EVALUATION OF PROCESS INDUCED RESIDUAL STRESSES IN CONTINUOUS FIBER-REINFORCED HYBRID THERMOPLASTIC COMPOSITES

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Abstract

The mechanical behavior of hybrid thermoplastic composites can be strongly influenced by process induced residual stresses. In this work studies for the evaluation of deformation and residual stresses are presented. The studies performed on a material consisting of a pure polypropylene layer and a glass fiber reinforced UD-Tape include measurements of the deformation, bending tests, residual stress measurements and accompanying finite element simulations. The results show that significant deformations and residual stresses exist, which are strongly influenced by the anisotropic material behavior of the thermoplastic laminate. It can be seen that annealing influences the deformation and the strength of the hybrid specimen.

1. Introduction

Especially in the automotive sector lightweight design has gained importance in the last years. Hybrid thermoplastic composites such as the combination of continuously and discontinuously fiber-reinforced materials show high potential for integrated processing of structural components in high-volume processes like injection molding. However, various process and material parameters lead to warpage and residual stresses in the component. Such residual stresses can strongly influence the mechanical behavior since they act as a preload on the structure. In the worst case the residual stresses lead to a premature failure of the hybrid composite.

In order to use the lightweight potential of hybrid material combinations, the residual stresses have to be considered in the design process. Extensive research has been conducted in this field of which [1] had been one of the first investigations related to thermal residual stresses in composite materials. In 1988 FAVRE [2] presented an overview of the literature at that time. More recently an extensive overview with a particular focus on thermoplastic composites was presented by PARLEVLIET et al. [3], [4], [5]. However, investigations of hybrid composites such as the work presented below are still relatively rare but also important to take full advantage of thermoplastic composites in high-volume applications.

2. Studies for the evaluation of deformation and residual stresses

For the evaluation of deformation and residual stresses in hybrid components, three different investigations were performed. First of all the deformation after production and after annealing was measured. Secondly the influence of annealing on the strength of the component was investigated using bending tests. And at last investigations using an adapted hole drilling method to measure residual stresses in polymers and fiber reinforced polymers were performed. The standard hole drilling method, on which the adapted variant is based, is mostly used for the measurement of residual stresses in metals.

The presented study investigates laminates made from thermoplastic UD-tapes that are combined with an injection molded polymer. For the UD-tapes a 70 weigth-% glass-fiber-reinforced polypropylene (PP GF70) was used. The one sided overmolding was performed with a neat polypropylene grade. The specimens are 120 mm wide and 240 mm long. The thickness of the PP GF70 is 1.9 mm and the thickness of the PP is 2.2 mm, so that the specimens have a total thickness of 4.1 mm. There were specimens with two different fiber orientations of the PP GF70 laminate in direction of the long side. After the production of the specimens in a flat plaque tool the specimens show significant warpage. Besides that in this material combination residual stresses are present on several levels. In the tape laminates the residual stresses are caused by the different behavior of fiber and matrix, as well as possible different orientations in the laminate. In the hybrid additional residual stresses are established due to the overmolding with the neat polymer. One possibility to influence residual stresses in thermoplastic materials is annealing. For annealing the hybrids were put into an oven at 80 °C for 15 hours.

2.1. Measurement of deformation

For the measurement of the deformation specimens with a side length of 100 mm were cut out of two different plates. The specimens were scanned using a Descam 3D Laser Scanner. After scanning a CAD model of the specimens was extracted. The CAD model of one of the specimens is shown in figure 1.

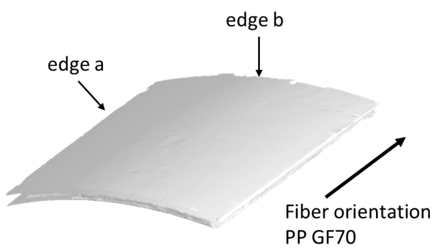

Figure 1. CAD model of a scanned specimen before annealing

After a postprocessing of the scanned CAD data using the CAD program Inventor the radius of the edges before and after annealing were measured. The measured radiuses are shown in table 1. Annealing results in a higher deformation perpendicular to the fiber orientation of the PP GF70 and in a lower deformation in fiber orientation.

Specimen	Radius edge a	Radius edge b
1 (before annealing)	1430	190
2 (before annealing)	1450	190
1 (after annealing)	2110	150
2 (after annealing)	2280	140

Table 1. Radiuses of edges in and perpendicular to fiber orientation of scanned hybrid specimens

2.2. Influence of annealing on the strength

The influence of annealing on the strength of the hybrid components was investigated using three-point-bending tests. The specimen was 15 mm wide and 120 mm long. The testing speed was 1 mm/min and the support distance was 6.3 mm in all tests. Four different variants were tested, the fiber orientation of the PP GF70 was changed (V1 and V2) and some samples were annealed before testing (V1a and V2a). The strength of specimens with fiber direction perpendicular to loading direction tend to have a higher scatter. Therefore for Variant V2a ten specimens were tested. For all other variants only five specimens were tested. The tested variants are summarized in table 2. In all cases the PP GF70 was at the tension side of the bending specimen. Results show that there is a influence of annealing on the strength when the PP GF70 is loaded in fiber direction. The annealing shows a positive effect (increase) on the strength. There is no influence of annealing for specimens with a fiber orientation perpendicular to the long side.

Variant	Fiber Orientation	Annealed	Maximum Force	
			mean value	standard deviation
V1	0	-	664 N	55 N
V1a	0	x	764 N	19 N
V2	90	-	73.3 N	5.4 N
V2a	90	x	72.3 N	6.1 N

Table 2. Tested variants of hybrid bending specimens

2.3. Measurement of residual stresses

Residual stresses can be evidenced by changes of the measured local surface strain around a small drilled hole in the material. To evaluate the residual stresses in the depth of the material an incremental hole drilling method is used. With this method it is possible to show the difference in the released strains and therefore the residual stresses before and after annealing. As the hole drilling method is mostly used for metals the method had to be adapted to the specific behavior of the polymer and the tape laminates.

The basic requirement for the application of the hole drilling method is the ability to drill holes with precise defined geometries into the material. The procedure should induce changes of the material at the hole walls and the hole ground only to a very low extend. In a preliminary study it was found that for PP as well as PP GF70 drilling a hole with a coated two-edged milling cutter is suitable to drill a hole and enlarge it to the final contour. There was low influence of the cutting speed between 20 and 6,000 rpm. When drilling the hole into the material the inherent residual stresses in the material cause the local straining of the hole. These released strains were recorded using strain gage rosettes of type Micro Measurements CAE06-062-UM-120 consiting of three single strain gages using quarter bridges adapted to a universal measuring amplifier of type HBM QuantumX 340A. Because the thermoplastic materials act as thermal insulators the supply voltage of the strain gages had to be reduced to 0,5 V to limit the local relative heating of the material below 2 °C. The residual stresses in the depth of the material were measured by an incremental drilling procedure with increments of 0,05 mm. To account for the creep of the material when releasing the strains a waiting time of 100 s between each drilling step was applied. The resulting strains are fitted by a polynomial function of the 5th grade to account for the uncertainties in the measurement procedure. Since edge effects can influence the results, the measurements were evaluated beginning at a depth of 0,1 mm of the surface. The released radial strains ϵ_r of every single strain gage can be converted to the inherent residual stresses using the following correlation:

$$\epsilon_r = A\left(\sigma_x + \sigma_y\right) + B\left(\sigma_x - \sigma_y\right) cos2\theta + C\tau_{xy} sin2\theta \tag{1}$$

σ_x are the stresses in fibre direction, σ_y the stresses perpendicular to the fibre direction and τ_{xy} the shear stresses. θ is the angle of every single strain gage related to the fibre direction. A, B and C are the calibration factors which correlate the strains and the stresses. These calibration factors have to be determined for each single strain gage direction. They can be determined experimentally by straining a sample of the same material system to a known stress state and conducting the hole drilling procedure. The simulation of the hole drilling procedure with a known stress state using finite element analysis is an appropriate tool to reduce the effort in the determination of the incremental calibration factors for the orthotropic material systems. For the PP an isotropic elastic material model was used. The PP GF70 was modeled with as transversal isotropic elastic model. Since there was no experimental data for the elastic constant for the PP GF70 the data was calculated analytically using micro mechanics. For G_{23} and ν_{23} the neat matrix data was assumeds. The used material data is summarized in table 3.

Material	$E_{(1)}$ **in MPa**	E_2 **in MPa**	G_{12} **in MPa**	G_{23} **in MPa**	$\nu_{(12)}$	ν_{23}
PP GF70	33755	2682	1791	1008	0.29	0.35
PP	1310				0.35	

Table 3. Material data of PP and PP GF70 for finite element simulation

The hole drilling procedure in PP and PP GF70 was simulated using a model of three-dimensional continuum elements in the FE-Code Abaqus. The subtraction of the material in the real hole drilling process was simulated by reducing the stiffness of the corresponding elements in the model by a factor of 10^{-6}. For the calculation of the calibration factors three different load cases were simulated to account for the released radial strains of the strain gages and the mechanical interdependencies of the materials. The released strains were evaluated by integrating the radial strains in the area of the strain gages of the real strain gage rosettes. In figure 2 the measurement of the released strains for each depth increment of 0,05 mm in the incremental hole drilling procedure of PP and PP GF70 is shown. It can be seen, that the released strains in PP are much higher because of the lower stiffness of the material.

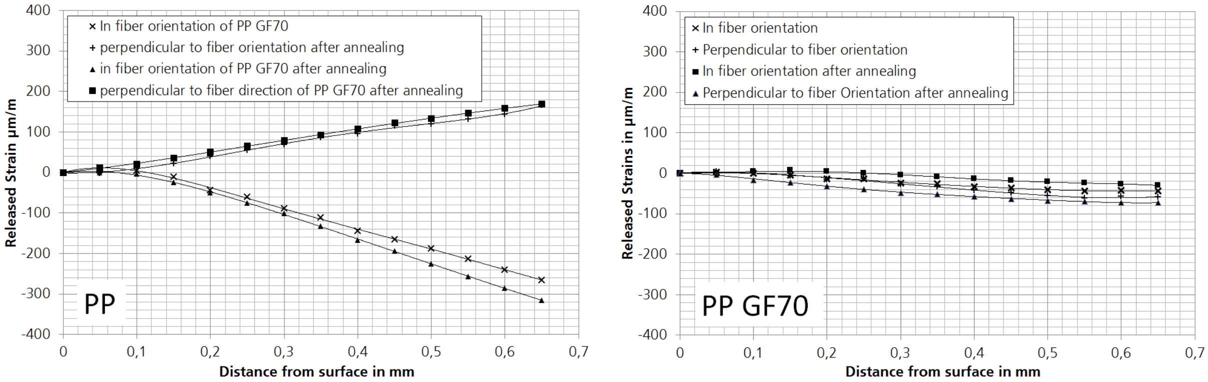

Figure 2. Released Strains in the PP (left) and the PP GF70 (right)

In figure 3 the calculated residual stresses in fiber direction and perpendicular to the fiber direction before and after annealing are shown. In fiber orientation of the PP GF70 the residual stresses are much higher than perpendicular to the fiber orientation in the PP GF70 as well as in the PP. This is in accordance with the warpage of the component, which is only apparent perpendicular to the fiber orientation. As expected from the material properties the residual stresses in the PP GF70 in fiber orientation are higher than the stresses perpendicular to the fiber orientation and the stresses in the PP. The residual stresses in the fiber direction are compression stresses in PP GF70 and tensile stresses in PP. The residual stresses in fiber direction in the PP GF70 drop starting from the surface and than rise again. After annealing the stresses rise less and therefore exhibit higher compression residual stresses. Perpendicular to fiber orientation the drop in stress is lower after annealing. In the PP annealing influences the residual stresses perpendicular to fiber orientation, instead of tension at the surface, compression is acting after annealing.

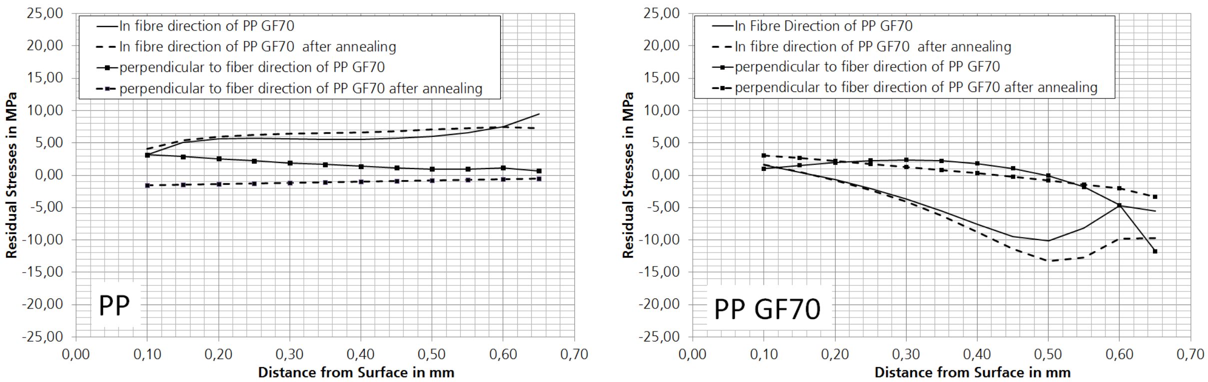

Figure 3. Residual Stresses in the PP (left) and the PP GF70 (right)

3. Finite Element Simulation

In order to get a better understanding of the residual stress distribution accompanying finite element simulations with a simplified model were performed. For this a quadratical specimen with the same size as the scanned specimen was modeled. The specimen was meshed with volume elements with an element edge length of 1 mm in plane. In thickness the specimen was meshed with ten elements, five for each material, in order to have an adequate mesh density.

In order to have results with a higher resolution through thickness a quarter model with a side length of 10 mm was simulated as well. In this case the element edge length in plane was 0,2 mm and the edge length through thickness was 0,05 mm. The material PP GF70 was modeled using the same material model and input data as for the calculation of the calibration coefficients for the residual stress measurements (table 3). The material model for PP was changed to a elastic-plastic material model. For simplicity the residual stresses were included in the model with a temperature load and coefficients of thermal expansion in order to describe the shrinkage. Knowing that for a precise description a process simulation including the crystallization of the polymer should be performed. The used coefficients of thermal expansion are summarized in table 4. The coefficients of PP GF70 was calculated using micro mechanics. 80 °C was picked as a starting temperature for the cooling to 23 °C because this corresponds to the annealing temperature.

Material	$\alpha_{(1)}$	α_2
PP GF70	$7.9 \cdot 10^{-6}$	$76 \cdot 10^{-6}$
PP	$110 \cdot 10^{-6}$	

Table 4. Materialdata of PP and PP GF70 for finite element simulation

Figure 4 shows the deformed specimen with the simulated stresses in (S11) and perpendicular (S22) to the fiber orientation of the PP GF70 in the middle of the specimen. The resulting radiuses at the edges are 1020 mm in fiber direction and 960 mm perpendicular to the fiber direction.

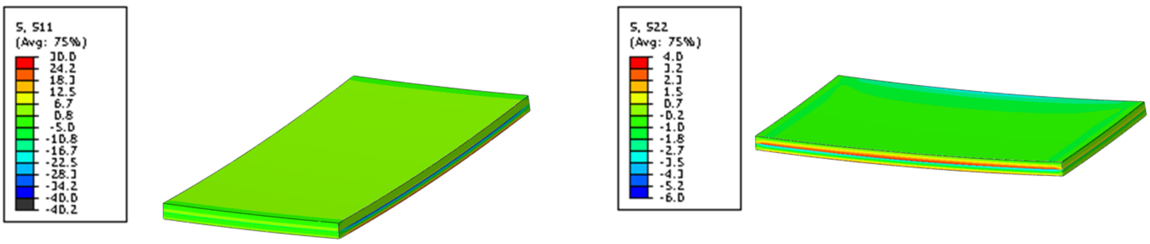

Figure 4. Simulated stresses in and perpedicular to fiber orientation of PP GF70

The stresses resulting from the simulations with the two different meshes are in good agreement. There is a different at the surfaces of the specimen. The stresses with the fine mesh are higher on the surface. In order to quantify the stresses, the resulting stresses in the hybrid components in and perpendicular to fiber orientation of the PP GF70 of the model with the fine mesh are shown in figure 5. It can be seen, that the highest stresses are in the PP GF70. There is tension at the surface and compression in the midface. The comparison of the simulation with the measurement of the residual stresses shows that the stresses in the PP and the stresses in PP GF70 perpendicular to the fiber orientation are in good agreement with the measurement after annealing. The stresses in the PP GF70 in fiber orientation have the same gradient. However the measurements do not show tension stresses at the surface of the PP GF70. There is also no rise of stress in the simulation at a distance from the surface of the PP of approximately 3,6 mm.

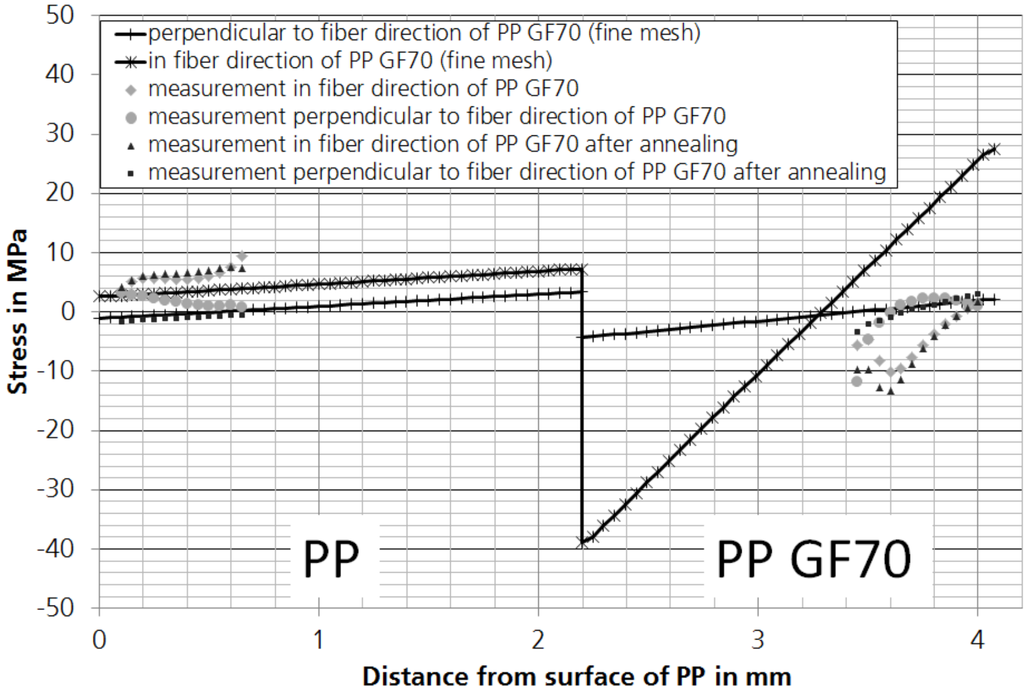

Figure 5. Residual Stresses specimens resulting from the accompanying finite element simulations compared to the measurements before and after annealing

4. Conclusions

The results of the performed experimental and numerical studies show that the investigated material combination of UD-Tapes (PP GF70) and injection molded polypropylene (PP) exhibit residual stresses and result in significant deformation of the specimens. Annealing influences the deformation, the residual stresses and the mechanical behavior. All bending specimens were tested with PP GF70 at the tension (bottom) side. Annealing increases the bending strength in fiber direction, which corresponds to higher compression residual stresses in fiber direction. It is also in agreement with a smaller deformation radius after annealing. The change of residual stress in the PP from tension to compression perpendicular to fiber orientation corresponds to the higher deformation after annealing.

The accompanying finite element simulations overestimate the deformation in fiber direction of the PP GF70. This results in non realistic tension stresses at the surface. An improved simulation should include the crystallization process and the heat flow during cooling. With a better agreement of the deformation it is expected that residual stresses are also in a better agreement with the measurement.

Residual stress measurements with the hole drilling method are appropriate for analyzing of areas near the surface. In order to get a better understanding of the residual stresses in the middle of the specimen, other methods should be applied. For example the closely related ring core method is promising because due to the higher strain release residual stresses at a higher distance to the surface can be measured. Another advantage is that the localization of the residual stress analysis is less for the measurement. Therefor investigations with residual stress measurements with the ring core method will be performed.

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