NUMERICAL TREATMENT OF THE EPOXY CURING USING FINITE ELEMENTS

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1. Introduction

The production of polymers on the basis of curing processes of epoxy resins is connected to exothermal reactions. The estimation of the resulting temperatures is necessary since too high temperatures degrade the material and deflagration is initiated. Furthermore, shrinkage is connected to this process, so that a final part is connected to residual stresses. Thus, a precise estimation of the temporal temperature evolution is of particular interest.

First, a curing model is required, where it turns out that the classical Kamal-Sourour model, see [4], is over-parameterized. Thus, a new model with less material parameters is proposed, see [6]. Second, curing- and temperature-dependent heat capacity and heat conductivity are considered as well. Finally, the curing model has to be connected to the heat equation to study the spatial and temporal evolution of both the temperature and the curing state, see, as examples for the numerical treatment using finite elements, [1, 3, 5, 7].

2. Numerical Treatment using Finite Elements

The curing evolution is defined by an ordinary differential equation (ODE). It turns out that these models have a region, where the ODE is inherently unstable, i.e. local small errors increase with time. Thus, high-order time integration schemes have to be applied to minimize the increase of temperature. Since we are not interested in a high-order scheme on Gauss-point level, we draw on the high-order diagonally implicit Runge-Kutta methods (DIRK), where the Backward-Euler method is embedded as a special case. These high-order methods are applied to the space-discretized heat equation and the curing variables, which have to be evaluated at the spatial integration points (Gauss-points). Moreover, time-adaptivity is provided (for free) and does not require more computational effort, see [8]. Fig. 1 shows a comparison of the temperature and curing evolution within one

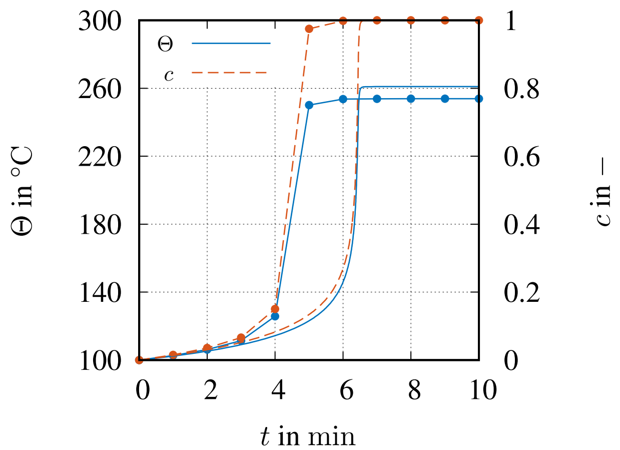

Figure 1: Stability investigation of the curing kinetics. Comparison of 10 time-steps using a Backward-Euler scheme and a time-adaptive, second order computation (dotted lines represent the Backward-Euler computations, whereas the undotted curves symbolize the time-adaptive computations).

element (adiabatic boundary conditions) of the Backward-Euler method with 10 time steps and a time-adaptive computation of Ellsiepen's method, see [2], which are applied to the heat equation and the curing equation.

A further misleading aspect is connected to the application of the non-linear solution scheme to solve the resulting coupled system of non-linear equations occurring after the time-discretization. It will be shown that the resulting space and time discretized coupled system is solved using the Multilevel-Newton algorithm (MLNA) proposed by [9] leading to the particular structure of solving on Gauss-point a non-linear equation to obtain within a global Newton-step the curing variable as well as the (consistent) tangent.

Finally, we apply the whole DIRK/MLNA concept to a validation example, where in an oil bath the temperature evolution of a curing epoxy resin is measured using thermographic measurements of the upper surface of a small cavity. These experiments are compared with the temperature evolution of the finite element computations.

3. Conclusions

On the basis of experimental data a new curing, heat capacity, and heat conductivity model is drawn on. This is implemented into a time-adaptive DIRK/MLNA finite element approach to compute the temperature evolution in a part, where it turns out that this is necessary due to the inherently instability of the curing ODE. The whole concept is compared to thermographic measurements of the temperature evolution of an cured epoxy resin.

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References

[1] C. Brauner, S. Bauer, and A. S. Herrmann. Analysing process-induced deformation and stresses using a simulated manufacturing process for composite multispar flaps. *Journal of Composite Materials*, 49(4):387–402, 2015.

[2] P. Ellsiepen and S. Hartmann. Remarks on the interpretation of current non-linear finite-element-analyses as differential-algebraic equations. *International Journal for Numerical Methods in Engineering*, 51:679–707, 2001.

[3] M. Hossain and P. Steinmann. Continuum Physics of Materials with Time-Dependent Properties: Reviewing the Case of Polymer Curing. *Advances in Applied Mechanics*, 48:141–259, 2015.

[4] M. R. Kamal. Thermoset characterization for moldability analysis. *Polymer Engineering & Science*, 14(3):231–239, 1974.

[5] R. Landgraf. *Modellierung und Simulation der Aushärtung polymerer Werkstoffe*. PhD thesis, Technische Universität Chemnitz, 2015.

[6] C. Leistner, S. Hartmann, D. Abliz, and G. Ziegmann. Modeling and simulation of the curing process of epoxy resins using finite elements. *submitted to Continuum Mechanics and Thermodynamics*, 2018.

[7] C. Liebl, M. Johlitz, B. Yagimli, and A. Lion. Three-dimensional chemo-thermomechanically coupled simulation of curing adhesives including viscoplasticity and chemical shrinkage. *Computational Mechanics*, 49(5):603–615, 2012.

[8] K. J. Quint, S. Hartmann, S. Rothe, N. Saba, and K. Steinhoff. Experimental validation of high-order time-integration for non-linear heat transfer problems. *Computational Mechanics*, 48:81–96, 2011.

[9] N. B. G. Rabbat, A. L. Sangiovanni-Vincentelli, and H. Y. Hsieh. A multilevel Newton algorithm with macromodeling and latency for the analysis of large-scale nonlinear circuits in the time domain. *IEEE Transactions on Circuits and Systems*, 26:733–740, 1979.