.49 kWh. The processing of the same material in the film stacking on the double-belt press leads to a required power of 0.53 to 1.13 kWh and thus the 2.3 times the amount of energy.

4. QUALITY OF DIRECT EXTRUDED CFRT

In the current prototype version only single-layer organic sheets can be produced. The experimental procedure used a central composite design, vary temperature, throughput, flow speed at impregnation and pull through speed. Hereby nonlinear coherences and interactions can be observed and evaluated separately. Influence of process parameters on resulting laminate failures and leverage on mechanical properties need to be considered in particular. The results shown below are produced with a fiber volume ratio of 25% and varying void content. Pore formation distinguishes at different production points through differences in micro- and macro-impregnation. The flow speed in and between fiber bundles influences the amount of air entrapments and their location [8]. The laminate produced and tested in this study consists of fiberglass canvas fabric with a grammage of 280 g/m² and polypropylene (Borealis Borflow HL508FB). Further experimental parameters are displayed in Table 1.

Table 1: experimental parameters

temperature	200 – 260 °C
throughput (melt)	3.6 – 10.7 kg/h
pull through speed	1 – 8 m/min

It is necessary to calculate viscosity and relative velocity between reinforcement material and matrix during impregnation to understand the effects of the parameters. The impact of viscosity and relative velocity on void content is displayed in Fig. 5.

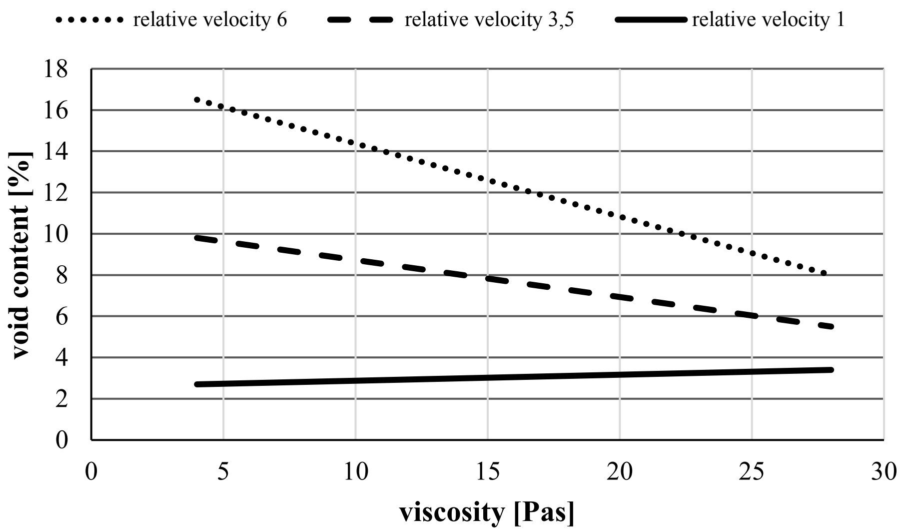

Fig. 5: interaction of viscosity and relative velocity on void content of CFRT

A relative velocity of 1 means a matching speed between melt flow and reinforcement pull through speed. The void content is minimal and little influenced by viscosity increase. Elevated viscosity requires an increase in impregnation pressure, which is held constant. The impregnation takes place vertical and the melt flows straight through the fiber bundles. Increasing relative velocity means the melt flow velocity is faster than pull through velocity. The melt flows faster between the fiber bundles, closing the melt front and entrapping air into the bundles. An increase in relative velocity leads to an increase in void content especially at low viscosity. Higher viscosity decreases the void content due to a braking effect at contact with the fibers. Melt slows down faster and reduces the amount of fast forward flowing between the fiber bundles. The increased viscosity won’t reach a void content below 4% due to constant pressure.

As it turned out a transversal melt flow during impregnation has a very high impact on the porosity content in the laminate. This effect occurs by an oversupply of melt during impregnation. The combination of fiber volume ratio and void content defines significantly mechanical properties of the laminate.
Fig. 6 shows the influence of unilateral und bilateral impregnation on void content and elastic modulus in warp direction. The calculated pressure necessary for bilateral impregnation is due square influence of the flow length only a quarter of the pressure necessary for unilateral impregnation.

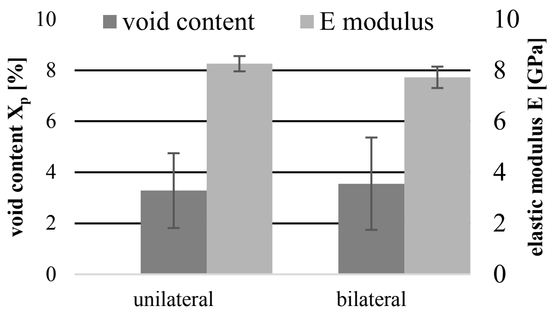

Fig. 6: influence of unilateral and bilateral impregnation

Bilateral impregnation of CFRT shows minimal influence on the void content but a significant influence on the elastic modulus. The difference in void content is only 0.27%. Air entrapments develop unpredictably in the rovings. Voids in bilateral impregnated laminate cumulate in the center and form a predetermined fracture point. It leads to a decrease of the elastic modulus in warp direction of 6.5 % even if the void content is equal.
Fig. 6 shows the influence of voids on the tensile strength of CFRT.

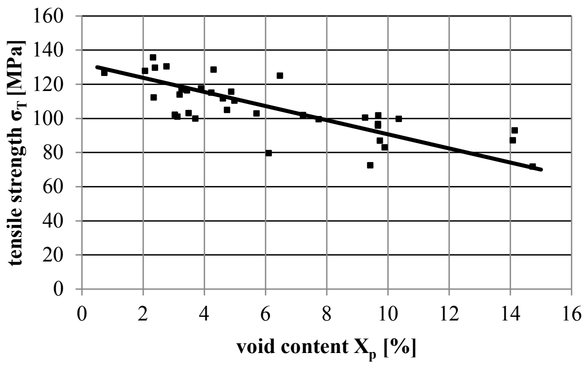

Fig. 7: Influence of voids on the tensile strength of CFRT in warp

The tensile strength decreases in a linear manner at a rate of 4 % with regard to the void content. The surface bonding between fiber and matrix is reduced due influence of voids. Force distribution in the laminate drops and is reduced on single fibers, which tend to break earlier reducing the bearable tension of the lamina.
Fig. 7 shows the influence of voids on the elastic modulus.

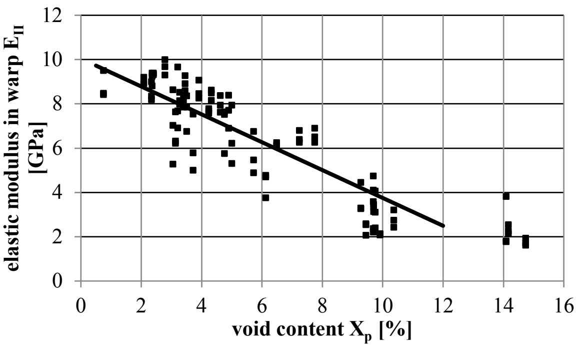

Fig. 8: Influence of voids on the elastic modulus of CFRT in warp

The intersection with the void-free state approximately marks a value describable with the classic laminate theory at 11 GPa. Per percent micro void content the elastic modulus drops at a rate of 6.3 % to a void content of approximately 12 %. Here the elastic modulus of the matrix material is reached. Higher void content leads to a reduced force transmission between matrix and roving. Tension has to be transmitted by a lower number of fibers while others are rearranging along the stretched laminate. Fibers are in different elongation stages and transmit different shares of the total load. The load cannot be transferred to fibers not being coated with the thermoplastic melt. This tears apart single fibers at once, leading to a flat stress-strain curve and therefore a lower elastic modulus and tensile strength.

5. CONCLUSION

The direct CFRT sheet extrusion process shows potential for considerable lower production cost and improved mechanical properties at consistent levels. By saving expensive equipment, reducing double melting and being more efficient in energy application the total operational cost in comparison to conventional production techniques can be reduced. The improved wetting and impregnation in the extrusion die are allowing a lower void content in the CFRT sheet structure and thus making sure that the consistency of the sheet and its mechanical property are considerably improved over existing processes. The result is an improved component property allowing further weight savings. The first prototype that was designed and put in operation shows promising results and allows the production of single-layer organic sheets. Further development work will focus on the development of a die, that allows the production of large scaled as well as multi-layered CFRT sheets.

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