Process induced shape distortions of self-reinforced poly(ethylene terephthalate) composites

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A B S T R A C T

This paper investigates shape distortion and tensile properties of hot consolidated Self-reinforced poly(ethylene terephthalate) (SrPET) by evaluating the influence from stretching before consolidation and annealing after consolidation. Spring-in angle and warpage is measured from V-shaped samples that are hot consolidated from a woven fabric that is stretched to different degrees during forming. Following the same process conditions, tensile stiffness is measured from plane laminates. This study confirms that stretching the SrPET-material during forming enhances the tensile modulus but introduces shape distortions with negative spring-in and increases warpage. However also non-stretched SrPET components experience spring-back in the same level as glass- or carbon reinforced PET composite, which is unexpected. The tensile modulus is reduced and spring-in angle further influenced when the SrPET-samples are exposed to higher temperature after consolidation. This study shows how easily the characteristics of a component made from SrPET-material are influenced by stresses developed during material forming and further by release of these stresses when exposed to higher temperatures as in post processes or even in the use phase of the component.

1. Introduction

Self-reinforced polymer composites (SrPC) is a family of materials consisting of one type of polymer in different morphologies creating a composite with improved mechanical properties, compared to the single morphology comparison, at maintained low material density. Thanks to the single polymer composition the recyclability is simplified and opens up for circular material handling\cite{1,2}. The potential usage is wide, covering everything from suitcases to vehicle components, therefore serving as promising material system for sustainable production in a wide range of applications\cite{2}.

Production of components out of SrPC-material is however challenging due to a narrow processing window where the temperature needs to be well controlled\cite{3}. A temperature too high will disorientate the molecular structure in the reinforcement, which will result in reduced mechanical performance, while a temperature too low will result in poor processing performance\cite{4}. The size of the processing window depends both on the material system and on the technique or route that is used for consolidation\cite{5}. One technology to manufacture SrPC is hot compaction, which is a technique where reinforcement fibres or tapes are welded together under pressure by melting only the surface of the reinforcement\cite{6}. This process requires more precise control of temperature, pressure and time compared to bi-component SrPC-materials that has a matrix material with lower melting temperature than the reinforcement\cite{7}.

In the component manufacturing process is the SrPC material normally heated before it is formed, and needs to be clamped in order to prevent temperature-induced material shrinkage and associated property loss\cite{4,8}. The heated and constrained material can be formed through stamping before consolidation with enhanced formability compared to traditional glass or carbon fibre reinforced materials, since the polymer fibres can be stretched during forming. This process advantage has been shown in previous studies on SrPP\cite{9,10} and today travel luggage cases are made in large series production by thermo-forming pre-consolidated sheets of SrPP\cite{11}. This shows that even though the process window for SrPC may be limited it is still possible to obtain a robust process to manufacture components out of SrPC materials.

For production of components with a complex three-dimensional shape it is necessary to have thorough knowledge about the manufacturing processes and how the process can influence the properties of the component. Process-induced distortions (PID) are frequently

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analyzed for both thermostet and thermoplastic composite materials based on glass- or carbon-fibres [12–20]. PID can be considered governed by intrinsic and/or extrinsic sources [16,21] where the former are driven by the constituent component of the composite material and the latter summarizes influences from the boundaries and the interaction with the surrounding equipment. Considering intrinsic sources, differences in thermal expansion (CTE) between the fibres and matrix, and the shrinkage in the matrix due to phase changes in the polymer are normally stressed as governing mechanisms [18,21]. For example, for moulded glass fibre reinforced thermoplastic poly(ethylene terephthalate) (PET), the CTE of amorphous PET (85 µm/m K [22]) is more than 15 times the CTE of glass fibre (5.4 µm/m K [23]), which gives rise to the increase in internal stresses in the interface between fibre and matrix as it goes from consolidation temperature to room temperature. For a SrPC the difference in thermal expansion between the reinforcement and the matrix is smaller or even negligible at lower temperature and therefore the thermal induced internal stresses are potentially small. However, residual stresses can be built up in the reinforcement fibre due to stretching of the material during forming and due to shrinkage as the oriented molecules disorientate at the consolidation temperature. Therefore intrinsic generated PID, both in terms of spring-in and warpage, are in focus of the current study which is further motivated in the following.

SrPC materials are frequently studied with respect to how mechanical properties are influenced by different process parameters in the manufacturing process [7] and there are several studies on how these materials can be formed into three-dimensional shaped components [9,10,24–27]. However none of the previous studies considers the aspect of PID. Investigations on stretching of the material in the forming process prior to consolidation has showed that 13% stretching increases tensile properties more than 40% [28] due to increased molecular orientation of the non-crystalline regions in SrPET [29]. However, an oriented non-crystalline phase in a PET fibre has been showed to be unstable at elevated temperature [30], which means that the mechanical properties for a component that has been formed with stretching of the material can lose its performance if exposed to elevated temperatures. This can be critical for a component made from SrPET material since products are designed to fulfill certain requirements, and mechanical performance is expected to be maintained over the lifetime. To the list of intrinsic sources causing PID in SrPET is therefore added internal fibre stresses from material stretching and its potential relaxation in its use phase.

SrPET has been proposed to be used for a high volume automotive component that is formed, consolidated and thereafter heated in ovens for paint curing in a paint process [31]. With this concept it was showed that the environmental impact can be reduced by 25% compared to current used technology sheet moulding compound for an air deflector parts for heavy trucks. If SrPET is to be used in semi-structural components as part of an assembled component, it is important to understand PID and if the mechanical properties can be influenced from elevated temperatures occurring in post-processes or during the use phase.

Therefore the aim of this study is to investigate how stretching, as in a forming process, and elevated temperature as in post processes, influence PID and tensile properties for hot consolidated SrPET. A comparison to manufacturing of glass and carbon fibre reinforced materials is made since the mechanisms are expected to differ between SrPET and traditional glass and carbon fibre reinforced composite materials.

2. Experimental

2.1. Material

The materials used in this study are listed in Table 1. All materials are woven fabrics made from fibre yarns of commingled reinforcement and matrix fibres. The SrPET is a bi-component material where the reinforcement is a high tenacity, low shrinkage PET fibre (HTPET) with an initial tensile modulus of 13 GPa [29]. All fabrics include the same matrix fibre made from essentially amorphous PET co-polymer, abbreviated LPET. All the materials were supplied by Comfil ApS, Denmark.

<table>
<thead>
<tr>
<th>Reinforcement</th>
<th>Matrix</th>
<th>Weave type</th>
<th>Surface weight[g/m²]</th>
<th>Fibre volume fraction[%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>SrPET</td>
<td>HTPET</td>
<td>LPET</td>
<td>4/1 plain</td>
<td>555</td>
</tr>
<tr>
<td>SrPET</td>
<td>HTPET</td>
<td>LPET</td>
<td>2/2 twill</td>
<td>710</td>
</tr>
<tr>
<td>Glass/PET</td>
<td>E-Glass</td>
<td>LPET</td>
<td>2/2 twill</td>
<td>750</td>
</tr>
<tr>
<td>Carbon/PET</td>
<td>Carbon</td>
<td>LPET</td>
<td>2/2 twill</td>
<td>500</td>
</tr>
</tbody>
</table>

2.2. Sample manufacturing and preparation

V-shaped profiles were manufactured by hot consolidation using a mould as shown in Fig. 1. By using this profile-mould, a potential extrinsic source from geometrical constraining of the material by the tool is avoided [21]. The SrPET samples were consolidated from 4 layers of twill fabric while glass/PET and carbon/PET samples were made from 6 and 7 layers respectively to get nominal thicknesses of 2 mm after consolidation. The stacked fabric was placed in the V-shaped mould and heated from room temperature to 215 °C while applying a pressure of 1.5 MPa. When the material had been at this temperature for 2 min, cooling was initiated with an average rate of 20 °C/min until the laminate had a temperature of 50 °C. The sample denominations are SrPET_V0, glass/PET_V and carbon/PET_V.

Further SrPET samples were manufactured where the V-profiles were stamp-formed with simultaneously stretching of the fabric. The clamping device and frame showed in Fig. 2 were used to keep the material constrained during pre-heating and forming. The material was pre-heated to 120 °C and forming was performed in a mould heated to 215 °C. The fabric was stretched in the major forming direction. Samples with different degrees of stretching were manufactured with this technique by simply changing the initial length of the material, using 400 mm between clamping for 10% stretching and 300 mm for 13% stretching. Denominations of samples with stretched material are SrPET_V10 and SrPET_V13 with respect to degree of stretching.

Flat SrPET sheets were manufactured by hot consolidation of 5 layer plain weave fabric using a clamping frame similar to the one used for manufacturing the V-profiles. Samples with 0, 6, 10 and 13% stretched material were manufactured with corresponding denomination of SrPET_V0, _6, _10 and _13. A detailed description of this process is described elsewhere [28]. All samples were manufactured with a fluorinated ethylene propylene (FEP) release film between the fabric and mould surfaces. After manufacturing the V-profile samples were cut into 75 mm wide specimens and the plates to 25 mm wide specimens.

2.2.1. Annealing

Five samples from each configuration were annealed in a preheated oven for 40 min. The annealing temperatures represents temperatures that occasionally can occur in post-processes for a manufactured component.

2.3. Characterization and evaluation

2.3.1. Measuring and evaluation of spring-in and warpage

Three-dimensional measurement data obtained with an optical 3D scanner from GOM GmbH was used to evaluate spring-in and warpage of V-profiles made from SrPET, glass/PET and carbon/PET. Spring-in is defined as the deviation from the nominal 90° profile angle θ, where a positive spring-in value means a decrease of θ. Each sample profile
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