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Procedia CIRP 131 (2025) 1–6

www.elsevier.com/locate/procedia

3rd CIRP Conference on Composite Material Parts Manufacturing

Manufacturing and Defect Characterization of Rotationally Molded Hybrid Composite Drive Shafts

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Abstract

One way of reducing greenhouse gas emissions is the consistent use of lightweight design. By reducing the moving mass, energy requirements can be lowered. Fibre-reinforced plastic composites are particularly suitable for lightweight components with very high mechanical requirements and a long service life. This article presents the production and investigation the influence of manufacturing process parameters on the defects of rotationally moulded parts using the example of a drive shaft. The hybrid components are manufactured using a rotational moulding process in which braided preforms and load introduction elements are processed in a single step. The elements are intimately bonded by a thermosetting matrix under the influence of temperature and centrifugal force. Different process parameters such as rotational speed, matrix temperature, mould temperature and mould unbalance are varied and the influence on the component properties are investigated. Furthermore, a catalogue of characteristics for the classification of manufacturing defects is created. It can be shown that different types of defects occur along the process chain and suitable measurements to minimize the defects are proposed.

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Keywords: shaft; carbon; reinforced plastic; centrifugal casting; rotational molding;

1. Introduction

In recent decades, climate change and the finite nature of resources have increasingly become the focus of public interest. In response to these challenges, new targets for reducing greenhouse gas emissions and environmental regulations are constantly being adopted. A major driver of greenhouse gas emissions is mobility, which will continue to be a key driver of global trade in the future [1]. One way to meet these challenges is the use of lightweight design methods in the sense of multi-material design in order to reduce weight and thus energy consumption. Multi-material design (MMD) involves combining different materials, such as metals, plastics or fibre composites, to optimally meet product requirements [2]. Due to their high specific mechanical properties, fibre-reinforced plastics (FRP) are suitable for components with high mechanical requirements and low mass. As a result, the energy consumption of moving systems can be reduced by increasing the load with the same mass in various applications. Due to the loads on the connection points of e.g. shafts to other parts it is necessary to distribute the load evenly across FRP to reduce the risk of local component failure. The load introduction (LI) transfers punctual or tribological loads into the FRP and are manufactured out of an adequate material e.g. metal or engineering plastic [3]. The connection can be designed as a frictional connection, form fit or material connection [4]. A distinction is made between extrinsic and intrinsic hybridization. Extrinsic hybridization is achieved by press-fitting, bonding or screwing the laminate and the LI together in

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10.1016/j.procir.2024.09.003

a subsequent joining step [5]. With an intrinsic connection, hybridization takes place during the shaping process of the fibre composite. This eliminates one process step in production and reduces the potential sources of errors. Possible areas of application for hollow profiles made of FRP in combination with LI are tension-compression struts or drive shafts. In drive technology, shafts are used in many applications, e.g. as output shafts for gearboxes, rotor shafts for engines or drive shafts for vehicles. Due to the anisotropic properties of FRP, the properties of the components can be adapted to the respective application. This leads to significantly higher torsional stiffnesses and critical bending stiffnesses of FRP shafts compared to metallic shafts with identical geometry [3], [6], [7]. This article discusses the influence of manufacturing process parameters of the rotational moulding process on the defects for hollow shafts in MMD.

1.1. Defects of fibre-reinforced plastics

Defects are irregularities in the fibre composite and lead to deviations in properties from the original specification. They are divided into three different categories, namely fibre defects, matrix defects and interface defects between fibre and matrix. On the one hand, fibre defects can be further divided in fibre defects, including fibre waviness, fibre misalignment and fibre breakage [8], [9]. Possible causes include bending of the fibres during the manufacturing process or friction during the production of the semi-finished fibre products. This form of error means that the fibres are either only partially able to transmit force or are no longer able to transmit it at all. As a result, the fibre composite no longer meets its original specification. Furthermore, there are interface errors between the matrix and the fibre. These include detachment of the matrix from the fibre or interlaminar delamination. With this group of defects, the force transfer between fibre and matrix is reduced. This means that smaller forces can be transmitted between fibres. In addition, crack growth in the laminate can occur as a result of delamination at the interface. The final group are matrix defects. These include pure resin areas, incomplete curing of the matrix and pores, i.e. areas that are not filled with matrix. This group also has a sometimes-significant impact on the mechanical properties of the laminate [10]. A defect-free laminate is not necessarily cost-effective, as it can only be produced with great effort. The key is to find an optimal operating point for the process through targeted identification of process parameters and their influence on the defects. [11]

1.2. Manufacturing of hollow fibre-reinforced structures

There are multiple techniques available for creating the FRP hollow structure for subsequent component use, such as pultrusion [12], [13], winding [14], and blow moulding [15]. Each method has its own set of advantages and disadvantages regarding productivity, initial costs, and hybridization possibilities. The winding process can employ either thermoset or thermoplastic matrix systems, with thermoset winding further categorized into wet winding and prepreg winding. In all winding processes, a core serves as the foundation, which must be extracted in a subsequent step. Pultrusion is a continuous process wherein dry fibre rovings, similar to wet winding, are passed through a matrix bath for impregnation. These impregnated fibres are then pulled through a tool to achieve the desired cross-sectional shape. In the RTM process, a preform is draped over a core, which may be foam (remaining in the component) or washable/metallic (removed later). Fibre preforms can be wound or braided. Another method involves the hose-blowing integral process, where a pressurized hose presses the fibre preform against the tool. With appropriate mould heating, thermoplastic preforms can also be processed. A novel technique for creating metal-FRP hybrid joints is the rotational moulding process [16], [17] . In this method, a dry fibre preform is placed in a tool alongside the LI. The preform is an integrated part of the joint formation and thus eliminates the need for a separate core that would have to be removed later. This leads to a simplified manufacturing process and cost reduction. The tool is then clamped in a spindle, rotated, and a thermoset matrix is casted into the tool. Under the influence of heat and centrifugal force, the dry fibre preform becomes impregnated and cures. Consequently, both the production of the FRP hollow structure and the co-cured bonding with the LI are achieved in a single step [18]. This approach offers cost advantages over current technologies by eliminating the need for subsequent joining steps. Additionally, it requires straightforward machine technology and no processing aids like cores.

2. Method and Materials

In this article, the influence of parameters of the centrifugal process on the occurring defects of a hybrid lightweight shaft is analysed. For this purpose, the influencing variables are varied according to a test plan and their influence on the defects are characterized, documented by a twofold inspection and classified according to their origin in the process chain. The selected parameters are the mould temperature, the mould unbalance, the matrix temperature and the rotational speed as an auxiliary variable for the matrix pressure. The component used is a simplified shaft with an outer diameter of 30 mm and an inner diameter of 24.5 mm with a total length of 180 mm, shown in Figure 1. The load introduction elements are made of a polymer and are manufactured using stereolithography.

Figure 1 Rotational moulded part with size reference

2.1 Manufacturing of test specimen

In the first stage of production, the LI were manufactured from Tough Resin 2000 by formlabs on a Prusa SL1S Speed using the SLA process to enable computer tomography (CT) scans by reducing the possibility of errors related to high differences in the density of components. At the same time, the manual preform was produced. Four layers of carbon fibre braided sleeves from Siltex Flecht- und Isoliertechnologie Holzmüller GmbH & Co.KG were mounted on a mandrel. A binder powder was applied between the second and third layers and on the fourth layer. The EPIKOTE 05311 binder powder from Westlake Epoxy was heated in a convection oven and then cooled at room temperature. This increases the flexural rigidity of the preform and prevents it from collapsing, making it easier to handle. An overview of the materials used is shown in table 1.

Table 1. Overview of the material system used

Description	Material
Ply stack	$\pm45°_1$ / $\pm45°_3$
	(Siltex 2425 3K / Siltex 2428 6K)
Binder powder	EPIKOTE 05311
Resin	Sicomin SR 8500
Hardener	Sicomin SZ 8525

The LI and the preform were then joined and inserted into a one-piece mould. After preheating, the mould was clamped in a lathe and set in rotation. A lance brings the epoxy resin into the mould as matrix. The rotation impregnates the dry fibre preform first in a radial direction and then in an axial direction on the overlapping surfaces. The matrix is SR8500/SZ8525 from Sicomin. The mould is tempered by infrared radiators during rotation. After 20 minutes of rotation, the mould was released and placed in a convection oven for 10 minutes for post-curing. The component was then demoulded. The process chain is demonstrated in Figure 2. During the test, the mould temperature, the matrix temperature, the rotational speed and the mould unbalance were varied. Currently no standard set of process parameters is available for the rotational moulding process. Thus, parameters needed to be chosen in the available parameter space in accordance with the limitation of the machine and process. The rotational moulding requires a minimum rotational speed due to effect of gravitational force on the matrix. The lower level of rotational speed is chosen to be approximately ten times the minimum speed. The maximum rotational speed was limited by the eigenfrequency of the machine and is approximately thirteen times the minimum speed. The lower level of tool and matrix temperature are set to room temperature. The upper level of matrix temperature and tool temperature are experience-based values from previous experiments. For the casting of the matrix a cartridge system was used and in previous experiments a save handling of the cartridge without leakage was assured at the upper level temperature. No additional tool unbalance was used as the lower level. For the upper level an additional screw was mounted to the tool. The tool has an outer radius of 80mm and the screw a weight of 7,985g which leads to the upper level of tool unbalance. The different factor levels and their adjustment methods are shown in table 2. To reduce the overall effort, a screening test plan of resolution 4 was used with a repetition of three tests per factor level combination. This results in a total of 24 tests.

Table 2. Test parameters

Factor	Level -	Level +	Adjustment method
Rotational speed	1600 rpm	2200 rpm	Machine Parameter
Matrix temperature	25°C	70°C	Heating time in water bath
Tool temperature	25°C	120°C	Heating time
Additional tool unbalance	-	+ 638,8gmm	Additional weight

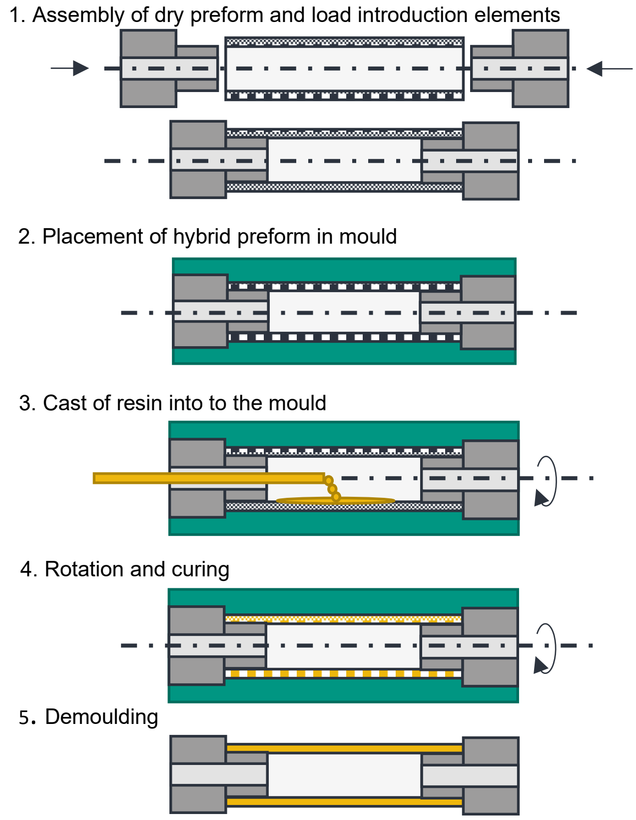

Figure. 2 Process chain of rotational moulding and intrinsic joining for CFRP-metal hollow shafts

2.2 Part inspection

After manufacturing, every part was inspected in a twofold inspection process. First step was a visual inspection of the part in a distance of approximately 50 cm under industrial lighting conditions. The second step was a CT scan of the part to inspect the internal defects. In this way, a deeper understanding of the internal structure could be gained. Every part was placed inside the CT on a dedicated holder made of foam to assure a secure position during the scan. The CT scans of the specimen were generated at 120 kV tube voltage, 125 µA target current, 1000 ms integration time and with a 1.0 mm Aluminium aperture on the Zeiss Metrotom 800. Each measurement took 87 minutes. The CT data sets were evaluated using the VG Studio MAX 3.4 software. An entire defect analysis of composite materials necessitates the evaluation of porosity. In this study, a quantitative approach was evolved to determine the level of porosity within the analysed components. This approach utilized threshold value analysis implemented within the VG Studio MAX 3.4 software. Thresholding allows for the identification and measurement of pores within the three-dimensional CT data set. The minimum detectable pore size was set at 8 voxels with an applied probability threshold of 1.0. which determines which detected defects will be considered real based on their calculated likelihood of being actual defects, there is no absolute value for the threshold applicable to all data sets.

3. Results and Discussion

In this section, the manufacturing and inspection results for classifying manufacturing defects in the specimen are shown.
And in addition, their interrelationships within the threshold analysis – which will be important for future work – are introduced.

3.1. Visual Inspection

In the first step of the twofold inspection visible defects on the surface were documented and categorized. The results of the visual inspection are show in Figure 3. A resin rich area as well as the deviating fibre orientation descend on poor preform quality and handling, see Figure 3 a). It does negatively affect the distribution of forces within the final composite structure, leading to increased susceptibility to failure and reduced mechanical properties. Also, fibre misalignment could be observed in several parts due to the handling of the preform and the assembly of the mould, see Figure 3 b). In Figure 3 c), the specimen is locally covered by colourless abrasion from the previous process. This can be addressed through a cleaning process of the mould. Unlike the aforementioned defects which are not linked to the centrifugal casting itself, internal pores and surface breakouts can be attributed to the inherent characteristics. The analysis revealed that only three out of the tested samples exhibited a surface free of visible pores. The impregnation quality is influenced through matrix temperature and rotation speed during the process. It was observed that the impregnation quality is depended on the rotational speed, with high speed resulting in better impregnation quality and no visible pores on the surface. The defects shown in Figure 3 d) on the surface affect the concentricity of the shaft and impairs the matrix functions: Maintaining the reinforcing fibres in their intended positions within the composite structure, ensuring optimal load-bearing capacity of the composite as well as shielding the reinforcing fibres from external mechanical and chemical degradation mechanisms. Following the demoulding process, a residual amount of the matrix material remains within the mould cavity which leads to small holes on the surface on the part, see Figure 3 d). These defects resulted from demoulding of the part and possible reasons could be a sticking of the part to the surface of the mould which shows the importance of tool design and the use of sufficient release agent. In Figure 3 f) large pores directly under the surface can be overserved result in a poor quality. They could be observed only in a few parts and could be the result of poor impregnation or poor mixing of the matrix before the impregnation.

3.2. CT Analysis

As illustrated in Figure 4 a), cracking within the matrix was observed in 33% of the analysed shafts and is likely attributed by thermal stresses induced during the cooling process. Rapid cooling can lead to significant temperature gradients within the shafts, resulting in stresses exceeding the material's tolerance and subsequent crack formation. Another defect that could also be seen without CT is the formation of fibre beads, see Figure 4 b). These beads arise at the fibre-LI interface regions caused by handling mistakes during joining of semi-finished products. This results in different distances between the fibre and the LI section in the important fibre-LI area. Deviations from the intended preform diameter were observed. This occurs due to a loose fit during preform fabrication. An oversized preform diameter has a detrimental effect on the fibre-inlay interface, a critical region for optimal load transfer within the composite structure, see Figure 4 c) and d). During the matrix infiltration process, there are also larger gaps formed between fibres and LI that hinder complete filling with the matrix material. This leads to the formation of voids or dry spots within the interface,

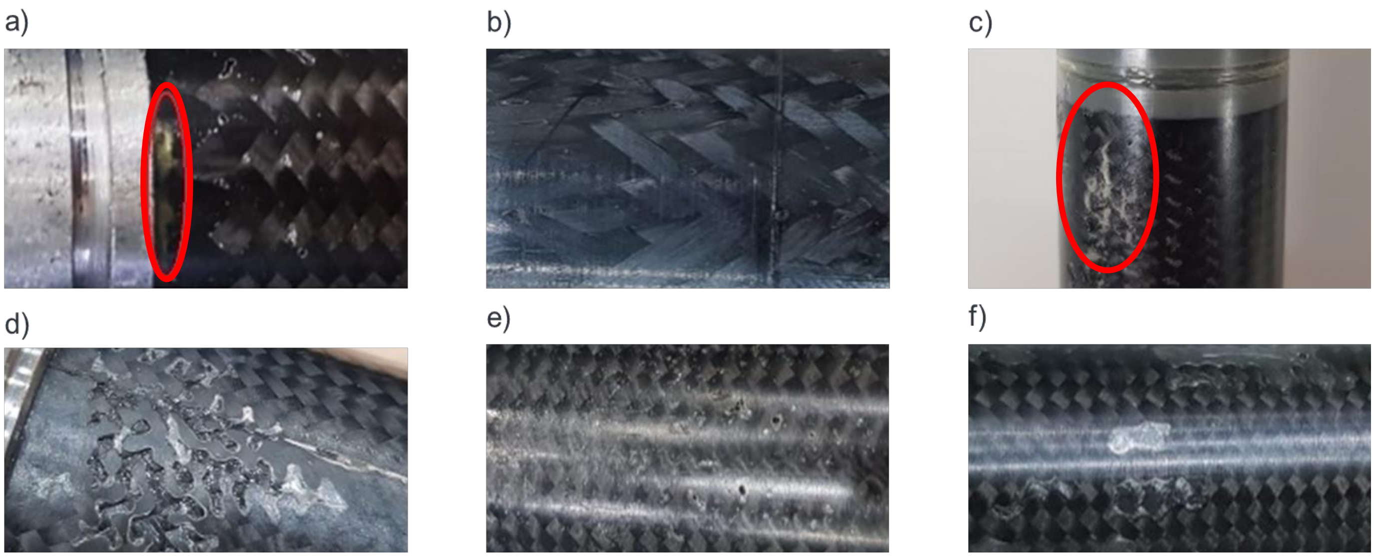

Figure 3. results of the visual inspection shows: a) resin rich area b) fibre misalignment c) contamination of surface d) large pin holes e) small pinholes f) porosity under the surface

reducing the overall strength and integrity of the composite. Figure 4 g) presents a complementary view of the phenomenon. In general, delamination is a critical failure mode specific to layered composite materials. This separation is primarily driven by interlaminar shear stresses acting at the interfaces between adjacent layers. As illustrated in Figure 4 e), delamination can only be observed with a CT scan. Figure 4 e) depicts a clear separation between the layers, indicating a complete loss of adhesion at the interface. Figure 4 f) showcases a distinct phenomenon, the preform appears to have lost its intended shape, with a visible distortion of the fibre architecture. However, unlike delamination, the matrix material remains filling the space between the deformed fibres. This damage mechanism is not a complete separation of layers but rather an intra-layer fibre misalignment. The CT scan analysis revealed the presence of porosity within the components by implementing a threshold analysis (Figure 5). It illustrates the limitations of using porosity analysis alone to compare test specimens. The left panel depicts a cross-sectional CT scan at the load introduction point, while the right panel highlighting all air inclusions identified by the software. It is important to acknowledge that these porosity values are influenced both by manual and process manufacturing errors. At this point the insights into the trend of various processing parameters on the porosity within the manufactured components should be stated. While increasing the rotation speed to a multiple of the minimum rotation speed initially resulted in a reduction of porosity, further speed increases did not yield significant additional benefits. These observations suggest an optimal speed range for minimizing porosity. Within the tested range, variations in matrix temperature and its associated viscosity appeared to have minimal influence on the observed porosity levels. Preheating the mould resulted in a higher mould temperature during the process brings a positive impact on porosity, possibly due to a more complete solidification of the matrix material during rotation. Additional unbalance of the tool, leading to a slight shift in the rotational axis, did not exhibit any detrimental effects on the porosity levels. The CT data additionally highlighted an area for potential improvement. The observed thickness of the inner resin layer suggests that the lightweight design potential might not be fully exploited. Future efforts reduce the matrix mass considering that the components have a fibre volume content of 32 %, which corresponds to about half the target value for CFRP. An optimal fibre-LI interface is crucial for efficient stress transfer between the fibre and the matrix. The non-uniform distances created by the oversized preform can disrupt this transfer, potentially leading to stress concentrations and premature failure under mechanical loading.

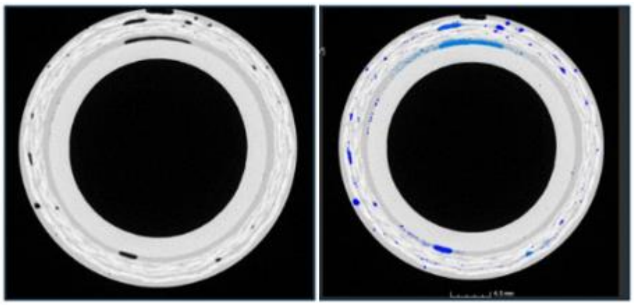

Figure 5. Left side: cross section of part, outer layer out of frp and inner layer load introduction element. Left side: threshold analysis of the same part

4. Summary and Outlook

In the present work, carbon-fibre reinforced plastic-shafts with load introduction elements were produced using the rotational moulding process using different combinations of process parameters according to a test plan. In a twofold inspection process consisting of a visual inspection and computer tomography scan, defects on the surface and inside the specimen were analyses and discussed. The visual inspection methods described have proven to be effective in identifying a number of defects introduced into the component in the process chain for future work They show a range of different defects from fibre defects like fibre misalignments which are visible on the specimen surface to interface defects like delamination. Minimizing these defects will be crucial for achieving greater

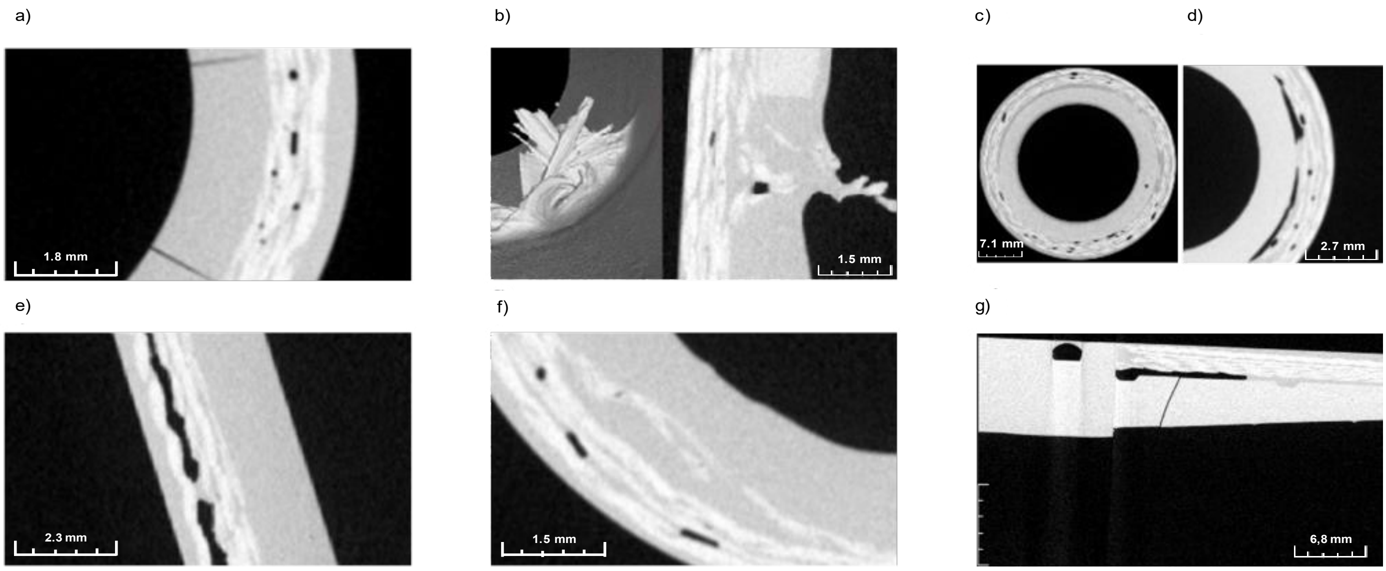

Figure 4. results of the CT analysis shows: a) matrix cracking b) fibre beads c) porosity d) delamination between LI and fibres e) delamination between fibres f) porosity and fibre distortion g) incomplete filling

part quality. These defects can now be assessed against failure mechanisms in future work. The DOE analysis revealed that the minimum number of voids was attained using a rotation speed of 1600 rpm, a matrix temperature of 70°C, a tool temperature of 120°C, and an applied unbalance. This outcome is attributed to the identified dependencies within the porosity analysis. This result also incorporates the previously discussed effects of defects. This work leads to a couple of proposals for future works and critical points in the process chain. First of all, the tool design is a crucial point and needs to be addressed. Tools made out of two parts seem to be favourable due to easier assembly of the part and demoulding. This leads to a minimized risk of fibre distortions and pinholes on the surface of the part. Furthermore, the preforming is a critical step in the process chain and for the moment not fully automated which leads to error and quality variations. Increasing the degree of automation and a detailed analysis of the parameters for preforming process of braided fibres can also increase the part quality over all und reduce the number of defects. For the rotational moulding process a deeper understanding of the void mechanism during the impregnation process is needed to find optimal parameters for the minimization of voids and manufacturing time. So, the full potential can be used in the future.

Acknowledgements

This research is supported by the Federal Ministry for Economic Affairs and Climate Action (BMWK) by the project FKVShaft (funding code KK5023902KU1) on the basis of a decision by the German Bundestag. The authors wish to express their gratitude to Wefoba GmbH for the production of the tool and load introduction elements. Furthermore, the authors wish to express their gratitude to Siltex Flecht- und Isoliertechnologie Holzmüller GmbH & Co.KG for providing the braided sleeves.

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