NEW PRODUCTION PROCESS FOR MANUFACTURING CONTINUOUS FIBER-REINFORCED THERMOPLASTIC HOLLOW PROFILE COMPONENTS

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Abstract

The article deals with the development of a production process for manufacturing functionalized, continuous fiber-reinforced thermoplastic hollow profile components. The developed production process aims at reducing the cycle times in manufacturing hollow profile components and at reducing the component cost in high-volume production. It is based on a separation of the continuous semi-finished product and the discontinuous component production processes. The article explains in detail the five main process steps required to produce the components, namely sealing, heating, forming, final cutting and functionalization. The experimental tests of this article focus on the main process step of forming. This step is based on a hollow profile semi-finished product made of fiber-reinforced thermoplastic in a continuous pultrusion procedure. The glass or carbon fiber reinforced semi-finished product is formed into a demonstrator component geometry via internal pressure in a newly developed test facility. The error patterns of the compent that typically occur in forming the semi-finished product are presented and their causes analyzed.

1. Introduction

Automotive engineering increasingly applies lightweight materials such as carbon fiber-reinforced plastics (CFRP) to reduce the vehicles' overall weight. Compared to fiber composite materials with duroplastic matrix systems, thermoplastic matrix systems still play a minor role in automotive engineering to date [1]. However, these materials may become a vital enabler in the future for the large-scale application of fiber composite materials in automotive engineering. This is primarily due to the benefits in material and process techonologies offered by carbon fiber-reinforced thermoplasts (CFRTP), such as their weldability and formability [2]. The car body makes an important contribution to reducing the vehicle weight, as 38 - 40 % of the entire vehicle weight can be attributed to the body [3]. When it comes to the structure of passenger car bodies, a general distinction can be made between frame structure construction and shell construction [4]. Numerous manufacturing processes are already known for the production of shell-shaped components made of thermoplastic fiber composite materials [5, 6]. This is why this article focuses primarily on the frame structures made of profiles. Profiles made of thermoplastic fiber composite materials can be divided in, firstly, open, usually ribbed profiles and, secondly, in profiles with closed cross sections [7]. At a comparable weight, closed profile cross sections offer higher torsional stiffness, which makes them an attractive option particularly for automotive

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lightweight construction. The manifold demands of today's car bodies require the construction of frame structures from complex hollow profile components with changeable cross sections. Various different manufacturing approaches are also known for the production of continuous fiber-reinforced thermoplastic hollow profile structures [8, 9]. The hollow profile structures made of shell components, for instance, make it possible to manufacture complex component geometries; however, their joining area constitutes a potential point for a defect as the joining area is not fiber-reinforced [10, 11]. Furthermore, the joining area increases the space required as well as the weight of the hollow profile component. Besides the component complexity, the production volume and the cycle time play an important role in evaluating the profitability of a component production process. Continuous procedures to manufacture hollow profile structures allow for high-volume production [12, 13]. However, a disadvantage is the low geometrical complexity of the produced hollow profile structures and/or semi-finished products.
This is why a production process has been developed that combines the advantages of a continuous production process (such as high-volume production) with the benefits of discontinuous production processes (such as geometrical complexity). The goal is to evaluate the discontinuous component production based on a continuously produced semi-finished product.

2. Production process

The developed production process is based on the separation between a continuous semi-finished product production (e.g. pultrusion) and a discontinuous component production. The component production starts with a semi-finished product made of continuous fiber-reinforced thermoplastics with closed cross section (hereinafter called 'semi-finished product'). As shown in Figure 1, the process of manufacturing a hollow profile component is divided into five main process steps: sealing, heating, forming, final cutting and functionalization.

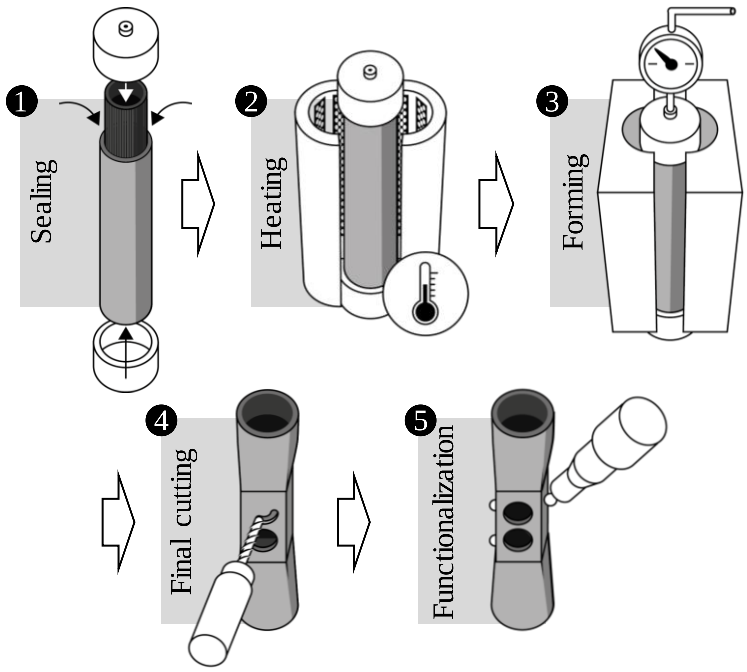

Figure 1. Main steps of the production process for the component manufacture.

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2.1 Sealing

The first step of the production process describes the sealing of the hollow profile semi-finished product for the subsequent internal pressure forming (see Section 2.3). To ensure sufficient draping and consolidation of the fiber composite material, in a first step a silicone tube is placed in the semi-finished product (comp. Figure 1, Step 1). Both ends of the semi-finished product are then fluid-proofed with a 'sealing plug'. Figure 2 illustrates the sealing plug concept developed for this purpose. To seal the semi-finished product, the piston rod of the sealing plug is loaded via an external pneumatic cylinder with axial force. Next, the piston rod is locked in place. The bellows, which expands due to the clamping force, stretches the silicone tube, consequently generating a radial force inside the semi-finished product. This way, the silicone tube is impermeably coupled to the sealing plugs. In addition, the arising radial force allows for gripping and handling the semi-finished product with the aid of the sealing plug. The outer sleeve of the sealing plug prevents the semi-finished product from heating up in the clamping area (see Chapter 2.2). For the subsequent internal pressure application as well as for the pressure measurements, the piston rods of the sealing plugs are equipped with an axial bore.

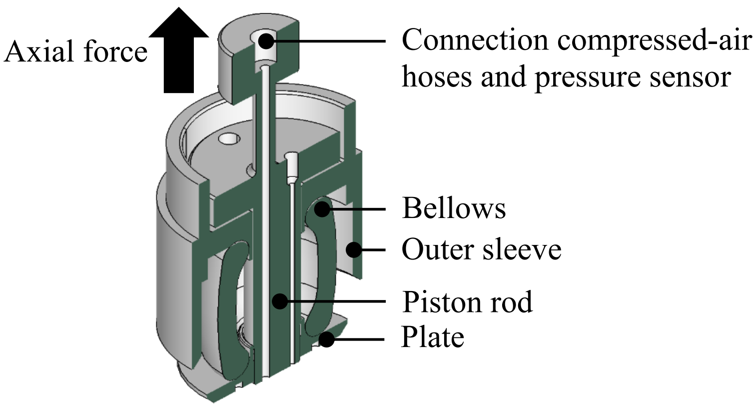

Figure 2. Schematic illustration of the sealing plug concept.

2.2. Heating

In the second step of the production process, the sealed semi-finished product is heated to the matrix-specific melting point via contactless infrared heating (IR). The vertical positioning of the semi-finished product prevents the hollow profile semi-finished product from collapsing (see Figure 3). The consequently arising free convection during heating is to the greatest extent compensated by the control of the IR radiators. To this end, the entire radiator field is divided into six areas, each of which is fitted with a pyrometer to measure the surface temperature of the semi-finished product. By varying the radiator output, the surface temperature of the semi-finished product can be kept almost constant so that the semi-finished product can be heated evenly throughout the entire length of the semi-finished product.

2.3. Forming

In the third production step, the semi-finished product heated up to its melting and forming temperature is formed to receive the shape of the final component geometry. The vertically positioned semi-finished product is enclosed in a vertically closing, two-part forming tool (see Figure 3). Pre-forming of the semi-finished product already occurs as the forming tool closes. When the forming tool is completely closed, the sealing plugs (see Section 2.1) apply the internal pressure to the silicone tube. The sealing plugs are connected to the closed forming tool with a tongue-and-groove joint. This way, the forces affecting the disk of the sealing plug during internal pressure application do not lead to an axial repositioning of the sealing plugs (see Figure 2). In addition, the tongue-and-groove joint ensures the exact positioning of

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the semi-finished product in the forming tool. The pressurized silicone tube drapes the semi-finished product into the respective tool cavity. The cavity of the tempered forming tool enables defined change of the cross-sectional geometry of the semi-finished product. Due to the continuous fiber reinforcement, changes in circumference during forming are impossible. The forming tool remains closed until the temperature has dropped at least below the matrix recrystallization temperature. Finally, internal pressure application of the silicone tube is reduced to atmospheric pressure. The hollow profile component can now be removed from the opened forming tool.

2.4. Final cutting

The fourth step of the production pocess is the mechanical final cutting (e.g. milling) of the semi-finished product formed to a hollow profile component. This process step includes, for instance, the insertion of functionally required openings (holes). The silicone tube needed in forming is removed prior to the final cutting. Depending on the specific component construction, a trimming of the unformed clamping area of the semi-finished product might be required as well.

2.5. Functionalization

The functional expansion of the hollow profile component depends on the subsequent welding on of a newly developed force application element. The ultrasonic welding procedure allows for the addition of the thermoplastic element despite accessability from only one side. Contrary to the functionalization of hollow profile components through injection molding, the profile does not need to be supported to prevent the component from collapsing [14]. The force application element is suited to, for instance, fixing cable harnesses or noise insulation covers to the hollow profile component.

3. Experimentals

The following chapter deals with the initial experimental tests of the forming behavior of the semi-finished products. Its aim is to examine the characteristic component error patterns that could occur during the production process step of forming (see Chapter 2.3).

3.1. Material

The experimental tests concerning the forming process were carried out on hollow profile semi-finished products by Ferdinand Stükerjürgen GmbH & Co. KG produced in a continuous PAZ procedure [15, 16]. These semi-finished products have a circular cross section, an external diameter of 78.3 mm and a wall thickness of 1.6 mm; with regard to the circular tube geometry, their layer setup is symmetrical (see Table 1). The fiber volume content (FVC) of the PA6-GF and PA6-CF semi-finished products was determined in a TGA analysis (threefold determination). The density of the semi-finished products was determined in line with DIN ISO 1183-1 (threefold determination). For the evaluation of the semi-finished product forming (see Section 4), all semi-finished products were dried in a convection oven at 80 °C for 120 hours prior to the start of testing.

Table 1. Characteristics of the semi-finished products.

Name	Matrix	Fiber type	FVC (%)	T_s (°C)	*Density* (g/cm³)	Layer setup (°)
PA6-CF	PA6	HT-Carbon	45,65	220	1,41	(0/0/+75/+75/0/0/0/-75/-75/0/0)
PA6-GF	PA6	E-Glass	34,70	220	1,62	(0/+75/0/-75/0)

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3.2. Equipment technology

For the evaluation of the production process steps of sealing, heating and forming, a pilot plant in accordance with Figure 3 was built. This pilot plant comprises a hydraulic press (not shown in Figure 3), a two-part aluminum forming tool tempered by heating cartridges (type: G7C-15185) by Watlow GmbH, and two radiator half shells. These are equipped with a total of 27 shortwave twin-tube infrared radiators (type: 23x11 construction form B; Heraeus Noblelight GmbH) for heating as well as 6 pyrometers (type: Imapc IN 520; LumaSense Technologies GmbH) for measuring the surface temperature of the semi-finished products. The compact component setup makes it possible to close the forming tool quickly following the heating process. The pressurizing for the forming of the semi-finished products is initiated 9 seconds after completion of the heating process (tool closing time) and takes 15 seconds. The forming pressure is provided by a nitrogen cylinder and controlled via a VPPM proportional pressure control valve by Festo AG & Co. KG. The system's maximum forming pressure is 18 bar. The forming pressure in the semi-finished product is measured with a pressure sensor (type: SEN-3349) by Kobold Messring GmbH.

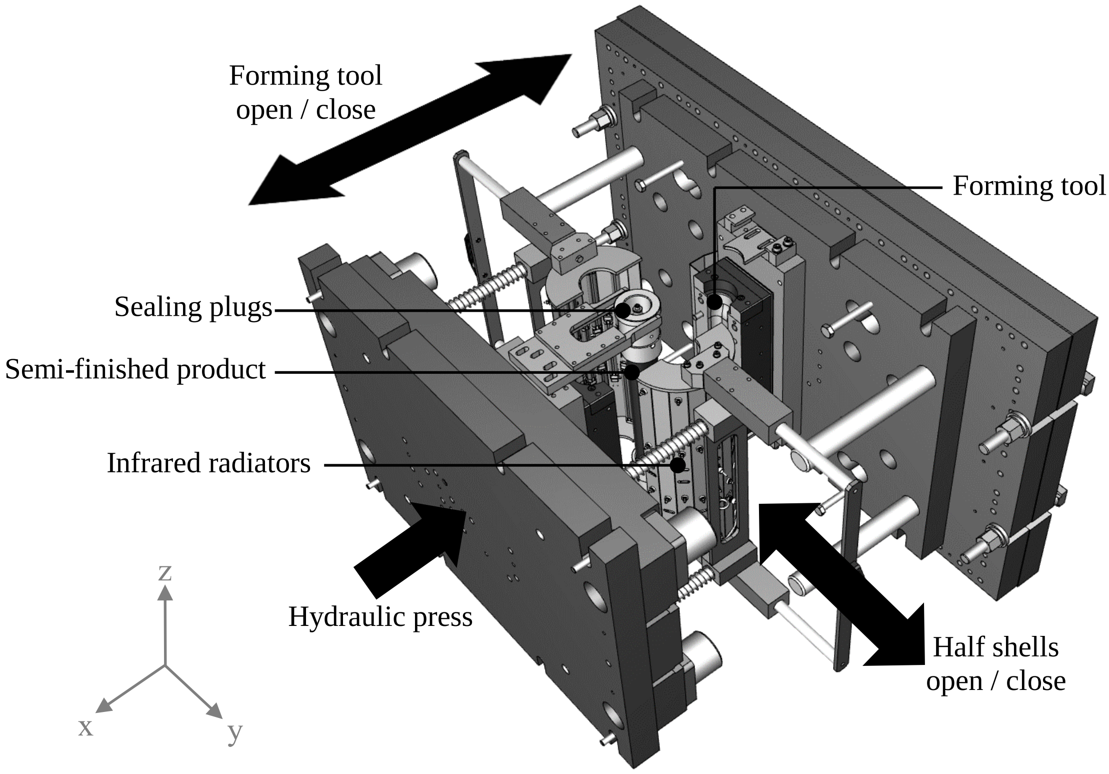

Figure 3. Pilot plant for forming continuous fiber-reinforced thermoplastic hollow profiles.

3.3. Component geometry

Figure 4 illustrates the geometry of the demonstration part, which is divided into three relevant areas. The clamping area (sealing plug), which remains unheated and unformed, is followed by a 95 mm long transition zone for the change of cross section of the semi-finished product. The circumference of the rounded-off rectangular cross section (see Figure 4, Section A-A) corresponds exactly to the circumference of 246.0 mm of the semi-finished product (diameter 78.3 mm; see Table 1). The length of the component part with a rectangular cross section is 230 mm. In keeping with the industry standard, the component has a draft angle of 1.5 degrees for the removal of the component, which is set up symmetrically to the xz plane along the entire length.

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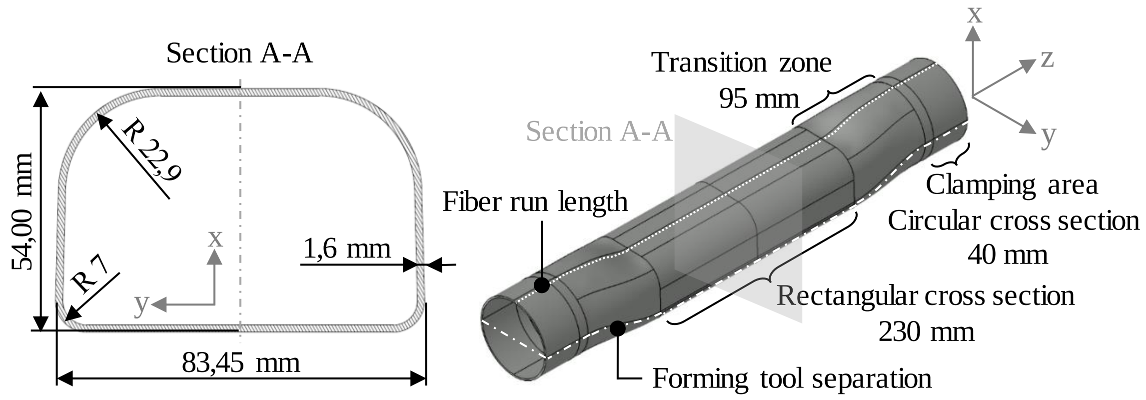

Figure 4. Demonstrator component geometry.

4. Results and discussion

The characteristic component error patterns after forming the semi-finished products are summarized in Figure 5. Forming errors occur both on the inside and the outside of the hollow profile component.

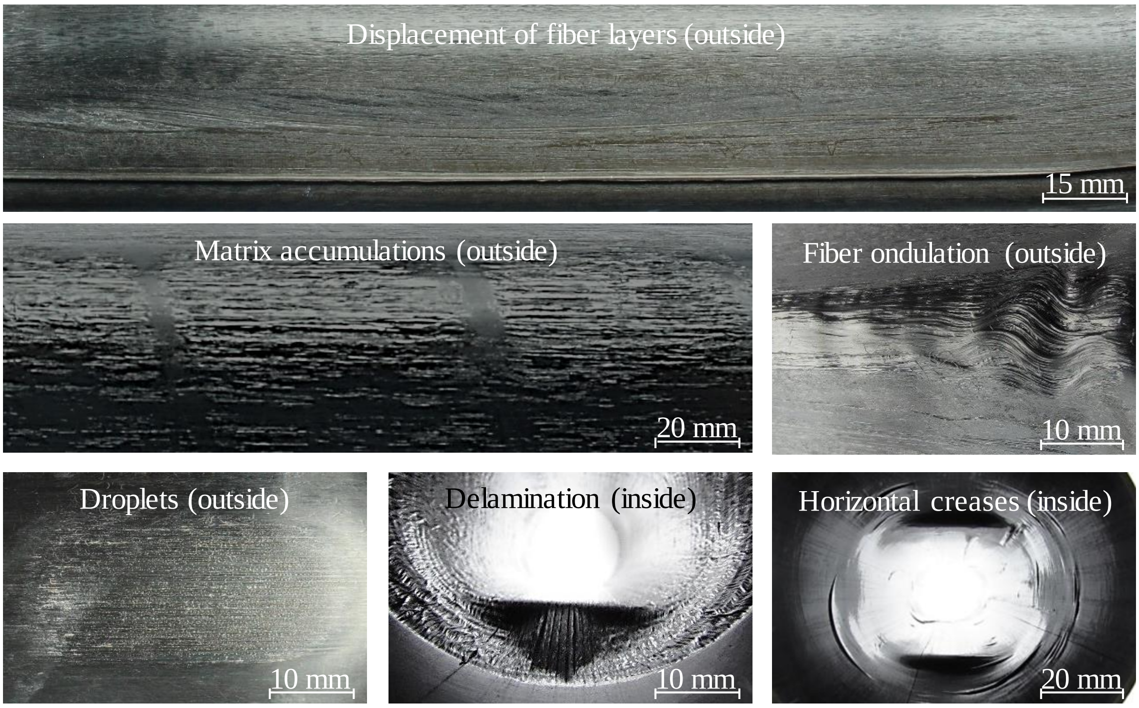

Figure 5. Overview of error patterns after forming the semi-finished products.

4.1. Displacement of fiber layers (outside)

This component error involves a fiber displacement of the outmost 0° layers of the semi-finished product. The error pattern occurs exclusively in the area of tool separation (see Figure 4). Both PA6-GF and PA6-CF components show the defect, although to varying degrees. There is no apparent correlation of the error and the tested tool temperatures (maximum temperature of the forming tool: 120 °C).

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The reason for the fiber displacement is that the semi-finished product may stick to the forming tool early in the process when it is heated to a surface temperature of 300 °C. In the pre-forming process during the closing of the forming tool (see Chapter 2.3), the initial circular cross section of the semi-finished product is compressed. Consequently, the semi-finished product bulges vertically to the closing direction and the cross section becomes elliptical. This bulging can lead to the semi-finished product sticking to the significantly cooler flanks of the tool cavity. Due to the further draping of the semi-finished product during internal pressure application, a relative movement between the semi-finished product and the tool occurs, which might lead to fiber displacement.

4.2. Matrix accumulations (outside)

This defect becomes apparent by matrix-rich areas on the component surface. These matrix accumulations occur at a distance of approx. 60 mm from each other. Furthermore, an angle of approx. 75° to the component's vertical axis can be detected (see Figure 5). The error pattern occurs almost exclusively in forming PA6-GF semi-finished products.
The reasons for a matrix accumulation are production fluctuations in manufacturing the semi-finished products. When winding up the ±75° layers in the pultrusion process, a certain share of the 60 mm wide and 0.3 mm thick PA6-GF tapes overlap, which is reflected after the forming of the semi-finished product in the form of matrix accumulations. As the PA6-CF tapes are only 0.13 mm thick, a potential tape overlap in the production process results in lower material fluctuations.

4.3. Droplets (outside)

The term droplets refers to small, circular matrix accumulations. These droplets occur equally in the transition zone of both variants of the semi-finished product (see Figure 5). In the defect area, no exact component geometry is achieved due to incomplete forming.
According to [17], the droplets are the result of a matrix solidification on the component surface. The low-viscosity matrix melting is pressed outward during internal pressurization. If the semi-finished product is not completely draped in the transition zone at this point, droplets occur.

4.4. Fiber ondulation (outside)

The defect of fiber ondulation is defined as an ondulation of the outer 0° fibers in the component level. The error occurs in both PA6-GF and PA6-CF components, primarily in the transition and the flange radius zones (see Figure 5).
Fiber ondulation can be put down to a compression of the 0° fibers in certain areas of the component with low fiber run lengths (see Figure 4). Forming the semi-finished product into another profile cross section necessarily results in different fiber run lengths. If the component geometry is formed in areas with long fiber run lengths, the 0° fibers with low fiber run lengths in particular are compressed. This compression frequently leads to ondulations in the component level on the outside of the component. The effect is amplified by some low fiber ondulation in the semi-finished product, which is the result of manufacturing the semi-finished product.

4.5. Horizontal creases (inside)

Horizontal creases are defined as ondulations of the 0° fibers from the component level outward (see Figure 5). Like fiber ondulation on the component's outside (comp. Section 4.4.), this type of ondulation is due to a compression of the 0° fibers in areas with low fiber run lengths.
According to [18], ondulation is caused by compressive stress resulting from the compression. On the inside of the hollow profile component, however, ondulation almost exclusively takes the form of horizontal creases, which appear vertically to the component's longitudinal direction.

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4.6. Delamination (inside)

The separation of the outmost 0° layers of the laminate stack from the inside of the component (see Figure 5) is referred to as delamination in the following. This defect may occur in the transition zones of areas with long fiber run lengths. In these areas, the inner 0° fibers do not follow the concave internal geometry of the component. The error appears almost exclusively in PA6-CF components, in particular at an internal pressurization of 6 bar.
According to Figure 6, when the internal pressure application is too low, the fiber pressure resulting from the forming process leads to a tangential delamination of the reinforcement fibers in the transition zone between the circular and rectangular cross sections, i.e. the layers delaminate from the rest of the laminate draped in the shape of the tool cavity. Insufficient pressure normal to the component level is described as a potential cause of delamination also in [18].

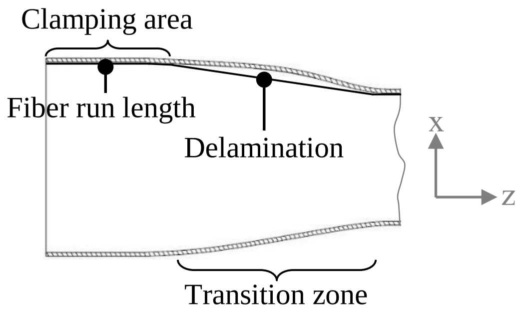

Figure 6. Schematic illustration of the 0°-Layer-delamination in the transition zone.

5. Conclusion

The article presented a new discontinuous production process for manufacturing hollow profile components made of continuous fiber-reinforced thermoplastics. This production process consists of the following main steps: sealing, heating, forming, final cutting and functionalization. The experimental tests detailed in the article focused on the requisite main process step of forming in the production of a demonstration part. On a pilot plant specifically built for this purpose, hollow profile semi-finished products were formed by applying internal pressure. The semi-finished products used had a circular cross section and consisted of glass- or carbon fiber-reinforced PA6. The tests showed six characteristic error patterns that appeared after the forming of the semi-finished products. It was possible to distinguish between error patterns on the inside and on the outside of the hollow profile component. The error patterns could be traced back to process-specific conditions (fiber displacement, delamination), quality fluctuations in the semi-finished product (matrix accumulation) or phenomena known from other CFRTP forming procedures (droplets, fiber ondulation, horizontal creases). To deepen understanding of this production process, future experimental tests will use demonstration parts to evaluate further geometry characteristics (e.g. beading). In doing this, the aim is to prevent, to the greatest extent possible, the occurrence of the characteristic error patterns in the future.

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