PROCESS-INDUCED DISTORTIONS OF COMPOSITE STRUCTURES DUE TO THROUGH-THICKNESS FIBRE VOLUME FRACTION GRADIENTS

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Abstract

During the production of composite parts unavoidable deformations occur. In order to meet the strict tolerance requirements of industry branches such as the automotive industry it is essential to understand the underlying mechanisms of these deformations. While much research has been done on the anisotropy driven spring-in effect and also on warpage caused by part-tool interactions, there are only a few studies on deformations driven by a fibre volume fraction gradient (V_f-gradient) in the through-thickness direction of a laminate. Especially for large, thin-walled parts with complex geometries, this effect leads to additional unwanted deformations either locally in curved part areas or even on a global level throughout the entire part. A comprehensive experimental study has been performed examining the effect of a V_f-gradient on process induced deformations. L-shaped carbon fibre reinforced, fast curing epoxy resin based specimens are investigated. The occurring deflections are compared with the predictions of an analytical model. The results are relevant for the future development of robust prediction methods for process induced distortions of large, thin-walled composite parts.

1. Introduction

The increased use of fibre reinforced plastics in industry branches such as the automotive branch leads to new challenges regarding the nature of production processes and their quality: In order to fulfil the demand of high production rates, classical processing technologies like autoclave-prepreg-production are substituted by faster strategies such as resin transfer-moulding (RTM), prepreg-press technology or wet compression moulding. At the same time narrow tolerance requirements have to be met. In a cost driven production environment neither scrap parts nor time-intensive rework can be tolerated. Therefore unwanted part deformations which may occur during processing must be counteracted early-on in the design process. In order to avoid or predict these deformations a deeper understanding of the different underlying mechanisms has to be obtained.

Past work on process induced deformations (PID) focused mainly on the anisotropy driven spring-in effect as underlying mechanism (e.g. [1], [2] or [3]). Spring-in occurs only in curved part areas and is mainly dependent on the thermo-chemical properties of the resin during cure, the process cycle and the

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enclosed part angle. Weak dependencies could also be found for different fibre properties [3], different lay-ups [4], and different part thicknesses [5]. The influence of the curvature radius on the spring-in distortions is discussed controversially. In [1, 2, 6] no dependencies were found whereas the studies in [7, 8] showed a weak dependency.

Another source for unwanted deformations is the warpage effect which is caused by part-tool interaction. It is also quite well investigated and occurs due to a difference in thermal strains between the composite part and the tooling material during the cool down phase of the process [5, 9]. It is especially relevant for autoclave processed prepregs produced on single-sided metal tools and it does not occur if the mould is kept at a constant temperature during cure [10].

A third and less investigated source for process induced distortions is discussed in [6] and [11]. A gradient in relative fibre volume fraction (V_f-gradient) in the trough-thickness direction of the laminate is suspected to cause an asymmetry, even though the stacking is symmetric, and thus additional deformations. In [11] an analytical approach to predict such deflections is presented but no experimental data to validate the findings is shown. In [6] the chosen experimental setup did not induce the desired gradient in fibre volume fraction and no significant deformations could be attributed to the mechanism. Still, both studies suspect a relevant contribution to the overall distortion and state that further investigation should be undertaken.

In general, the majority of the past work reports on autoclave processing and prepreg materials mainly from the aerospace industry. However, this paper will focus on RTM processed carbon fibre reinforced plastics (CFRP) and fast curing epoxy matrices. This combination represents the state of the art in a high-rate production environment. In [10] it could be shown that spring-in is still one of the most dominant mechanisms leading to unwanted part distortions under such circumstances. At the same time it was shown that part-tool interaction did not contribute to the total deformation if the mould temperature was kept isothermal. Additional deflections caused by local asymmetries were not investigated in the paper. Nevertheless, such asymmetries are suspected to be an important contributor to the total deformation in state of the art RTM processing. Whereas for prepreg parts V_f-gradients may occur due to one sided

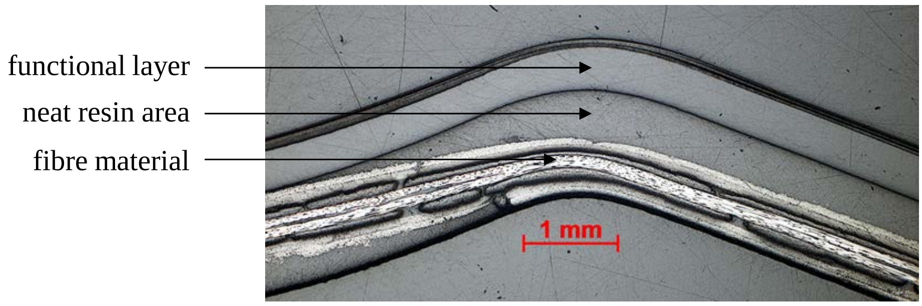

Figure 1: Cross-sectional view of a state of the art automotive CFRP-part. The part is produced in a closed mould RTM-process. The effect of fibre bridging and the resulting neat resin area are depicted. Besides the unwanted neat resin area an intentional functional layer can be seen. Source: AUDI AG.

breather fleece or peel ply layers, which support drainage of the resin [11], for RTM parts there are different causes for asymmetry. One factor that may lead to local neat resin areas and therefore local asymmetry is fibre clamping. Fibre clamping is a technique used in state of the art RTM processes to assure reproducible resin flow within the part: When the double-sided tooling is closed the textile fibre material is usually clamped around its outer edges. The injection canal is placed inside the clamped area. Using this method resin is prevented to rush along the outer edges of the textile and a straight

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resin front is maintained. Moreover, fibre clamping simplifies the positioning of the textile and also serves as additional sealing. Besides these obvious advantages it often leads to an unwanted effect called fibre bridging. It occurs in curved part areas because of the in-plane tension which is induced by the clamping of the fibres. As shown in figure 2 the textile material is pulled into the direction of the inner radius whereas the outer area of the tool remains empty. After the injection process a resin rich area develops near the concave tooling surface and a fibre rich area develops near the convex tooling surface. Thus, a local V_f-gradient in through-thickness direction occurs. A microscopic cross-section of a typical automotive CFRP skin part with occurring fibre bridging is depicted in figure 1. The fibre bridging and a neat resin area close to the outer tooling radius can be clearly recognized.

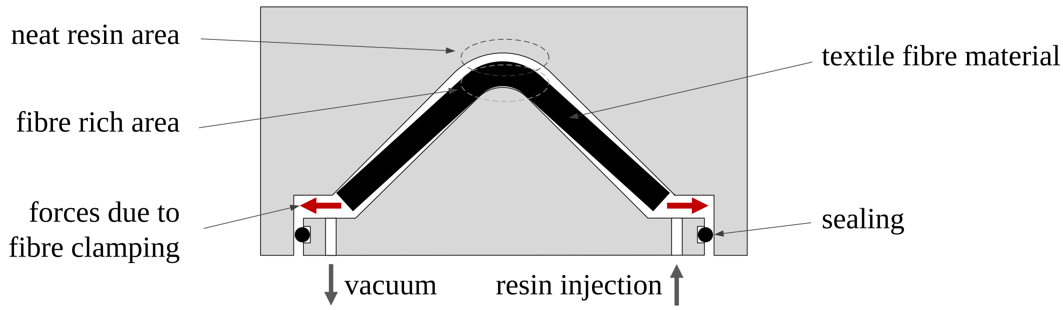

Figure 2: Schematic of fibre bridging effect and immersion edge tool: In a typical state of the art closed mould RTM-process fibre clamping may lead to in-plane tensional forces in the preform. As a result the fibre bridging effect develops. After the resin injection process a fibre rich area close to the inner radius occurs (convex tooling side) whereas at the outside a resin rich area develops (concave tooling side). In pronounced cases a neat resin sector develops at the outer radius. A circumferential sealing surface around the vertical plane of an immersion edge tool enables production of parts with variable wall thickness.

Asymmetry may not only occur on a local but also on a global level. Examples for global asymmetry through-out the entire part are: functional layers on only one side of the part or one sided paint application during a one-shot RTM process (see fig. 1). A global through-thickness V_f-gradient can also develop as a result of the wet compression moulding process wherein the direction of infusion is oriented in transverse direction along the z-axis of the part. Another source for asymmetry, independent of the fibre volume content, are the knitting yarns used in unidirectional as well as bi- or multi-axial textiles. These knitting yarns are mainly oriented transverse to the fibre direction and their thermo-mechanical behaviour during processing could have an influence on the shape distortion behaviour of a part.

2. Influence of asymmetry on process induced distortions during processing

In this paper, as a representation for possible asymmetries, neat resin layers on L-shaped CFRP specimens are investigated. Their influence on the process induced distortions is studied. Since the L-shape offers a curved area, spring-in will also occur for the parts. Spring-in is mainly a result of the out-of-plane chemical and thermal shrinkage, which takes place during curing and cool down. On the contrary the distortion driven by asymmetry mechanisms depends mainly on the in-plane strains in the different areas throughout the parts thickness. As shown in figure 3 an area with lower V_f will contract more than an area with higher V_f. These strains are driven by the chemical and thermal shrinkage of the resin as well but also depend on the thermomechanical properties of the fibre to a higher degree. This leads to a warpage of the entire part analogous to a bi-metal strip under thermal loading. The spring-in effect and

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the deformations caused by the asymmetries superpose each other in the investigated specimens and lead to a total deflection of the part as depicted in figure 4.

The goal of this paper is to study the magnitude of deflections caused by thin neat resin layers and to set them in a relation to distortions caused by spring-in. Furthermore a linear analytical modelling approach is used in order to predict the occurring deformations for both effects.

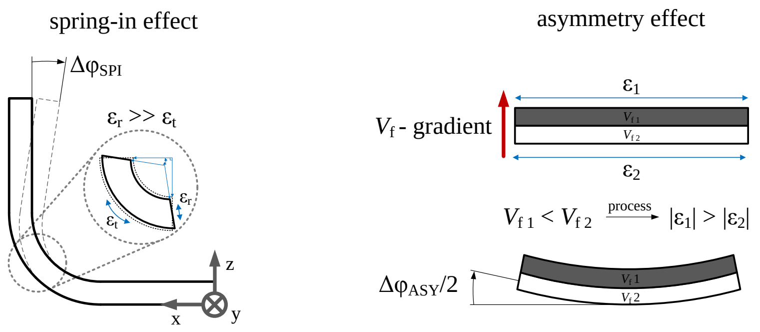

Figure 3: Underlying mechanisms for process induced deformations in RTM-FRP-manufacturing: On the left hand side a schematic of the spring-in effect resulting from anisotropic shrinkage during processing is shown. On the right hand side additional deformations due to a V_f-gradient in thickness direction leading to asymmetry. The layer with lower V_f contracts more during processing than a layer with a higher V_f which results in a curvature of the entire affected part area. The strains in both mechanism occur due to thermal and chemical shrinkage during processing.

3. Analytical modelling

A classical laminate plate theory (CLPT-) based approach is chosen to predict the occurring deformations. The spring-in component of the total deformation is derived analogous to [10]. Neat resin chemical shrinkage ΔV_c is taken from rheometry measurements conducted during the study. Chemical shrinkage is introduced into the model following Kappel's approach [8] wherein for each layer an additional chemical strain is considered in both transverse directions. The chemical strain parallel to the fibre direction is assumed to be negligible ($\varepsilon_\mathrm{chem} = 0$). Thermoelastic strains are introduced into the model by using classical rules of mixture [12]. Neat resin coefficient of thermal expansion (CTE) data is derived from standard thermo-mechanical analysis (TMA). For the fibre material CTEs literature data is considered (see table 1). Previous studies showed that classical rules of mixture are not a sufficient way to calculate the global CTE in thickness direction of the laminate ($\alpha_\mathrm{z,lam}$). Therefore a measured value from a TMA analysis is used. Young's modulus, shear modulus and poisson's ratio of matrix and fibre are taken from the manufacturer's data sheet or common literature, respectively. As a result of the CLPT analysis under thermal loading ($\Delta T = T_\mathrm{process} - T_\mathrm{ambient}$) the thermo-chemical strains for in transverse and in-plane direction of the laminate are derived. In a final step these values are translated into a spring-in deformation of the L-shaped specimen by using Radford's equation [4]. It describes the kinematic relation between tangential and radial strains in a curved part area:

$$\Delta\varphi_\mathrm{SPI} = \frac{\varepsilon_\mathrm{t} - \varepsilon_\mathrm{r}}{1 + \varepsilon_\mathrm{r}}(180^\circ - \varphi') \qquad (1)$$

wherein ε_t and ε_r are the strains during processing in tangential and in radial direction respectively. φ' denotes the desired part angle (90° for an L-profile) and $\Delta\varphi_\mathrm{SPI}$ is defined as the deviation from the desired angle with positive values for smaller angles than the desired one.

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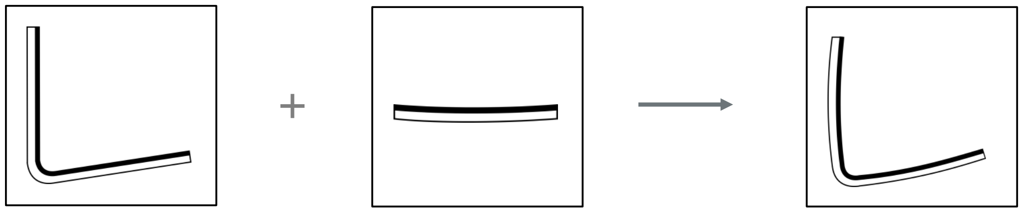

Figure 4: The total deflection of RTM-parts is driven by two main underlying mechanisms: spring-in and asymmetry. As representation for possible asymmetries and V_f-gradients in thickness-direction, neat resin layers on L-shaped CFRP-specimens are investigated.

The additional curvature due to asymmetry is also derived by the means of a CLPT analysis under thermal loading. An asymmetric V_f distribution in the trough-thickness direction leads to an asymmetric deformation behavior: Through a displacement-bending-coupling, the thermo-chemical in-plane strains, lead to an out-of plane bending of the part. It is assumed that this bending only takes place along the x-axis of the part whereas the stiffening influence of the curved area prevents a bending along the y-axis. To account for the V_f-gradient each layer of the laminate is given a separate V_f that may vary throughout laminate thickness. In case of a neat resin layer this value is set to zero. Using classical beam theory the resulting curvature from the CLPT analysis can be translated into an additional angular change of the L-profile resulting from asymmetry $\Delta\varphi_\mathrm{ASY}$ (see fig.???). Both angular components are finally superimposed by adding the respective values. Thus, the total deformation is given by:

$$\Delta\varphi_\mathrm{Total} = \Delta\varphi_\mathrm{SPI} + \Delta\varphi_\mathrm{ASY} \tag{2}$$

4. Experimental setup

A closed mould RTM tool made from a standard tooling steel is used in this study. In order to generate neat resin layers it was built with an immersion edge (see fig. 2). The immersion edge makes it possible to produce different wall thicknesses within one tool. Two different male inlays are available with a design part thicknesses of 2 mm and 3 mm respectively. The tool is water heated. The length of the produced profile along the y-axis is 240 mm, the flange length 50 mm and the outer radius of all parts is 7 mm. As fibre material *Toray T620* fibres in form of a biaxial textile are used. A quasi isotrop lay-up is selected: $[(\mp 45)_2(90/0)]_\mathrm{S}$. The matrix material is a fast curing epoxy resin from the automotive industry with a standard curing time of three minutes and a pot life of approximately 30 seconds. The corresponding material properties can be found in table 1. Processing took place at a temperature of 115°C. Ambient temperature was measured at 20°C. A curing time of seven minutes was selected. The curing time was set longer than given in the manufacturer's specifications in order assure full cure of the material and to avoid unwanted post curing effects. For each parameter set three specimens were produced. The neat resin areas are generated in a two-step process: In a first step reference L-angles without neat resin layers are produced. Subsequent to curing the specimens are trimmed and put back into position. Subsequently the profiles are fixed either on the male or the female side of the tool. A strong tape that also acts as sealant is used to hold them in place. The mould is closed again but not as narrow as in the first step to provide a cavity for the neat resin layer. With a second injection step the void is filled and a neat resin layer develops either on the outer or inner region of the L-profile, respectively. The measurement of the occurring deformations was conducted with a *GOM 3D ATOS* optical scanner. It provides a three-dimensional point cloud with a density of 0.8 pt/mm^2 as virtual representation of the part. The software *GOM INSPECT* was used for evaluation purposes. Different angles were measured. Points close to the radius region (max. 10 mm from the radius region) were used to generate best-fit planes in order

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Table 1: Material data. Fibre and matrix properties are taken from common literature. Values for matrix' and the laminate's CTE are measured by means of standard TMA analysis and values for matrix' chemical shrinkage are measured by means of two plate rheometry.

	property	symbol	unit	fibre T620	matrix	source
fibre	modulus (fibre direction)	$E_{f\|\|}$	[N/mm^2]	230000		[12]
	modulus (tranverse to fibre)	$E_{f\perp}$	[N/mm^2]	15000		[12]
	shear modulus	$G_{f\perp\|\|}$	[N/mm^2]	50000		[12]
	poisson's ratio	$\nu_{f\perp\|\|}$	[-]	0.23		[12]
	CTE (fibre direction)	$\alpha_{f\|\|}$	[10^{-6}/K]	-0.56		[12]
	CTE (tranverse to fibre)	$\alpha_{f\perp}$	[10^{-6}/K]	12.5		[12]
matrix	tensile modulus	E_m	[N/mm^2]	2850		[12]
	poisson's ratio	ν_m	[-]		0.35	[12]
	CTE	α_m	[10^{-6}/K]		85.1	measured value
	chemical shrinkage	ΔV_c	[-]		-0.036	measured value
laminate	CTE (thickness direction, z)	$\alpha_{z,lam}$	[10^{-6}/K]	81.6		measured value

to measure the distortions of the radius area were spring-in acts dominantly. Analogous points on the complete flange area were used to generate best-fit planes to investigate the total deformation of the part including spring-in and additional deformation due to asymmetry.

5. Results

As shown in figure 5 neat resin layers on the outside of the L-shaped specimens lead to a reduction of the total deflection as flanges tend to warp outwards.. The asymmetry effect counteracts the spring-in distortions. This case represents the conditions shown in figure 1: fibre bridging leads to a neat resin area on the outer side of the RTM-part and reduces the deformation. 1.4 mm and 0.7 mm were selected as thicknesses for the neat resin layers respectively. This equals a 70% and 30% raise in total part thickness compared to the original 2 mm. Compared to figure 1 this seems to be a realistic range. The difference to a part without neat resin layer is significant. For the 0.7 mm parts, total deflection is reduced by 83% and for the 1.4 mm parts even a spring-out occurs. The total deflection angle in this case is negative and equals to 1.7°. Even the evaluation of deflection close to the radius shows significant differences compared to a part without neat resin sectors. That means that limited local neat resin sectors already do have an impact on part deformation. Typical processing defects as shown in figure 1 contribute to the total process induced distortion and reduce the spring-in effect.

As expected the specimens without additional neat resin layers showed no flange warpage: The measurements including the whole flange area and the measurements close to the radius sector are approximately equal. The only acting mechanism leading to distortions is spring-in in this case.

Additional layers on the inside of the L-profiles lead to an increase in total deflection. Analogous to the layers on the outside flange warpage occurs due to asymmetry mechanisms. For a neat resin layer thickness of 1.4 mm the total deflection amounts to 5.31° which is 3.85 times higher than the original spring-in deformation of 1.34°.

The investigated CLPT based linear analytical model used in this study is able to account for the occurring deformations quantitatively. For thinner neat resin layers of 0.7 mm on either the outside or the

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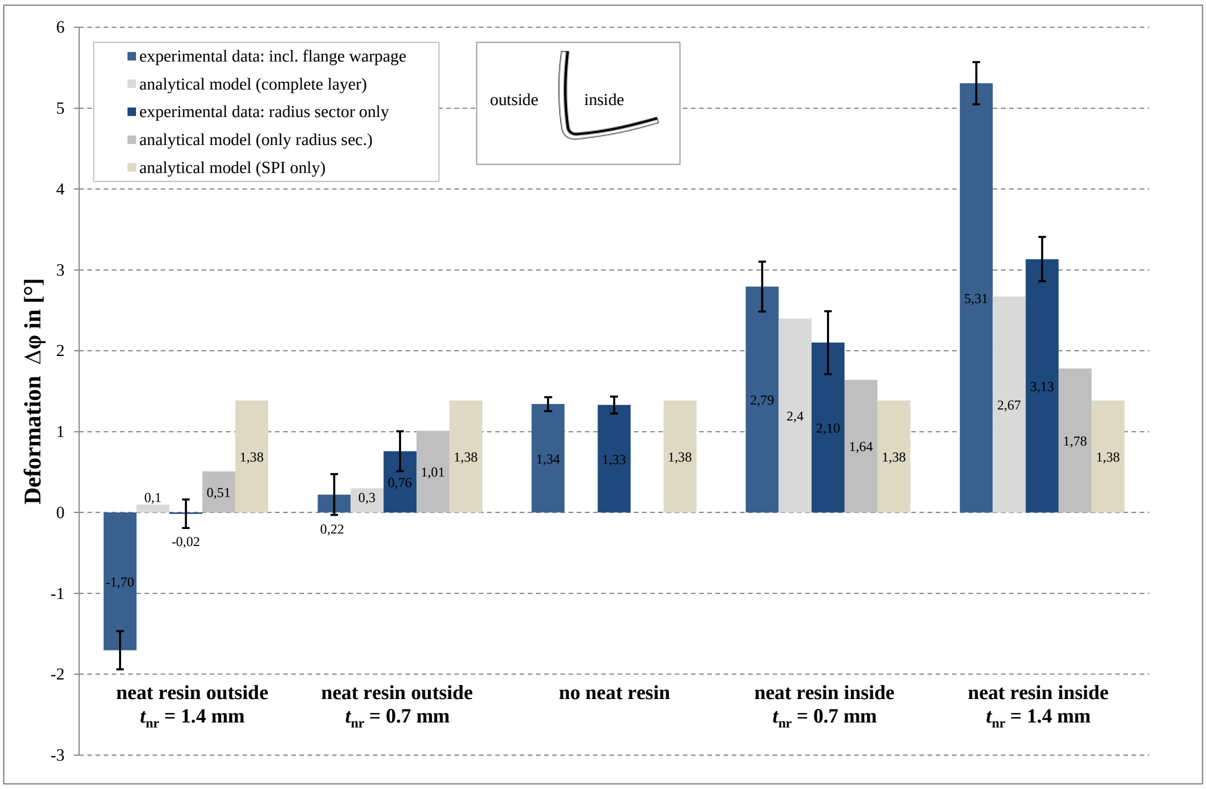

Figure 5: Experimental data. The influence of neat resin layers of different thicknesses on process induced distortions is investigated. The layers are applied either on the inside or on the outside of the L-shaped part. Deformation measurement is conducted close to the radius to account for the additional distortions of the curved area. Measurements are also conducted including the whole flange area to account for the deformation behaviour of the entire part. The experimental data is compared to the results of the analytical modelling.

inside it provided prediction with deviations of 24% and 14%, results with satisfactory agreement compared to experimental data. For thicker layers the model is not able to give quantitatively satisfactory results. Linear theory may not be sufficient in this case since deformation becomes rather high. Also the assumption that no deformations occur along the y-axis of the part loses validity for thick layers. The produced parts showed noticeable deformation around that axis. This may lead to an interaction in transverse contraction which is not accounted for in the model. Further modelling strategies should be developed.

6. Conclusions

In state of the art closed mould RTM processes V_f-gradients and neat resin areas are very likely to occur. As a representation for such areas neat resin layers on L-shaped specimens were investigated experimentally in this study in order to analyse their effect on process induced deformations. A superposition of classical spring-in and additional deformations driven by an asymmetry mechanism can be observed.

A linear analytical approach was found beforehand to predict resulting deformations and to investigate influencing parameters. For thin neat resin layers the results were in good agreement with the experimental data. For thicker neat resin layers the deformations became comparably large and linear theory seemed not to be sufficient as representation of the material behaviour. In future approaches non-linear

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strategies and FE-analyses that also account for deformations along the longitudinal axis of the part will be investigated.

The applied neat resin layers lead to considerable additional deformation besides classical spring-in. Especially with increasing flange length the deformations became very influential. Measurements close to the radius sector of the part showed that small neat resin sectors, similar to the one in figure 1, already have a considerable impact on total distortion of the part. Therefore deformations due to asymmetry and V_f–gradients are a second important source for process induced distortions in state of the art RTM parts. Further investigations are indispensable to develop a deeper understanding of the phenomena and to find prediction methods for the occurring deformations.

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