Residual stresses in rubber formed thermoplastic composites

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ABSTRACT: The rubber pressing process is applied for the rapid production of thermoplastic composite products. However, rubber pressed products show geometrical distortions, such as warpage, due to process-induced residual stresses. An experimental study is performed to measure the curvature after rubber pressing of initially flat woven fabric glass/poly(phenylenesulphide) composite panels. A material model is proposed that incorporates the solidification of the composite in order to predict the residual stresses and the warpage due to inhomogeneous cooling. The model is employed in finite element simulations of the rubber pressing process. The simulations are compared to the experimentally obtained curvatures. It shows that unbalanced cooling has a minor effect on the warpage in this case. It is demonstrated that transverse shear loading of the composite during consolidation, for example by a non-flat rubber tool, results in warpage-inducing residual stresses.

Key words: rubber press forming, warping, transverse shear

1 INTRODUCTION

Thermoplastic composite systems offer a well-known advantage over composites based on a thermosetting resin: the absence of a time-consuming chemical reaction allows for the relatively fast production of complex product shapes. The simplicity of the forming principle offers a good basis for automation of the production processes involved with thermoplastic composites forming, making them commercially competitive to the relatively cheap thermosetting composites.

In the recent years, a number of relevant production processes has been developed, such as diaphragm forming, matched die forming, deep drawing and rubber pressing. These processes generally involve the reheating of the pre-consolidated laminate above its melting temperature, transfer to the die or tool, consolidation of the shaped laminate to a temperature at which it is solid and finally release and further cooling to the room temperature. In the particular case of rubber pressing, the shaping and consolidation take place between a rigid steel tool and a deformable rubber mould that is driven by a press. A drawback of the production is the generally highly unbalanced thermal and mechanical loading of the composite during forming. As a result, the final product shows distortions such as warpage of intended flat parts, see figure 1.

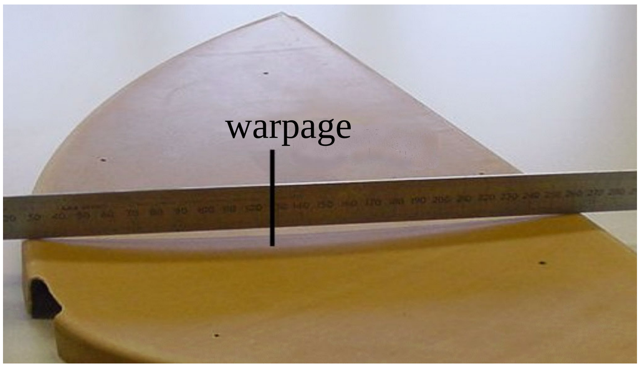

Fig. 1. Rib of a wing leading edge showing warpage.

It is difficult to reduce these distortions without altering the forming processes and losing their specific benefit of high production speed. Generally, the narrow tolerances on the product geometry are met by means of costly trial-and-error. Numerical tools such as the finite element method (FEM) have the potential to reduce development costs and scrap material, as well as to optimise the production process used. This paper considers the warpage of rubber pressed panels consisting of glass weave reinforced poly(phenylenesulphide) (PPS). The effect of the highly non-isothermal cooling on warping is studied experimentally and numerically, as well as the effect of the mechanical loading on the composite during processing.

2 WARPAGE OF RUBBER PRESSED COMPOSITES

2.1 *Pressing flat panels*

Glass weave reinforced PPS laminates (Cetex®) supplied by Ten Cate Advanced Composites), consisting of four plies stacked balanced and symmetrically, were equipped with fine-gauged thermocouples equally distributed through the laminate thickness. The plate dimensions measured 180×360 mm^2, the thickness 0.96 mm. At Stork Fokker Special Products, these laminates were reheated to a temperature above the melting temperature of 280 °C and rubber pressed between flat tools. The temperature of the laminates was logged during reheating, pressing and further cooling. The laminates were cut to strips with a length-to-width ratio of 15. The strips had a concave shape with respect to the rubber upper tool. The resulting curvatures were measured, they showed to be in the order of 3…4 m^{-1}.

2.2 *Cooling stresses*

Generally, the modelling of forming processes of composites comprises the following components, for example see [1,2]: the solution of the heat balance with the process-specific thermal boundary conditions; the prediction of changes in the material morphology, such as crystallisation, cure conversion and/or the glass transition; the computation of the stress induced by volumetric changes such as thermal and crystallisation shrinkage. It is recognised that the change in material properties and the resulting change in constitutive behaviour (e.g., viscous to elastic) as a function of the morphology and temperature give rise to “skin-core” or “cooling” stresses when a composite solidifies under transient cooling conditions [3].
Here, the pressing cycle was simulated using the in-house developed finite elements (FE) package DiekA. A viscoelastic composite material model was implemented. It describes the transition from viscous to elastic material behaviour of the composite upon solidification of the resin. The solidification is driven by the crystallisation of the semi-crystalline PPS resin. Non-isothermal crystallisation kinetics [4] were fitted on differential scanning calometry (DSC) measurements at constant cooling rates. Implicitly, these kinetics provide the solidification temperature. Both thermal contraction and shrinkage due to crystallisation were taken into account. The mechanical boundary conditions consisted of imposing slip or stick between the tools and the laminate, allowing free contraction or not, respectively. The heat balance was solved with conductive heat transfer to the tools.
Both experiments and modelling showed that the temperature profile was rather symmetrical during the pressing cycle, resulting in a residual stress profile that does not induce the amount of warpage as measured, see figure 2.

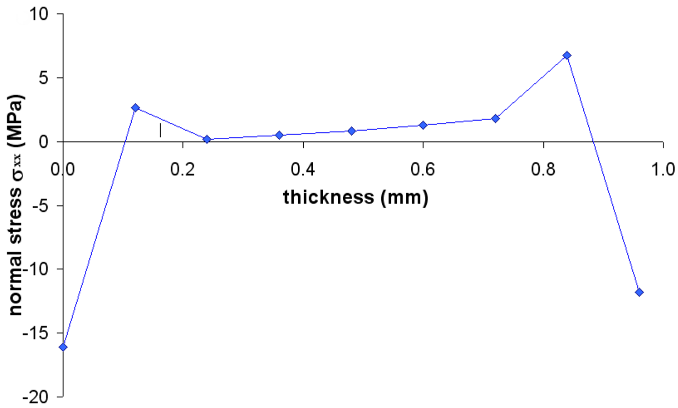

Fig. 2. Residual stress profile as a result of a cooling gradient through the laminate thickness in combination with viscoelastic material behaviour.

The computed curvatures were an order of magnitude smaller than the experimentally obtained curvatures. The influence of imposing either stick or slip conditions on the interfaces with the tools appeared to be negligible.
It can be derived that a linear stress distribution before release ranging from –40 to +40 MPa is required to obtain the measured curvatures. Obviously, residual stresses build up as a result of another mechanism. Here, it is supposed that the laminate is subjected to transverse shear loading during forming, which is frozen-in and released through warpage.

3 TRANSVERSE SHEAR LOADING

3.1 *Observation of interply slip*

Visual inspection of the strips that were subjected to the rubber pressing cycle learned that they had been sheared transversely. The plies appeared to have slipped with respect to each other, see figure 2. The slip distance is approximately 2 mm over a strip length of 300 mm.

Fig. 3. Microscopic picture of an edge of a rubber pressed specimen. The bundles in warp direction have been highlighted.

The resin rich layers between the glass weaves are viscous at temperatures above the solidification temperature. Consequently, the laminate responds extremely compliant when subjected to transverse shear. It is imaginable that the shearing is accompanied by the stretching of the individual plies, which remain fairly stiff as the in-plane elastic properties are dominated by the glass weave. When the resin solidifies, the pre-stretched individual plies are “bonded” together. The resulting stress is relieved by warping of the laminate after release from the tools.

Relating this to the rubber forming process, two conceivable causes that induce the shear-stretch loading are suggested: non-flatness or misalignment of the rubber tool and penetration of the laminate into the rubber tool, see figure 3.

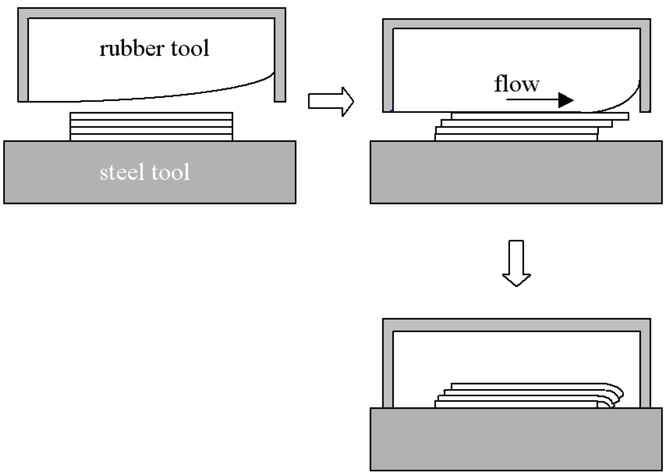

Fig. 3. Transverse shearing of a laminate due to non-flatness of the rubber tool during rubber pressing

The first results in flow of the rubber. The top ply will follow the rubber tool assuming stick conditions on the interface. The bottom ply will not deform as it is assumed to stick on the rigid steel tool. Subsequently, the top plies are pulled over the bottom plies on penetration of the rubber tool.

The hypothetical shear-stretch loading due to non-flatness of the rubber tool is confirmed with a numerical exercise.

3.2 Numerical exercise

Consider a laminate consisting of two plies of 0.5 mm thickness that is pressed between a non-flat rubber tool and a rigid tool. The FE mesh using axi-symmetrical, isothermal elements is shown in figure 4.

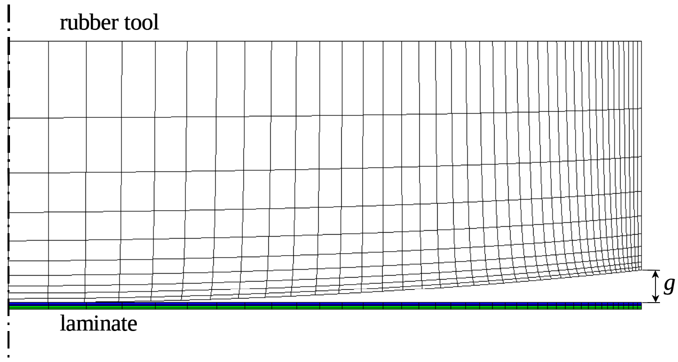

Fig. 4. Finite element mesh of the rubber pressing of a two-ply laminate

Symmetry conditions are imposed on the left hand side. Appropriate boundary conditions represent the enclosement of the rubber tool by a steel box that is present in the actual press. The rubber is modelled as an isotropic, elastic, incompressible solid as a first approach. Mesh-locking that may occur with incompressible materials is avoided by reduced integration of the volume terms. The two plies are modelled as isotropic, elastic solids with elastic properties representing glass weave reinforced PPS.

Contact between the rubber tool and the laminate is modelled by employing contact elements. Complete stick is enforced upon contact. The same contact elements are placed between the two plies of the laminate, enabling slip when the resin is assumed to be viscous and stick when the resin has solidified. The rigid tool is modelled by applying constraints: suppression of the radial displacements and coupling of the vertical displacements of the bottom ply. The bottom surface of the rubber pad is assigned an ellipsoidal shape with a gap width *g*. This gap is varied from 5 to 0.5 mm or 5% to 0.5% of the plate length of 100 mm.

The closing of the press is simulated by incrementally moving the laminate upwards until the pressure in the rubber tool reaches 100 bar (10 MPa). At this point, the press is not necessarily completely closed. The top and bottom ply are

allowed to slip freely with respect to each other.
The rubber tool shows flow of material to the right hand side. The top ply, which sticks to the rubber tool upon contact, builds up a tensile stress in the plane of the laminate. The maximum stress, listed in table 1, is found at the axis of symmetry. The tensile stress decreases towards the edge of the laminate.

Table1. Maximum stress in the top ply after closing the press

gap width *g* (mm)	stress (MPa)
5	74
2	49
1	34
0.5	20

The bottom ply is only subjected to the transverse normal loading, which also results in a compressive stress in radial direction due to the radial constraint. Now, changing the slip condition between the plies to stick corresponds to the solidification of the resin. Removing the tools results in a non-uniformly curved plate with local curvatures in the order of 1…3 m^{-1}.
This highly simplified simulation of the rubber forming process shows that a small non-flatness of the rubber tool causes a large amount of warpage-inducing tensile stress in the top ply of the laminate.

3.3 Prospect: a multilayer plate element allowing interply slip

The interply slip plays an important role in the hypothesis described above regarding the rubber pressing of flat parts. Also, it is well known that interply slip occurs with the forming of curved products. Two-dimensional FE simulations using contact elements are convenient for the examination of these effects, for example see the work by McEntee and Ó Brádaigh [5]. Considering the process simulation of complex composite products, a fully three-dimensional approach including contact elements between plies is undesirable from the perspective of CPU time. The application of composite plate elements reduces the computational effort considerably. Plate elements, however, lack the degrees of freedom (DOF's) to allow for interply slip. Currently, a multilayer plate element that allows for interply slip without additional DOF's is being developed, similar to the work of Lamers et al. on intraply shear [6].

4 CONCLUSIONS

The warpage of rubber pressed glass weave reinforced PPS panels has been studied experimentally and numerically. Finite element simulations showed that the thermal gradient through the thickness during consolidation, in combination with the viscoelastic material behaviour of the composite has a minor contribution to the buildup of internal stresses. It was demonstrated that transverse shear-stretch loading combined with interply slip results in residual stresses causing the amount of warpage as observed experimentally. Consequently, the current implementation of interply slip in plate elements contributes to computationally efficient process simulations of complex, composite products.

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