THERMAL PERFORMANCE OF A COMPOSITE MOULD TOOL WITH TWO INTEGRATED HEATING/COOLING ZONES

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Abstract
The paper considers the curing process of a thermosetting unidirectional glass/epoxy composite material system. The curing is designed as a two-stage cycle, where the two-stage curing refers to the curing of one area of the laminate prior to the other. The purpose of this is to develop cure induced residual stresses in the laminate aiming for a future examination of their effect on the mechanical properties. The aim of this paper is to confirm that the developed mould tool has the ability to achieve a well-defined two-stage curing cycle. Furthermore, the predictions of a numerical model of the curing process against measured T_g values for the considered glass/epoxy system is validated.

1 Introduction

Fabrication of fibre composite parts often involves temperature controlled moulds to secure the requested cure cycle and the required mechanical properties. Moulds may be temperature controlled in several ways; one possibility may be heating with electrical wires or mats. These wires or mats are typically integrated in the mould or placed on top or inside the mould laminate. However electrical temperature controlled moulds do not give the possibility of active cooling. To facilitate such a feature a mould tool could have integrated channels for the transport of heating or cooling media. Examples of a possible media could be water or steam.

The curing of composite parts may be conducted in various ways, and several researchers have conducted tests and numerical simulations to achieve a better understanding of the curing process. In addition it is well accepted in the composites community that the curing process may give rise to the inducement of residual stresses and component distortions.

Among the first to present a method for predicting the inducement of residual stresses during the curing of fibre composite laminates were Hahn and Pagano [1] and Hahn [2]. Hahn and co-workers presented a total stress-strain temperature relationship and explored the stress-free temperature for various laminate configurations. Later Bogetti and Gillespie [3] included material models for the thermal expansion and the chemical shrinkage together with temperature and cure dependent elastic properties. This was adopted into a 1D finite difference scheme to analyse the curing process of a thick graphite/epoxy laminate. White and Hahn [4, 5] added viscoelastic material behaviour to the transverse direction of a graphite composite laminate to the curing process, and the model was validated experimentally.

Extensive material characterization was carried out by Ruiz and Trochu [6], which was later applied to the thermo-mechanical modelling of a curing process [7].
Residual stresses may be quantified using several techniques. A classical approach is the hole-drilling method, which measures the strain relief through strain gauge measurements as a hole is being drilled in the area of interest. This technique has been applied by several authors [8, 9]. Among alternative techniques to quantify residual stresses are the contour-method and also the use of optical strain gauges [10, 11].

The present paper considers the curing of a thermosetting glass/epoxy composite material system. The curing process was carried out using a two zone mould tool, which has been developed with a future objective to introduce residual stresses in composite materials for characterization purposes. However, the present paper only describes the mould tool design, the thermal cure modelling and a comparison between a simulated T_g temperature and the measured T_g value.

2 Experimental investigation of mould tool performance

A special two-zone mould tool has been designed with a future purpose to investigate the effect of a global residual stress field in a fibre composite laminate. In this context, it is necessary to distinguish between the local and global residual stress fields. The local residual stress field is characterized by inter-laminar or inter-fibre bundle residual stresses. This further means that a local residual stress field is created due to phase mismatch in the micro structure of the composite material. A consequence of this definition is that it excludes the presence of local residual stresses in homogeneous materials. Both homogeneous and heterogeneous materials (like e.g. fibre composite material) may develop global residual stress fields. The concept of a global residual stress field is well known and may be conceptually explained with thermal stresses in a metallic bar due to boundary conditions which restrict free deformations. In a similar way global residual stresses may be locked into a component/part when it is being processed. For a composite part global residual stresses may be induced due to an inhomogeneous curing history.

The mould tool in this work comprises of two heating/cooling zones which can be thermally controlled independently from each other. This mould is designed such that one heating/cooling zone surrounds the other. The surrounding outer zone is referred to as zone 1, and the circular centre zone will be referred to as zone 2 (see Figure 1).

The outer dimensions of the mould are 400x400mm and the diameter of zone 2 is 50mm. Zones 1 and 2 are thermally insulated from each other by a 5mm Nylon cylinder. Heating and cooling of the two zones is achieved by water, which is pumped into the individual zones. Two different target temperatures may be set for the two zones (Figure 1 - thermal image).

The two zones are both made from aluminium, which will give an almost uniform temperature distribution within the individual zones. To obtain a vacuum tight mould surface a 1mm thin glass/epoxy laminate is bonded to the aluminium surface. This layer will be referred to the mould vacuum layer. Between the aluminium and the mould vacuum layer several thermo couples are installed. The thermo couples are installed to give thermal feedbacks. In addition, the recorded thermal response will be used as boundary conditions in numerical models.

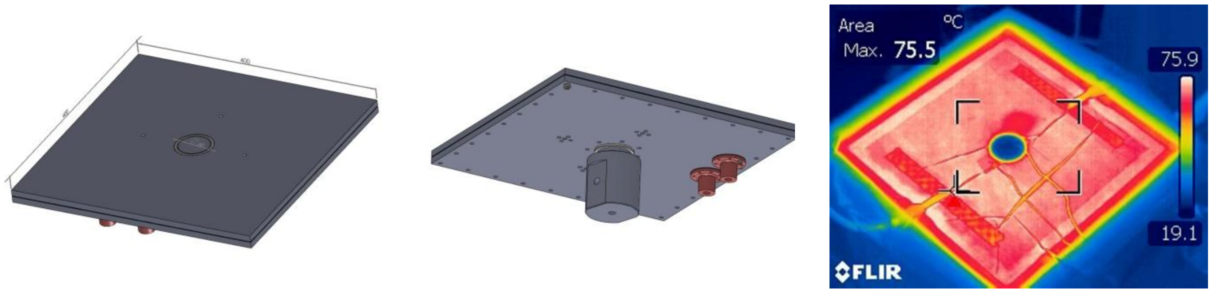

Figure 1. Mould tool with two heating/cooling zones to facilitate large temperature gradients. Right: thermal image of laminate curing.

A two-stage curing of a UD glass epoxy laminate is carried out in the presented mould. Stage 1 of the curing process involves curing of the outer part of the laminate and leaving the centre area almost uncured for the entire stage 1 curing. The duration of the stage 1 curing is 231 min with temperatures roughly around 85°C and 25°C for zones 1 and 2, respectively. The stage 2 curing has a similar duration (230 min) with temperatures of 15°C and 75°C for zones 1 and 2, respectively. The slight differences in thermal history between the two areas of the laminate will cause different amount of molecular crosslinking within the epoxy resin.

3 Numerical cure analyses

An axisymmetric numerical model of the two stage curing described in the previous sections is developed. The model curing experiment carried out is by nature not axisymmetric, but this simplification can be justified by the fact that the heat transfer almost exclusively takes place out-of-plane, and by the isotropic approximation of the thermal conduction coefficient for the curing layer. The model used for the analysis is sketched in Figure 2, where the axis of symmetry is located at the left most edge. The gray area in the sketch symbolizes the aluminium mould. It is not included in the analysis since well-defined boundary conditions exist. The upper blue area is used for the analysis and includes the four layers; PE-foam, Teflon plate, curing layer and mould composite layer.

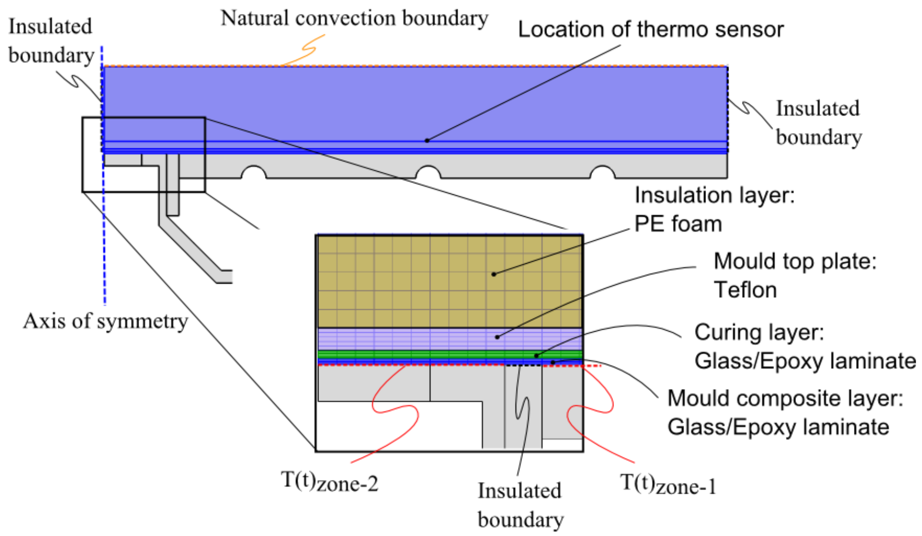

Figure 2. A sketch explaining the numerical model.

The model solves the heat transfer equation Eq. (1) and only the curing layer has a contribution to the internal energy (Q_{int}). This contribution is defined through a Karmal-Sourour [12] type cure kinetic model, which is established from DSC measurements.

$$k\left(\frac{\partial^2 T}{\partial r^2}+\frac{1}{r}\frac{\partial T}{\partial r}+\frac{\partial^2 T}{\partial z^2}\right)+Q_{int}=\rho\, C_p\,\frac{\partial T}{\partial t}$$
$$Q_{int,PE-foam}=Q_{int,Teflon}=Q_{int,mold\ comp\ layer}=0 \qquad (1)$$
$$Q_{int,curing\ layer}=H_{ult,dyn}\,v_m\,\rho\,\frac{\partial c}{\partial t}$$

The model boundary conditions are: insulated boundary on the left and right edges, the lower edges are time dependent temperature boundaries, and the upper edge is a convective boundary. The convection is assumed to be natural convection from a horizontal surface, and 293K (room temperature) is used as the far distance temperature.

The model is solved with a multiphysic finite element code as a transient problem with a maximum time step size of 10 sec. Second order rectangular elements are used for the model discretisation. Each of the four model layers has at least 5 elements through the thickness. The model consists of 2700 elements. The degree of conversion in the curing layer above zones 1 and 2 are shown in Figure 3, and it is seen that the two-stage curing does not result in a similar degree of conversion. The conversions are 0.980 and 0.963 for the curing layer above zones 1 and 2 respectively.

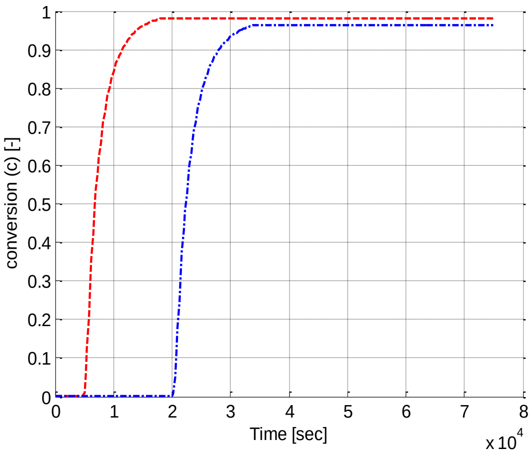

Figure 3. Simulated progression in degree of conversion at the two zones.

The simulated conversions are transformed to glass transitions temperatures ($T_{g,sim}$) and compared with the measured values ($T_{g,meas}$),. This comparison is stated in Table 1.

	$c_{end,sim}$	$T_{g,sim}$ [°K]	$T_{g,meas}$ [°K]
Zone-1	0.980	355.4	354.2/356.9
Zone-2	0.963	351.9	349.7/351.8

Table 1. Simulated T_g levels after end curing analysis are compared with measured T_g's from the two zones. The measured T_g's where repeated to have two measurements from each curing zone.

The simulated and measured glass transition temperatures are in good agreement, which suggests that assumptions adopted for the model are reasonable.

4 Conclusions

A two-stage curing mould tool was designed and produced. It has been shown that the mould tool can provide two distinct temperature zones during the curing of a glass/epoxy laminate. A unidirectional glass/epoxy laminate was cured in a two stage curing cycle and T_g measurements from the two zones were made to obtain an impression of the degree of cure for the chosen cure cycle. Moreover, a numerical model of the same cure cycle was developed, and the end T_g values from the two zones were simulated. A good agreement between the measured and simulated T_g values was achieved.

5 Acknowledgements

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6 References

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