

Rotational moulding for small diameter continuous fibre reinforced thermoplastics structures

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Abstract

Continuous-reinforced thermoplastic composites are becoming increasingly important for mass production of lightweight components across various industrial sectors. This paper describes a novel process chain for the production of continuous fibre reinforced thermoplastic matrices with a rotationally symmetric cross-section, using rotational moulding technology. The process chain is based on wound and pre-consolidated preforms, which are then formed into the final geometry by rotational moulding. To support the manufacturing of smaller diameters, a composite core is used to increase the pressure during manufacture. The experimental results are examined by cross-sectional micrographs and show the approach's feasibility.

Keywords

thermoplastic matrix, rotational moulding, FRP-tubes

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Introduction

In times of climate change, the demand for sustainable and energy-efficient products is increasingly taking centre stage in society. Due to the growing environmental awareness of the population and the resulting growing demand for environmentally friendly products, lightweight construction as a key technology is progressively becoming the focus of research and development.^{1,2} The use of fibre-reinforced composites (FRP), in particular, has enormous potential in industrial applications to significantly reduce CO₂ emissions during the operation of dynamic systems both economically and effectively. Components with a rotationally symmetrical cross-section, in particular, have a wide range of applications, such as drive shafts in vehicles, wind turbines, or tension-compression struts in aircraft.³ In contrast to wind turbines, the components in vehicles or airplanes are typically linked with smaller dimensions and therefore pose a particular challenge. The use of thermoplastic matrix systems can significantly increase the impact resistance, chemical resistance and fatigue strength of FRP, especially in humid and hot

environmental conditions.⁴ High-performance thermoplastics can therefore achieve added value compared to thermoset systems so that the high requirements of the aviation industry with regard to efficient and qualifiable production processes can be met. Compared to thermosets, thermoplastic matrix systems have the disadvantage of a high melt viscosity of the polymer, which is relevant for impregnation. Subsequent wetting of the fibres is therefore only possible to a limited extent. Thermoplastics can be injected as monomers with the addition of an activator and polymerize in-situ, achieving similar processing properties to thermoset processes.⁵ Alternatively, premixed or pre-impregnated semi-finished products such as hybrid yarns and thermoplastic UD tapes

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are used in the winding and braiding process to minimize the impregnation paths in the consolidation process. Consequently, various manufacturing processes for thermoplastic composites have been developed, particularly for hollow profiles, including automated fibre placement, pultrusion, shrink tape consolidation, rotational moulding, bladder-assisted moulding, and winding.^{1,6-9} Many of these processes require a preform, typically produced by winding or braiding fibres onto a mandrel. Winding is characterized by high fibre tension, excellent dimensional accuracy, and a high degree of automation. Consolidation can occur in situ during processes such as automated tape laying (ATL) or winding, or subsequently under controlled temperature and pressure, for example, through pultrusion, blow moulding, or hot pressing. Among the available manufacturing processes for thermoplastic hollow profiles, pultrusion offers the highest productivity as a continuous process. Other processes, such as winding, rotational moulding, and bladder-assisted moulding, are discrete processes with specific advantages, including lower investment costs or the potential for intrinsic hybridization.¹

Rotational moulding of composites with continuous fibres

Initial investigations into the manufacture of pipes from thermoplastic FRP with continuous fibres were carried out by Ehleben.⁸ The reinforcement fibres, for example, glass or carbon fibre are wound on a non-reinforced thermoplastic pipe of either polypropylene (PP) or polyamide-6 (PA6). The fibres are dry wound and aligned exactly according to the load the component is designed to carry during normal service. The thermoplastic pipe with reinforcement material wound on it is then inserted into a one-piece mould. The mould is heated during slow rotation via multiple infrared heaters until the thermoplastic material is melted and functions as matrix material. The actual centrifugation procedure takes place in the fourth step. The rotation rate of the mould is increased. Due to centrifugal force the thermoplastic melt infiltrates the fibre reinforcement and impregnation takes place. The last manufacturing step is cooling and removal of the fabricated FRP pipe. In his work, a cylinder with an outer diameter of 100 mm was manufactured from PA6. The mould was heated to the process temperature of 250°C at 1650 r/min within 27 min. After the heating phase, the 13-min spin cycle was started at a speed between 4000–6000 r/min. This corresponds to a pressure of 0.28 bar–0.63 bar at the outer diameter of the test specimen. The mould was then cooled at a speed of 4000 r/min for 10 min which leads to a total manufacturing time of 50 min, if the winding process of dry fibres on the thermoplastic pipe is neglected. It was demonstrated that hollow profiles can be produced from thermoplastic composites using this process approach.¹⁰ However, the investigations were limited to large diameters and it remains unclear whether the

findings can also be transferred to smaller diameters. This would bring new applications into focus and open up a wide range of applications for the process. Furthermore, rotational moulding for thermoset composites in hybrid construction was examined by Fleischer et al. In this process, a dry preform is inserted into a mould together with load introduction elements, clamped in a lathe and set in rotation. A resin is then casted into the mould and impregnates the dry preform through rotation. The component then cures under the influence of rotation and temperature and can then be demoulded. The production of components with polygonal cross-sections and cross-sectional changes was also investigated. For this purpose, a composite core made of lead and silicone was developed, which exerts an additional pressure that acts homogeneously on the resin by optimizing the core.¹¹ It was shown, for example, that a hexagonal cross-section can also be produced using the rotational moulding process. Cross-sections with an outer diameter of up to 80 mm were considered. In addition, the load transfer mechanisms for hybrid connections have been investigated, thus demonstrating the suitability of the process.¹²⁻¹⁵ Also, a numerical model for the impregnation behaviour with complex geometries of the load introduction element has been developed.¹⁶ Both approaches require the dry fibres to be impregnated by the matrix. However, thermoplastic and thermosetting matrix systems differ enormously in terms of their viscosity and thus their flow properties. Higher viscosity therefore represents an obstacle to the production of hollow profiles with smaller diameters, as the pressures in the centrifugal process are naturally lower in this case. For this reason, other semi-finished products are coming to the fore in order to minimize or eliminate flow paths.⁸ For this reason, UD tapes are used to test the suitability of the rotational moulding for small diameters with thermoplastic matrices. These are pre-impregnated tapes, which means that impregnation is no longer a priority. Furthermore, the presented work is an initial investigation into the development of the process chain for later hybridization, and the focus is on the general feasibility of forming hollow profiles from UD tapes. Against the background of climate change and thus the increasing demand for sustainable and cost-efficient products, the rotational moulding process with a thermoplastic matrix is to be transferred to small diameters in this work. For this purpose, approaches from the thermoset rotational moulding process are considered. As preform a wound and pre-consolidated tube made in automated tape laying out of UD-tapes is used. This allows, in the first place, to examine the feasibility of forming the preform into the desired shape. The experimental results are supported by micrographs of cross-sections from manufacturing.

Materials and methods

Manufacturing setup

A modified lathe is available for the tests, with a heating chamber integrated into the lathe. The heating chamber

consists of three layers. The innermost and outermost layers are made of aluminium sheet and there is an insulating layer of rock wool in the middle. In addition, the heating chamber has a flap on the top to bring the tool in and out of the heating chamber. The flap can also be operated outside the machine during the process using a pull mechanism. The chamber is heated by four 1.5 kW infrared heaters from Optron GmbH. The opposing heaters are connected to a power controller and operate together. The power controllers can be adjusted via an external setpoint. A control circuit has been set up for this purpose consisting of a type K thermocouple, which measures the temperature inside the heating chamber. The temperature data is then processed by a PID controller on an Arduino Mega and the power of the controllers is adjusted. In addition, a type K thermocouple is installed in the area of the spindle. This ensures that there is no thermal damage to the spindle, as the machine itself has no active cooling, and damages to the lathe should be prevented. The test rig is

presented in Figure 1. In the upper part, the outside of the heating chamber with open flap can be seen, also the spindle of the lathe is visible on the left side. The lower part presents the view into the heating chamber with active infrared heaters and tool clamped into the lathe.

Process flow

In this work, wound and pre-consolidated preforms, which are manufactured in automated tape laying ATL, are used. This allows the general feasibility of moulding composites using rotational moulding to be tested in the first step. The first stage of production involves the manufacturing of the preform. In addition, a composite core is produced from lead balls and silicone. The next step is to prepare the tool. In this case, the one-piece mould is cleaned with isopropanol. The inside of the mould is then treated with the release agent Frekote 770 NC from Henkel GmbH. This prevents the

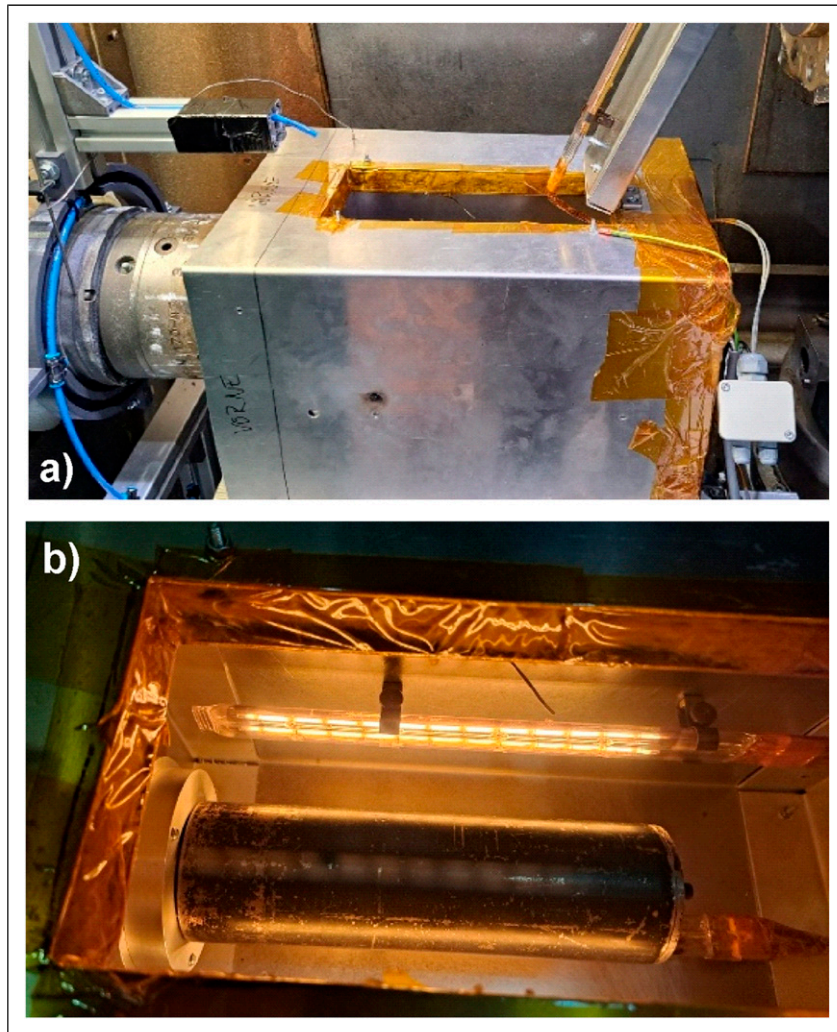


Figure 1. Experimental test setup for rotational moulding of composites with continuous fibres (a) View from the outside of the heating chamber with open flap; (b) View inside of heating chamber with active infrared heaters and tool clamped to the spindle.

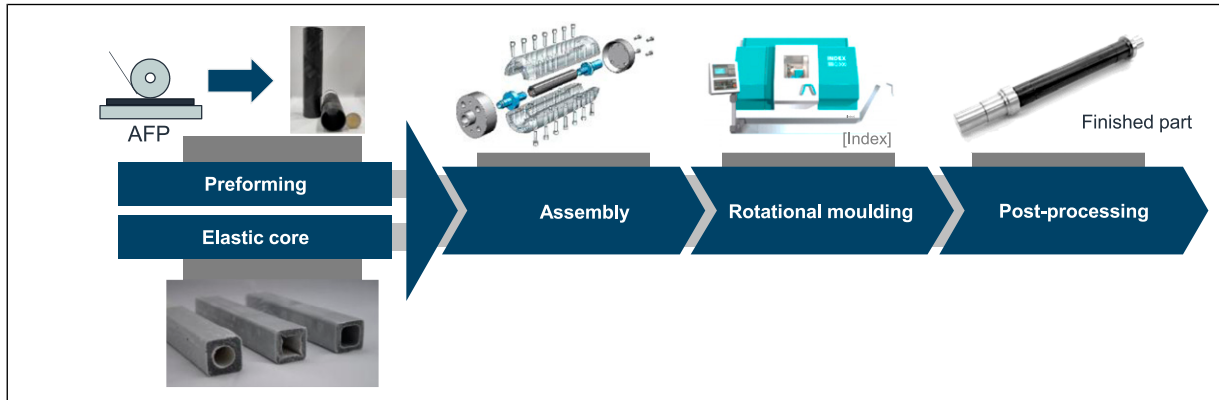


Figure 2. Presented process flow of rotational moulding with continuous fibres.

matrix from sticking during the process and makes demoulding easier. The assembled mould with the preform in it is then clamped in the lathe. In the first step of production, the tool is preheated to process temperature. For this purpose, the temperature inside the heating chamber is taken as a reference. The tool is then set in rotation, causing pressure onto the preform due to centrifugal force due to the preform mass. The mould is kept rotating and at temperature for a defined time. The infrared radiators are then switched off and the flap of the heating chamber is opened. Once the mould has cooled down, it is removed and the part is demoulded. The process can then start again. The first experiments are conducted as reference only with the preform in the mould. In further experiments, a composite core is used. The core is intended to increase the pressure on the fibre composite in the rotational moulding and thus positively influence the results. The silicone rubber is mixed according to the manufacturer's instructions and mixed with the lead beads. The mixture is then poured into a 3D-printed plastic mould and cured overnight. A thin covering layer of silicone is also prepared and then joined to the core. This is intended to minimize breakage and premature ageing of the core. The preform is brought in the mould and the core is placed in the preform.¹⁷ The dimensions of the core are presented in the result section of the paper. The whole process flow is visualized in Figure 2.

Materials

As preform, a wound and pre-consolidated tube is used. The tubes are manufactured in an automated tape-laying process by Alformet GmbH with an outer diameter of 38 mm and a wall thickness of 1.5 mm, see Figure 3. The preform has a total length of 180 mm and the UD-tapes are wound in an $\pm 45^\circ$. As UD-Tape CELSTRAN CFR-TP PA6 CF60-3 from Celanese is used.¹⁸ The preform consists of PA6 matrix and a carbon fibre (CF) reinforcement with a fibre volume content of 60%. Furthermore, Type 3 HB silicone rubber from TFC was used to manufacture the composite core with

a shore A33 hardness. This silicon is made for tin casting and, according to the supplier, can withstand high temperatures for short periods of time. Lead balls with a diameter of 0.6–1.5 mm are used as filling material for the composite core. This allows the density of the core to be increased and thus higher pressures to be achieved.

Results and discussion

In the first step, the rotational moulding process is investigated for smaller diameters using PA6-CF preforms. The preform is inserted into the mould together with a load introduction element (LI) made of metal. The LI is used for the subsequent production of hybrid components but is not the focus of the present work; it will be examined in more detail in further work. The mould has an internal diameter of 40 mm and a length of 200 mm. This results in an annular gap of 1 mm between the preform and the mould, which is to be closed by forming the preform in the rotational moulding process. The first step is the heating phase of the mould. The pre-assembled mould is clamped in the machine and is located inside the heating chamber. For this purpose, 260°C is selected as the setpoint for the heating chamber, which is around 40°C above the melting temperature of 220°C and between the value of Eheleben and the guidelines of the tape manufacturer. The temperature inside the heating chamber is reached within 10 minutes. The mould is then rotated and kept at process temperature for 20 min. The machine itself is limited to $n = 4000 \text{ rpm}$ due to the mechanical design. As a result of natural frequencies, the full-speed spectrum of the machine cannot be utilized. As a result, a rotational speed of $n = 2750 \text{ rpm}$ was selected for the first tests. The pressure p acting on the preform results from the centrifugal force F , which acts on the surface of the preform A_M . The mean radius r_m of the preform is assumed for the radius of the lateral surface and the centrifugal force. In addition, the mass m of the preform results from its density $\rho = 1450 \text{ kg/m}^3$ and the volume of the circular ring. The

outer radius of the preform $R_{f,o}$ is 38 mm and the inner diameter $R_{f,i}$ is 35 mm, resulting in an average diameter R_m of 36.5 mm. The length L is 180 mm, resulting in a pressure of 0.034 bar which is around 85% lower than the pressure in the works of Ehleben due to lower diameter and lower rotational speed of the equipment available. After the forming phase, the tool and therefore the component must be cooled down to be demoulded. To do this, the infrared heaters are switched off, the flap of the heating chamber is opened, and the rotational speed is maintained. It is possible to cool the heating chamber from 260°C to 70°C within 20 min, which corresponds in average to a cooling rate of 9,5 °C/min. This results in a total cycle time of about 50 min for one component if preform and demoulding is neglected.

Figure 4 shows the resulting temperature–pressure–time curve of the first tests showing the full cycle for manufacturing.

Due to the one-piece design of the mould and the different thermal expansion coefficients of the mould and preform, it is necessary to press out the component. A hand lever press and a specially manufactured punch are used for this purpose. The results of the first tests are shown in Figure 5. In the left part, the outside of the formed part is displayed. Clearly visible are small gaps in between the fibres due to a lack of matrix. The gaps follow the path of winding direction from the preform. A possible explanation is the lack of pressure while forming so matrix cannot migrate into the gaps while the preform is expanding. The lack of pressure theory is supported by looking at the inside of the moulded part (see Figure 5(b)). Clearly visible is the waviness of the inner surface which results from a delamination of the pre-consolidated UD-tapes from one another while the preform is expanding into the final form.

In the next step, the composite core will be introduced to increase the pressure on the preform during rotational moulding to reduce the waviness on the inside of the part and close the gaps between the fibres due to matrix migration. The Lamé–Navier equation is coupled with the deformation tensor and Hooke’s generalized law.¹¹ The pressure of the core Δp_c is shown here, which is caused by the elastic core as a result of the centrifugal forces with the angular velocity $\omega = n/(2\pi)$. The elastic core has a modulus of elasticity E_c which is determined by the shore hardness via an empirical relation,¹⁹ a poisson ration ν_c and a density ρ_c .



Figure 3. Wound preform of PA6 and carbon fibre.

$$A^\circ = \frac{t^*}{2\nu^2 + t^*(\nu + 1) - 2} \quad (3)$$

The normalized inner radius of the preform

$$R_{f,i}^* = \frac{R_{f,i}}{R_{c,o}} \quad (4)$$

and the normalized wall thickness of the core

$$t_c^* = \frac{R_{c,o} - R_{c,i}}{R_{c,o}} \quad (5)$$

The outer diameter $R_{c,o}$ of the core is selected to be 32 mm which is a little smaller than the inner diameter $R_{f,i}$ of the preform. This is to ensure smooth assembly in

$$\Delta p_c = \rho_c \cdot R_{c,o}^2 \cdot A^\circ \left(\frac{\omega^2}{4} \left(2\nu_c^2 + 2(1 - t_c^*)^2 \nu_c^2 + \nu_c - (1 - t_c^*)^2 \nu_c - 1 - 3(1 - t_c^*)^2 \right) - M \left(\sqrt{\varphi_f} R_{f,i}^* - 1 \right) \right) \quad (1)$$

with

$$M = \frac{E_c}{\rho_c \cdot R_{c,o}^2} \quad (2)$$

the preparation of the mould with maximum pressure build-up during manufacturing. The inner diameter of the core $R_{c,i}$ is set at 18 mm in accordance with Fleischer et al. methodology. The density ρ_c of the core for the

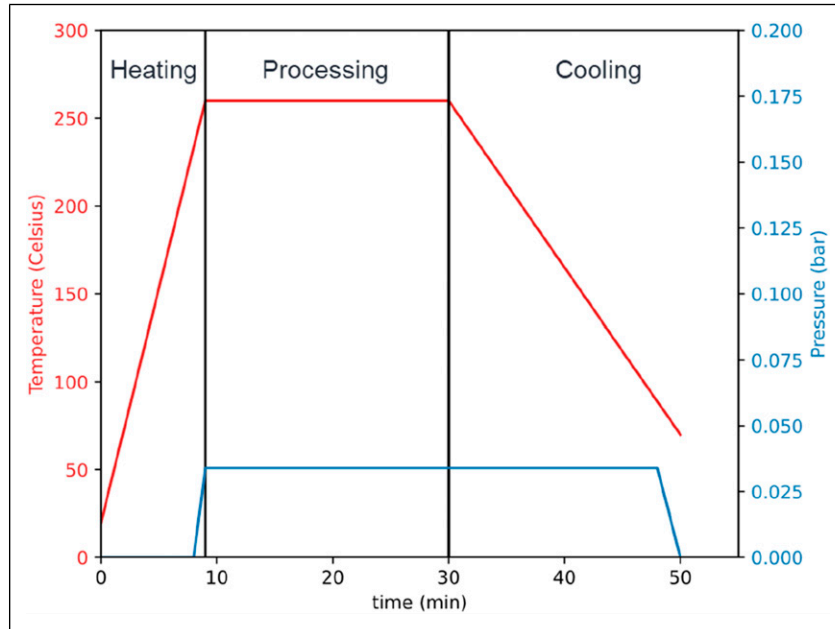


Figure 4. Pressure and temperature profile for the first experiments.

design results from the densities of the sub-components according to the rule of mixture. In this case, the density of the silicone rubber type 3 HB from TFC is $\rho = 1170 \text{ kg/m}^3$ and the density of the lead is $\rho = 11350 \text{ kg/m}^3$. The selected ratio of the components is $\phi_{fill} = 50\%$. The corresponding geometry is transferred to a CAD model and then printed as a multi-part mould using an FDM process. The additional pressure of the core due to the rotation in the process can now be calculated using the determined geometry. The total

pressure in the process is calculated by adding the core pressure and the pressure from the centrifugal force onto the preform. In Figure 6 the three different pressure types are plotted over the rotational speed. As shown in Figure 6, the pressure of 0.17 bar during manufacturing at $n = 2750 \text{ rpm}$ is five times the pressure without elastic core but still lower than the lower value of 0.28 bar used in Ehleben.⁸

The temperature–time curve was retained for further tests but pressure–time curve changes due to the

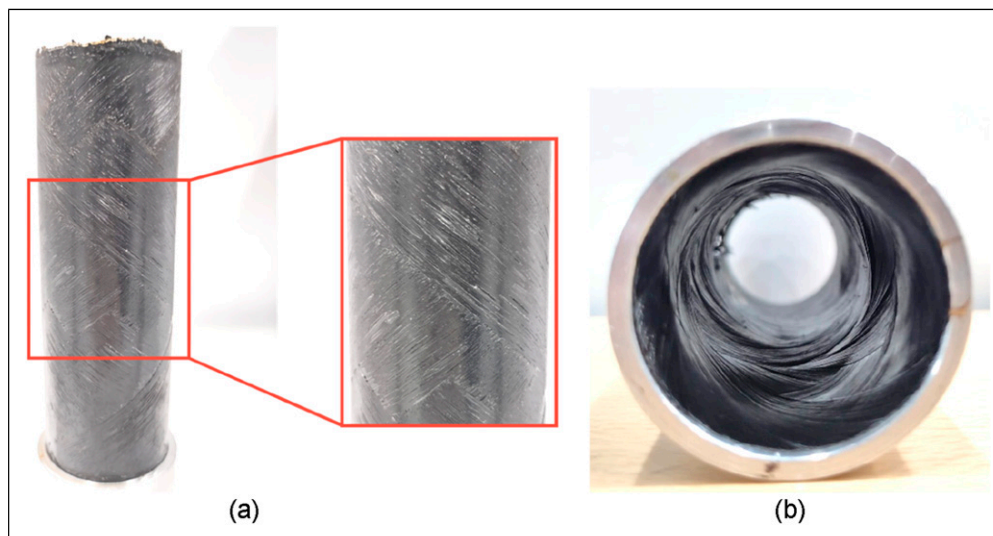


Figure 5. Results of first experiments: (a) Surface of formed part with visible gaps between the fibres due to a lack of matrix; (b) View of the inside of the moulded part with visible waviness of tapes.

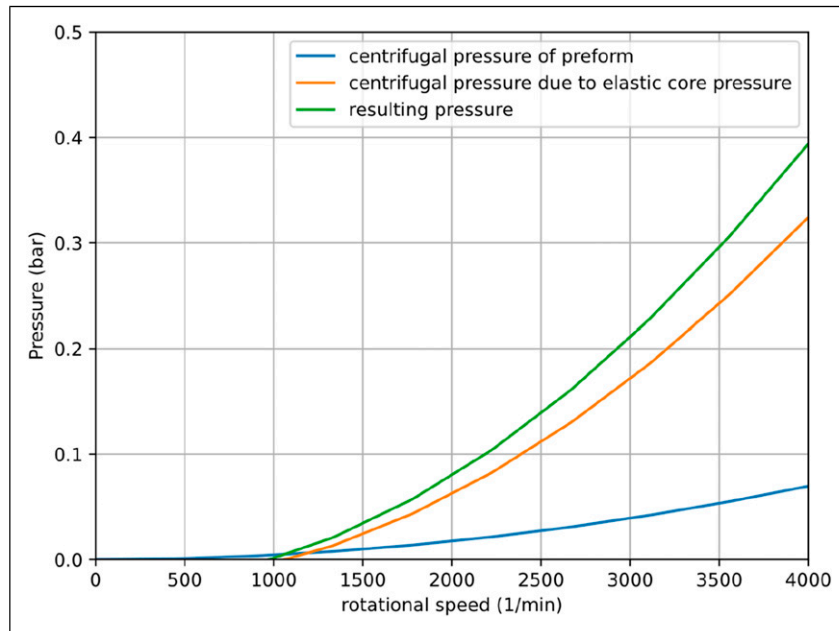


Figure 6. Different type of pressures occurring in rotational moulding with elastic core.

additional pressure of the core. Another set of experiments were conducted with the new experimental set up. As shown in Figure 7, the further tests show a significantly better forming result on the outside than the

previous series of tests. The left side of the figure shows an area where no deformation happened due to uneven temperature distribution. On the right side the completely formed part is displayed. The effect of the core can

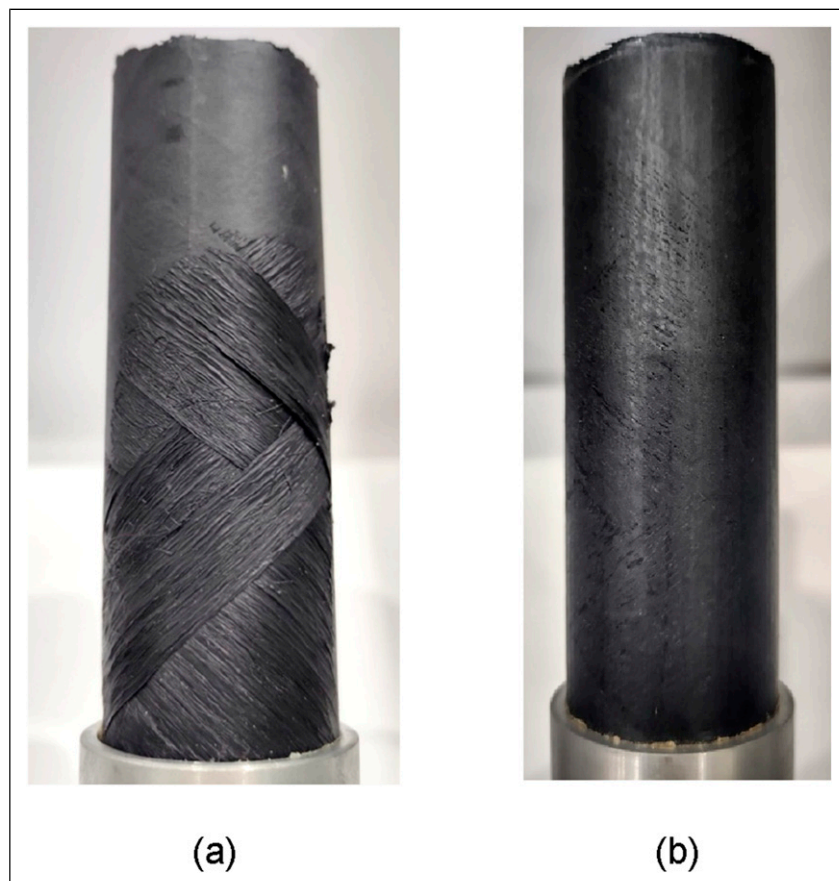


Figure 7. Experimental results of forming experiments with elastic core (a) Uneven forming results due to lack of temperature in clamping area of tool (b) completely formed part.

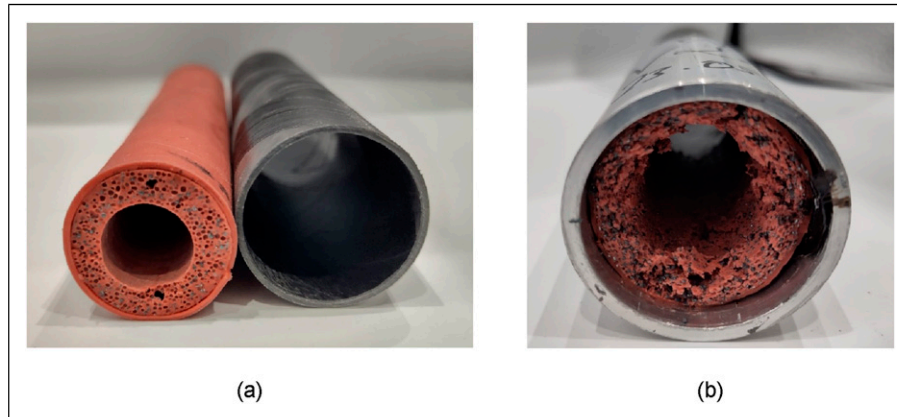


Figure 8. Elastic core before and after a set of experiments: (a) Elastic core and wound preform before the experiment; (b) Degraded core sticking to inside of formed part due to degradation.

therefore be assessed as positive. However, there is a lack of deformation of the component on one side. In consequence, the position of the preform inside the mould as well as the position of the mould in the heating chamber was marked. This is to ensure that the exact position of the single components can be tracked and reproduced over a series of experiments. It could be observed that the lack of deformation is always present on the mould side towards the chuck. This is due to the heat conduction between the tool and the chuck. Due to the heat conduction in this direction, the tool part in the spindle direction is below the forming temperature. As a countermeasure, a holding time is introduced between reaching the process temperature and the start of the rotation cycle. Experimental tests have shown that a holding time of 15 min for the utilized geometry is practicable. This results in a new total process time of 65 min for the production of a part. As a result of the first series of tests, it was shown that a rotationally symmetrical part made of PA6-CF can be moulded with the help of an elastic core. But also, the limits of the elastic core could be observed. Several cores were either partially or completely torn due to thermal degradation of the silicone material. Others stuck to the inside of the preform. However, the sticking could be prevented by applying release agent Frekote 770 NC from Henkel GmbH to the outside of the core. However, on average a new core is required every three tests. Figure 8(a) shows a newly cast composite core with wound preform next to it. In Figure 8(b), the part is demonstrated after an experiment with the degraded core on the inside. During the experiments, the heating of the tool was one major issue and led to the uneven results on the outer side of the

tubes. To improve the inner surface, the test set up was iteratively modified to assure a defined position of the elastic core before and after the process.

In order to support the results from visual inspection, micrographs of the cross-section were prepared. The micrographs were taken with a Keyence VHX-7000. Figure 9 shows one of the micrographs with a wall thickness of 1.5 mm, which is in accordance with the specifications from the manufacturer of the semi-finished product. This supports the hypothesis that continuous reinforced thermoplastics can be formed by rotational moulding, but statistical analysis should be conducted to get a better understanding. The results demonstrate the feasibility of rotational moulding

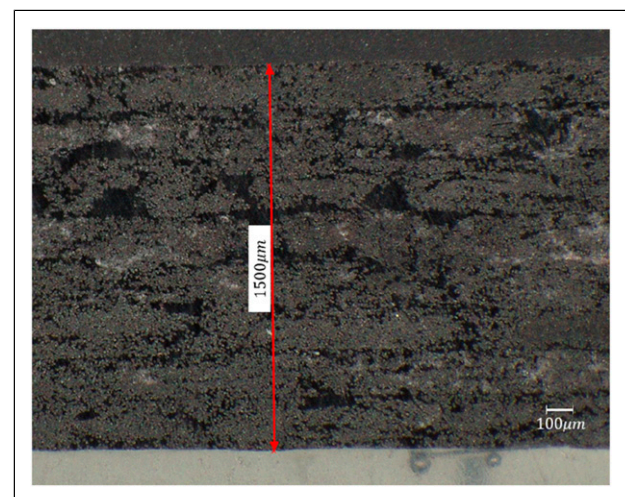


Figure 9. Micrograph of forming result from manufactured specimen.

also for small diameters. The use of an elastic core and a holding time during heating phase increase the results significant and are therefore recommended.

Conclusion

The aim of this work was to develop the rotational moulding for continuous reinforced thermoplastics with small diameters as a first step of a process chain to manufacture hybrid hollow profiles. The experiments were conducted on a lathe with an integrated heat chamber. The heat chamber consists of multiple layers with insulation and three infrared heaters. A process routine consisting of heating, forming and cooling phase was developed based on existing approaches and recommendation of the semi-finished product manufacturer. During an iterative approach, occurring errors were systematically analysed and the process routine was adapted. In addition, an elastic core was used to increase the pressure during rotational moulding with a significant effect on manufacturing results. The core consists of silicon rubber material in combination with lead balls to maximize the pressure. Furthermore, a holding time in the heating time was introduced to overcome the heat conduction into the lathe. This leads to a total manufacturing time of 65 min per part at a pressure of 0.17 bar. The results demonstrate the feasibility of this approach for forming continuous reinforced thermoplastics with small diameters into a desired shape. Future studies should investigate the manufacturing of hybrid structures, in a combination of fibre reinforced plastics and metallic load introduction elements, will be interesting. The use of elastic cores also allows the production of parts with varying cross-sections and should be investigated in combination with thermoplastic semi-finished products. Furthermore, the mechanical characteristics should be considered for further work. This will provide a base for comparison with other manufacturing technologies. For processing of high-performance thermoplastics such as PEEK-CF, further investigations are necessary, particularly with regard to the core system. This necessity arises from the higher processing temperatures.

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Author contributions

Patrick Schaible: Writing – review and editing, writing – original draft, visualization, software, methodology, investigation, formal analysis, and conceptualization.

Jonathan Ehret: Writing – review and editing, validation, software, and investigation.

Sebastian Schabel: Writing – review and editing and Project administration.

Jürgen Fleischer: Writing – review and editing, resources, funding acquisition, and supervision.

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Declaration of conflicting interests

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Data Availability Statement

Data will be made available on request.

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