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MODELLING VARTM OF WIND TURBINE BLADES UNDER NON-ISOTHERMAL BOUNDARY CONDITIONS

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SUMMARY: Vacuum Assisted Resin Infusion (VARI) is one of the most commonly used methods nowadays for producing wind blades. This paper presents a short review on current design configurations and materials used in wind blades and the variables that should be taken into account in VARI simulations. Particularly, it highlights the need of assuming non-isothermal boundary conditions. A kinetic study of an epoxy resin widely used for wind blade manufacturing is included. Experimental results of differential Scanning Calorimetry (DSC) are modeled with CureKinetics software®.

KEYWORDS: Wind blades, VARI, flow simulations, non-isothermal analysis, resin kinetics.

INTRODUCTION

In the wind energy market, there is an increasing demand for larger blades with improved performance and lower cost. Improving the quality of the manufacturing process and reducing the development and manufacturing times have become one of the main purposes of wind turbine blade manufacturers.

Most modern wind turbine blades are designed with a load carrying structural member (spar cap) that supports an outer aerodynamic shell (see Fig. 1). The spar cap consists usually of a thick monolithic composite laminate which for some large blades is made of a hybrid glass/carbon laminate. The lay-up of this laminate includes UD layers as well as off-axis ply layers. The thickness of the spar cap can vary from the root of the blade to the tip from 80-40 mm (depending on the blade size) to a few millimeters. The shell skins and shear webs are usually made of sandwich constructions with biaxial or triaxial skins (see Fig. 2)

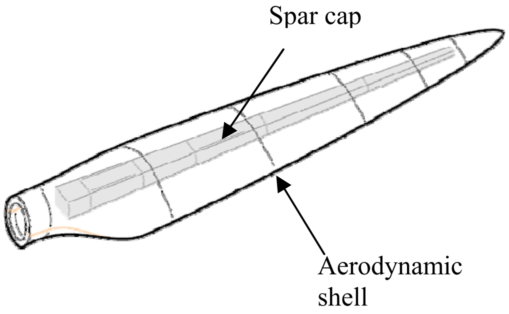


Fig. 1 Composite wind turbine blade.

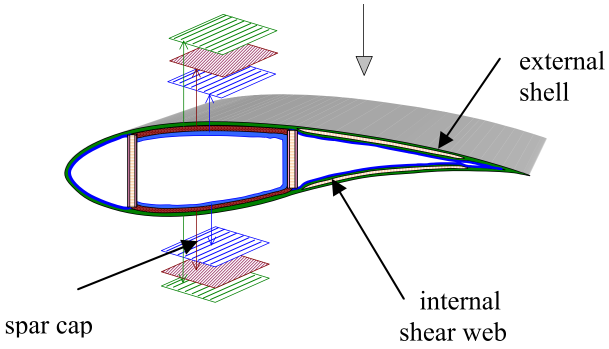


Fig. 2 Airfoil section of a wind composite blade.

Depending on the design, the spar is based on a compact spar box or is made of shear webs. If a compact spar-box is used, this part is built separately and bonded afterwards to the blade shells. In case of working with shear webs, the spar cap is built integrally into the shell halves. Usually the two semi-shells are manufactured separately and then joined with the shear webs. Some manufacturers have also adopted a manufacturing technique where the entire blade, including internal shear webs, is manufactured in one single infusion process [1].

VARIM is intensively used by wind blade manufacturers for large parts. The quality and mechanical performance of the parts meets also the requirements of the application. However, as the blades become larger, the process is more and more challenging. A large area of variable thickness has to be infused (100-200 m^2) with different material configurations. Particularly challenging is the infusion of the root section and spar cap especially when carbon fiber is used. It is necessary to use special lay-up sequences or materials and optimize the processing parameters in order to achieve a good infusion. The large number of material properties and processing parameters that must be specified requires an extensive experimental program. This makes the trial and error approach difficult. A key issue is therefore to be able to predict as closely as possible the outcome of new configurations.

SIMULATION OF VARI FOR WIND TURBINE BLADES

Most of the computer simulation software packages have been developed to describe the Resin Transfer Moulding (RTM) process. The simulation tools are based on Darcy's law. The boundary condition problem is solved by the Finite Element Methods (FEM) and/or Control Volume (CV) techniques.

The resin impregnation is usually modeled as a flow in porous media. The model equations describing this flow are given by Darcy's law, which states that the flow rate per unit area v is proportional to the pressure gradient

$$\underline{v} = -\frac{\underline{\underline{K}}}{\mu}\nabla P, \tag{1}$$

where $\underline{\underline{K}}$ is the preform permeability tensor, μ the fluid viscosity and P the resin pressure. The incompressibility of the fluid is expressed by $div\ \underline{v} = 0$. The evolution of the resin volume fraction I in the mould is governed by the following linear advection equation:

$$\frac{dI}{dt} = \frac{\partial I}{\partial t} + \underline{v} \cdot \nabla I = 0 \tag{2}$$

These tools have been used with success for modeling RTM parts. In the case of VARI for wind turbine blades, some differences must be taken into account in the model:

- In the RTM process, the mould is rigid, but in VARI due to the flexible nature of the vacuum bag, there is a change in thickness of the cavity and consequently of the fiber volume fraction. Therefore it is necessary to taken into account preform compaction [2, 3].

- The parts manufactured by RTM are often thin shell assemblies. Therefore mould filling can be considered as the result of an in-plane flow, so the finite element problem becomes two dimensional. For wind turbine blades the effect of the flow in the thickness direction cannot be omitted because of the thickness of the part, thus 3D simulation is required and the full 3D permeability tensor must be known [4].

- The injection time for a typical RTM part is usually a few minutes. Therefore the process can be considered as isothermal, and the viscosity assumed to be constant. Wind turbine blades are large structures with long processing times. One of the most common problems found when manufacturing a wind blade is the incomplete impregnation because of the increase of resin viscosity or resin gelation. Moreover, in high thickness areas, the reaction rate can increase because of the exothermic nature of the resins used. This creates zones with different degrees of conversion. Therefore it is necessary to predict resin kinetics during the manufacturing process.

Viscosity can be expressed as a function of the degree of cure (α) and temperature (T) as follows:

$$\mu = f\,(\alpha, T) \tag{3}$$

The temperature is related to the heat generated during the chemical reaction (ΔH) and the heat capacity (Cp) is also function of the degree of cure and temperature:

$$\Delta H = f\,(\alpha, T) \text{ and } Cp = f\,(\alpha, T) \tag{4}$$

One of the first steps necessary to perform numerical simulations is to know the variation of the degree of cure with time and temperature $\alpha = f\,(T, t)$. This work is part of a project in order to develop suitable experimental and numerical techniques for VARI modelling of wind turbine blades. The results of the kinetic modelling will be presented in the following sections.

CURE KINETICS

In this study an epoxy system of low viscosity, specially devised for resin infusion, was used. The resin is PRIME 20LV and the hardener PRIME 20 slow, both from Gurit with a mix ratio of 100:26 p.b.w. Differential Scanning Calorimetry (DSC) measurements were performed in a DSC model 823 from Mettler-Toledo. The DSC was calibrated with high purity indium. Samples of 15 mg in average were weighted in small DSC aluminium spans, sealed with holed aluminium lids. Experiments were conducted under a nitrogen flow of 20 cm^3/min. Both dynamic and isothermal scans were carried out. The isothermal scans were conducted by heating the sample rapidly from -10ºC to the selected isothermal temperatures at 300ºC/min and holding the sample at this temperature. All the samples were then subjected to a dynamic scan from -10 to 300ºC at 10ºC/min to determine the residual heat of reaction. Fig. 3 shows the results from the isothermal scans.

As seen in Fig. 3, the heat was maximum at the beginning of the reaction, showing a non-autocalalytic behaviour. This means that the reaction speed and the heat liberated are maximum at the beginning of the process. Therefore curing should not be neglected in the simulation. The DSC experimental results were directly imported in the software CureKinetics [5]. With this tool it is possible to obtain the conversion curves and kinetic parameters in an easy and quick way.

Firstly, the results were fitted to a second order reaction:

$$\frac{d\alpha}{dt} = k_o \; e^{\frac{-E_a}{RT}} \left(1-\alpha\right)^2 \qquad (5)$$

with $k_o = 1.55\text{x}10^8 \text{min}^{-1}$ and $E_a = 62$ kJ/mol

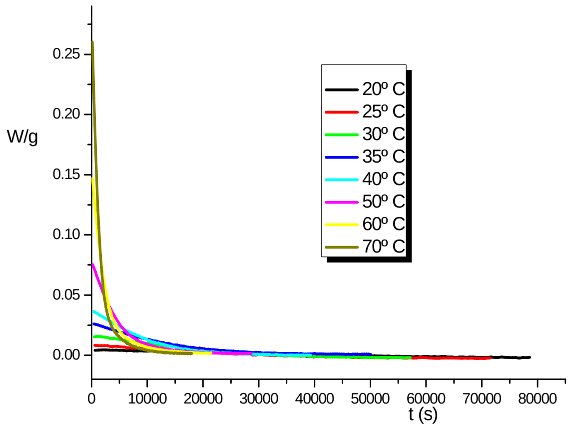


Fig 3. Isothermal DSC scans.

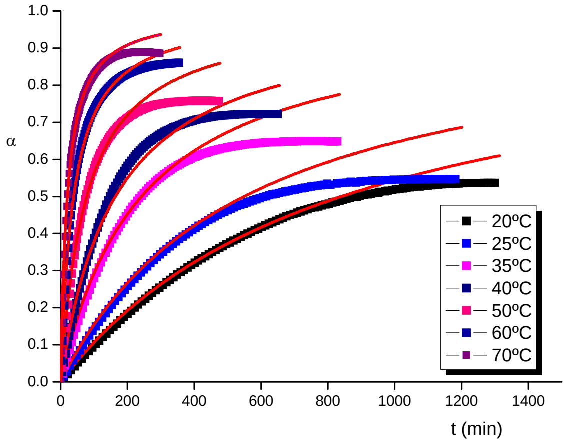


Fig 4. 2nd order fit of the conversion curves.

Fig. 4 shows the comparison between the conversion experimental results (dots) and the model (lines). Experimental data are well fitted until the reaction becomes controlled by diffusion.

Conversions at different temperatures were shifted along the logarithmic time axis to form a master curve in Fig. 5. A good overlay was obtained for conversions lower than 0.5. This means that an assumption on time-temperature superposition is correct and the reaction is kinetically controlled with single activation energy. The activation energy obtained by plotting the shift factor as a function of temperature gave an activation energy of 57 kJ/mol, which is equivalent to that obtained with CureKinetics.

In order to obtain an expression of the conversion dependent rate capable of fitting the entire conversion curve, a diffusion model was also included. The maximum conversion obtained at each temperature ($\alpha_{\max}$) was fitted to the following equation:

$$\alpha_{\max} = 1-(1-\alpha_{\min})\left[\frac{T_{g\infty}-T}{T_{g\infty}-A}\right]^{\beta} \qquad (6)$$

where $T_{g\infty}$ is the T_g at $\alpha = 1$, $\alpha_{\min}$ the conversion at the minimum temperature studied, and A and β are adjustable parameters. For the Prime 20LV resin, A = 275 and $\beta = 1.21$ (Fig. 6). Then, the model was modified, setting $d\alpha/dt = 0$ and $\alpha = \alpha_{\max}$ when $\alpha \geq \alpha_{\max}$ (Fig. 7).

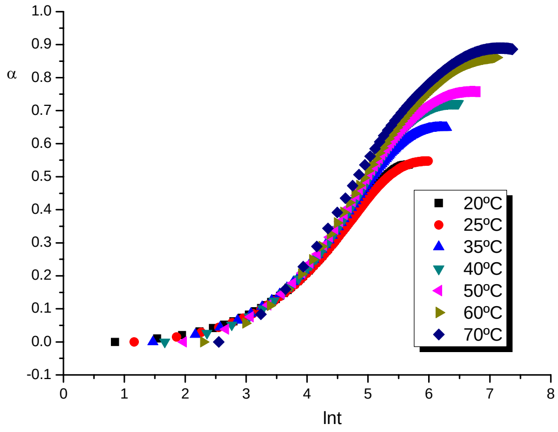


Fig. 5 Superposition of the conversion curves.

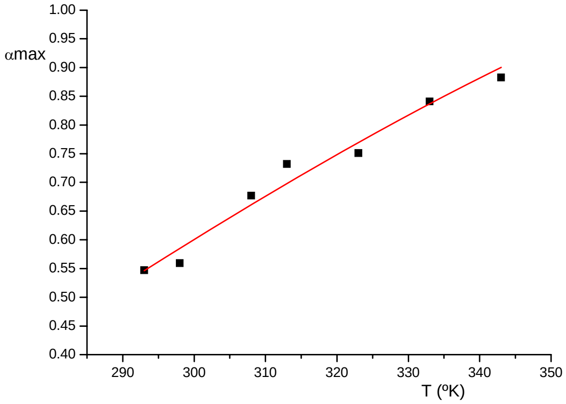
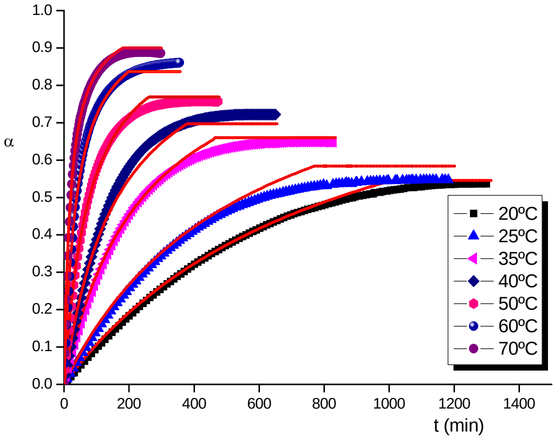


Fig. 6 Maximum degree of cure as a function of temperature.

$$\frac{d\alpha}{dt} = k\left(\alpha_{\max} - \alpha\right)^{n} \qquad (7)$$

Finally, $\alpha_{\max}$ was included in the equation (7). In this case, the results were better fitted to a first order equation (n = 1) with E_a = 41 kJ/mol. As seen in Fig. 8, the results where slightly worse during the first part of the reaction. Both α_{max} model and equation (7) gave a good fitting of the experimental results. However, the infusion takes place for degrees of conversion between 0 and 0.5 (before gelation). Therefore the α_{max} model was chosen to produce a better fit in this interval.



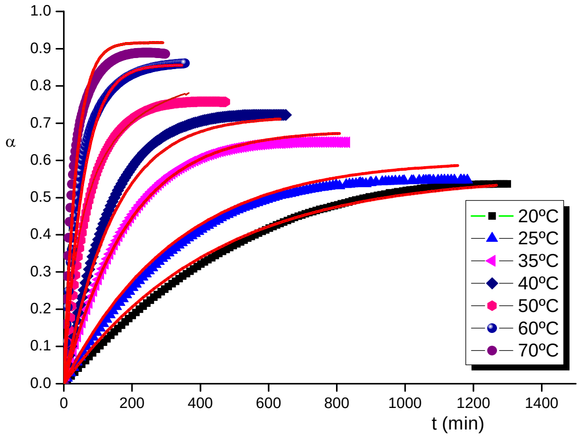
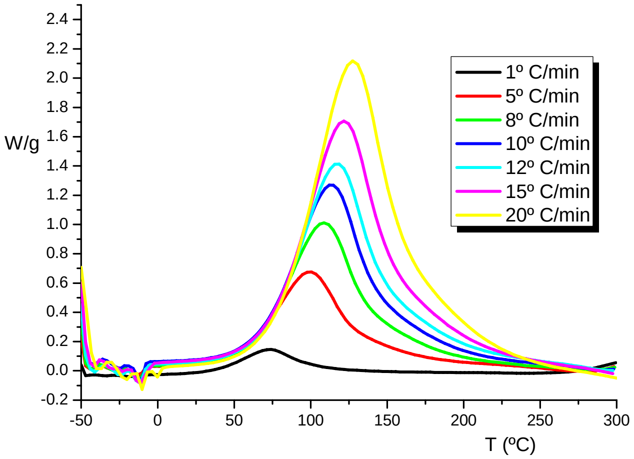


Fig. 7 Fit to $\alpha_{\max}$ model.

Fig. 8 Fit to equation 7.

Fig. 9 shows the dynamic DSC scans. The activation energy calculated with the heating rate and maximum peak temperature was 55 kJ/mol. This value is very similar to the activation energy obtained with the 2nd order kinetic equation and shift factor.



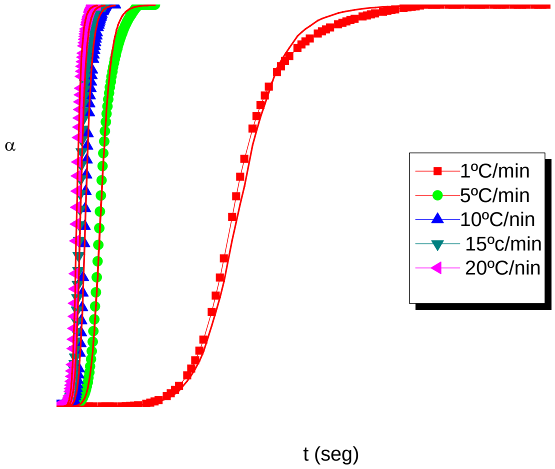


Fig. 9 Dynamic DSC scans.

Fig. 10 Fit to $\alpha_{\max}$ model.

Fig. 10 shows a comparison between the experimental dynamic conversion (dots) and the one predicted by the $\alpha_{\max}$ model (lines). A good fit was observed for all the heating rates studied showing that this model is capable of giving a good prediction for both the isothermal and dynamic cures.

CONCLUSION

The cure behaviour of a widely used epoxy system for wind turbine blades manufacturing was studied by Differential Scanning Calorimetry. A good fit was obtained between the experimental results and the models derived with CureKinetics. VARI modelling for wind blades manufacturing could be a powerful tool for reducing development costs. However, in order to carry out realistic numerical simulations, preform compaction, 3D flow analysis under non isothermal conditions should be taken into account. Knowing that modelling of resin kinetics is one of the first steps, CureKinetics software turned out to be a useful tool here.

ACKNOWLEDGMENTS

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